

Search for supersymmetry in the first
 $\sqrt{s} = 13$ TeV pp -collisions using the
 α_T variable with the CMS detector

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Abstract

An inclusive search for supersymmetry is performed in final states with jets and missing transverse energy, in the first pp -collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. The dimensionless kinematic variable, α_T , is employed to discriminate between events with genuine and misreconstructed missing energy, providing sensitivity to signatures with low hadronic activity. The data sample analysed corresponds to an integrated luminosity of 2.3 fb^{-1} collected by the CMS detector at the LHC in 2015. The search is categorised in total jet multiplicity, multiplicity of jets arising from b -quarks and the total hadronic energy. The results are interpreted in the context of squark and gluino pair produced simplified models.

In addition, a study of a new jet algorithm for the Level-1 calorimeter trigger upgrade to operate effectively in conditions exceeding the LHC design instantaneous luminosity is presented. The performance of the upgrade algorithm jet and energy sum triggers at high luminosity is evaluated and the effectiveness of several different pileup subtraction techniques compared.

Declaration

I declare that the work contained within this thesis is my own and that materials and results produced by others are appropriately referenced. Studies of upgrade jet algorithm described in Chapter 4 are a continuation of an existing algorithm [120] for which I independently researched. The analysis was performed in collaboration with the α_T group, for which my primary contribution were the design of the analysis trigger strategy Chapter 6, the estimation of the QCD background Section 7.2 and the commissioning of early data Section 7.3. Figures from CMS public preliminary and unpublished CMS documents are labelled “CMS Preliminary” and CMS publications are labelled “CMS”, in the case of experimental data, and “CMS Simulation” where the data is simulated, these include works produced by author.

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CHAPTER 1

Theory and Motivations

The theory of particle physics seeks to provide a description of the Universe at its most fundamental scale. The current best description is provided by the Standard Model (SM), a theory whose predictions have been verified experimentally to incredible precision. Limitations and discrepancies in the theory however motivate the search for more comprehensive physical theories, such as supersymmetry, to succeed the SM as a step towards a Theory of Everything (TOE).

In the following chapter an overview of the theoretical constituents of the SM and its underlying symmetry principles are summarised. Motivations for a new theory of physics are presented in Section 1.2, with an overview of the theory of supersymmetry presented in Section 1.3. The state of experimental supersymmetry searches are presented in Section 1.4, with a focus on hadronic searches. Throughout, the standard Einstein summation convention is utilised and natural units, $c = \hbar = 1$, are assumed.

1.1 The Standard Model

The SM of particle physics is the culmination of efforts to provide an understanding of the underlying structure of the Universe, the predictions of which have been experimentally verified to incredible precision. The development of the SM has been the result of a progressive refinement of ideas through experimental and theoretical breakthroughs which have been inextricably linked, with revolutions in one fuelling discoveries in the other. A summary of the events that led to the development of the theoretical framework of the SM are presented in the following, a more complete overview can be found in the literature [1, 2, 3].

In the early 20th century the Universe at the fundamental scale was explained by semi-classical quantum mechanical theories, with subatomic physics described by a single *electromagnetic force* and a total of three particles: the photon (γ), the electron (e), and the proton (p). With the advent of the theory of relativity [4] more complete relativistic quantum theories of particles were constructed, one of the notable results being the Dirac equation which posited the existence of a new form of matter known as *antimatter* [5].

These concepts were further evolved to form a quantum description of electromagnetic interactions, *Quantum Electrodynamics (QED)* [6, 7], and the Quantum Field Theory (QFT) formalism which became the theoretical basis upon which subsequent theories were built.

In the 1930s theoretical descriptions of the fundamental forces of nature were expanded to include a description of the *weak force*, responsible for radioactive decay, and the *strong force*, which binds the nucleus together, both of which led to the prediction of new particles. An apparent violation of the conservation of energy in beta decay led Pauli to postulate the existence of a new neutral particle, the neutrino (ν), which was incorporated by Fermi in his theory of the weak interaction [8], as was the mediator of the strong force, the pion (π), which was proposed by Yukawa in 1935 [9].

At this time experimental measurements were predominantly a study of cosmic rays, high energy particles of extra-terrestrial origin, which were detected with the use of cloud chambers and photographic emulsions. Through a study of these rays by Anderson in 1932, Dirac's prediction of antimatter was validated with the discovery of the antimatter partner of the electron, the positron [10]. In 1937 however there was an upset with the discovery of the muon (μ) [11], a particle not predicted by any theory, to which Rabi famously remarked: "Who ordered that?". What followed was a period of experimental discovery that outpaced theory, uncovering a plethora of new and unexplained subatomic particles, leading Fermi to quip to a student: "Young man, if I could remember the names of these particles, I would have been a botanist". The fundamental theory required a new revolution.

Working on the classification of these new particles, Gell-Mann noticed that they could be arranged in a structured group formalism which he presented in 1961 in his 'eightfold way' [12]. From this structure, Gell-Mann was able to successfully predict the existence and mass of a missing particle, the Ω^- , which was subsequently discovered in 1964 [13]. It was in this year that the underlying cause of this structure was explained, subatomic particles were composite particles composed of fundamental constituents known as *quarks* [14]. These quarks could exist in three flavours: up (u), down (d) and strange (s); and could exist only in bound states as either mesons: quark-antiquark doublets ($q\bar{q}$), or baryons: quark/antiquark triplets ($qqq/\bar{q}\bar{q}\bar{q}$).

The new quark theory was however not without problems, the existence of the Ω^- whose quark composition of sss with collinear spins appeared to violate the Pauli exclusion

principle. Han and Nambu provided a resolution with the introduction of new colour quantum numbers associated with the strong interaction [15], which were formulated into a colour QFT known as *Quantum Chromodynamics (QCD)*, with the gluon (g) as the force mediator. Additionally, the failure of the theory to explain the absence of Flavour Changing Neutral Currents (FCNCs) decays and CP violation in the decay of Kaons [16] were resolved by the introduction of new quarks: the charm quark (c), which through the GIM mechanism suppressed FCNCs [17], and the bottom (b) and top (t) quarks, which provided a mechanism for CP violation in weak interactions [18].

In the 1960s, with the addition of a unified theory of the electroweak force and electroweak symmetry breaking, the SM of particle physics was established [19, 20, 21]. This predicted the existence of the massive vector bosons: W and Z , the mediators of the weak force and a massive Higgs boson, h^0 . It was however not until the 1970s, with the advent of GeV-scale colliders and a revolution in electronic detector technology that provided improvements in the frequency, precision and selection of data, that experimental measurements caught up with theory. Following this predictions of the SM were verified, with the discoveries of the τ lepton at SPEAR [22], the charm and bottom quarks in the J/ψ [23, 24] and Υ [25] bound states respectively, the gluon at DESY [26, 27] and the W and Z bosons at LEP [28, 29]. The final pieces of the SM were verified with the access to TeV scale colliders, with the discovery of the top quark at the Tevatron in 1995 [30] and the Higgs boson at the Large Hadron Collider (LHC) in 2012 [31, 32].

1.1.1 Forces and fermions

The SM is an $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory which provides the current best description of the fundamental constituents of matter and the forces that act between them as summarised in Table 1.1. Within the SM all known matter in the Universe is comprised of spin- $\frac{1}{2}$ fermions categorised into two species: *quarks* and *leptons*. In total there are six quarks, three of up-type: up (u), charm (c) and top (t); and three of down-type: down (d), strange (s) and bottom (b). In addition there are six leptons, three are charged leptons: electron (e), muon (μ), tau (τ); and three are neutrinos: electron neutrino (ν_e), muon neutrino (ν_μ) and tau neutrino (ν_τ). In addition, each of the fermions have associated anti-particles which are charge conjugates of their particle counterparts.

Categories	Particles	Mass	Spin	Colour charge (C)	Electric charge (Q)	Weak isospin (T^3)
Quarks (Up-type)	u	$m_u = 2.3^{+0.7}_{-0.5} \text{ MeV}$ [33]	$\frac{1}{2}$	r, g, b	$+\frac{2}{3}$	$+\frac{1}{2}$
	c	$m_c = 1.275 \pm 0.025 \text{ GeV}$ [33]				
	t	$m_t = 173.21 \pm 0.51 \pm 0.71 \text{ GeV}$ [33]				
Quarks (Down-type)	d	$m_d = 4.8^{+0.5}_{-0.3} \text{ MeV}$ [33]	$\frac{1}{2}$	r, g, b	$-\frac{1}{3}$	$-\frac{1}{2}$
	s	$m_s = 95 \pm 5 \text{ MeV}$ [33]				
	b	$m_b = 4.18 \pm 0.03 \text{ GeV}$ [33]				
Charged leptons	e	$m_e = 0.5110 \pm 1.1 \times 10^{-8} \text{ MeV}$ [33]	$\frac{1}{2}$	0	-1	$-\frac{1}{2}$
	μ	$m_\mu = 105.7 \pm 3.5 \times 10^{-6} \text{ MeV}$ [33]				
	τ	$m_\tau = 1776.86 \pm 0.12 \text{ MeV}$ [33]				
Neutrinos	ν_e	$m_{\nu_e} < 225 \text{ eV}$ [33]	$\frac{1}{2}$	0	0	$+\frac{1}{2}$
	ν_μ	$m_{\nu_\mu} < 0.19 \text{ MeV}$ [33]				
	ν_τ	$m_{\nu_\tau} < 18.2 \text{ MeV}$ [33]				
Gluon	g	$m_g = 0$ (Theoretical)	1	$r\bar{g}, r\bar{b}, g\bar{r}, g\bar{b}, b\bar{r}, b\bar{g}, \frac{1}{\sqrt{2}}(r\bar{r} - g\bar{g}), \frac{1}{\sqrt{6}}(r\bar{r} + g\bar{g} - 2b\bar{b})$	0	0
Photon	γ	$m_\gamma = 0$ (Theoretical)	1	0	0	0
Charged weak bosons	$W^\pm$	$m_W = 80.385 \pm 0.015 \text{ GeV}$ [33]	1	0	± 1	± 1
Neutral weak boson	Z^0	$m_Z = 91.1876 \pm 0.0021 \text{ GeV}$ [33]	1	0	0	0
Higgs boson	h^0	$m_H = 125.09 \pm 0.21 \pm 0.11 \text{ GeV}$ [34]	0	0	0	$-\frac{1}{2}$

Table 1.1: A summary of the particles of the SM including their measured masses and quantum numbers. The value of weak isospin refer to the left-handed states only and the masses of gluon and photon are their theoretical values.

The interactions between these particles are mediated by three fundamental forces: the *electromagnetic force*, *strong force* and the *weak force*; which are each formulated as a QFT.

The strong force is described by the $SU(3)_C$ gauge theory QCD, which provides a description of the interaction between the quark fields, which possess colour charge $C = (r, b, g)$, with eight massless gluon gauge fields. The messenger particle of strong force, the gluon (g), possesses a colour and anti-colour charge. Although massless, the non-Abelian nature of the gauge theory leads to gluon self-couplings, which results in the strong force having a short range. These self-couplings additionally modify the strong coupling constant, α_s , which grows larger with decreasing energy of the interaction, an effect known as asymptotic freedom [35] which leads to non-perturbative QCD calculations.

An additional consequence of the coloured nature of quarks is that they are confined to colour-singlet states, known as *hadrons*, as either: *mesons*, quark-antiquark bound states $q\bar{q}$, or as *baryons* in a triple-quark or triple-antiquark bound state $qqq/\bar{q}\bar{q}\bar{q}$. The energy required to liberate the coloured quarks and gluons from their bound states is sufficiently high to produce quark-antiquark pairs from the vacuum in a process known as *hadronisation*. As a result of confinement, in high-energy collisions of hadrons the liberation of quarks and gluons from hadrons results in a collimated emission of hadrons from fragmentation and hadronisation known as *jets*.

The remaining electromagnetic and weak forces are responsible for interactions between particles with electric charge, Q , and weak isospin, T^3 , respectively. These forces are mediated by four vector bosons: the photon (γ) which is responsible for the electromagnetic force and the weak vector $W^\pm$ and Z^0 bosons which mediate the weak force. Although apparently distinct, the electromagnetic and weak forces are inextricably linked and are unified to the *electroweak* theory, a non-Abelian gauge theory of the group $SU(2)_L \times U(1)_Y$. The spontaneous breaking of the electroweak symmetry results in a massive scalar Higgs boson, h^0 , which is described in Section 1.1.3.

A mixing of the three weak isospin $SU(2)_L$ gauge fields, W_μ^i ($i = 1, 2, 3$), and the weak hypercharge $U(1)_Y$ gauge field, B_μ , produce the $W_\mu^\pm$, Z_μ and A_μ gauge fields of the $W^\pm$,

Z^0 and γ respectively:

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}} (W_\mu^1 \mp W_\mu^2) \\ Z_\mu &= \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu \\ A_\mu &= \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu. \end{aligned} \tag{1.1}$$

Where θ_W is the Weinberg angle, which is given by the ratio of the coupling strengths of the weak isospin gauge field, g , and weak hypercharge gauge field, g' , by the relation:

$$\theta_W = \frac{g}{\sqrt{g^2 + g'^2}}. \tag{1.2}$$

Unlike the photon and Z boson of electroweak theory, which are agnostic to the chirality of particle states, the W gauge bosons only couple to left-handed states. The fermions in the SM that are left-handed form weak isospin quark and lepton doublets, Q_L and e_L , comprised of up and down type quarks and charged leptons and neutrinos respectively. The right-handed fermions form weak isospin singlets, Q_R and e_R , with $T^3 = 0$, excluding the neutrinos which are massless in the theory:

$$\begin{aligned} Q_L &= \begin{pmatrix} u \\ d \end{pmatrix}_L, & Q_R &= u_R, d_R \\ e_L &= \begin{pmatrix} e \\ \nu_e \end{pmatrix}_L, & e_R &= e_R. \end{aligned} \tag{1.3}$$

Charged-current interactions of the W boson act between up and down type particles in the doublet. The mass basis of the quarks however is not the same as its weak interaction basis, resulting in a mixing between the flavour states in charged current interactions which is governed by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [36].

1.1.2 Symmetries and gauge invariance

An underlying principle in many theories in physics is the concept of a symmetry, structures of a theory for which physical observables remain unchanged under specific transformations. By Noether's theorem [37] continuous symmetries of a theory are shown to corresponding conserved quantity, for instance time invariance corresponds to a conservation of energy. Field theories whose theoretical observables are invariant under a transformation of its fields are known as gauge theories and their fields as gauge fields. An important

property of gauge theories are that they are renormalisable, providing finite predictions of probability for all times, making the invariance under gauge transforms important in their construction.

To demonstrate the power of this approach, consider a free theory of Fermion fields, ψ , which in the Lagrangian formulation is given by:

$$\mathcal{L}_{\text{Dirac}} = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\psi\bar{\psi}. \quad (1.4)$$

Where γ^μ are the gamma matrices, ∂_μ is the 4-gradient and m is a constant related to the mass of field. Under the application of a local phase transformation of the fields:

$$\psi(x) \rightarrow \psi'(x) = e^{i\alpha(x)}\psi(x). \quad (1.5)$$

The Dirac Lagrangian under this transformation is shown to not be invariant:

$$\begin{aligned} \mathcal{L}_{\text{Dirac}} \rightarrow \mathcal{L}'_{\text{Dirac}} &= i\bar{\psi}'\gamma^\mu\partial_\mu\psi' - m\psi'\bar{\psi}' \\ &= i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\psi\bar{\psi} + \bar{\psi}\gamma^\mu\psi\partial_\mu\alpha \\ &= \mathcal{L}_{\text{Dirac}} + \bar{\psi}\gamma^\mu\psi\partial_\mu\alpha. \end{aligned} \quad (1.6)$$

In order to provide a theory that is invariant under local gauge transformations the derivative term, $\partial_\mu\psi$, which breaks the gauge invariance, is substituted for a gauge invariant derivative known as the covariant derivative:

$$D_\mu = \partial_\mu - ieA_\mu, \quad (1.7)$$

where e is a coupling constant and A_μ is a new vector field which transforms as:

$$A_\mu \rightarrow A_\mu + \frac{1}{e}\partial_\mu\alpha. \quad (1.8)$$

Substituting the gauge-violating terms leads to the gauge invariant Lagrangian of QED:

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(i\gamma^\mu\partial_\mu - m)\psi + e\bar{\psi}\gamma^\mu A_\mu\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (1.9)$$

where $F_{\mu\nu}$ is the gauge invariant electromagnetic field strength tensor given by:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \quad (1.10)$$

By requiring that the free Dirac Lagrangian be symmetric under a local gauge trans-

formation a new gauge field, A_μ , is introduced with interaction terms with the Dirac field. In addition, the terms in the Lagrangian that are quadratic in the field, known as *mass terms*, are gauge violating when non-zero, requiring that particles in the theory are massless. Physically this is interpreted as a coupling of fermions to a photon field which, to maintain gauge invariance, is required to be massless in the theory. It can be seen that the application of symmetry principles to a theory is incredibly powerful, transforming a simple non-interacting theory of fermions into a theory of electromagnetism with the requirement of a massless photon. The application of symmetry principles is also effective in producing a renormalisable theory of the strong and weak interactions. The gauge violating mass terms however lead to the prediction of massless weak vector bosons and fermions, a clear discrepancy with experimental measurement. This, in combination with predictions of non-unitarity in the WW -scattering cross section, are problems which were resolved by the principle of spontaneous symmetry breaking.

1.1.3 The Higgs mechanism

Providing mass terms to the weak gauge bosons and fermions in a gauge invariant way was resolved by the combined works of: Brout and Englert [38], Higgs [39], Guralnik, Kibble and Hagen [40]. Through the spontaneous breaking of the electroweak symmetry, known as the *Higgs mechanism*, they demonstrated a gauge invariant method of generating the masses of the weak vector bosons which left the photon massless.

The action of the spontaneous symmetry breaking can be demonstrated by considering the Lagrangian of an $SU(2)$ theory of complex scalar fields:

$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2. \quad (1.11)$$

Where ϕ is a doublet of the complex scalar fields: ϕ_+ and ϕ_0 , with a total of four degrees of freedom:

$$\phi = \begin{pmatrix} \phi_+ \\ \phi_0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (1.12)$$

Considering a local $SU(2)$ gauge transformation, $\alpha_a(x)$ ($a = 1, 2, 3$), in the limit of an infinitesimal rotation we obtain:

$$\begin{aligned} \phi(x) &\rightarrow \phi'(x) = e^{\frac{1}{2}i\alpha_a(x)\tau_a} \phi(x) \\ &\sim \left(I_2 + i\alpha_a(x) \cdot \frac{\tau_a}{2} \right) \phi(x), \end{aligned} \quad (1.13)$$

where I_2 is the 2×2 identity matrix and τ_a are the generators of the SU(2) group.

For the Lagrangian to be invariant under SU(2) rotations, the derivatives of the Lagrangian are replaced by their covariant counterparts:

$$D_\mu = \partial_\mu - ig \frac{\tau_a}{2} W_\mu^a. \quad (1.14)$$

Where W_μ^a are gauge fields which transform under SU(2) as:

$$W_\mu^a \rightarrow W_\mu^a - \frac{1}{g} \partial_\mu \alpha^a - \alpha^a \times W_\mu^a. \quad (1.15)$$

Modifying the Lagrangian of Equation 1.11 we obtain the gauge invariant Lagrangian:

$$\mathcal{L} = \left(\partial_\mu \phi + \frac{1}{g} \tau^a \cdot W_\mu^a \phi \right)^\dagger \left(\partial^\mu \phi + \frac{1}{g} \tau^a \cdot W^{a\mu} \phi \right) - V(\phi) - \frac{1}{4} W_{\mu\nu}^a \cdot W^{a\mu\nu}. \quad (1.16)$$

Where the final term is the kinetic term for the gauge fields which is given by:

$$W_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a - g W_\mu^a \times W_\nu^a \quad (1.17)$$

and the penultimate term is the potential of the field given by:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2. \quad (1.18)$$

It can be seen that the behaviour of theory is dependent on the choice of the parameters: λ and μ . Considering a theory with $\lambda > 0$, the shape of the potential takes a different form dependent on the choice of μ^2 , as illustrated in Figure 1.1. For $\mu^2 > 0$, the potential takes a parabolic form with a central minima, corresponding to a vacuum state that is symmetric under SU(2) transformations. In this case the Lagrangian is interpreted as a theory of seven particles, four scalar particles: ϕ_1, ϕ_2, ϕ_3 and ϕ_4 ; with mass, μ , which couple to the three massless gauge bosons: W_μ^1, W_μ^2 and W_μ^3 .

Considering the case with $\mu^2 < 0$, the potential takes the topology of a ‘Mexican hat’ with a central unstable local maximum surrounded by global minima. The vacuum states in this case acquire a non-zero value, satisfying the relation:

$$\phi^\dagger \phi = \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 = -\frac{\mu^2}{2\lambda}. \quad (1.19)$$

Without loss of generality, we can select a specific point in the minima for $\phi_1 = \phi_2 = \phi_4 = 0$,

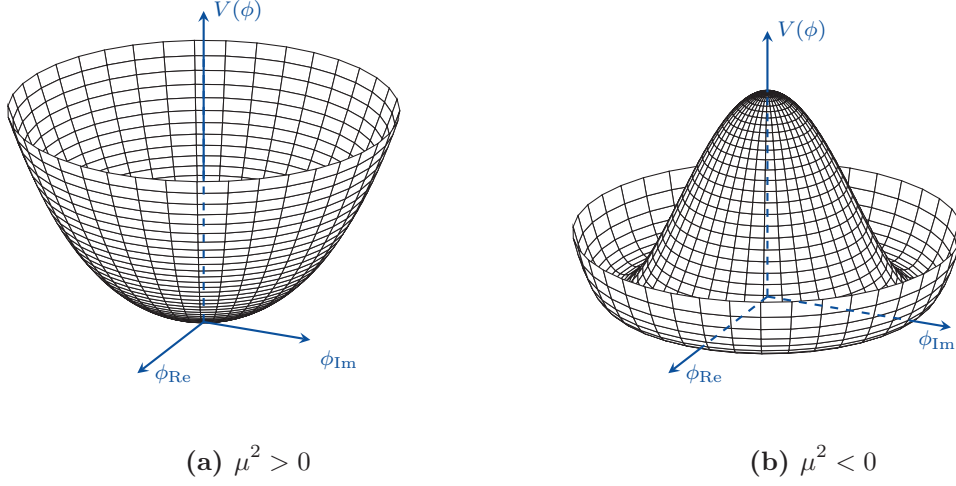


Figure 1.1: Shape of the Higgs potential for $\lambda > 0$ as a function of the real and imaginary components of the complex field ϕ with $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right).

to evaluate the vacuum expectation value of ϕ , $v = \phi^\dagger \phi$:

$$\begin{aligned} \phi^\dagger \phi &= \phi_3^2 \\ &= -\frac{\mu^2}{2\lambda}. \end{aligned} \tag{1.20}$$

From gauge invariance this particular solution for $\mu^2 < 0$ can be applied to Equation 1.12 to obtain a new general form:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \tag{1.21}$$

It can be seen in Equation 1.21 that the initial four scalar fields of Equation 1.12 are reduced to a single scalar field, h , the scalar Higgs field, with the remaining three scalar fields becoming entangled in the gauge fields. Substituting the field into the Lagrangian Equation 1.11, the mass terms of the gauge field become:

$$\frac{g^2 v^2}{g} \left[(W_\mu^1)^2 + (W_\mu^2)^2 + (W_\mu^3)^2 \right]. \tag{1.22}$$

As can be seen, through the spontaneous breaking of the symmetry the gauge bosons have acquired mass, without violating the gauge invariance of the theory.

In the SM this spontaneous breaking of electroweak symmetry occurs when the tem-

perature of the Universe falls below a critical temperature, resulting in the generation of masses of the weak vector bosons, whilst leaving the photon massless:

$$\begin{aligned} M_W &= \frac{1}{2}vg \\ M_Z &= \frac{1}{2} \frac{vg}{\cos \theta_W} \\ M_\gamma &= 0. \end{aligned} \tag{1.23}$$

In addition, there is a massive scalar Higgs boson with a mass given by the relation:

$$M_h = \sqrt{2v^2\lambda}, \tag{1.24}$$

where v is the Higgs vacuum expectation value, which is computed in the theory to have a value: $v = 246 \text{ GeV}$. The value of the coupling λ however is not predicted by the theory and must be measured experimentally. The masses of the fermions are acquired via Yukawa couplings with the Higgs field, where the magnitude of the mass is related to the strength of particle's coupling to the field.

1.2 Beyond the Standard Model

Although incredibly successful, the SM is known to only be a low-energy effective field theory valid below an energy scale Λ . There are several outstanding issues in the SM which can only be resolved by a Beyond the Standard Model (BSM) theory that provides a valid description of the Universe at higher energy scales.

One such discrepancy in the SM is the choice of massless neutrinos and hence the conservation of lepton number in weak interactions. The experimental discovery of neutrino flavour oscillations in measurements of the fluxes of atmospheric [41] and solar neutrinos [42] however require a non-zero neutrino mass, conflicting with the massless neutrino hypothesis. A resolution to this problem is however possible within the SM framework, with the addition of seven new parameters: three neutrino masses, three mixing angles and a CP-violating phase. This is encoded in the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [43], which describes the mixing between neutrino mass and flavour eigenstates. Although this problem is reconcilable, there are several outstanding problems in physics for which the SM cannot provide a resolution. These include issues of naturalness within the SM, outstanding problems in cosmology and the development of a Grand Unified Theory (GUT) of physics.

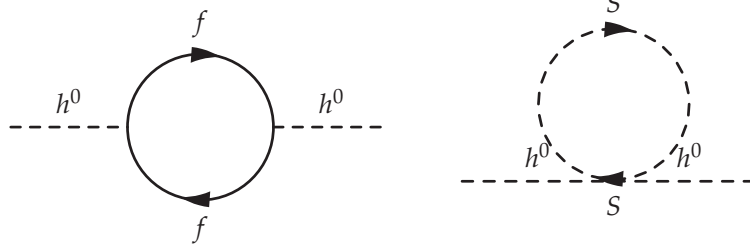


Figure 1.2: First-order correction to the mass of the Higgs boson from fermion, f , (left) and scalar, s , (right) loops.

One hint of the potential of new physics arises from the problem of naturalness within the SM as a result of a light Higgs boson, which is known as the *hierarchy problem*. The observable mass of the Higgs boson is given by its bare mass, m_H^{bare} , with additional mass corrections from fermion and scalar loops, as shown in Figure 1.2, which are of the form:

$$m_H = m_H^{bare} + \Delta m_H. \quad (1.25)$$

The loop correction to the Higgs mass, Δm_H , is approximately given by the relation:

$$\Delta m_H^2 \sim \frac{\Lambda^2}{8\pi^2} (\lambda_s - |\lambda_f|^2), \quad (1.26)$$

where Λ is the cutoff scale of the theory and the coupling strength to the Higgs field from the fermion and scalar fields are given by λ_f and λ_s respectively. Although the true value of the cutoff scale Λ is unknown, this must occur by the Planck scale, $\Lambda_{Planck} \sim 10^{19}$ GeV, when the effects of gravity become important. In order for the theory to maintain the light Higgs mass observed experimentally with a Planck scale cutoff, $\Lambda \sim \Lambda_{Planck}$, there must be a perfect cancellation of the Higgs bare and corrected masses to a precision of 36 orders of magnitude. Although this is not physically forbidden, the high degree of fine tuning to maintain a light Higgs is seen as unpalatable to some and indicative of some other underlying physical effect that regulates the Higgs mass.

Further shortcomings of the SM are its failure to provide resolutions to several outstanding problems in cosmology. Cosmological studies of: the rotation speed of galaxies [44, 45], gravitational lensing [46] and underlying structure in the distribution of galaxies [47] and the Cosmic Microwave Background (CMB) [48, 49], indicate that the majority of the mass content of the Universe is not Baryonic but rather composed of

weakly-interacting matter, known as Dark matter (DM), for which there is no viable candidate particle within the SM. In addition, the observed asymmetry in the matter-antimatter composition of the Universe exceeds what can be explained by known CP-violating processes within the SM.

There are additional problems in the description of a unified theory of the fundamental forces. The SM was successful in the unification of the electromagnetic and weak forces however it fails to provide a unified theory incorporating the strong and gravitational forces. An extrapolation of the coupling constants of the forces in the SM however fail to unify at high energy scales. Additionally, the SM fails to provide a quantum theory of gravity, which remains one of the outstanding problems in modern physics.

There are many BSM theories that can provide resolutions to the problems within the SM through the introduction of new particles and forces, of these Supersymmetry (SUSY) is a particularly well motivated extension to the SM, providing possible resolutions to many problems that exist in the SM including: the hierarchy problem, a unification of the force coupling constants and candidates for DM [50, 51].

1.3 Supersymmetry

Utilising the only remaining extension to the Poincaré symmetry group, SUSY postulates a new space-time symmetry between bosons, b , and fermions, f . Through translations in superspace with the operator Q , particles can be transformed between fermionic and bosonic states:

$$\begin{aligned} Q|f\rangle &= |b\rangle \\ Q|b\rangle &= |f\rangle . \end{aligned} \tag{1.27}$$

As a consequence of this new symmetry, SUSY predicts the existence of new supersymmetric ‘superpartners’ of the known SM particles, that possess identical quantum numbers except for a spin- $\frac{1}{2}$ difference. As these predicted superpartners have not yet been observed, if SUSY is a true description of the Universe it must be a broken symmetry, with the masses of the superpartners exceeding those of their SM counterparts. The method by which this symmetry breaking occurs however is not predicted by the theory, leading to a plethora of potential supersymmetric models described by many parameters, one of the most popular being the Minimal Supersymmetric Standard Model (MSSM).

1.3.1 The Minimal Supersymmetric Standard Model

The MSSM [52] is a minimal extension of the SM model that incorporates supersymmetry. This however is not a simple extension, with the original 19 parameters of the SM ballooning with the addition of 105 parameters. Additionally the particle content is greatly increased, with the introduction of a plethora of new particles which are summarised in Table 1.2.

In the MSSM for each of the SM fermions, f , there is a corresponding left-handed, $\tilde{f}_L$, and right-handed, $\tilde{q}_R$, scalar superpartner which share the name of their SM counterpart prefixed by ‘s’. For the third generation squarks there is a mixing of the gauge eigenstates to form the $\tilde{b}_1$, $\tilde{b}_2$ and $\tilde{t}_1$, $\tilde{t}_2$ mass eigenstates. Similarly the spin-1 gauge bosons have spin- $\frac{1}{2}$ superpartners, denoted by their SM name with the suffix ‘-ino’, such as the superpartner of gluon which is known as the *gluino*, $\tilde{g}$. The electroweak gauge fields: W^+ , W^- , W^0 and B^0 ; have associated gaugino superpartners: the *winos*: $\tilde{W}^+$, $\tilde{W}^-$ and $\tilde{W}^0$; and the *bino*, $\tilde{B}^0$. Identically to their SM counterparts, after electroweak symmetry breaking the $\tilde{W}^0$ and the $\tilde{B}^0$ gaugino eigenstates mix to form the *zino*, $\tilde{Z}^0$, and the *photino*, $\tilde{\gamma}$, mass eigenstates. In the Higgs sector there are two Higgs doublets: $H_u = (H_u^+, H_u^0)$ with weak hypercharge $Y = +1/2$ which gives masses to the up-type quarks and $H_d = (H_d^0, H_d^-)$ with weak hypercharge $Y = -1/2$ which gives masses to the down-type quarks and the charged leptons.

The gauge eigenstates of the Higgs and electroweak superfields of the theory mix to form observable mass eigenstates known as *charginos* and *neutralinos*, in addition to new Higgs bosons. The chargino mass eigenstates, $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$, are composed of linear combinations of the charged higgsino and wino eigenstates: $\tilde{H}_u^+$, $\tilde{H}_d^-$ and $\tilde{W}^\pm$ respectively. Similarly, the neutralino mass eigenstates: $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$ and $\tilde{\chi}_4^0$; comprise of linear combinations of the gauge eigenstates of the neutral bino, wino and higgsinos: $\tilde{B}$, $\tilde{W}$, $\tilde{H}_u^0$ and $\tilde{H}_d^0$. Finally there is a mixing of the higgsinos: $\tilde{H}_u^+$, $\tilde{H}_u^0$, $\tilde{H}_d^0$ and $\tilde{H}_d^-$; to form five Higgs boson mass eigenstates, the light Higgs of the SM, h^0 , in addition to two neutral and two charged Higgs bosons: H^0 , A^0 and $H^\pm$.

In contrast to the SM, where the total baryon and lepton number are conserved, within supersymmetric models baryon and lepton violating terms are not explicitly forbidden. If present such terms would theoretically allow baryon violating processes, such as proton decay, which have experimentally been excluded [53]. In order to remove these violating

Names	Sparticle	Spin
Squarks (Up-type)	$\tilde{u}_L, \tilde{u}_R, \tilde{c}_L, \tilde{c}_R, \tilde{t}_1, \tilde{t}_2$	0
Squarks (Down-type)	$\tilde{d}_L, \tilde{d}_R, \tilde{s}_L, \tilde{s}_R, \tilde{b}_1, \tilde{b}_2$	0
Charged sleptons	$\tilde{e}_L, \tilde{e}_R, \tilde{\mu}_L, \tilde{\mu}_R, \tilde{\tau}_L, \tilde{\tau}_R$	0
Sneutrinos	$\tilde{\nu}_{eL}, \tilde{\nu}_{eR}, \tilde{\nu}_{\mu L}, \tilde{\nu}_{\mu R}, \tilde{\nu}_{\tau L}, \tilde{\nu}_{\tau R}$	0
Gluino	$\tilde{g}$	$\frac{1}{2}$
Neutralinos	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$	$\frac{1}{2}$
Charginos	$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$	$\frac{1}{2}$
Higgs bosons	$h^0, H^0, A^0, H^\pm$	0

Table 1.2: Summary of the particles within the MSSM and their associated spins.

terms the MSSM introduces a symmetry of the R -parity multiplicative quantum number, $R \equiv (-1)^{3(B-L)+2s}$, where B , L and s are the baryon number, lepton number and spin of the particle respectively. In addition to resolving the issue of baryon and lepton violating processes within the MSSM, the conservation of R-parity has consequences to the production and decay of sparticles. As supersymmetric particles possess $R = -1$ and SM particles $R = +1$, R-parity conservation enforces that supersymmetric particles be produced and decay in even sparticle and antiparticle numbers and ensures that the Lightest Supersymmetric Particle (LSP) is stable.

1.3.2 Resolutions to problems in the Standard Model

The aforementioned stability of the LSP in R -parity conserving models with a neutral and weakly interacting LSP, such as the neutralino, provide a natural candidate for DM which is not present in the SM. The addition of the superpartners to the SM particles in the MSSM provides a resolution to several other outstanding problems within the SM.

The issue of fine-tuning to maintain a light Higgs mass can be naturally explained within the MSSM by the introduction of scalar superpartners. As the loop contributions to the Higgs mass are opposite for fermions and scalars, the scalar superpartners act to cancel the loop contributions from their SM counterparts. This modifies the behaviour of the mass correction from the quadratic divergence observed in Equation 1.26 to a logarithmic divergence dependent on m_{soft} , the mass scale of the superpartners:

$$\Delta m_H^2 \propto m_{\text{soft}}^2 \ln \left(\frac{\Lambda}{m_{\text{soft}}} \right). \quad (1.28)$$

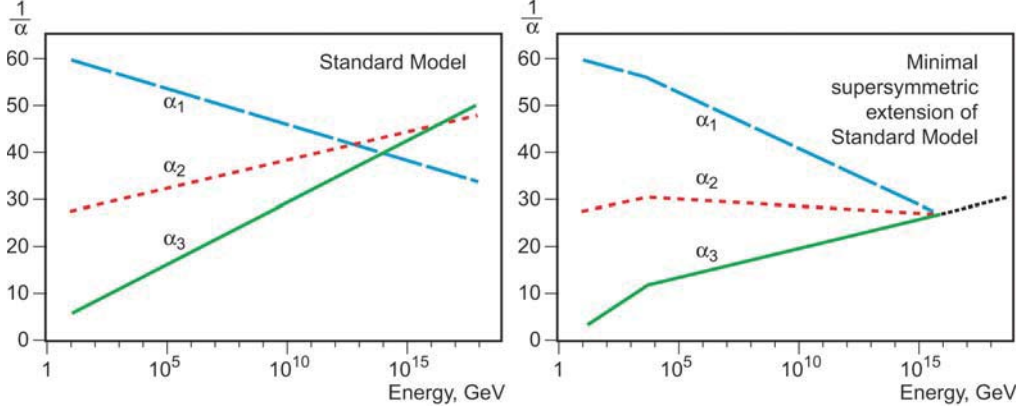


Figure 1.3: Evolution of the inverse of the coupling constants with energy for the electroweak U(1) (α_1), electroweak SU(2) (α_2) and strong (α_3) forces for the SM (left) and the MSSM (right) [55].

A natural resolution to the problem of fine-tuning within the SM however enforces that the masses of the superpartners be approximately of the energy scale $\mathcal{O}(1 \text{ TeV})$ to maintain cancellations with top loop corrections.

The addition of new supersymmetric particles also provide a resolution to problems in the theoretical predictions within the SM. One of the largest divergences between theoretical prediction and experimental measurement within the SM is the magnitude of the anomalous magnetic moment of the muon, $g_\mu - 2$. A crowning achievement of the SM was precise prediction of the value of the anomalous magnetic moment of the electron, with an agreement to ten significant figures making it the best tested theory in physics. The corresponding predicted value for the muon however is divergent from experimental measurements [54]. The cause of this divergence can be explained from a modification of $g_\mu - 2$ by loop corrections of new particles, such as those in supersymmetric theories. These new particles would also provide additional CP-violating processes that could resolve the observed matter-antimatter asymmetry.

These new superpartners could also resolve problems in unification within the SM. Shown in Figure 1.3 the force gauge couplings at high energy scales fail to unify within the SM. The loop corrections from new particles in supersymmetric theories can act to unify the coupling at a mass scale of $\lambda \sim 2 \times 10^{16} \text{ GeV}$. This apparent unification of the strong force at high energy hints at the possibility of an extension to a unification of gravity in a TOE such as, string theory [56], for which SUSY is a prerequisite.

1.4 Searches for supersymmetry

There are many signatures of supersymmetry, which are typically categorised by the visible products in the final state. Hadronic searches, which are characterised by a high multiplicity of jets, are particularly challenging searches to perform at hadron colliders, where the signature of jets can be difficult to distinguish from QCD processes. Although searches with other final states, such as leptons and photons, can provide very clean signatures, the larger branching fraction of W bosons to hadrons and the strong interaction of sparticles make hadronic searches very sensitive for a range of SUSY models.

This thesis focuses on SUSY searches in fully hadronic final states with the Compact Muon Solenoid (CMS) experiment at the LHC. In the following, the discussion of the searches for SUSY is restricted to hadronic searches at the hadron colliders, a general summary of the state of modern searches of SUSY can be found elsewhere [33].

1.4.1 Signatures of supersymmetry

A challenging aspect of SUSY searches is that the large number of parameters of the theory leads to a wide phenomenology of signatures. The large parameter space available however can be constrained with the application of well-motivated assumptions. Naturalness arguments, for instance, require that the stop mass be $\mathcal{O}(1 \text{ TeV})$ to provide a resolution to the hierarchy problem [51]. In addition, the requirement of a dark matter candidate motivate R -parity conserving theories to ensure a stable LSP, which is typically assumed to be the neutralino.

Assuming R -parity conservation dictates that supersymmetric particles are produced and decay in even numbers, typically in pairs. In the pp -collisions of the LHC, the theoretical production of supersymmetric particles is predominantly through the strong production of squarks and gluinos in: squark-squark ($\tilde{q}\tilde{q}, \tilde{q}\tilde{\bar{q}}$), squark-gluino ($\tilde{q}\tilde{g}$) and gluino-gluino ($\tilde{g}\tilde{g}$) pair production. These Sparticles subsequently decay to sparticle-particle pairs in cascades that terminate with the LSP which, to be a candidate for dark matter, is neutral and weakly interacting. Decay cascades for the gluinos and sparticles are illustrated in Figure 1.4. The quarks produced in these decays hadronise to form jets, with gluino decays typically resulting in the production of a higher multiplicity of jets.

Considering the signature of these events in a detector, pair produced Sparticles with subsequent hadronic decays typically result in a large hadronic activity which is recon-

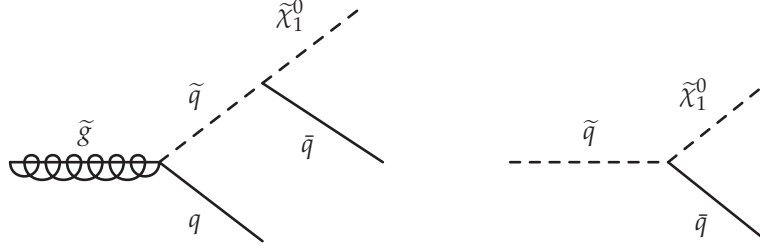


Figure 1.4: Feynman diagram of the hadronic decay of a single gluino (left) and single squark (right) where the LSP is the neutralino.

structured as events with multiple jets. The weakly interacting LSP in these decays traverse the detector without interacting, escaping detection. The recoil of the jet system against the LSP however leads to a momentum imbalance in the plane transverse to the collision, from which the missing-energy signature can be inferred. The degree of visible and invisible energy in the event is dependent on the configuration of the mass spectrum of the decay.

1.4.2 Simplified models

Due to the large number of parameters of supersymmetric models, historical searches for SUSY utilised constrained models, such as the Constrained Minimal Supersymmetric Standard Model (CMSSM) which contains just five parameters [57]. Although parametrically simple, these models produce complex particle hierarchies, as illustrated in Figure 1.5, that make interpretations model-dependent and limited in their topological complexity. To provide a full coverage of the supersymmetric parameter space, modern searches favour the interpretation in the context of the Simplified Model Spectra (SMS) framework [58, 59], known as *simplified models*, which provide more flexible interpretations of SUSY searches.

Simplified models are effective models where the majority of the particle content of the theory is decoupled at a high mass scale, leaving a limited range of particles and interactions. These models are described by a limited set of parameters, typically a production cross section, a parent particle mass and a daughter particle mass. Such models enable complex spectra to be factorised into individual decay modes with 100% branching ratio, illustrated in Figure 1.6, enabling any model to be recast as a combination of simplified models.

The event topologies of supersymmetric decays described by simplified models are encoded by the mass spectrum of the model. Configurations of models where there is a large separation in the mass of the parent and daughter sparticle, known as *large mass*

splittings, typically result in events with large hadronic energy and, in the case of the daughter being the LSP, missing-energy signatures. Models with smaller mass separations, known as *compressed spectra*, however exhibit less visible and missing energy. Compressed spectra are challenging to observe without low-energy selections or reliance on additional signatures such as Initial State Radiation (ISR).

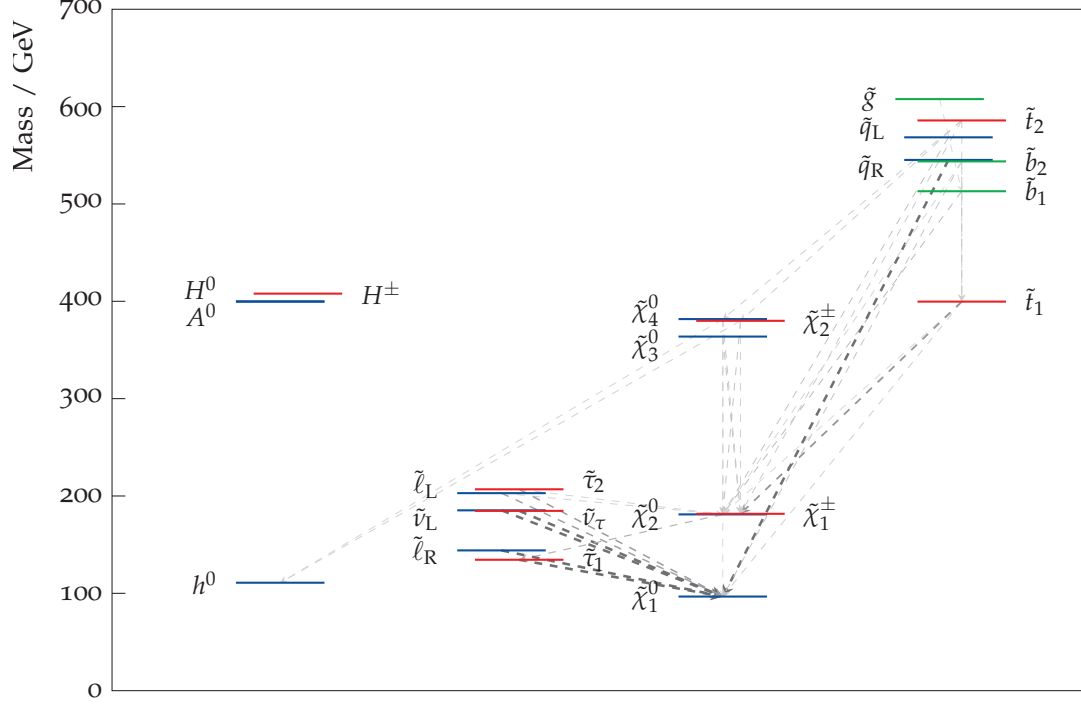


Figure 1.5: Spectrum of particles masses for an example supersymmetric model. The decays of particles in the theory are shown by the dashed lines, where the shade is representative of the specific branching fraction.

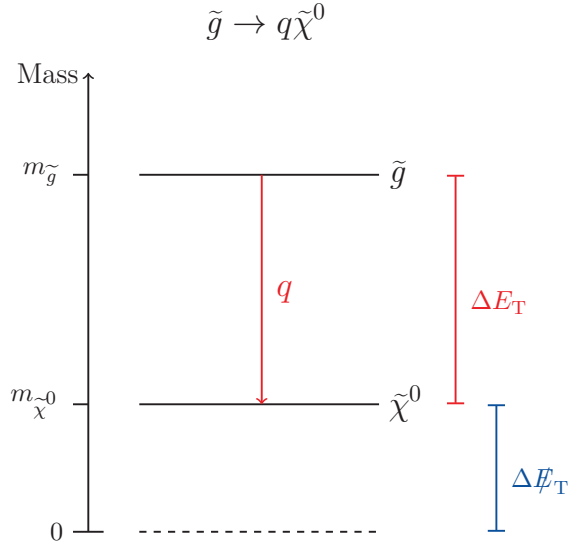


Figure 1.6: Schematic of the decay of a single gluino: $\tilde{g} \rightarrow q\tilde{\chi}^0$ in the T1qq simplified model ($pp \rightarrow \tilde{g}\tilde{g}$, $\tilde{g} \rightarrow q\tilde{\chi}^0$). The total visible energy and maximum missing energy from the decay of a single gluino are labelled by ΔE_T and $\Delta \cancel{E}_T$ respectively.

1.4.3 Experimental searches for supersymmetry

There have been extensive direct searches for SUSY at colliders, with the experiments at HERA (ep) [60, 61], LEP ($e\bar{e}$) [62] and the Tevatron ($p\bar{p}$) [63] excluding signatures of SUSY in a large area of search space. The reach of much of these searches has recently been surpassed by SUSY searches at the LHC, which was designed to probe physics at the TeV scale, the expected scale of SUSY in natural models.

Searches for supersymmetry with the ATLAS and CMS experiments in the first data taking period of the LHC did not find signs of SUSY in their respective accumulated datasets of $\mathcal{L} = 4.7 \text{ fb}^{-1}$ and $\mathcal{L} = 4.98 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$ and $\mathcal{L} = 20 \text{ fb}^{-1}$ and $\mathcal{L} = 19.7 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$. From these searches, upper limits on the production cross sections of simplified supersymmetric models covering a range of production and decay modes were determined. The simplified models for the pair production of gluinos and squarks are categorised as T1 and T2 models respectively, whose final state are encoded in the suffix of the model. Examples of the Feynman diagrams for the T1bbbb ($pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow b\bar{b}\tilde{\chi}_1^0$), T2tt ($pp \rightarrow \tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0$) and T2cc ($pp \rightarrow \tilde{t}\tilde{t}, \tilde{t} \rightarrow c\tilde{\chi}_1^0$) models are illustrated in Figure 1.7. In the case of the T2cc model, decays to charm quarks via flavour changing neutral current loops are enforced by the kinematic requirement that the mass splitting between the stop and LSP are smaller than the W boson mass ($m_{\tilde{t}} - m_{\tilde{\chi}_1^0} < m_W$).

Limits set by the CMS experiment in the context of these simplified models are shown in Figure 1.8. This shows the 95% confidence limit (C.L.) upper limit on the production cross section as a function of the masses of the mother sparticle, m_{SUSY} , and LSP, m_{LSP} , assuming a 100% branching ratio to the specified final state. The limits show an asymmetry in the $m_{\text{SUSY}}-m_{\text{LSP}}$ mass plane, with the strongest limits on parent sparticle mass achieved for models with large mass splittings where the mass of the LSP is smallest. The limits weaken approaching the $m_{\text{SUSY}} = m_{\text{LSP}}$ mass diagonal where the visible energy and missing energy in the event is limited, making the effective selection for these event topologies challenging.

A summary of the strongest limits set by all CMS searches in Run 1 for each considered simplified model is shown in Figure 1.9. Although the limit on the mass of sparticles approach the TeV scale, the favoured scale for natural SUSY, the strongest limits assume a maximal mass splitting with a massless LSP, for more compressed scenarios the limit on sparticle mass is weaker.

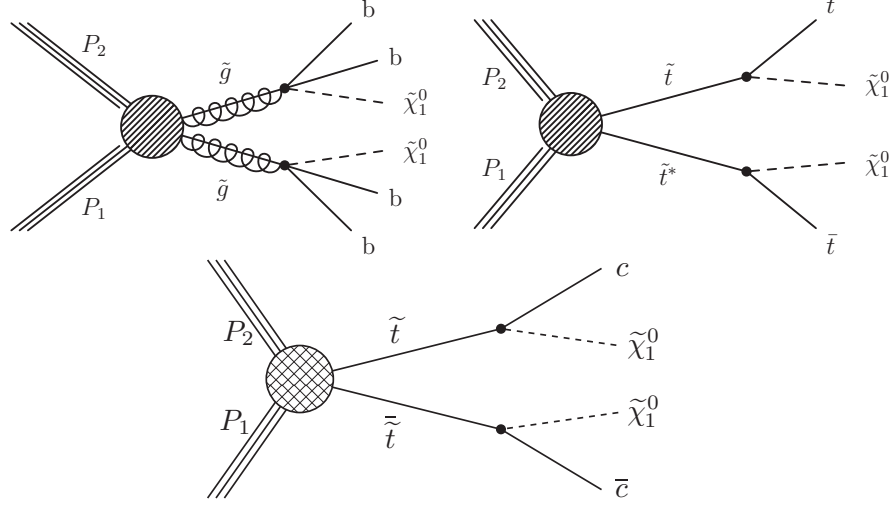


Figure 1.7: Feynman diagrams for the T1bbbb (top left), T2tt (top right) and T2cc (bottom) simplified models.

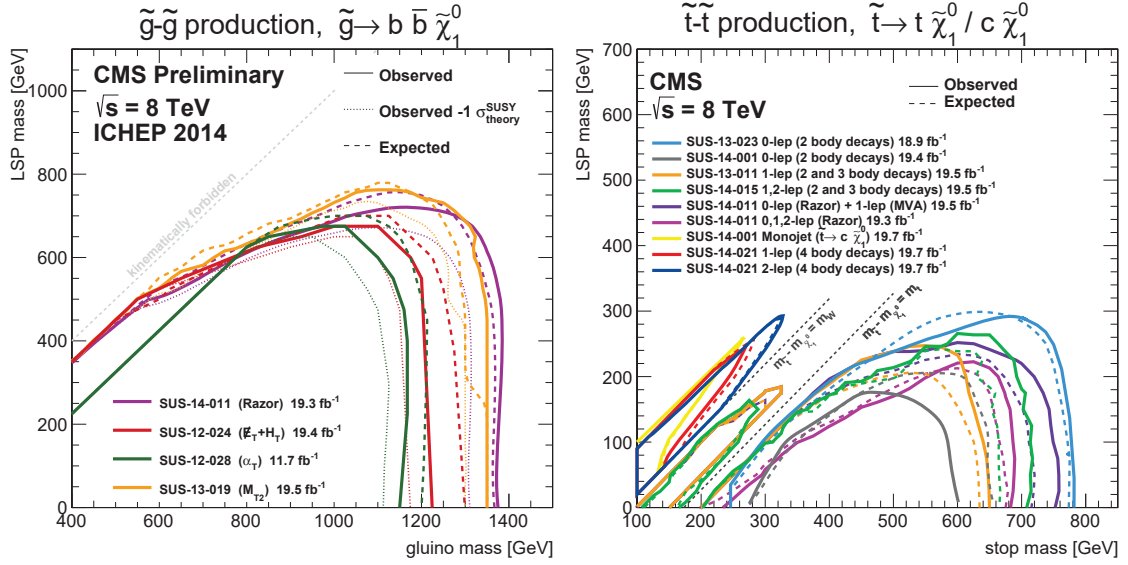


Figure 1.8: Limits on the production cross section of gluinos and stops interpreted in the T1bbbb (left) and the T2tt and T2cc (right) simplified models for searches with the CMS experiment at a beam centre-of-mass energy $\sqrt{s} = 8$ TeV [64]. The solid and dashed contours show the observed and expected 95% upper limit on the production cross section of the respective process for a specified mother and daughter sparticle mass. The colour of the contour references the search that measured the exclusion, as described in the legend.

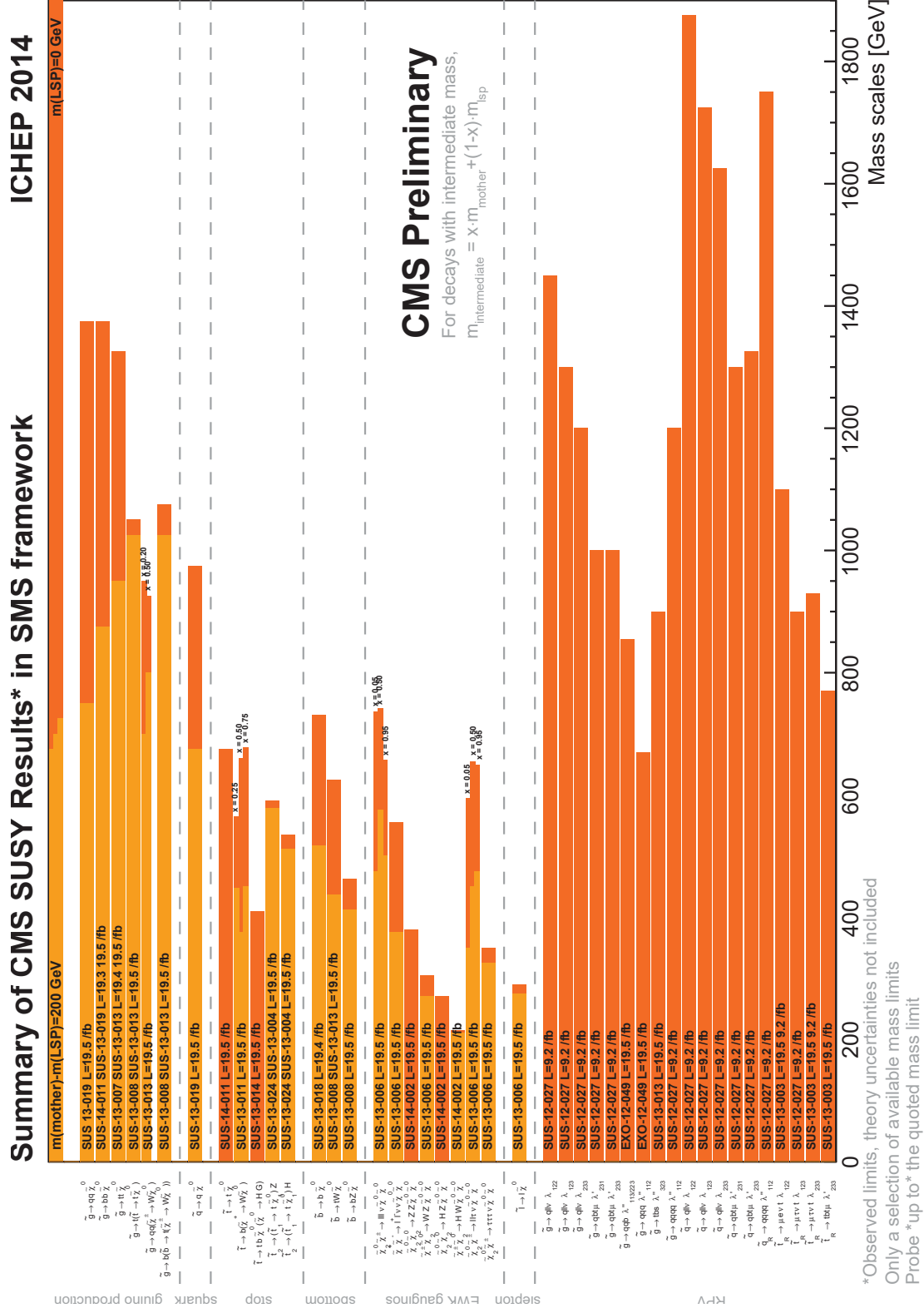


Figure 1.9: Summary of the strongest exclusion limit for the production of supersymmetric particles in CMS $\sqrt{s} = 8 \text{ TeV}$ searches as a function of the simplified model of the search. The limits assuming a massless LSP ($m_{\text{LSP}} = 0$) and for a 200 GeV mass splitting ($m_{\text{susy}} - m_{\text{LSP}} = 200 \text{ GeV}$) are represented by the darker and lighter shades respectively [64].

CHAPTER 2

The LHC and CMS Detector

In order to further the understanding of the SM and search for new physics, state-of-the-art accelerators and detectors that push beyond the current energy frontier are required. The LHC was designed to achieve these aims, being the largest and highest-energy collider ever constructed, enabling a probe of physics at the TeV-scale. One of the main experiments at the LHC, the CMS experiment performs precision measurements in the challenging high-intensity environment of the LHC.

In the following chapter a description of the LHC and CMS detector is provided. Section 2.1 provides an overview of the LHC describing the operation of the accelerator and its performance. Section 2.3 presents an overview of the CMS detector with dedicated subsections describing the operation of its individual subsystems, including: their detection technologies within the context of design considerations, their modes of operation and physics reconstruction performance with a focus on aspects pertinent to hadronic searches.

2.1 The Large Hadron Collider

Situated at the European Organisation for Nuclear Research (CERN), the LHC is a hadron synchrotron designed to resolve the origin of spontaneous symmetry breaking within the SM and perform exhaustive searches for new physics at the TeV-scale. In its primary mode of operation, the LHC acts as a proton-proton (pp) collider with a design operating centre-of-mass energy and instantaneous luminosity of $\sqrt{s} = 14 \text{ TeV}$ and $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ respectively, enabling a probe of the energy frontier with high statistical precision [65, 66]. In addition to performing pp -collisions, the LHC also has shorter heavy ion-ion and proton-ion runs where the dynamics of high energy physics interactions in high parton densities are studied.

The use of protons as colliding particles presents advantages over lepton colliders for the potential of discovery, with the increased mass of the accelerated particle enabling higher centre-of-mass energies to be achieved as a result of a suppression of energy loss via synchrotron emission. Hadron colliders however present a challenging environment

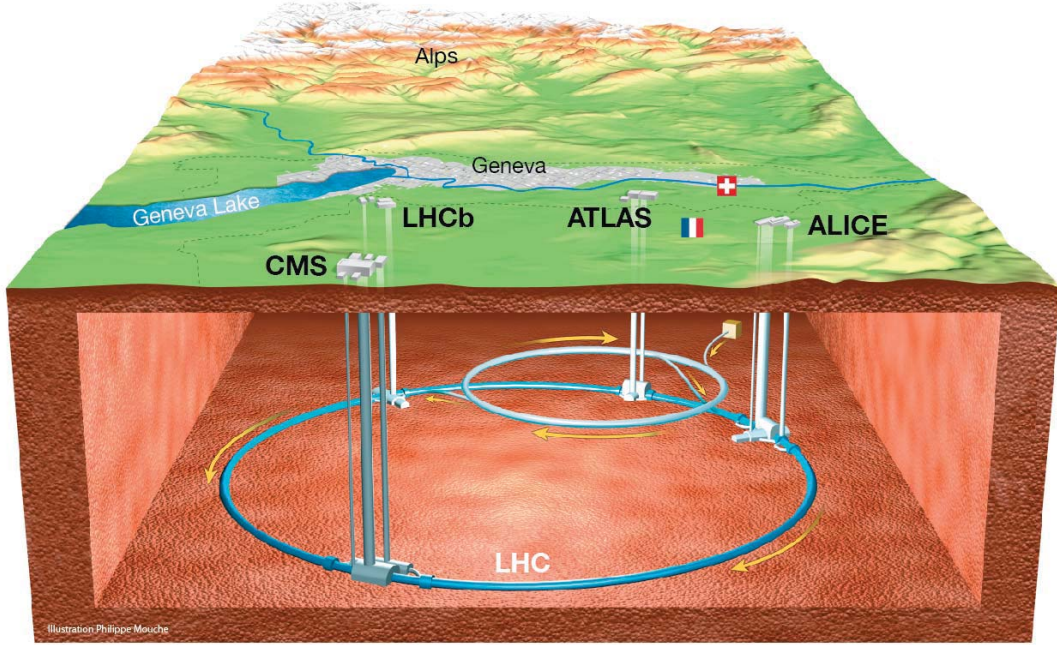


Figure 2.1: Diagram of the LHC and the position of its constituent experiments: ALICE, ATLAS, CMS and LHCb [67].

for detectors, with high particle fluences in collisions requiring radiation-hard and high-granularity detectors to reduce occupancy.

Utilising the same 26.7 km tunnel as its predecessor the Large Electron-Positron Collider (LEP) [68], the LHC lies beneath the territories of France and Switzerland at an average depth of 100 m. Illustrated in Figure 2.1, the LHC is not perfectly circular but instead consists of eight sectors of 2.45 km arc length with inter-connecting 545 m straight sections. Each of the sectors possess a cavern however in only four of the caverns are the beams brought to collide, which are instrumented by the major LHC experiments. On diametric opposites of the ring, points 1 and 5, the two general purpose detectors: A Toroidal LHC Apparatus (ATLAS) [69] and the Compact Muon Solenoid (CMS) [70] detectors perform a wide range of physics measurements, from searches for new physics to precision measurements of the SM. Neighbouring ATLAS at points 2 and 8, two specialised experiments: A Large Ion Collider Experiment (ALICE) [71] and LHC-beauty (LHCb) [72] primarily focus on the measurement of heavy-ion physics and b -physics respectively.

Prior to acceleration in the LHC, protons undergo several stages of pre-acceleration by a pre-injection chain [73]. The acceleration chain begins with the ionisation of protons from Hydrogen gas and subsequent acceleration with a linear accelerator, achieving an energy of 50 MeV. These protons are then injected into and accelerated by a series of synchrotrons, increasing the energy of the beam and sculpting the bunch structure prior to injection into the LHC. The final pre-accelerator in this chain, the Super Proton Synchrotron (SPS), increases the beam energy to 450 GeV prior to injection into the LHC as two counter-rotating beams formed of bunches. In the 25 ns mode of operation, 2808 bunches circulate in the LHC, with each bunch containing approximately 115 billion protons at the beginning of each fill. The bunches orbit in two separate vacuum beam pipes, confined by strong magnetic fields provided by 1,232 superconducting dipoles, enabling continuous acceleration and circulation. Acceleration within the LHC is performed at point 4 by 16 Radio Frequency (RF) cavities with a potential of 2 MV, enabling protons to be accelerated to 7 TeV per beam at the design energy. After acceleration to full energy the LHC acts as a storage ring, enabling continuous collisions of bunches for 10-20 hours at a peak collision rate of 40 MHz. When the number of protons in each bunch becomes insufficient for the required instantaneous luminosity, the beams are dumped and the process of acceleration begun again.

In order to provide the high 8.33 T magnetic field strength required to constrain the high-energy particles in their orbits, the dipoles utilise superconducting Niobium-titanium (NbTi) fibres cooled to 1.9 K with liquid-helium [66]. These are used in conjunction with a sophisticated system of focusing magnets, with 858 quadrupole magnets reducing the beam of the circulating beams to approximately a millimetre in width. Inner triplet magnets further focus the beam to 16 μm at the collision points 1 and 5 [66]. At the end of the run or in the event of a risk of damage to the accelerator and its detectors, kicker magnets can extract the beam and direct it into a beam dump at point 6, an 8 m graphite-composite absorber [66].

The first run of the LHC, known as Run 1, started in 2009 at low energies and instantaneous luminosities. By March 30th 2010, the LHC began the first collisions at a centre-of-mass energy of $\sqrt{s} = 7 \text{ TeV}$, before finally increasing to $\sqrt{s} = 8 \text{ TeV}$ in 2012. In Run 1 the LHC delivered a total integrated luminosity of 6.1 fb^{-1} (7 TeV) and 23.3 fb^{-1} (8 TeV), reaching a peak instantaneous luminosity of $\mathcal{L} = 7.7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. Run 1 ended in February 2013 and a two year programme of upgrades and maintenance began,

known as Long Shutdown 1 (LS1). This enabled upgrades and checks of both the accelerators and detectors to be performed, enabling operation at $\sqrt{s} = 13$ TeV. On the 21st May 2015 the LHC performed the world's first collisions at 13 TeV, beginning the second data run, Run 2.

2.2 LHC Run 2

In the first data run of the LHC no large tensions were observed by CMS, with agreement observed between SM predictions and experimental measurements over several orders of magnitude in cross section as shown in Figure 2.2. In order to improve sensitivity for the second data run, the beam centre-of-mass energy and luminosity were increased to operate for the first time at $\sqrt{s} = 13$ TeV and a peak instantaneous luminosity of $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This presented both opportunities and challenges, which required a program of accelerator and detector upgrades to best exploit [74].

With an increase in the operating dipole magnetic field strength, the LHC centre-of-mass energy was able to be increased to $\sqrt{s} = 13$ TeV, providing a significant improvement to the sensitivity for searches of heavy particles. Shown in Figure 2.3, the relative production cross section of particles at the $\sqrt{s} = 13$ TeV LHC receive a significant increase with respect to $\sqrt{s} = 8$ TeV operation. For the highest mass SM processes, such as Higgs boson and $t\bar{t}$ production, there is a modest 2–3 enhancement in production cross section. For searches of hypothetical new massive particles this increase in cross section can be more significant. The strongest Run 1 exclusions for gluino pair production of $m_{\tilde{g}} \gtrsim 1.4$ TeV receive an enhancement in production cross section of approximately 20 times for quark-quark production, increasing to 50 times in the case of gluon-gluon production.

In addition, the peak instantaneous luminosity of $\mathcal{L} = 7 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ achieved in Run 1 was increased to reach the LHC design luminosity of $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This is facilitated by increased focusing of the proton beams, in conjunction with a reduction of the proton bunch spacing from 50 ns in Run 1 to 25 ns. Operating at a higher instantaneous luminosity enable experiments at the LHC to more rapidly accumulate datasets of high statistical power, enabling more rare processes to be probed.

The change in beam configuration however also presents a more challenging environment for the accelerator and its detectors to operate, particularly from increases in *pileup* and *beam photoelectrons*.

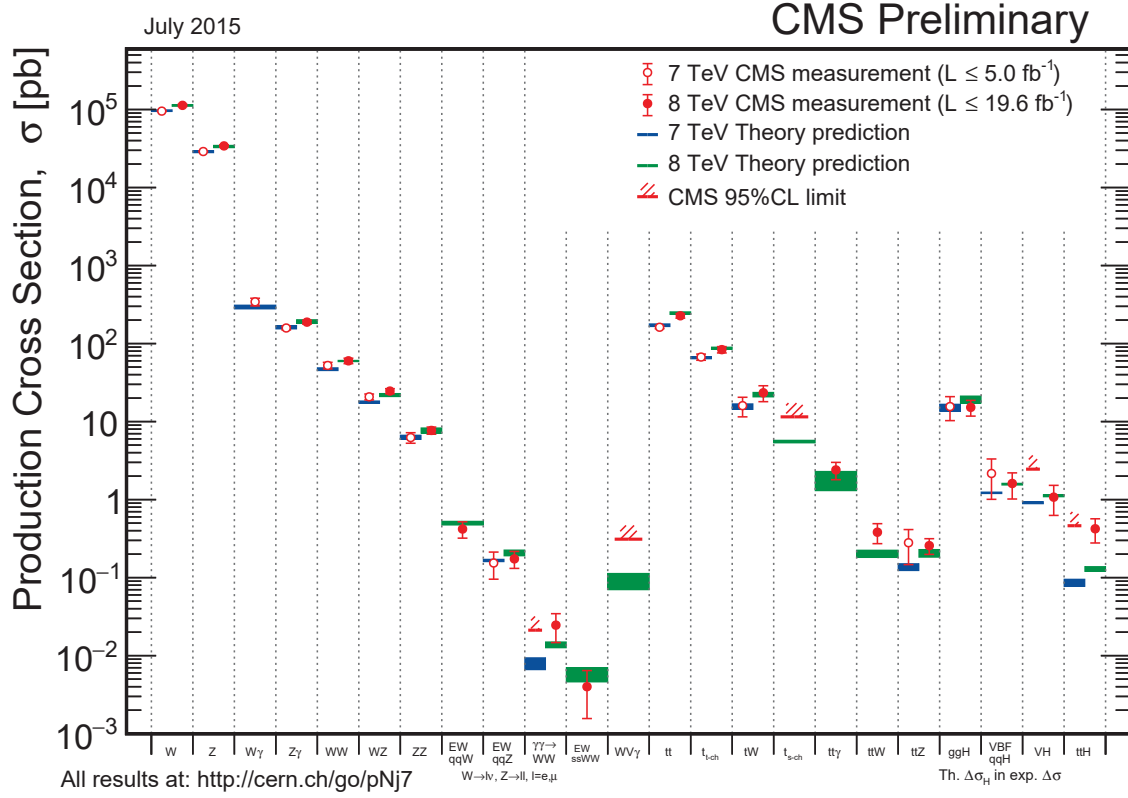


Figure 2.2: Summary of CMS measurements in LHC Run 1, comparing the SM production cross section predictions (bars) with the experimental measurements (points) at $\sqrt{s} = 7 \text{ TeV}$ (hollow circles) and $\sqrt{s} = 8 \text{ TeV}$ (filled circles).

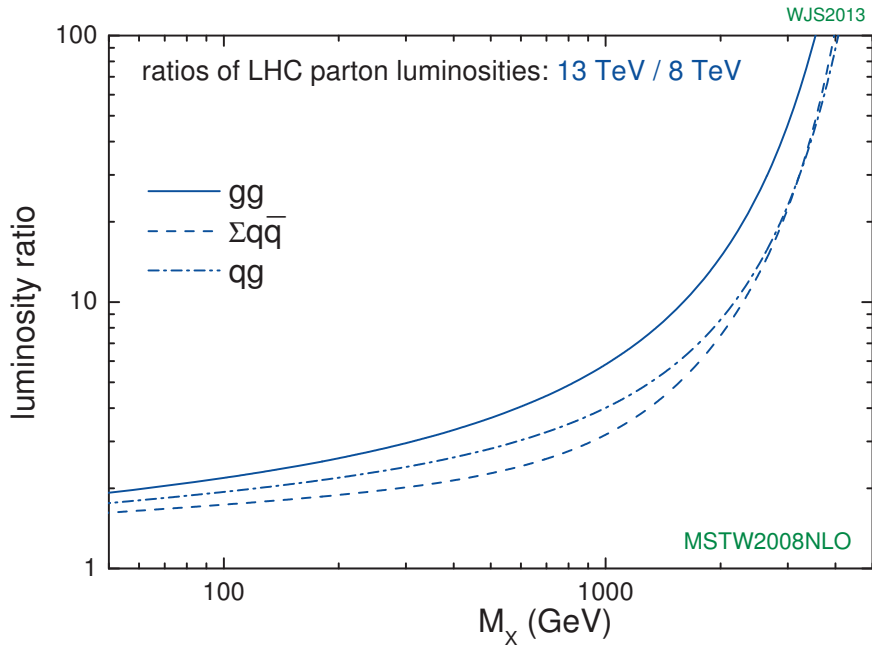


Figure 2.3: Ratio of parton luminosities at $\sqrt{s} = 13 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ as a function of the system mass M_X for production via: gluon-gluon fusion (gg), quark-antiquark annihilation ($q\bar{q}$) and quark-gluon scattering (qg) [75].

In each bunch crossing of the LHC multiple pp -collisions occur, resulting in overlapping interactions known as *pileup interactions*. Shown in Figure 2.4, the most common process at the LHC, and hence the predominant component of pileup, is QCD inelastic scattering. Particles from pileup degrade reconstruction by depositing additional energy in subdetectors via two methods: *in-time pileup*, energy contamination from pileup particles in the same bunch crossing as the signal process, and *out-of-time*, where residual pileup energy is present in subdetectors from previous or subsequent bunch crossings as a result of limited detector response time.

The LHC design of 20 simultaneous interactions per bunch crossing was exceeded in Run 1 where the average number of pileup interactions per event was 21. In Run 2 the pileup is projected to surpass 40 simultaneous interactions, which in conjunction with increased Out-of-time pileup (OOTPU), present challenges to the event selection that require upgrades to the detector and trigger systems described in Section 2.4.

Additionally, the operation at a higher collision frequency presents problems from an increased production of beam photoelectrons, known as the electron cloud, as a result of interactions with the LHC beam pipe. Photoelectrons that are parasitically accelerated by the LHC beam can result in the further production of photoelectrons in a chain reaction that disturbs the stability of proton bunches and the cryogenics of the LHC. To mitigate the risk of the electron cloud, the LHC performs regular beam scrubbing runs to remove impurities and contaminants from the LHC beam pipe that can initiate photoelectron emission [76].

2.3 The Compact Muon Solenoid detector

One of the primary experiments at the LHC performing searches for new physics, CMS is designed to perform high precision measurements of electrons, photons and muons in the high-luminosity environment at the LHC. To achieve these aims CMS is instrumented with a range of subdetectors with technologies selected to provide high-precision measurements of particles within events of high particle fluence. Although physically large, at 21.6 m in length and 14.6 m in diameter, CMS is relatively compact with respect to its sister experiment ATLAS, which is twice as large. This is afforded by the high magnetic 3.8 T field strength provided by its superconducting solenoid which facilitates a compact detector design without comprising detector resolution, enabling the tracking and calorimetry

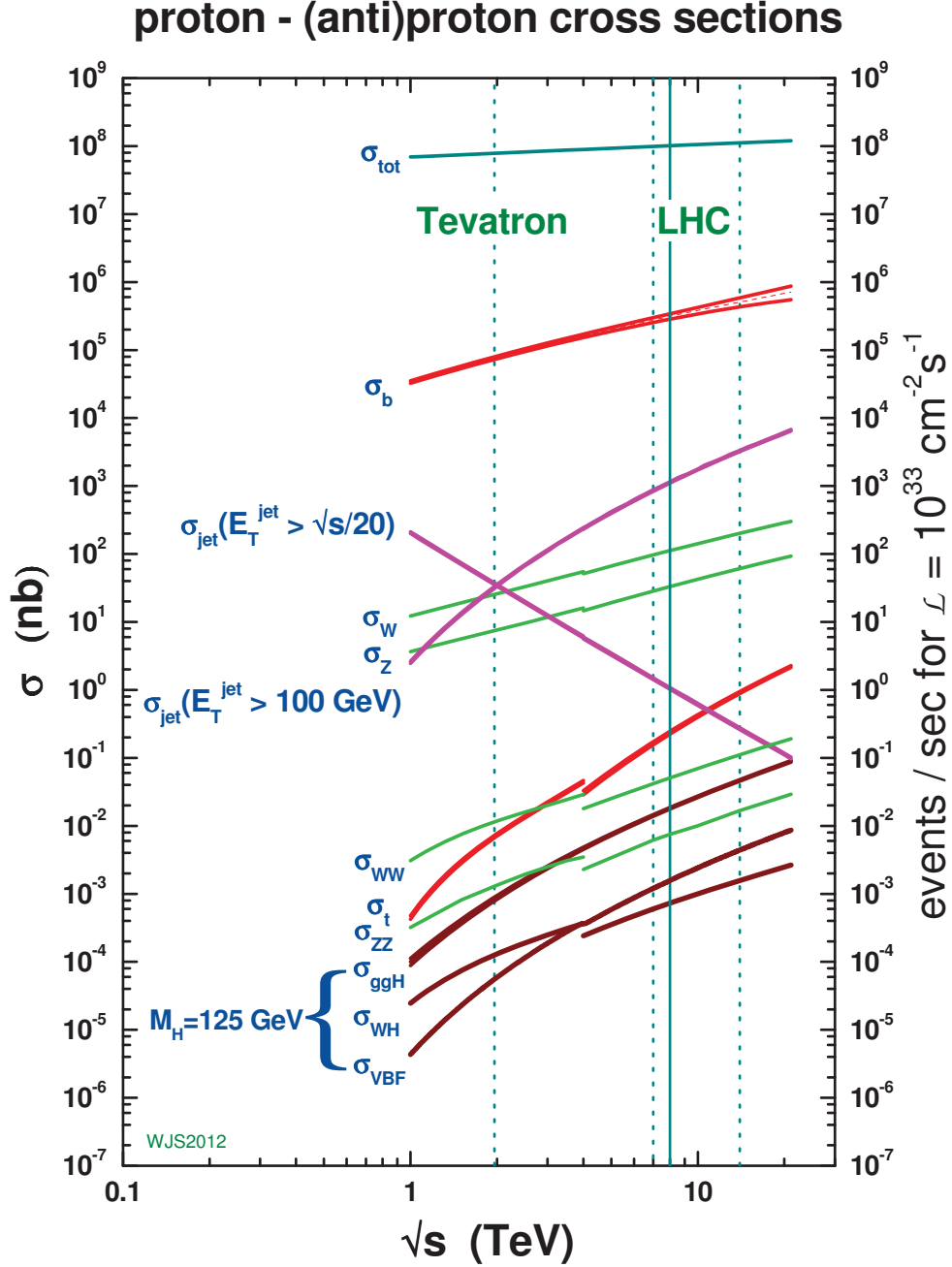


Figure 2.4: Summary of the production cross sections for SM processes in pp -collisions as a function of centre-of-mass energy. The total interaction cross section (turquoise) as a function of the centre-of-mass energy is shown in addition to a selection of SM processes, which includes: b -jet production (red), jet production (magenta), weak vector boson production (green) and Higgs boson production (brown) [75].

systems to reside within the bore of the solenoid.

The trajectories of particles within the detector are described by a right-handed coordinate system, illustrated in Figure 2.5, with the origin centred at the nominal interaction point, x -axis pointed towards the centre of the ring, y -axis directly up and z -axis in the anti-clockwise beam direction. In addition two angles, the azimuthal (ϕ) and polar (θ) angles, are defined as the angle subtended with respect to the x -axis and z -axis in the $x-y$ and $z-y$ planes respectively. The polar angle is also used to construct the quantity pseudorapidity (η) by the relation: $\eta \equiv -\ln[\tan(\theta/2)]$.

The CMS detector, illustrated in Figure 2.6, uses a combination of complementary detection technologies to provide precision measurements of particles for a large range of different physical properties, kinematics and spatial projections. Near-hermetic, CMS possesses full azimuthal coverage and a large pseudorapidity acceptance of $|\eta| \leq 5.2$, enabling accurate measurements of missing transverse energy ($\cancel{E}_T$), which is crucial in the triggering and analysis of many physics events.

The CMS detector possesses the classic cylindrical onion-layer design, with subdetector layers concentrically arranged around the interaction point. Close to the beam pipe, the *tracking system* utilises a combination of silicon pixel and strip sensors, which in conjunction with a 3.8 T magnetic field from the superconducting solenoid, enable an accurate determination of the trajectories and momenta of charged particles. Enclosing the tracker, the lead tungstate (PbWO_4) crystal *Electromagnetic Calorimeter (ECAL)* and brass sampling *Hadronic Calorimeter (HCAL)* provide measurements of particle energies in the pseudorapidity range $|\eta| < 3$. The very forward region of the detector ($3 < |\eta| < 5.2$) is covered solely by the *Hadron Forward Calorimeter (HF)* which, functioning in a high radiation environment, utilises a iron-quartz fibre detector. The exterior of the detector is encased by the *muon system* which performs measurements of muon trajectories in the pseudorapidity range $|\eta| < 2.4$. Embedded in the return yoke of the solenoid, it exploits the return magnetic field to enable a better determination of muon momenta.

In the following sections an overview of the detector subsystems of CMS is presented, a more complete description of the CMS detector can be found in the literature [78].

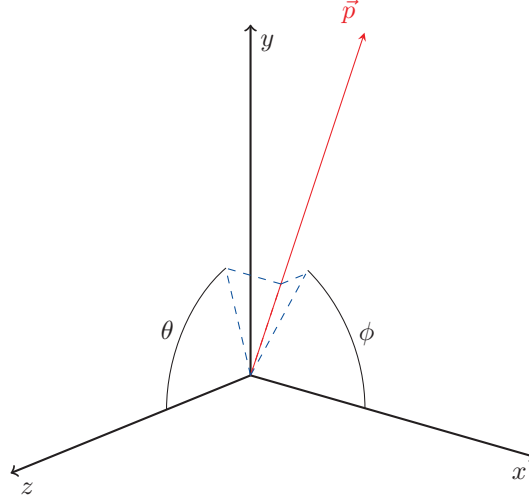


Figure 2.5: Schematic of the polar coordinate system utilised at the LHC, illustrating the corresponding azimuthal (ϕ) and polar (θ) angles for a particle with momentum $\vec{p}$.

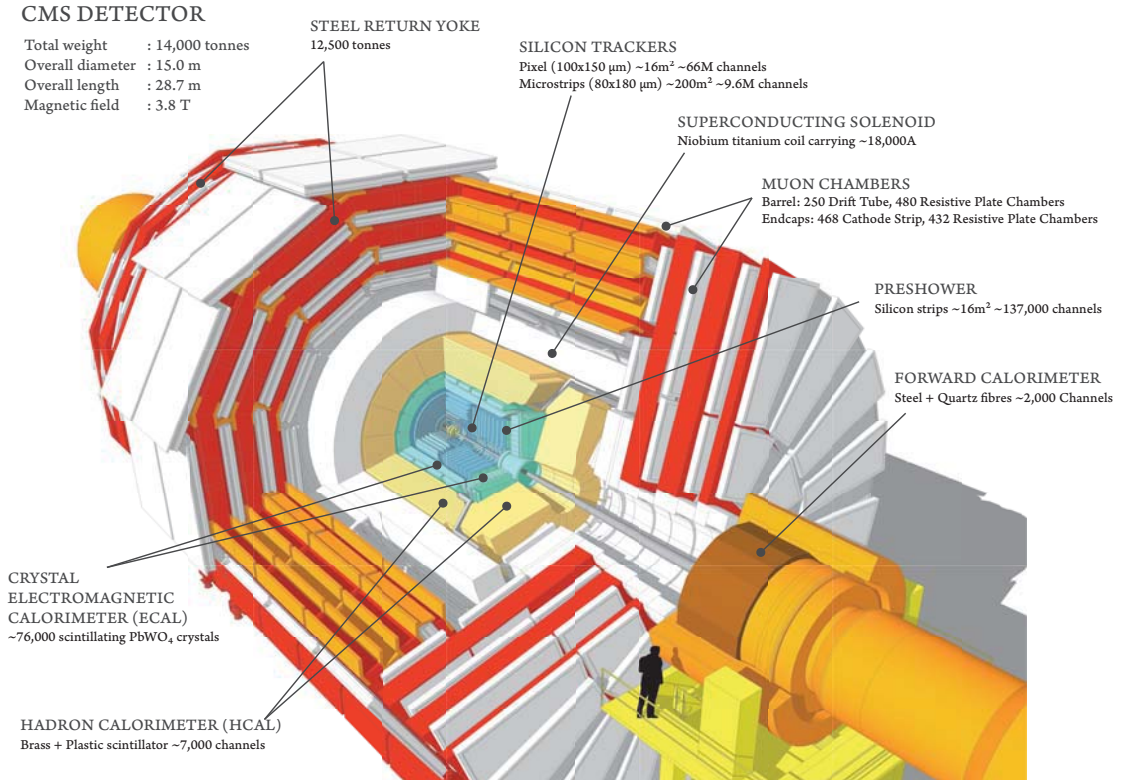


Figure 2.6: Diagram of a cross-section of the CMS detector displaying the position, coverage and composition of its constituent subdetectors [77].

2.3.1 Tracker

The closest subdetector to the interaction point, the CMS tracker system performs high-precision measurements of the trajectories of charged particles in three dimensions over the pseudorapidity range $|\eta| \leq 2.5$. Coupled with the strong 3.8 T magnetic field provided by the solenoid, the tracker system provides precise measurements of the momentum of charged particles and their properties.

To operate in the challenging conditions close to the LHC interaction point, the design of the tracker required several criteria be met. To operate effectively in high instantaneous and integrated particle fluxes, a radiation-hard technology with fast response time was required, reducing detector occupancy and enabling individual bunch crossings to be resolved in the 25 ns bunch spacing scenario. With 1000 particles produced per event at design luminosity, the high particle fluxes of the LHC necessitates high-granularity detectors, particularly close to the interaction point, to maintain the low occupancy required to provide efficient and high-precision measurements of tracks. Its design should additionally minimise the attenuation of measured particles, minimising track deflections from multiple scattering and energy losses from detector interactions.

To meet these design requirements, CMS utilises a fully silicon detector [70] to perform measurements of the tracks of charged particles. With an active area of 200 m^2 , it is the largest of its kind ever constructed. Silicon is not only intrinsically radiation hard with a fast charge collection time but also structurally robust, enabling thin sensors with small material attenuation to be utilised. These properties make it well suited to perform high-resolution measurements in the high-luminosity scenarios of the LHC.

Due to the differing particle fluxes and geometries within the CMS detector, the tracker utilises two different tracking module technologies. Close to the interaction point, where high particle fluxes are present and high precision track measurements for vertexing are required, a silicon micropixel detector is utilised. Silicon strip sensors are used in the outer volume where fluxes are lower and lower precision is required. Both tracking detectors consist of modules arranged in a split barrel-endcap design, illustrated in Figure 2.7. In the barrel region a cylindrical configuration of 13 concentric layers is utilised, the inner three comprising of silicon micropixel layers from an inner radius of 4.3 cm and the remaining ten layers using silicon strips extending to an outer radius of 1.1 m. The forward region is covered by two pixel endcap disks and 12 silicon strip disks.

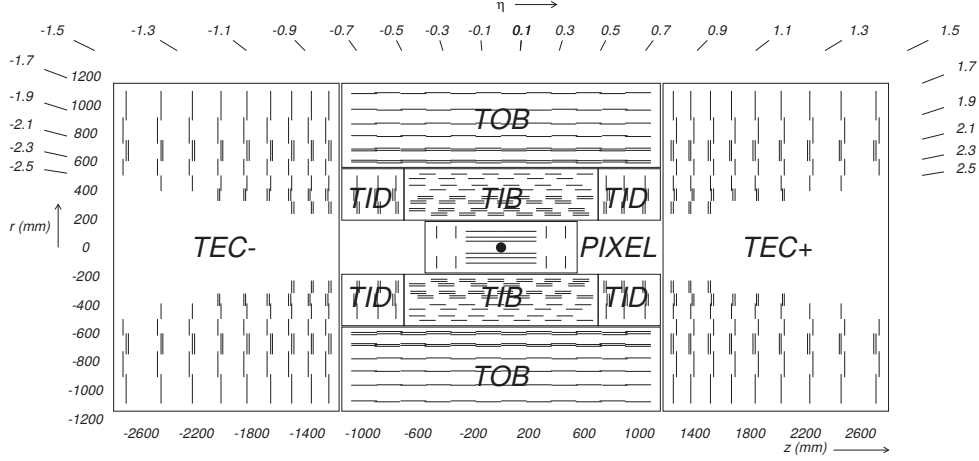


Figure 2.7: Longitudinal cross-section of the tracking system illustrating the positions and coverage of the individual tracking modules [70].

The closest subdetector to the beam pipe, the pixel tracker is designed to perform high-resolution measurements of tracks close to the interaction point. This enables individual collision vertices to be resolved and provides an accurate measurement of secondary vertices, signatures typical of long-lived particles such as hadrons containing b -quarks. In addition, the detector must maintain an occupancy below $\times 10^{-4}$ in an environment with high particle fluxes from the main interaction and from the subsequent traversals of low-momentum particles looping within the high magnetic field. These design criteria motivate the use of modules with high granularity pixels, with dimension $100\,\mu\text{m} \times 150\,\mu\text{m}$ and $285\,\mu\text{m}$ thickness, providing position resolutions in the transverse and longitudinal planes of $r - \phi = 10\,\mu\text{m}$ and $r - z = 20\,\mu\text{m}$ respectively [70].

In total 1440 pixel modules cover a $1.1\,\text{m}^2$ active area with 66 million individual pixels arranged in a split barrel-disk configuration. The barrel region is instrumented by the Barrel Pixel detector (BPIX), which consists of three concentric cylindrical layers arranged at 4.3 cm, 7.2 cm and 11 cm. The forward region is covered by the Forward Pixel detector (FPix), which consists of two endcap disks at $z = \pm 34.5\,\text{cm}$ and $z = \pm 46.5\,\text{cm}$.

Enclosing the pixel tracker, the strip tracker covers the remainder of the tracker volume. Comprising of 15,148 strip modules, mounted in pairs with a $\sim 100\,\text{mrad}$ stereo angle, the strip tracker has a total of 9.6 million strips covering an active area of $198\,\text{m}^2$. In the barrel these are arranged in ten concentric cylindrical layers, which range in radius from

25 cm to 110 cm. The Tracker Inner Barrel (TIB) covers the innermost four layers with modules of thickness $320\text{ }\mu\text{m}$, with the Tracker Outer Barrel (TOB) covering the remaining six utilising $500\text{ }\mu\text{m}$ thick modules. The forward region is instrumented by the Tracker Inner disk (TID) and Tracker Endcap (TEC) which are composed of three and nine endcap disks respectively. The endcap strips have trapezoidal sensors which are $320\text{ }\mu\text{m}$ thick with dimensions $100 \times 150\text{ }\mu\text{m}^2$ ($r - \phi, z$) for the TID modules and $500\text{ }\mu\text{m}$ thick with an average strip dimension of $10\text{ cm} \times 80\text{ }\mu\text{m}$ ($r - \phi, z$) for the TEC modules [70].

2.3.2 Electromagnetic calorimeter

A guiding design aim of CMS was the high precision measurement of the energy and position of electrons and photons in high-luminosity conditions, which are distinctive signatures of Higgs boson decays. This is also important in the reconstruction of jets where $\sim 27\%$ of the total jet energy is carried by photons which, in the absence of electron pair production, cannot be measured directly by any other subdetector. These requirements motivate the use of a radiation hard, highly-granular calorimetry technology with good energy resolution.

The CMS ECAL [70] is a homogeneous calorimeter which utilises high granularity lead tungstate (PbWO_4) crystals to precisely measure the position and energy of light and neutral particles. Its high density ($\rho = 8.28\text{ g/cm}^3$) enables a compact design, fitting within the bore of the solenoid with a small radiation length of $X_0 = 0.89\text{ cm}$. The ECAL comprises in total of 75,848 crystals, which are aligned off-axis with respect to the interaction point in both the $\eta - z$ and $\phi - r$ planes to reduce gaps in coverage. These are divided into two regions: the ECAL Barrel (EB) which covers the pseudorapidity range: $|\eta| < 1.479$ and the ECAL Endcap (EE) which covers: $1.479 < |\eta| < 3.0$. In addition, in the forward region: $1.653 < |\eta| < 2.6$, the Preshower (ES) provides improved energy and position resolution measurements of particles and enables a distinction between π^0 and γ . The geometry of the detector is illustrated in Figure 2.8.

The crystals operate by inducing electromagnetic cascades in traversing particles, resulting in the production of scintillation light in wavelength range $420 - 430\text{ nm}$ which is totally internally reflected to the backend of the crystal. The scintillation light yield from the PbWO_4 crystals is relatively low, producing 4.5 photoelectrons per MeV, requiring on-detector photoamplifiers. To operate in the high field strength and particle flux within

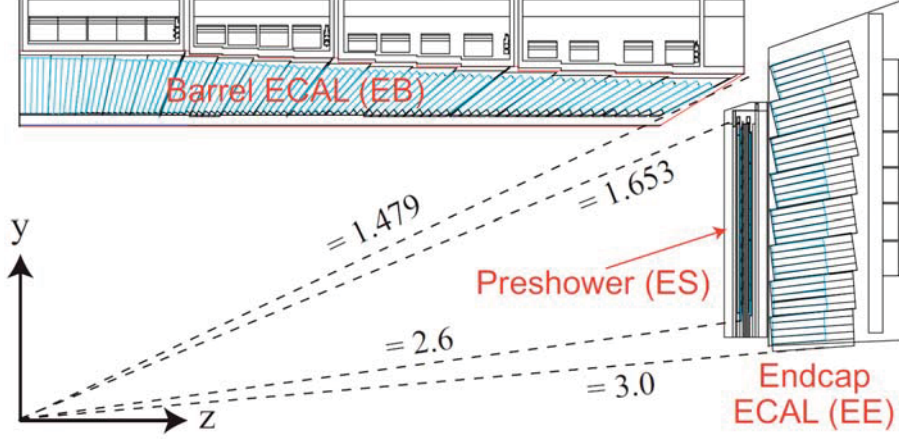


Figure 2.8: Longitudinal cross-section of the ECAL showing the position of individual crystals in the barrel (EB) and endcap (EE), in addition to the preshower (ES) [79].

CMS, silicon Avalanche Photodiodes (APDs) [80] are used in the barrel and Vacuum Phototriodes (VPTs) [81] in the endcap. The crystals are well suited to the LHC conditions, being intrinsically radiation hard and possessing a fast response time, with 80% of the light signal being collected within 25 ns. The ES is a sampling calorimeter comprised of two layers of lead and silicon strip tracker planes provide a combined $3X_0$ radiation lengths.

In the barrel the crystals are 230 mm in length providing $25.8 X_0$ radiation lengths. The crystals exhibit a tapered design, with the dimensions of the front face of $22 \text{ mm} \times 22 \text{ mm}$, corresponding to a coverage of $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$. In the endcap larger crystals of front face dimension $28.6 \text{ mm} \times 28.6 \text{ mm}$ and length 220 mm provide $24.7 X_0$ radiation lengths. The Molière radius of the crystal, $r_m = 22 \text{ mm}$, is comparable to the dimensions of the crystal, ensuring good containment of energy from electromagnetic showers within a single crystal, improving energy and position resolution. The energy resolution of a 3×3 cluster of PbWO_4 crystals has been measured in test beam in the absence of a magnetic field to be given by the empirical formula [82]:

$$\left(\frac{\sigma_E}{E[\text{GeV}]} \right)^2 = \left(\frac{2.8\%}{\sqrt{E[\text{GeV}]}} \right)^2 + \left(\frac{12\%}{E[\text{GeV}]} \right)^2 + (0.30\%)^2. \quad (2.1)$$

Due to the temperature dependence of the crystal light yield and photodetector gain, the ECAL crystal temperature is maintained at 18°C . Changes in crystal transparency as a result of irradiation are corrected by in-situ measurements of light yields produced

using a laser of wavelength $\lambda = 440 \text{ nm}$ for each of the crystals. These measurements are performed every 40 minutes, enabling a time-dependent calibration to correct for any darkening of the crystals [83].

2.3.3 Hadronic calorimeter

Enclosing the ECAL, the HCAL performs measurements of hadrons over the pseudorapidity range: $|\eta| < 5.2$. Positioned within the bore of the solenoid the HCAL is required to be non-magnetic, highly attenuating and structurally robust. The HCAL is of particular importance in reconstructing the energy and position of jets and their constituents, particularly neutral hadrons, and in the measurement of missing energy. The HCAL [70] is a sampling calorimeter consisting of four distinct subdetectors: the HCAL Barrel (HB) and Hadron Outer Calorimeter (HO), which perform measurements in the barrel, and the HCAL Endcap (HE) and HF, which cover the forward regions. The geometry of the HCAL is displayed in Figure 2.9.

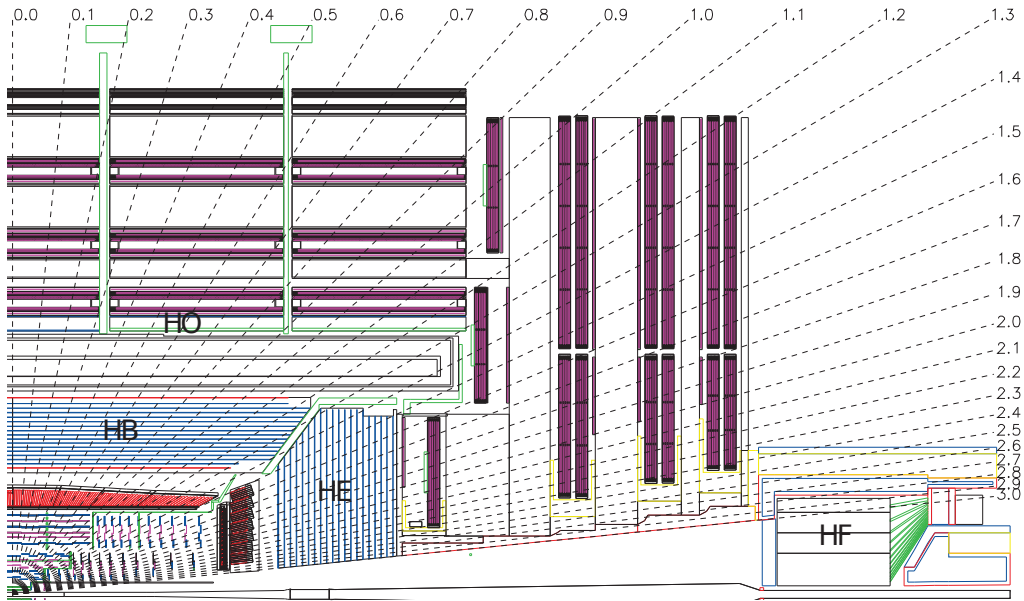


Figure 2.9: Longitudinal cross-section of the HCAL displaying the positions and coverage of the constituent subdetectors: HCAL Endcap (HE), HCAL Barrel (HB), Hadron Outer Calorimeter (HO) and Hadron Forward Calorimeter (HF) [70].

In the barrel, the cylindrical HB covers the pseudorapidity range $|\eta| < 1.3$, which is divided into 36 segments in η and 36 wedges in azimuth. The wedges are further

subdivided into sectors that have a coverage of $\Delta\phi = 5^\circ$, yielding calorimeter cells of dimensions $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$. In addition the HO, which is external to the magnet, measures energy from punch-through particles over the range: $|\eta| < 1.26$.

In the forward region the HE provides coverage over the pseudorapidity range: $1.3 < |\eta| < 3$. Similar to the HB, the HE is divided into 36 wedges possessing identical $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$ segmentation, with decreasing $\Delta\eta$ granularity above $|\eta| \sim 1.74$ which ranges from 0.09 to 0.35. The very forward region is covered by the HF, which performs measurements over the pseudorapidity range: $3 < |\eta| < 5.2$ with wedges of azimuth $\Delta\phi = 20^\circ$, providing a segmentation of $\Delta\eta \times \Delta\phi = 0.175 \times 0.175$, with reduced $\Delta\phi = 0.35$ segmentation above $|\eta| = 4.7$.

The HB and HE utilise attenuating brass plates ranging in thicknesses 40 – 75 mm interspersed with 17 layers of scintillation tiles acting as the active material. Hadronic showers induced in the brass layers produce scintillation light from electromagnetic showers in the plastic scintillation tiles. Wavelength-shifting fibres embedded in the tiles collect the scintillation signal and pass it to clear fibres which are connected to all of the tiles within a cell, accumulating and transferring the total scintillation signal of a tower to on-detector amplifiers. In Run 1 the HB, HE and HO utilised Hybrid Photodiodes (HPDs) [70] to measure the scintillation signal. The HPDs however have a dependence on orientation with respect to the magnetic field direction which, due to difficulty in modelling the field inside the return yoke, was found to be non-optimal for the HO. For Run 2 the HO HPDs have been replaced with Silicon Photomultipliers (SIPMs) which have no magnetic field dependence [84].

Within the barrel the HCAL is constrained to fit within the bore of the solenoid, restricting the total attenuation that can be achieved. From the detector geometry, the attenuation has a pseudorapidity dependence with a total interaction length ranging from: $7 - 10.6\lambda_I$, over the pseudorapidity range: $\eta = 0 - 1.3$, in addition to the $\sim 1.1\lambda_I$ provided by the ECAL. To provide better containment of punch-through particles and suppress false signatures of $\cancel{E}_T$, an additional HO layer encloses the solenoid which provides an additional $3\lambda_I$ interaction lengths, giving the HCAL a total attenuation of $10 - 15\lambda_I$ interaction lengths.

The HF operates in the forward region where particle fluxes are higher, requiring a radiation-hard technology to be utilised. The HF utilises iron attenuators impregnated with quartz fibres to measure the energies of particles from their emitted Cherenkov light

which is measured with Photomultiplier Tubes (PMTs) [84]. A combination of short and long fibres are used to enable a differentiation between hadronic showers and those arising from electrons and photons.

The energy resolution of the barrel combined ECAL and HCAL systems have been measured in test beam to be [85]:

$$\left(\frac{\sigma_E}{E[\text{GeV}]}\right)^2 = \left(\frac{84.7 \pm 1.6\%}{\sqrt{E[\text{GeV}]}}\right)^2 + (7.4 \pm 0.8\%)^2. \quad (2.2)$$

In addition, in-situ calibration is performed via UV laser and $^{137}\text{Cs}/^{60}\text{Co}$ sources that can be inserted into scintillation tiles in the HB and HE source tubes.

The signal pulse collection time of the scintillator is relatively large with respect to the LHC design collision frequency, with only 68% of the pulse from scintillator tiles being contained within 25 ns, requiring several 25 ns collisions to fully dissipate. This effect makes the HCAL susceptible to OOTPU [70].

2.3.4 Solenoid

Influential in dictating the design of the CMS detector is its superconducting solenoid [70], the largest superconducting magnet ever constructed. Enclosing the central detectors, it generates a 3.8 T homogeneous magnetic field that facilitates a compact design via the strong bending of charged particles. To enable a high field to be maintained, a 10,000 tonne return yoke encloses the solenoid, which consists of five barrel wheels and six endcap disks. This provides structural integrity to the detector and additionally acts as an absorber to separate muons from punch-through particles in the muon system.

The solenoid itself comprises of five modules, each of inner diameter 6.3 m and length 2.5 m, which weigh a total of 220 tonnes. Each module has four winding layers of NbTi wires co-extruded with aluminium within a aluminium support, enabling the solenoid to withstand the large stresses of the magnetic field. Enclosing the magnet, a vacuum cryostat provides insulation and cooling, with liquid helium used to maintain a temperature of 4.5 K. A detailed calibration of the magnetic field within the detector was performed on the surface prior to installation in the cavern, providing a magnetic field map with a precision of 5×10^{-4} [86].

2.3.5 Muon system

Muons provide a distinct event signature which are present in the final states of many physics searches, including: Higgs boson decays via the golden channel, $h \rightarrow ZZ^*$, with subsequent decays to muons, and supersymmetric decays with leptonic final states. The efficient selection and precise measurement of muons over the full detector acceptance was therefore a primary design goal for CMS. The choice of a strong magnetic field and compact design enables the efficient trigger selection and high resolution momentum measurements of muons over a large rapidity range. This in addition enables an excellent charge identification, with a charge misassignment inefficiency of $< 0.1\%$ at $p_T = 100$ GeV over a large kinematic range [70].

The CMS muon system encloses the exterior of the detector, performing measurements of muons over the acceptance $|\eta| < 2.4$ with an active area of $25,000 \text{ m}^2$ [70]. The muon system utilises three different gaseous chamber technologies to perform measurements of muons in different operating environments. In the barrel region where there is a uniform magnetic field and low radiation flux Drift Tubes (DTs) are utilised, which cover the region: $|\eta| < 1.2$. In the endcap where the radiation and muon flux is higher and the magnetic field strength is strong and non-uniform Cathode Strip Chambers (CSCs) are used, providing coverage over the range: $0.9 < |\eta| < 2.4$. For redundancy, an additional Resistive Plate Chamber (RPC) system instruments the barrel and endcap in the range: $|\eta| < 2.1$, providing additional spatial measurements but primarily to provide temporal measurements. In total the muon system comprises of 1400 individual chambers: 250 DTs, 540 CSCs and 610 RPCs, the geometry and coverage of the individual elements are shown in Figure 2.10.

The DT subsystem utilises chambers of dimension $2 \times 2.5 \text{ m}^2$ filled with an Ar/CO₂ gas mix. These are segmented into 12 layers in depth, each containing an array of $13 \text{ mm} \times 42 \text{ mm}$ rectangular cells that span the length of the chamber, with each housing a $50 \mu\text{m}$ sense wire providing a fast 380 ns maximum drift time. These layers are collected into superlayers, layer quadruplets, which are stacked with an orthogonal arrangement of an Rz -superlayer sandwiched between two $R\phi$ -superlayers, providing a position resolution of $80 - 120 \mu\text{m}$ per chamber. The barrel is instrumented with four layers of DT chambers, with a chamber inside and outside the yoke and a further two within the yoke itself.

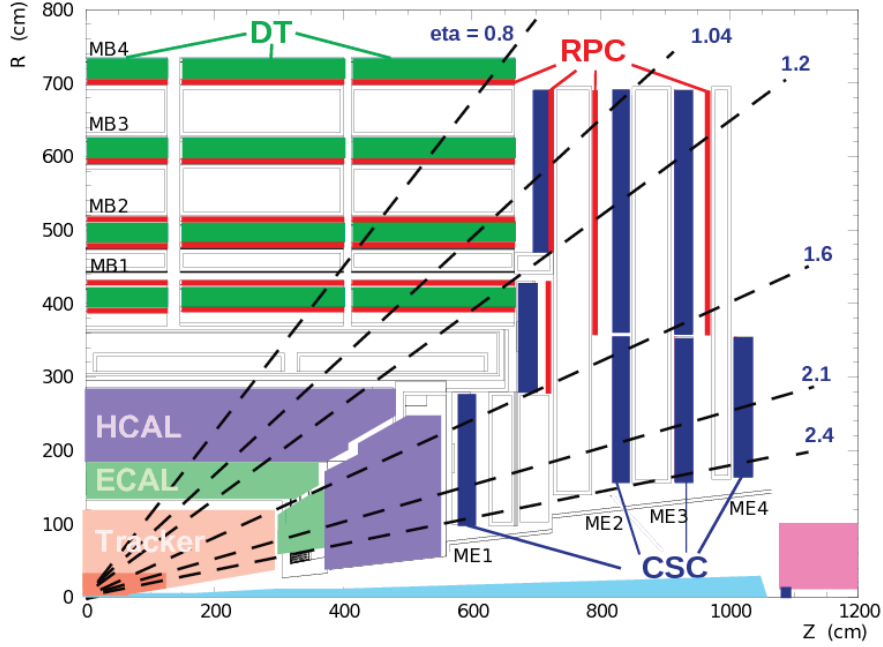


Figure 2.10: Longitudinal cross-section of a quadrant of the Muon system showing the positions of the Drift Tube (DT), Resistive Plate Chamber (RPC) and Cathode Strip Chamber (CSC) subsystems [87].

The CSCs are trapezoidal chambers, containing an Ar, CO₂ and CF₄ gas mix. Within each chamber there are six detection layers which consist of arrays of 50 μm anode wires of 3.2 mm spacing, sandwiched between copper cathode strips with widths ranging from 6.7 – 16.0 mm, enabling a determination of the muon ϕ -position with a resolution of 75 – 150 μm . The chambers are arranged in disks of four layers per endcap, providing a measurement of muon tracks with a resolution of 40 – 150 μm .

The RPC modules consist of two RPC units, oppositely charged bakelite plate electrodes separated by a 2 mm gas gap, which sandwich a sensitive strip layer. These possess poorer position resolutions of 0.8 – 1.2 cm per chamber but provide an excellent temporal resolution of 3 ns. Six layers of RPCs instrument the barrel, with a further four layers arranged in disks in the endcap. During LS1 an additional 4th layer of RPCs were installed in the endcap to further improve the measurement of muon momenta in the forward region.

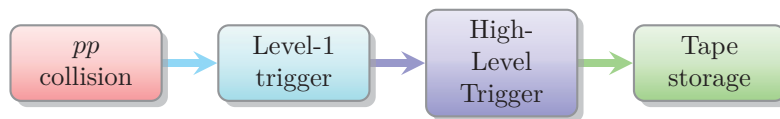


Figure 2.11: Schematic of the processing path of data, from: the recorded collision with the CMS detector, processing with the L1 trigger and HLT and permanent storage on tape.

2.4 Trigger system

A major challenge in many high energy physics experiments is the efficient and swift selection of candidate signal events within constraints in data bandwidth, storage and latency. For this purpose, particle physics experiments utilise sophisticated trigger systems that perform fast reconstruction and selection, retaining events of interest and discarding those of lesser importance. Trigger selection at the LHC is particularly challenging with a ~ 100 mb total pp interaction cross section at the design energy yielding a peak interaction rate of 10^9 pp -collisions per second. In addition, the short 25 ns bunch spacing of the LHC requires that events are reconstructed and analysed with low latency.

To operate effectively at the LHC, where huge data rates are required to be processed within a low latency, CMS utilises a high performance two-tier trigger system, illustrated schematically in Figure 2.11. The first selection is performed by the Level-1 (L1) trigger, high performance electronics, which perform a fast reconstruction and selection which reduces the data rate from 40 MHz to 100 kHz. This rate is further reduced by the High Level Trigger (HLT), software running on a computer farm, which performs a fast analysis of the event to make the final decision of whether to retain the event, outputting at a peak data rate of ~ 1 kHz to tape to be properly reconstructed.

2.4.1 Level-1 trigger

The first stage in the selection of the CMS trigger system is performed by the L1 system [88]. Event selection begins with a precise timing pulse sent by a local clock synchronised to the LHC bunch collision, which initiates the partial readout of subdetector signals off-detector and of the on-detector storage of data in L1 pipelines.

The limited pipeline depth restricts the L1 trigger to a total latency budget of $3.2 \mu\text{s}$, of which $\sim 2 \mu\text{s}$ is required for the transmission of data to and from the detector. The L1 trigger system therefore requires the use of fast, high-performance electronics and optical links to perform a fast event reconstruction and trigger decision. Due to constraints

in latency and bandwidth, the L1 trigger processes a reduced level of information from only the calorimeter and muon system. This is processed in dedicated electronics units that reconstruct physics objects and quantities in local regions of the detector which are passed to the global trigger which performs the final trigger decision. In the event of a L1 trigger accept, a full detector readout is performed and transmitted off-detector to the final triggering stage.

2.4.2 The High Level Trigger

In the occurrence of a L1 accept, the full detector information is readout from the on-detector Front End Drivers (FEDs) and sent to the final stage in the CMS trigger chain, the HLT. The HLT [89] is a high-performance computer farm that performs a complete event reconstruction using the complete detector information. With a larger ~ 4 ms latency budget and access to the full detector information, the HLT is able to perform a full reconstruction with all subdetectors, giving performance more similar to offline reconstruction. Due to the latency constraints however, simplified reconstruction algorithms are utilised at the HLT.

To mitigate latency, the HLT uses a trigger-chain model with reconstruction performed in a modular fashion known as *HLT paths*. Each HLT path sequentially executes reconstruction and filter steps which terminate at the first instance a filter step fails to meet a selection criterion. HLT paths use faster reconstruction stages, such as calorimeter reconstruction, as early pre-filters to reduce the pass-through rate of the trigger prior to execution of time-intensive reconstruction stages such as track reconstruction. The selection of HLT trigger paths are also tuned to meet both rate and timing constraints.

Events passing the HLT selection are then transmitted to the CERN main Tier-0 data center for permanent storage and event reconstruction. A GRID infrastructure [90] provides distributed data storage and processing across the globe at dedicated computing sites. The GRID operates on a four ‘tiered’ computing model, with each tier representing the importance of the site and the access available to users. Data are replicated from the CERN Tier-0 across the globe to 13 Tier-1 computing centres which are subsequently accessed and processed by analysts at Tier 2 and Tier 3 sites.

CHAPTER 3

Reconstruction

The precise measurement of the properties of all particles produced in collisions at the LHC is the primary goal of the CMS detector, making the efficient reconstruction and identification of particles a priority. This is however a challenging task at the LHC where pp -collisions produce a high-multiplicity of particles of a range of species and energies with high frequency. To perform an effective event reconstruction in this challenging environment CMS utilises state-of-the-art techniques in the reconstruction, selection and calibration of physics objects to ensure optimal physics performance.

3.1 Detector reconstruction

Prior to the reconstruction of particles, the processing of signals from individual subdetectors must first be performed to produce the necessary information for the physics object reconstruction algorithms. Each subdetector uses specialist reconstruction algorithms to suppress background contributions, mitigate pileup and ensure high precision energy, position and temporal measurements. Although diverse in their use of algorithms, subdetector reconstruction can be categorised as either the reconstruction of the trajectories of charged particles, known as *tracks*, or the measurement of energy in calorimetric reconstruction.

3.1.1 Track reconstruction

The tracking detector reconstructs the trajectories of charged particles from ionisation energy deposits left as they traverse the detector which are known as *hits*. In the tracking detector track reconstruction is performed using the Combinatorial Track Finder (CTF) algorithm [91], which performs a recursive seeding, finding and filtering of tracks. The details of the algorithm are described below:

- Tracks are seeded from hits in the innermost layer of the tracking detector, with quality selections applied to reduce the probability of fake tracks from combinatorial combinations of tracking detector hits. Candidate seeds are required to consist of a minimum of three hits, with a looser two hit requirement if the trajectory is compatible with the beamspot and meets a minimum p_T requirement;

- The trajectories of candidate tracks are extrapolated into the next tracking layer using the Kalman filter method [92], which projects the trajectory of the particle accounting for deviations in trajectory from energy losses and multiple scattering. As the magnetic field within the tracking volume is approximately uniform, the algorithm uses a helical tracking hypothesis when performing the track fit;
- A recursive extrapolation and fitting of tracks into subsequent layers of the tracking detector is then performed. For each extrapolated track, multiple candidate tracks are constructed from the inclusion of tracker hits in proximity to the track trajectory. These candidate tracks are then filtered, retaining those with the highest quality;
- The tracks are extrapolated in parallel to subsequent tracking layers until reaching the outer-most tracking layer or until a specified stopping condition is met. These tracks are finally filtered, removing duplicate reconstructed tracks and ensuring a high quality track fit.

Track finding is repeated up to a total of six times, removing hits associated with reconstructed tracks in each iteration, reducing the combinatorial complexity of further iterations and enabling the use of looser tracking criteria to reconstruct low momentum tracks. Tracks in the muon system are reconstructed independently of the tracker system using the CTF algorithm, with hits in the muon system reconstructed to form muon proto-tracks called *muon track-stubs*.

The use of high-granularity silicon detectors in a strong magnetic field enables the tracking detector to perform an efficient and precise reconstruction of the position and energy of charged particles in the inner detector. This is demonstrated in Figure 3.1, which shows the performance of track reconstruction for muons and charged pions in simulated $t\bar{t}$ decays. Both pions and muons are efficiently reconstructed to low momenta over a large pseudorapidity range, with charged pions of momenta $p_T > 0.9 \text{ GeV}$ in the regions $|\eta| < 0.9$ and $0.9 < |\eta| < 2.5$ being reconstructed with a 94% and 85% efficiency respectively. As muons do not undergo nuclear interactions with the tracking detector, they are reconstructed with near full efficiency across the entire tracking detector. In addition the detector provides high precision measurements of track momentum, with a momentum resolution of less than 2% achieved for tracks $p_T < 10 \text{ GeV}$ in the central region: $|\eta| < 1$.

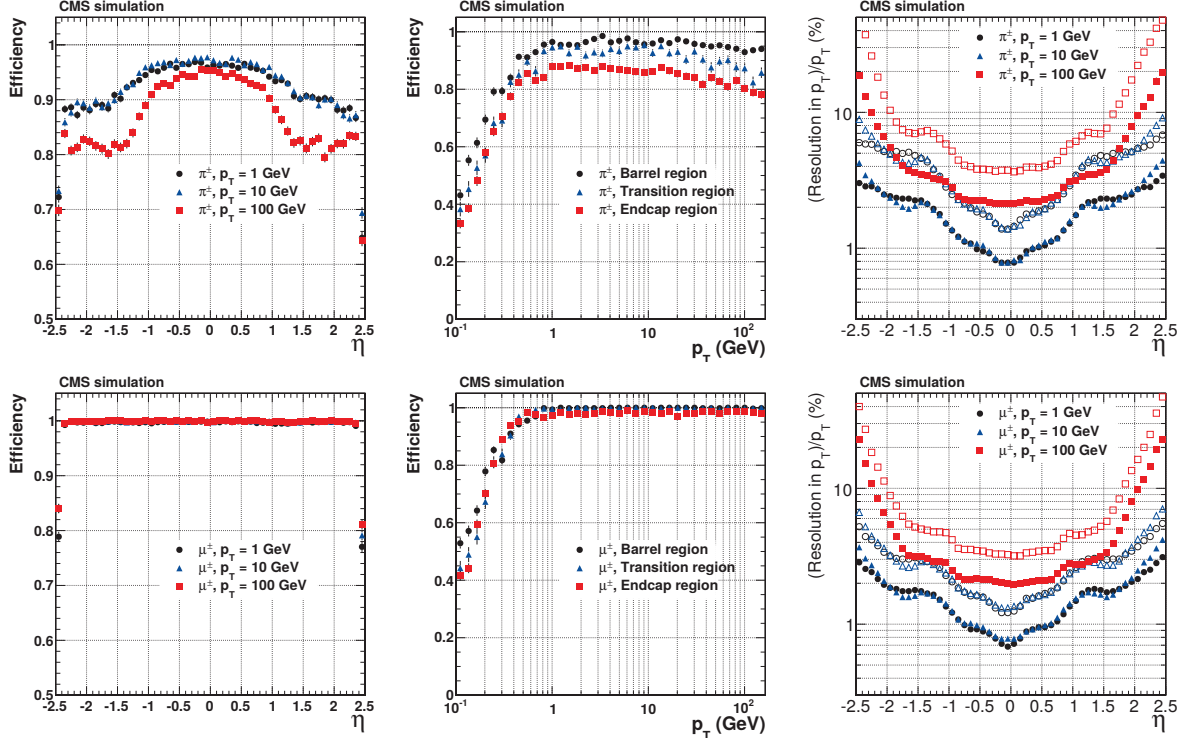


Figure 3.1: Tracking performance of isolated charged pions (top) and muons (bottom) measured in simulation for a range of momenta and localities. Track reconstruction efficiency is shown both as a function of pseudorapidity (left) and track p_T (middle). Track p_T resolution is shown as a function of pseudorapidity (right), where the solid and open circles correspond to the half-width for the 68% and 90% intervals [91].

3.1.2 Vertex reconstruction

In addition to track reconstruction another important task of the tracking detector is the reconstruction of the position of individual pp -interactions, known as *interaction vertices*. These are not only important in the reconstruction and selection of particles but also in the determination of the luminous focal region of the beam where pp -collisions take place, known as the *beamspot*, and in the estimation and correction of pileup. Vertices are reconstructed by specialist algorithms that, utilising reconstructed tracks, perform the selection and clustering of tracks into individual vertices as described below:

- Vertex reconstruction begins with quality selections on the candidate tracks, with requirements applied on the χ^2 of the track fit and the minimum number of hits in the tracking detector. In addition, a selection of a $< 5\sigma$ significance of the transverse impact parameter with respect to the beamspot is applied, ensuring tracks

are compatible with the interaction point;

- Vertex candidates are seeded by combinations of two or more selected tracks separated by a distance of less than $z = 1$ cm. Additional tracks are aggregated into these candidate vertices by the *deterministic annealing algorithm* [93] which performs track selection, clustering and a fitting of the vertex position;
- The x, y, z position of these candidate vertices is then determined by the *adaptive vertex fitter* [94] which ascertains the most probable position of the vertex.

To reject fake vertices, each track associated to a vertex is assigned a weight, w_i , with value between 0 and 1. This weight is computed from the compatibility of the track to a vertex using the deterministic annealing algorithm, with a value of 1 being assigned for the most compatible match. From these weights the number of degrees of freedom of a vertex, N_{dof} , is computed by the relation:

$$N_{\text{dof}} = 2 \sum_i^{N_{\text{tracks}}} w_i - 3. \quad (3.1)$$

A selection of $N_{\text{dof}} > 4$ provides a good rejection of fake vertices whilst remaining efficient for real vertices, which typically have a large number of tracks compatible with the vertex.

After the selection of collision vertices the determination of the signal vertex, known as the *primary vertex*, is performed. For each vertex the sum of the square of the track momenta is computed, with the vertex that possesses the greatest sum selected as the primary vertex and the remaining defined as pileup vertices. Figure 3.2 shows the performance of the position reconstruction of the primary vertex in the x and z dimensions measured in minimum bias and jet-enriched events in data. Position resolution is shown to be improved for tracks with high momentum, as illustrated by the improved performance in the high momentum selections of the jet-enriched sample. Vertex resolution also improves with greater track multiplicities, achieving resolutions of $\sim 10 \mu\text{m}$ in x , y and $\sim 15 \mu\text{m}$ in z for primary vertices with 40 reconstructed tracks.

3.1.3 Calorimeter reconstruction

Calorimetric reconstruction aims to fully reconstruct the initial energy of the incident particle in the calorimeters via the calibration and clustering of calorimeter energy deposits. The calorimeters provide supplementary measurements of the energy and position of particles, complementing the measurements performed in the tracking detector and acting as

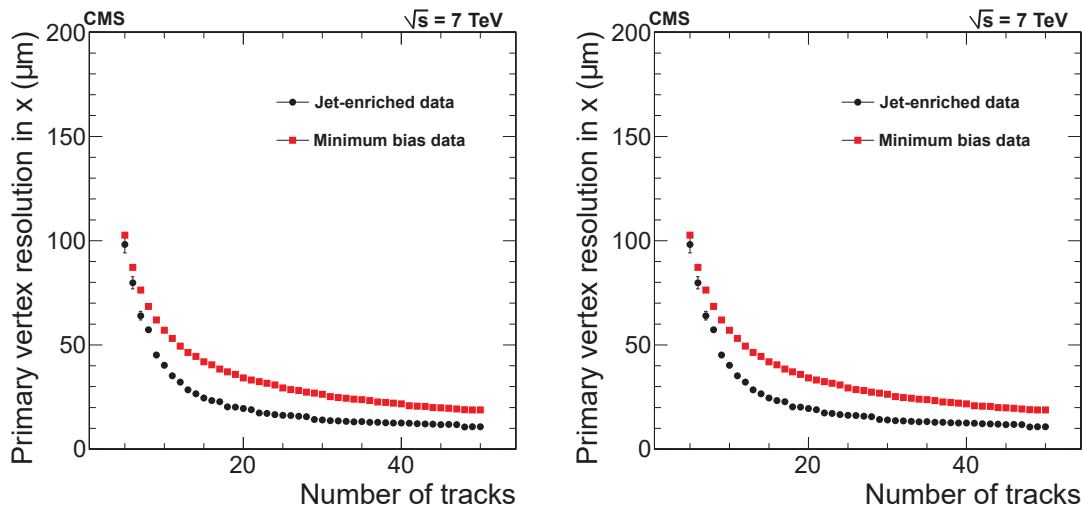


Figure 3.2: Position resolution of the primary vertex as a function of reconstructed track multiplicity in the x (left) and z (right) dimensions measured in data for jet-enriched and minimum bias events. The resolution in the y -dimension is similar to that shown in the x -dimension [91].

a redundancy in the event of track misreconstruction. In addition they play important roles in the reconstruction of neutral particles, particle identification and in rapid event reconstruction for the trigger system.

Calorimeters reconstruct energy by sampling amplified light pulses from their photodetectors over multiple 25 ns time sampling windows, calibrating the measured signal to an absolute energy. Operating at a 25 ns bunch crossing rate can however result in particle energies from previous and subsequent bunch crossings being integrated in this sampling, inflating the estimate of energy. To compensate for this effect, customised reconstruction techniques were developed to correct the OOTPU contribution for Run 2. Adapting the Run 1 method of reconstructing ECAL energy from a weighted sum of ten 25 ns time samples, the new ECAL multi-fit method [95] utilises a fit with pulse templates measured in low-pileup conditions to better extract the signal pulse from OOTPU. A similar calibration scheme is used in the HCAL to correct for OOTPU, significantly improving the energy resolution of low- p_T particles.

3.2 Physics object reconstruction

After the reconstruction of detector signals, the final stage of reconstruction is the identification and selection of individual particles and jets, which are collectively referred to as *physics objects*. Reconstruction is performed by a combination of dedicated local detector algorithms and the global event Particle-Flow (PF)-algorithm to ensure high efficiency reconstruction over a large range of energies. Selections are applied to these reconstructed objects to reduce the probability of fakes whilst maintaining a high reconstruction efficiency. For this purpose different Working Points (WPs) are utilised whose selections offer differing levels of background rejection and signal efficiency.

3.2.1 e/γ reconstruction

Although electrons and photons physically have very different properties, the mechanisms by which they interact with the detector are similar and hence share similar reconstruction techniques. Interactions of electrons and photons are fully contained within the ECAL and are reconstructed with a combination of information from the tracking detector and ECAL. Electrons are reconstructed by the matching of tracker and ECAL energy deposits using two methods: a tracker-driven reconstruction, which is performed by the Particle-Flow (PF)-algorithm described in Section 3.3, which gives high efficiency for low- p_T electrons and an ECAL-driven reconstruction described below.

Interactions of electrons with the tracking detector lead to increased energy loss via bremsstrahlung emission, requiring dedicated reconstruction techniques. Electrons lose on average 33% of their initial energy prior to reaching the ECAL for central rapidities and up to 86% at $|\eta| \sim 1.4$ where the total material traversed is largest [96]. As energy loss through bremsstrahlung is non-Gaussian, the Gaussian energy loss model of the Kalman filter leads to tracking inefficiencies, requiring instead a specialist track reconstruction with the Gaussian Sum Filter (GSF) algorithm [97]. To fully reconstruct the energy of electrons, the energy deposits from bremsstrahlung photons must also be clustered with the electron energy deposit. Due to bending of electrons in the magnetic field, the energy emission from bremsstrahlung is extended in azimuth around the electron ECAL deposit, motivating the clustering of electrons and their associated bremsstrahlung with rectangular ECAL windows called *superclusters*.

Supercluster reconstruction is performed by the *hybrid* and *multi-5×5* algorithms which are utilised in the barrel and endcaps respectively. The algorithms perform a dynamic clustering of ECAL energy deposits that are spatially connected to a local energy maxima seed crystal. The hybrid clustering algorithm starts with a seed ECAL crystal, and clusters additional ECAL strips of single crystal width in azimuth and three or five width in η , which are dynamically extended in azimuth up to a total of $\Delta\phi \pm 0.3$. The 5×5 clustering algorithm is more simple, aggregating 5×5 clusters of crystals that are centred on a seed ECAL crystal. These reconstructed superclusters are used in the reconstruction of all electrons and photons in the event. Superclusters matched to tracks from the primary vertex with hits in the pixel detector are reconstructed as electrons, with the remaining superclusters reconstruction as photons.

Selections on the electron track transverse and longitudinal impact parameters of $d_{xy} < 0.118$ cm and $d_z < 0.822$ cm are applied to suppress backgrounds from: misreconstructed jets, secondary electrons produced in photon conversions in the tracker and semi-leptonic decays of heavy quarks. Additionally, as the majority of electrons and photons are fully contained within the ECAL, selections on the ratio of energies in the ECAL and HCAL are applied to suppress hadron fakes.

3.2.2 Muon reconstruction

As Minimally Ionising Particles (MIPs), Muons are distinctive signatures of the decay of vector bosons and the heavy quarks, traversing the entire detector without leaving significant energy in the calorimeters. Muon reconstruction is performed using a combination of trajectories from the tracking detector and muon systems. To ensure high efficiency across the muon momentum spectrum two algorithms are used in the reconstruction of muons, the ‘outside-in’ *global muon* algorithm and *PF-muon* algorithm, described in Section 3.3, and the ‘inside-out’ *tracker muon* algorithm described below.

The tracker muon algorithm performs an inside-out reconstruction, extrapolating tracks in the inner detector with momentum above 0.5 GeV into the muon system, using the Kalman filter to account for energy loss in the calorimeters. Tracks that can be matched to at least one muon chamber with a track hit are reconstructed as muons. Performing an extrapolation of tracks into the muon system, the tracker muon algorithm provides a higher reconstruction efficiency for low-momentum muons, which have a lower probability of traversing the entire muon system.

Muons with higher momentum are more effectively reconstructed by outside-in algorithms such as the global muon algorithm. Muon track stubs are first reconstructed with the standalone muon algorithm, which uses hits in muon chambers to provide an initial estimate of the energy, position and direction of seed candidate muons. The global muon algorithm takes these reconstructed standalone muons and searches for candidate matching tracks in the tracking system, combining tracks that are measured to be a good fit with the Kalman filter algorithm.

Muons are required to be reconstructed by either of the PF, global or tracker muon algorithms, which combined provide a $\sim 99\%$ reconstruction efficiency. The use of complementary information from the tracking and muon detectors provides significant improvements in muon reconstruction performance which, illustrated in Figure 3.3, surpasses the performance that can be achieved independently by the tracking and muon systems. For muons of momenta $p_T^\mu < 200 \text{ GeV}$ the tracking detector provides the highest resolution of the energy measurement of muons. Tracker reconstruction also provides a recovery of efficiency for muons with momentum below $p_T < 5 \text{ GeV}$, which have a smaller probability of traversing the full muon system. At higher momenta, where the trajectories of the muon have smaller curvature, the muon system becomes dominant in the measurement of track

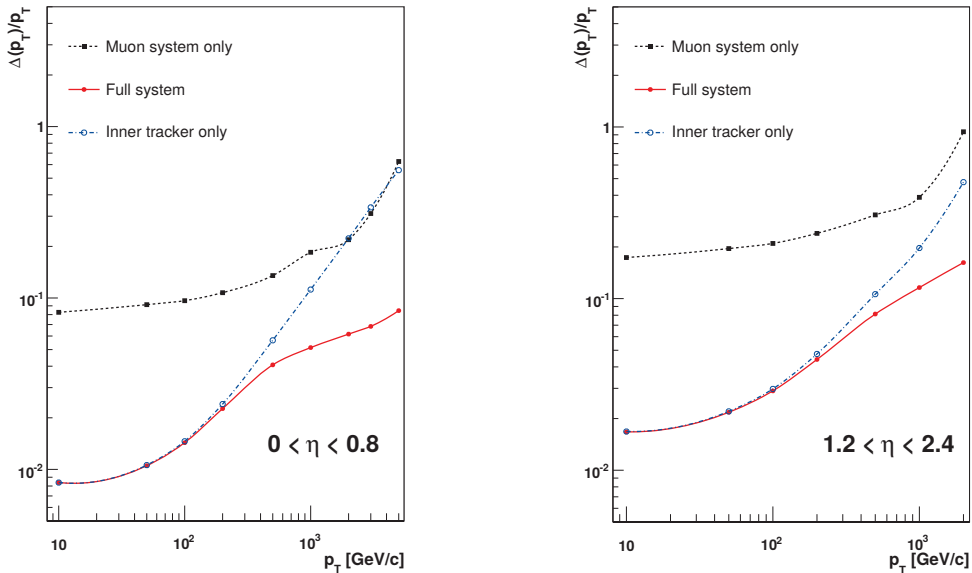


Figure 3.3: Momentum resolution of reconstructed muons using the tracker detector alone (blue dashed-line), the muon system alone (black dashed-line) and combined reconstruction with the muon and tracking detectors (red solid line) [78].

momentum.

After reconstruction, a series of selections are applied to reduce the rate of fake muons from hadronic punch-through and non-prompt muons, whilst maintaining a high efficiency for genuine muons. This includes quality selections on the χ^2 compatibility of the muon track fit and on the minimum number of valid tracker hits. In addition, requirements on the transverse and longitudinal impact parameters of $d_{xy} < 0.05$ cm and $d_z < 0.1$ cm, respectively, are made to ensure consistency with prompt production and reduce cosmic-muon fakes.

3.3 Particle-Flow reconstruction

After the local reconstruction of detector signals in individual subdetectors is performed, the reconstructed tracks and calorimeter energy deposits are passed to the Particle-Flow (PF) algorithm for the final reconstruction. The PF algorithm combines information from all the subdetectors to provide particle-based event reconstruction, providing an output not dissimilar to particle-level information obtained from simulation. Exploiting the information of all subdetectors enables the PF algorithm to provide significant improvements to the measurements of particle properties, energies and trajectories than could be achieved by any one subdetector alone. This provides a compensation for the changing resolution of the subdetectors in different kinematic regimes and geometries to obtain the best possible reconstruction performance.

The design of the CMS detector is well-suited for PF reconstruction, with a strong magnetic field and full-silicon tracker enabling high-resolution measurements of charged particles, a high granularity ECAL which enables the identification of photons within jets and a calorimetry system that is internal to the solenoid enabling a continuous measurement of the particle energy flow. PF reconstruction uses a sophisticated link algorithm which iteratively checks the compatibility of the trajectory, energy and temporal information between pairs of subdetector measurements. When a compatible match is successfully found, a single particle hypothesis known as a *PF-candidate* is created, whose energy and momentum are determined from the combined measurement of the subdetectors. The energy and tracks associated with the PF-candidate is removed from the event and the process repeated until all signals in the event are fully reconstructed.

Although hundreds of different species of particles are produced at the LHC, only a small fraction have sufficiently long lifetimes and interaction strengths to be directly measured by the detector subsystems. Of these stable species, eight are predominant in measurements of the CMS detector: γ , $e^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$, $p^\pm$, K^0 and n , motivating the classification of reconstructed PF particles into five categories: *photons*, *electrons*, *muons*, *charged hadrons* and *neutral hadrons*. The behaviour of the matching performed by the link algorithm follows the particle-dependent process described below:

- First an independent clustering of energy in the ECAL and HCAL from selected seed clusters, calorimetric local energy maxima, above a specified energy threshold is performed. These seeds undergo a dynamic extension via the clustering of neighbouring calorimeter energy deposits to form *topological clusters* until all energy is clustered. The total energy in each topological cluster is then shared between all encompassed seed clusters to become independent *PF-Clusters*. These PF-clusters and reconstructed tracks form the basis for the PF reconstruction of the event;
- A selection of *PF-muons* is then performed using reconstructed global muons, with a requirement that the track momentum measurement is in agreement with that of the combined muon track within three standard deviations of the momentum resolution. The tracks associated with muons passing selection are removed from the event and the expected energy deposition in the calorimeters along the muon trajectory are removed. This has been measured from cosmic ray muons to be 3 GeV and 0.5 GeV in the HCAL and ECAL respectively;
- In the next stage tracks are tested for consistency with an electron hypothesis by applying a loose electron pre-identification. Energy from bremsstrahlung losses are recovered by linking ECAL energy deposits that are tangential to the electron's trajectory at each tracker layer. Tracks consistent with supercluster hits are classified as *PF-electrons* and the corresponding tracks and ECAL energy deposits are removed;
- Finally, the linking algorithm iterates through all remaining tracks and calorimeter energy deposits to reconstruct hadrons and photons. For charged hadrons, tracks are extrapolated to the surrounding subdetectors and a match made if an energy deposit is found within a specified distance window. If the track energy measurement is compatible with a linked calorimeter deposit, within the calorimeter energy resolution, the composite is defined as a *PF-charged hadron* with a pion mass hypothesis and is removed from the event. If the calorimeter energy measurement is

larger than the track measurement, then the remaining ECAL energy is clustered as *PF-photons* and the remainder HCAL energy clustered as *PF-neutral hadrons*. If the reconstructed energy in the calorimeter is significantly smaller than the track measurement, the track is reconsidered as a PF-muon using a new track fit with looser requirements applied.

Following reconstruction, a calibration is performed on the ECAL and HCAL energy components of PF-hadrons to correct the energy response of the calorimeters assuming a pion hypothesis. As the ECAL is calibrated to the response of electrons and photons, a correction is applied to compensate for the expected pion response. Additionally corrections are applied on HCAL measurements to compensate for non-linearity and correct for test beam calibrations which were performed without the presence of the ECAL.

3.3.1 Pileup estimation

An important aspect of reconstruction is the estimation and correction of particles arising from pileup, for which several dedicated techniques are utilised. Tracking information can be used to remove charged particles that are not associated with the primary vertex however cannot directly correct the neutral particle component of pileup. From the relative composition of neutral to charged particles in simulation however, an estimate of the ratio of the energies carried by neutral and charged particles in pileup can be estimated. This motivates the correction for the neutral component of pileup by applying an additional multiplicative factor to the measured charged pileup component, which in the barrel is estimated to be 50% of the energy of the neutral pileup component.

Additional mechanisms of pileup subtraction estimate the pileup energy density, ρ , from which the energy contamination over an object's active area, A , can be determined by the relation:

$$p_{\text{T}}^{\text{Corr}} = p_{\text{T}}^{\text{Raw}} - \rho \cdot A. \quad (3.2)$$

In Run 2 the pileup energy density is estimated from the energy density of all PF-candidates within a square grid of cells with length 0.55. The pileup energy density is then estimated as the median energy density of all cells, including those with no energy [98].

3.3.2 Isolation

An important task in the identification of leptons is the separation of *prompt* leptons, leptons produced in the primary *pp*-collision, from those produced in secondary decays of

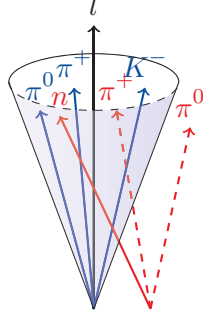


Figure 3.4: Schematic of the computation of isolation in a cone centred on a lepton, l , from particles associated with the primary vertex (blue) and a pileup vertex (red). Solid lines represent particles whose momentum is used in the scalar sum of momentum and dashed lines represent particles excluded from the calculation.

unstable particles, known as *non-prompt*. These two species can be distinguished by the level of hadronic activity that surrounds the lepton, as non-prompt leptons are typically produced within jets and prompt leptons in regions of low hadronic activity. The degree of activity around a particle is measured by its *isolation*, which is computed as the fraction of total energy of all particles within a cone centred on the lepton with respect to the lepton energy. As prompt particles typically have a lower local particle activity, lower values of relative isolation can be used as a method of distinguishing prompt from non-prompt particles.

The standard method of the computation of isolation used by CMS is *PF relative isolation*, $I_{\text{PF}}^{\text{rel}}$, which is computed as the ratio of the total momentum of PF-particles within a cone of radius ΔR centred on the lepton direction and the momentum of the lepton:

$$I_{\text{PF}}^{\text{rel}}(p_{\text{T}}^l) = \frac{1}{p_{\text{T}}^l} \left[\sum_{\text{PF}_{\text{PV}}} p_{\text{T}}^{\text{CH}} + \sum_{\text{PF}} p_{\text{T}}^{\text{NH}} + \sum_{\text{PF}} p_{\text{T}}^{\gamma} - \sum_{\text{PU}} p_{\text{T}}^{\text{Neutral}} \right], \quad (3.3)$$

where p_{T}^l is the momentum of the lepton and p_{T}^{CH} , p_{T}^{NH} and p_{T}^{γ} are the momentum of charged hadrons, neutral hadrons and photons respectively. To reject particles from pileup, only charged hadrons that are associated with the primary vertex are utilised in the isolation computation. As no vertex can be assigned to reconstructed neutral hadrons and photons, all the energy of neutral particles within the cone are utilised and an additional correction for neutral pileup, $\sum_{\text{PU}} p_{\text{T}}^{\text{Neutral}}$, is applied.

An illustration of the computation of isolation is shown in Figure 3.4. In this example although the charged pion from the pileup vertex within the cone is removed, the pileup neutron however cannot be distinguished from other prompt neutral particles and is included in the computation of isolation. This contamination must be corrected by pileup correction methods, such as the $\Delta\beta$ -correction and *Effective Area (EA)*-correction, which are commonly used by CMS. In both cases to avoid over-correction, the magnitude of the neutral pileup energy correction is constrained by the total PF neutral hadron and photon energy measured within the cone.

The $\Delta\beta$ -correction estimates the energy of pileup neutral hadrons within the cone from the charged particles that are associated with pileup vertices. Using the 1:2 ratio of neutral to charged particles determined in simulation, the correction for the neutral component is estimated from the pileup charged component by the relation:

$$\sum_{\text{PU}} p_{\text{T}}^{\text{Neutral}} = \frac{1}{2} \sum_{\text{PF}_{\text{PU}}} p_{\text{T}}^{\text{CH}}. \quad (3.4)$$

The *EA*-correction corrects the expected neutral pileup energy contained within the footprint of the particle, A_{Eff} , which is measured as a function of particle species and pseudorapidity. The product of the particle's footprint and the grid pileup energy density computed from neutral particles, $\rho_{\text{grid}}^{\text{Neutral}}$, is utilised as the estimate of the total pileup energy contamination by the relation:

$$\sum_{\text{PU}} p_{\text{T}}^{\text{Neutral}} = \rho_{\text{grid}}^{\text{Neutral}} \cdot A_{\text{Eff}}(l, \eta). \quad (3.5)$$

In the decay of massive particles, such as top decays, jets produced in association with the lepton can be boosted into a collinear configuration, increasing the hadronic activity within the isolation cone and hence reducing the efficiency of isolation. An alternative method for the determination of isolation is *mini-isolation*, $I_{\text{PF}}^{\text{mini}}$, which uses a dynamic isolation cone size to account for the boost of objects, recovering efficiency for lepton selection in boosted decays. Mini-isolation is computed in the same manner as relative PF-isolation, however utilises a cone radius that scales with boost. The radius of the cone ranges from $\Delta R = 0.2$ for a lepton momentum of $p_{\text{T}}^l < 50 \text{ GeV}$, decreasing with increasing lepton momentum to a minimum cone radius of $\Delta R = 0.05$ for $p_{\text{T}}^l > 200 \text{ GeV}$.

3.3.3 Isolated tracks

A significant background for hadronic searches with missing energy are ‘lost-lepton’ events, prompt leptonic decays with missing energy from the associated neutrino where the lepton fails to be reconstructed. Lost-lepton events can arise from a range of sources including misreconstructed e^- , μ^- decays and in hadronic decays of τ leptons. As prompt leptons are typically isolated, lost-lepton decays that occur within the tracker acceptance can be mitigated by a veto of isolated high-energy tracks. Isolated tracks are therefore selected from isolated charged PF-candidates that are associated with the primary vertex and pass selections on track quality.

3.4 Jet reconstruction

The coloured nature of the constituents of protons makes jets production a common occurrence in pp -collisions. Jet algorithms seek to reverse the fragmentation and hadronisation processes responsible for jets, to reconstruct information from the initial partonic interaction. To perform this effectively, clustering algorithms have to be insensitive to the addition of soft-particles, *infrared safe*, and to the collinear splitting of particles, *collinear safe*. Algorithms meeting these criteria are said to be *infrared collinear safe*, and theoretically provide a link between the jet and the underlying partonic interaction. The k_T -algorithm is an infrared collinear safe jet algorithm that is commonly used for the purpose of jet reconstruction in high energy physics.

3.4.1 The k_T -clustering algorithm

The k_T -clustering algorithm performs a sequential clustering of input objects, known as protojets, into jets of a specified minimum separation. The algorithm iterates through the list of protojets and for each possible combination computes two ‘distance measures’: the distance measure between pairs of pseudojets, d_{ij} , and between the pseudojet and the beam, d_{iB} , which are defined:

$$\begin{aligned} d_{ij} &= \min(k_{Ti}^{2p}, k_{Tj}^{2p}) \frac{\Delta R_{ij}^2}{\Delta R^2} \\ d_{iB} &= k_{Ti}^{2p}, \end{aligned} \tag{3.6}$$

where i , j , and k_{Ti} , k_{Tj} , are the indices and momenta of the protojets, $\Delta R_{ij}^2 = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$ is the pseudojets separation and ΔR is the radius parameter of the jet. In each iteration of the algorithm the following logical operations are performed until all the pseudojets have been clustered as jets:

- If $d_{ij} < d_{iB}$, the four-momenta of the pseudojets i and j are combined to form a new pseudojet and the original pseudojets are removed;
- If $d_{iB} < d_{ij}$, the pseudojet i is defined as a jet and is removed from the list of pseudojets.

The clustering behaviour of the algorithm is dependent on the exponent p used in the computation of the distance parameter. For the k_T algorithm the exponent is chosen as $p = 1$, which results in jets being clustered initially from the softest pseudojets to successively harder pseudojets. The anti- k_T clustering algorithm utilises a negative exponent $p = -1$ which has the converse behaviour, clustering first the hardest pseudojets to progressively softer pseudojets. A special case with $p = 0$ is used in the Cambridge/Aachen algorithm, in which case only the distance information between the pseudojets is utilised which is of interest in the clustering of boosted jets.

Jet clustering within CMS is primarily performed by the anti- k_T algorithm due to its greater resilience to pileup and tendency to cluster circular jets. In Run 1 anti- k_T jets were clustered with a radius parameter of $\Delta R = 0.5$, which has been reduced in Run 2 to $\Delta R = 0.4$ to mitigate pileup contamination. Several different types of jets are utilised by CMS which differ in their choice of input pseudojets, the most common are: Particle-Flow jets (PFJets) and Calorimeter jets (CaloJets), which are clustered from PF-candidates and calorimeter energy deposits respectively. In addition, Generator jets (GenJets) are utilised in simulation to obtain the particle-level jet energy, which are reconstructed from all visible Monte Carlo (MC) particles.

Jets are predominantly comprised of charged particles and photons which, in the central region, typically have a fractional composition of: 65% charged hadrons, 25% photons and 10% neutral hadrons. As a much higher position and energy resolution can be achieved with measurements from the tracking system than in the calorimeter, PF-reconstruction of jets provides significant advantages over calorimeter reconstruction. As illustrated in Figure 3.5, the momentum resolution that can be achieved by PFJets is significantly better than CaloJets, particularly at low momentum, in addition to providing an improvement

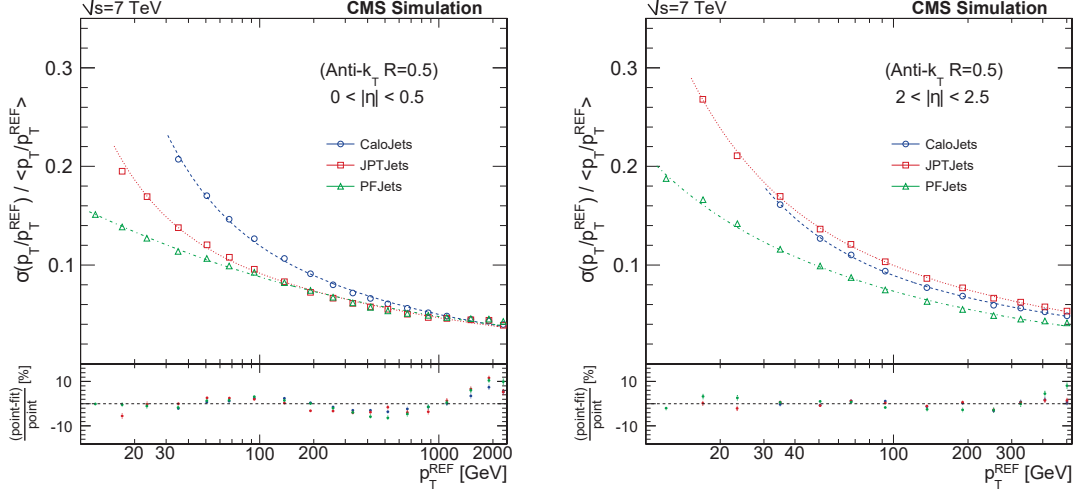


Figure 3.5: Momentum resolutions for jets reconstructed using Particle-Flow and calorimeter based reconstruction algorithms in the barrel region (left) and endcap (right), measured in simulation from the Gaussian width of the matched generator jet momentum p_T^{REF} [100].

in angular resolution by a factor of 2-3 [99]. For these reasons, only PFJets are utilised for physics analyses. However, due to their fast reconstruction CaloJets are heavily used in intermediate filters of the HLT, where low-latency is required.

After clustering jets undergo selection to reject fake jets. The ‘loose’ jet WP has requirements on the jet multiplicity of signals and energy fraction in the calorimeters and tracking detector to suppress jets from fake sources such as calorimeter noise. This has been measured in minimum bias simulation to provide an 84% suppression of fake jets whilst maintaining a greater than 99% efficiency for real jets.

3.4.2 Jet energy corrections

After reconstruction, the energy of clustered jets is approximately Gaussian-distributed around that of their true constituent partonic energy, as a consequence of random fluctuations in the particle composition in hadronisation and their varying detector responses. To recover the true energy of the hadronised parton, reconstructed jets undergo Jet Energy Corrections (JECs) that aim to correct their energies such that the mean of the jet energy distribution is in agreement with the particle-level. As the modelling of particles interactions with the detector in simulation is well understood, the correction is derived from the measuring response of reconstructed jets with their matched GenJets counterpart,

$p_T^{\text{RECO}}/p_T^{\text{GEN}}$. This provides a jet-dependent correction factor, C^{Corr} , which transforms the uncorrected jet transverse momentum, p_T^{Raw} , to obtain the corrected transverse momentum, p_T^{Corr} , by the relation:

$$p_T^{\text{Corr}} = C^{\text{Corr}}(p_T^{\text{Raw}}, \eta, \rho, A_j) \cdot p_T^{\text{Raw}}. \quad (3.7)$$

This correction is factorised into a sequence of independent corrections which compensate and correct for specific effects. The full correction can be deconstructed as the following sequential multiplicative corrections:

$$C^{\text{Corr}}(p_T^{\text{Raw}}, \eta, \rho, A_j) = C^{\text{Off}}(p_T^{\text{Raw}}, \rho, A_j) \cdot C^{\text{Rel}}(\eta) \cdot C^{\text{Abs}}(p_T^{\text{Rel}}). \quad (3.8)$$

The first stage of calibration is the *offset correction*, $C^{\text{Off}}(p_T^{\text{Raw}}, \rho, A_j)$, which corrects for energy contamination of pileup within the jet cone, as described in Section 3.4.2.1. Following this a *relative correction*, $C^{\text{Rel}}(\eta)$, is applied which compensates for the non-uniform detector response in pseudorapidity, correcting the response of forward jets to be in agreement with central jets. Finally an *absolute correction* is applied, $C^{\text{Abs}}(p_T^{\text{Rel}})$, which corrects the reconstructed jet p_T to be in agreement with that measured at the particle-level. An additional *residual* correction, $C^{\text{Res}}(p_T^{\text{Abs}}, \eta)$, is applied to jets reconstructed in data to correct for any small differences in the modelling of jets between data and simulation [101].

An illustration of the effect of the sequential corrections on the jet response in simulation can be seen in Figure 3.6. Without corrections the jet response of reconstructed jets shows a strong pileup-dependence, with a higher response measured as the pileup contamination increases, an effect that is dominant at low jet p_T . After the application of the offset correction this pileup dependence is removed, with only a p_T and η dependence remaining which is compensated for after all corrections are applied.

3.4.2.1 Offset correction

Prior to response corrections, the pileup energy contamination within the jet cone is corrected. This increases the stability of the calibration by reducing the overall magnitude of correction that is required. The degree of pileup energy contamination within the jet cone is correlated with the multiplicity of reconstructed vertices, N_{vtx} , which was measured in Run 1 to contribute on average an additional energy of $\Delta p_T = 0.72 \text{ GeV}$ per pileup

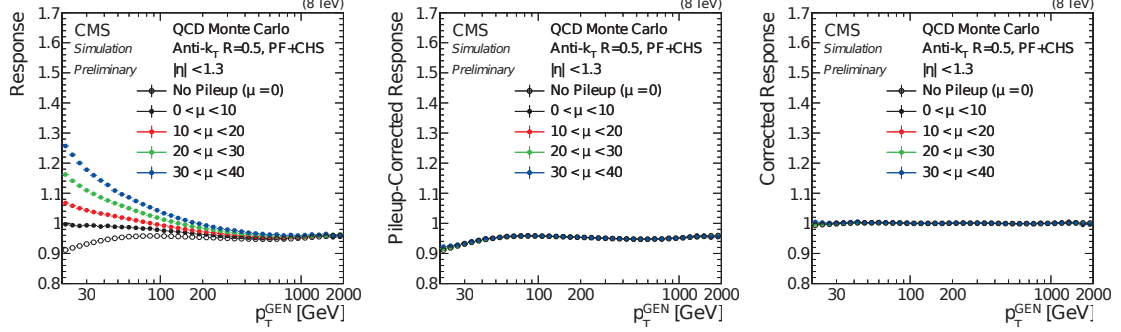


Figure 3.6: Measured jet response of central PFJets with radius parameter $\Delta R = 0.5$ in simulated QCD events for a range of pileup multiplicities (μ) as a function of their matched GenJet without corrections (left), after the offset correction (middle) and after the offset, relative and residual corrections (right) [102].

vertex [103]. Many different methods of pileup subtraction have been developed to correct for this energy contamination [104, 105], CMS analyses favour a dual correction with the *Charged Hadron Subtraction (CHS)* and *jet area subtraction* methods [106].

Utilising information from the production vertex of charged particles is an effective method at suppressing the charged component of pileup. CHS removes charged PF-candidates associated with pileup vertices prior to clustering of jets, greatly reducing energy contamination from charged pileup particles. Following this correction only the neutral component of pileup and a residual charged component, from track and vertex misreconstruction, remain within the jet. To correct for this, an additional pileup correction using the jet area method [106] is applied, which suppresses the neutral pileup particles in addition to misidentified pileup charged particles. The jet area method performs a jet-by-jet pileup correction using the average pileup energy density in the event, ρ , and the active area of each jet, A_j , by the relation:

$$p_T^{\text{Corr}} = p_T^{\text{Raw}} - \rho \cdot A_j. \quad (3.9)$$

In Run 1 the pileup energy density was estimated by sampling the population of reconstructed k_T -jets with radius parameter $\Delta R = 0.6$. As the k_T -algorithm performs a clustering of soft objects with a uniform area, the population is dominated by pileup jets, making the median energy density of the population of k_T -reconstructed jets a good proxy

for the pileup energy density in the event:

$$\rho = \text{median} \left(\frac{p_{\text{T}}^{\text{kt6}}}{A_j} \right). \quad (3.10)$$

In Run 2, the grid- ρ determination using the energy density of PF-candidates across the entire detector is utilised.

3.4.3 b -tagging

A prominent feature of events containing top and bottom quarks is the presence of jets from the decay of b -hadrons, known as b -jets. The properties of b -hadrons endow distinct features to b -jets, enabling an effective discrimination from jets arising from gluons and light quarks (u , d , s), which are collectively referred to as ‘*light-jets*’. The relatively $\tau = \mathcal{O}(1 \text{ ps})$ long lifetime of b -hadrons for example, results in a propagation of several millimetres from the interaction point prior to a secondary decay, leading to a signature of a displaced secondary vertex.

In Run 2 CMS uses the Combined Secondary Vertex version 2 (CSVv2) algorithm in the identification of b -jets, an improved version of the CSV algorithm used in Run 1. The CSVv2 algorithm uses secondary vertex and lifetime information in a neural net, providing a single discriminator for the likelihood that the jet arises from the decay of a b -hadron [107]. A background to b -jets are light-jets that are misidentified, the probability of this misidentification is known as the mistag rate.

The CSVv2 distribution and mistag rates for b -jets and light-jets measured in $\sqrt{s} = 13 \text{ TeV}$ data and simulation are shown in Figure 3.7. From this distribution, the loose, medium and tight b -tag working points are determined, which provide a range of b -tag efficiencies by the CSVv2 selections of: 0.605, 0.890 and 0.970, for mistag rates of: 10%, 1% and 0.1% respectively. Scale factors are used to correct for the mismodelling of CSVv2 in simulation, where the mistag rate for the loose WP is measured to be 10% higher in data than simulation.

3.4.4 Cross cleaning

As the reconstruction algorithms operate independently of one another, the same detector signatures can be reconstructed as different physics objects. To avoid multiple reconstructions of the same object, a *cross-cleaning* of: jets, leptons and photons is performed,

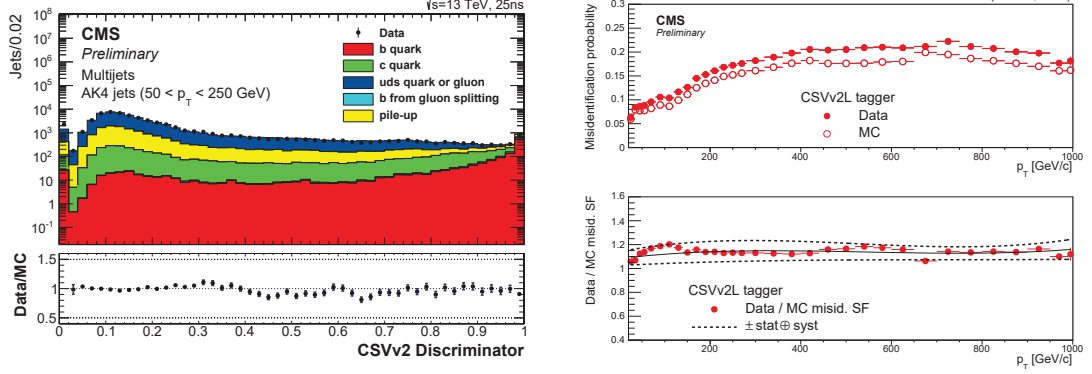


Figure 3.7: Distribution of the CSVv2 discriminator measured in $\sqrt{s} = 13$ TeV data and simulation for PFJets reconstructed with radius parameter $\Delta R = 0.4$ and momentum selection $50 < p_T < 250$ GeV (left). Data is represented by the black filled circles and simulation by the filled coloured bands which have been normalised to data. Underflow and overflow are included in the first and last bins respectively. Mistag rate as a function of jet p_T for data (filled circles) and simulation (open circles) for the CSVv2 loose working point (top right). Ratio of data and simulation mistag rate (bottom right) [108].

ensuring a one-to-one correspondence between detector signals and reconstructed objects. To achieve this, reconstructed jets that are within a $\Delta R = 0.4$ radius of isolated leptons and photons are removed.

3.4.5 Energy sums and missing energy

The total and missing energy in an event are useful variables in the selection and discrimination of signal processes from backgrounds. The decay of massive particles hypothesised in supersymmetric theories can result in a large energy transfer in the production of both visible and invisible particles, which can be measured by energy sums and missing energy variables. The hermetic design of the CMS detector provides a good containment of particles in the event, enabling a precise measurement of the total and missing energy.

Energy sums compute the total energy of particles in an event, giving a measure of the energy scale of the signal process produced in the event. By reconstructing the total energy of the particles from decay, information of the parent process can be determined, which is effective in the separation of low-energy scale QCD interactions and new hypothesised massive particles. Energy sums are computed from the scalar sum of the particle energies in the event, which is commonly performed using the total transverse energy, E_T , the scalar sum of all reconstructed PF-candidates, and the total hadronic transverse energy,

H_T , which is computed from calibrated jets within a chosen acceptance, which are defined:

$$E_T = \sum |\vec{p}_T^{\text{PF}}| \quad H_T = \sum |\vec{p}_T^j|. \quad (3.11)$$

Missing energy is a distinctive signature of neutral weakly interacting particles, such as neutrinos in vector boson decays, and hypothesised new particles in BSM theories, such as the LSP of R -parity conserving supersymmetry models. Although these particles cannot be measured directly, their presence can be inferred from the measured imbalance in momentum transverse to the beam direction. The missing transverse momentum vector, $\vec{\cancel{E}}_T$, is defined as the negative vector sum of the momenta of all reconstructed particles in an event, the magnitude of which is defined as the total missing energy, $\cancel{E}_T$. Two commonly used quantities in estimating missing energy are the hadronic missing energy, $\cancel{H}_T$, which is computed from jets in the event and the missing transverse energy and PF- $\cancel{E}_T$, which is computed from all reconstructed PF-candidates with $|\eta| < 5$. $\cancel{H}_T$ and $\cancel{E}_T$ are computed from the vectorial sum of the respective input object four-momenta by the relations:

$$\begin{aligned} \vec{\cancel{E}}_T &= - \sum \vec{p}_T^{\text{PF}} & \cancel{E}_T &= | \sum \vec{p}_T^{\text{PF}} | \\ \vec{\cancel{H}}_T &= - \sum \vec{p}_T^j & \cancel{H}_T &= | \sum \vec{p}_T^j |. \end{aligned} \quad (3.12)$$

An additional missing energy quantity *calorimeter- $\cancel{E}_T$* , is computed from the vector sum of calorimeter towers above an energy threshold, which is utilised in the trigger where a fast reconstruction of missing energy is required. A comparison of the performance of calorimeter- $\cancel{E}_T$ and PF- $\cancel{E}_T$ illustrated in Figure 3.8, shows that the performance of the $\cancel{E}_T$ measurement using PF is greatly improved with respect to the calorimeter quantity, as a result of the improved energy and position resolution of PF-reconstruction.

An additional *type-I $\cancel{E}_T$ correction* [109] is used to further improve the resolution of $\cancel{E}_T$ measurements by exploiting the improved energy resolution that can be achieved with calibrated jets with respect to their clustered constituents. The type-I correction replaces particles that are clustered in jets by their calibrated jet counterpart in the computation of $\cancel{E}_T$, providing significantly improved energy resolution. For the purpose of the type-I correction, CHS-corrected PFJets with $p_T > 15 \text{ GeV}$ are utilised, with the uncertainty in jet energy correction propagated to the final $\cancel{E}_T$ uncertainty.

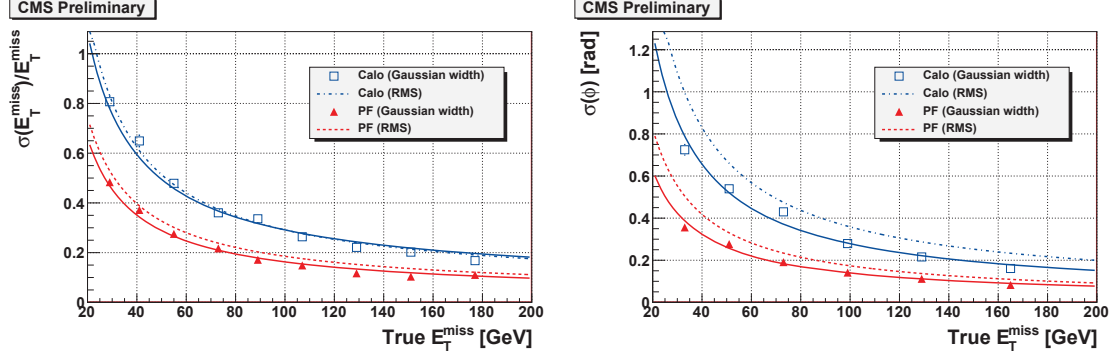


Figure 3.8: $\cancel{E}_T$ energy (left) and azimuthal (right) resolution for PF and calorimeter reconstructed $\cancel{E}_T$ in simulated $t\bar{t}$ events. The dashed line represents the RMS of resolution distribution and the solid line is measured error from a Gaussian fit to resolution [99].

3.5 Simulation

To enable a test of theoretical hypotheses against experimental observations, an accurate simulation of physics processes and their interactions with the CMS detector is required. The simulation of pp -collisions at the LHC are extremely challenging, requiring accurate modelling of the production and decay of events with a wide range of particle multiplicities, species and momenta. To perform this task efficiently, the simulation of pp -collisions within CMS is factorised into several stages: *the hard interaction, fragmentation, hadronisation, decay and detector simulation*. A complete description of simulation techniques used at the LHC can be found elsewhere [110].

The first stage of simulation is the modelling of the *hard scattering*, the interaction between the collision partons, which simulates the initial and final states of the partonic interaction. The fractional energy of the proton carried by the each of the colliding partons is sampled from their respective Parton distribution function (PDF), which are measured experimentally. The scattering of the partons in the hard interaction can be simulated to different orders in theory, typically Leading order (LO) $2 \rightarrow 1$ or $2 \rightarrow 2$ processes, with some samples simulated at Next-to-leading order (NLO). The matrix element calculation is performed by dedicated Monte Carlo generators such as **MadGraph** [111].

After the hard scattering, the simulation of the fragmentation and hadronisation of the final state partons is performed by dedicated MC showering and hadronisation algorithms. In fragmentation, a simulation of the splitting of the partons from the hard scatter is performed, with the emission of soft quarks and gluons continuing until the cut-off scale

of QCD, $\Lambda_{\text{QCD}} \sim 200 \text{ MeV}$, where calculations become non-perturbative. In addition to the hard scattering, a simulation of the underlying event, multi-partonic interactions of the proton remnants, is also performed.

The coloured final state partons are subsequently clustered with hadronisation algorithms into colourless bound hadron states. Common hadronisation algorithms, such as **PYTHIA** [112] and **Herwig** [113], utilise different techniques to perform a connection of the colour-flow from the initial partons to the final state partons. Unstable particles additionally undergo specialist decay simulation with dedicated MC algorithms, completing the simulation of the particles in the interaction. Finally, the interaction of the final state particles with the detector is modelled using dedicated detector simulations. CMS utilises **GEANT4** [114] to perform a full detector simulation, which provides detector information identical to real data over which standard reconstruction can be performed.

To perform a realistic simulation of real collisions at the LHC, in addition to the simulation of the signal process the accompanying pileup interactions must also be simulated. To perform this simulation efficiently a large minimum bias QCD sample is simulated, from which single pileup events are sampled and overlaid on the signal process. In addition to the in-time pileup, additional events are simulated in a 12-bunch crossing window of the signal event to simulate the effect of OOTPU.

Level-1 trigger upgrade

Although there are many opportunities from the increase in beam energy and luminosity in LHC Run 2 there are also associated challenges, particularly in the operation of the trigger system. To maintain efficiency for the selection of signatures of interest during Run 2, an upgrade of the L1 trigger system and its associated algorithms was performed. In the following, a description of the development of the upgrade L1 jet algorithm is provided, detailing the optimisation of: clustering, pileup correction and calibration techniques, with an evaluation of their performance with respect to the Run 1 algorithm.

4.1 Run 2 trigger upgrade

A major challenge of trigger selection in Run 2 is the increase average number of pileup interactions per event which, as a result of increased energy deposited in the calorimeters, degrade the effectiveness of trigger selections. The increased occupancy of the calorimeters act to inflate both the energy and multiplicity of reconstructed trigger objects, increasing the probability of triggers firing. In addition, the increased energy in the calorimeter reduces the effectiveness of isolation selections, necessitating looser isolation requirements to maintain selection efficiency. These effects conspire to increase the total trigger rate beyond the bandwidth capabilities of the Run 1 Global Calorimeter Trigger (GCT) system which, without improvements in selection algorithms, necessitating higher trigger thresholds that would degrade the sensitivity of some physics searches [115]. Limitations in the bandwidth and processing capabilities of the Run 1 L1 GCT electronics and architecture however limit the potential for improvement in selection, failing to fully compensate for the expected degradation in performance.

4.1.1 Level-1 trigger upgrade

To retain sensitivity for physics signatures in Run 2, the L1 calorimeter trigger system was upgraded to use the high-performance, all-optical data-stream Imperial Master Processor Virtex-7 (MP7) [116, 117] as the main algorithmic trigger processor platform. The ability of the MP7 to process data at a high rate when configured in the Time-Multiplexed Trigger

(TMT) architecture [118] provides significant improvements over the Run 1 trigger system, enabling for the first time the information of the entire calorimeter to be concentrated and processed in a single processor.

The TMT architecture of the calorimeter trigger upgrade possesses several advantages over the conventional Run 1 trigger architecture. Illustrated in Figure 4.1, in both architectures after each bunch crossing the complete detector information is processed by Trigger Primitive Generators (TPGs), known as the Regional Calorimeter Trigger (RCT). The RCT clusters calorimeter energy deposits into Trigger Towers (TTs), an accumulation of the energy contained within 5×5 arrays of ECAL crystals and the respective HCAL cell behind. Due to limitations in bandwidth in the Run 1 architecture, these towers are further grouped into coarse grained 4×4 TT clusters, known as *calorimeter regions*, which are distributed according to locality to separate trigger processors. These processors perform individual regional reconstructions of calorimeter objects which are concentrated in the GCT for the final trigger selection.

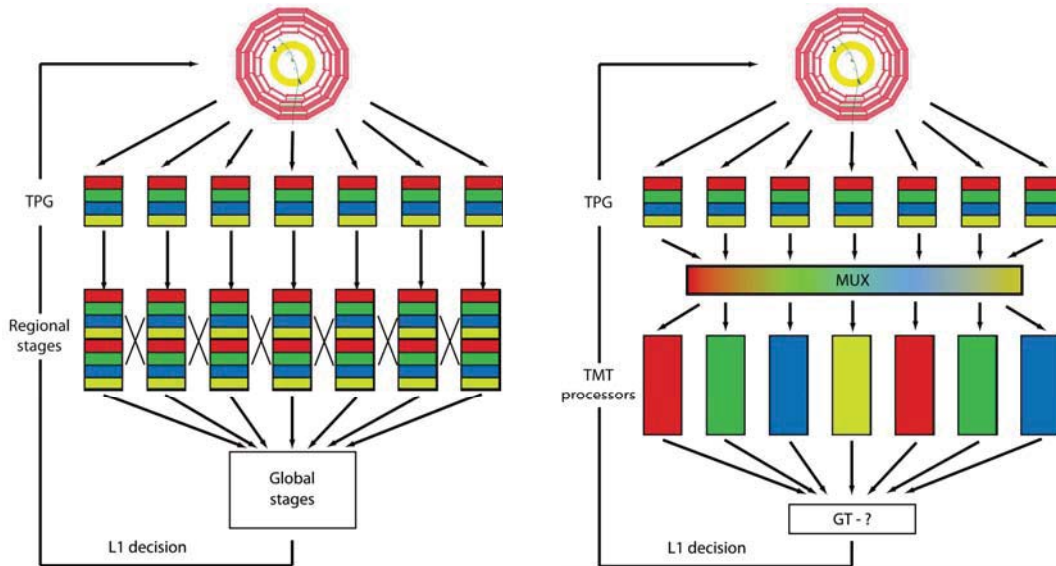


Figure 4.1: Schematic of the operation of the Run 1 conventional (left) and TMT (right) architectures, where the flow of data from the detector to the final global trigger decision is illustrated by the arrows. Data that belong to the same bunch crossing are represented by a common colour [118].

In the TMT architecture, after the TPG processing there is an additional multiplexing

stage, where data are accumulated into trigger processors over several bunch crossings, enabling the full detector information to be concentrated into a single trigger processor. The use of the TMT architecture in conjunction with the increased processing power of the MP7, provides a 16-fold improvement in the input granularity to the calorimeter trigger, increasing from the region-level granularity of the Run 1 GCT to use the full TT granularity of the calorimeter as shown in Figure 4.2. To capitalise on improvements in processing hardware, new algorithms were developed to fully exploit the benefits of the upgraded L1 trigger hardware. These algorithms were designed to employ more sophisticated algorithms and reconstruction techniques, including the use of L1 pileup subtraction and novel clustering techniques, to improve the capabilities of the L1 trigger in selecting of signatures of interest.

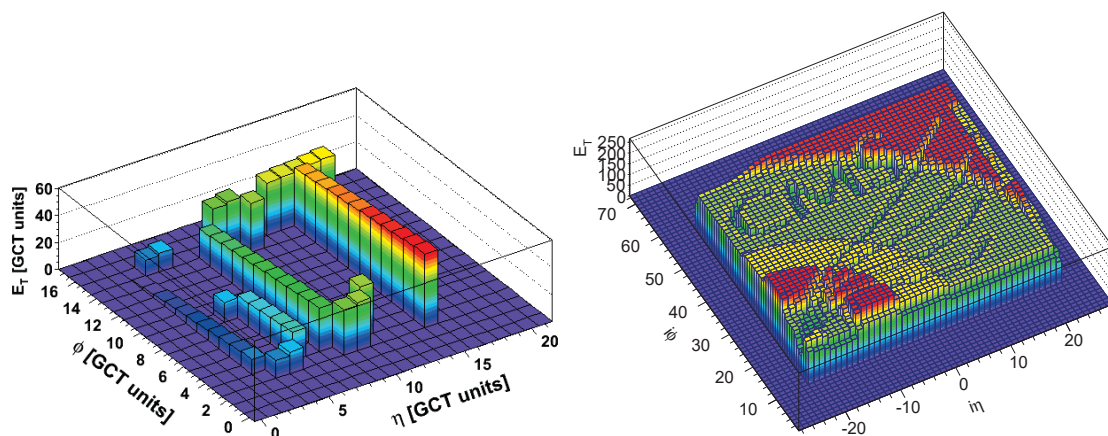


Figure 4.2: A comparison of the input calorimeter granularity of test patterns for the GCT [119] (left) and the upgraded calorimeter trigger (right).

4.2 Level-1 jet trigger upgrade

The increase in pileup interactions in LHC Run 2 presents a major challenge to the triggering of jets with the Run 1 trigger system, requiring an improved jet algorithm to maintain low thresholds and sensitivity for a range of physics measurements. To operate effectively in the high-pileup environment of Run 2, the upgrade algorithm exploits the increase in input granularity and processing power provided by the upgrade trigger system. In addition, improved clustering and reconstruction techniques are employed, such as online pileup subtraction, to enable the upgrade algorithm to mitigate the effects of pileup in Run 2.

4.2.1 GCT Level-1 jet trigger

The Run 1 GCT jet algorithm, illustrated in Figure 4.3, utilises a 3×3 calorimeter region sliding jet window with a central seed to reconstruct jets in the pseudorapidity range $|\eta| < 5$. The algorithm scans the calorimeter in single region-increments and clusters jets where the energy in the central seed region exceeds that of each of the eight surrounding regions. With an increase in the number of pileup interactions in 2012, a threshold of 5 GeV on the seed region was employed to reject softer pileup jets, reducing the rates of the jet trigger. Following reconstruction jet candidates are classified, with candidates that have fewer than two regions above an energy threshold neighbouring the central region being identified as τ -jets. The remaining candidates are classified as either: central or forward jets, if they reside in the pseudorapidity acceptances of: $|\eta| < 3$ and $3 < |\eta| < 5$ respectively. In total up to 12 jets per event are reconstructed: four central, four forward and four τ jets, which are sent to the global trigger for the final event decision. A more detailed description of the operation of the L1 GCT jet algorithm can be found elsewhere [70].

4.2.2 Upgrade jet algorithm

The upgrade jet algorithm, shown in Figure 4.3, utilises a similar sliding window design with a higher-granularity TT calorimeter input. Exploiting the capabilities of the upgraded trigger system enables a variety of jet shapes and sizes to be utilised, however these are restricted to be of an odd number of TTs in length to ensure a unique central seed tower can be defined. For comparisons with Run 1 selections, an (11×11) TT window is utilised

to better match the Run 1 anti- k_T jet radius parameter of $\Delta R = 0.5$. A smaller (9×9) TTs window is used in Run 2 to match the smaller radius parameter of $\Delta R = 0.4$.

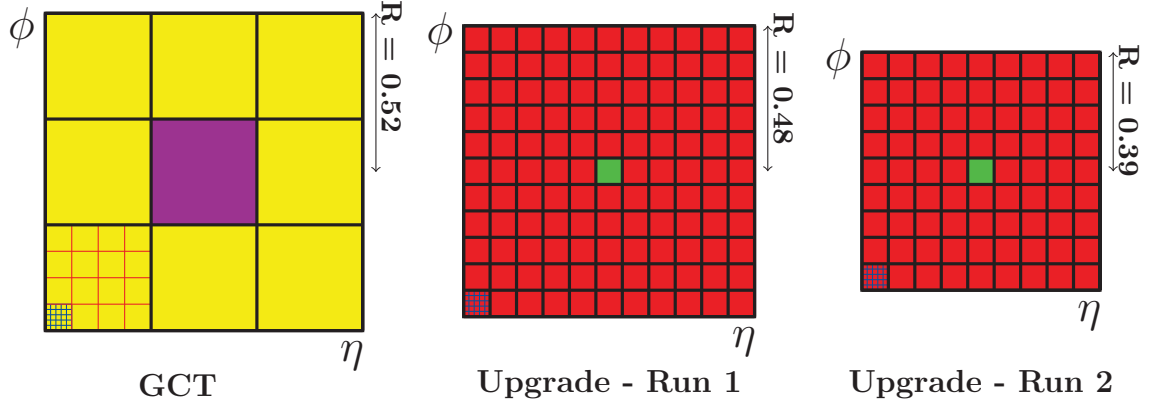


Figure 4.3: A comparison of the jet windows for the GCT algorithm (left) and the upgrade algorithm for Run 1 (middle) and Run 2 (right). The scale of the jet windows are shown relative to their constituent: ECAL crystals (blue squares), TTs (red squares) and calorimeter regions (yellow squares). The central seed region and TT for the GCT and upgrade algorithms are represented by the purple and green squares respectively.

The baseline upgrade algorithm [120] reconstructs jets by scanning the central seed tower of an $N \times N$ jet window across the calorimeter in single tower increments, indexed by an integer $i\eta$ and $i\phi$ value, constructing ‘proto-jets’ at every TT site. In order to avoid the multiple counting of energy in the event, these proto-jets are subsequently filtered using the jet p_T and the *asymmetry parameters*: A_ϕ and A_η ¹, to remove overlapping jets using the following algorithm:

- Proto-jets in each $i\eta$ -strip are ordered in decreasing p_T and, in the case where jets possess degenerate energies, by decreasing values of the modulus of the A_η asymmetry parameter;
- The highest ordered jet in the sorted proto-jet list is retained and all the possible $(N - 1)$ overlapping jet positions in the same $i\eta$ -strip are vetoed. This continues with the next highest-ranked non-vetoed jet until either every possible non-vetoed

¹ The asymmetry parameters of a jet in the ϕ and η directions are a measure of the difference of the constituent energies above and below the jet centre, which are defined: $A_\phi \equiv \sum_{i=1}^{N_{TT}} E_T^{\phi^{rel} > 0} - \sum_{i=1}^{N_{TT}} E_T^{\phi^{rel} < 0}$ and $A_\eta \equiv \sum_{i=1}^{N_{TT}} E_T^{\eta^{rel} > 0} - \sum_{i=1}^{N_{TT}} E_T^{\eta^{rel} < 0}$ respectively. The quantity ϕ^{rel} is the relative distance from a specified TT energy deposit and the jet window centre and is defined: $\phi^{rel} = \phi^{TT} - \phi^{Jet\ centre}$, η^{rel} is similarly defined.

jet in the strip of $i\eta$ has been selected or a specified jet multiplicity for that strip has been met;

- These η -filtered jets then pass a second stage of filtering in which all remaining proto-jets are filtered simultaneously. The remaining jets are again ranked by p_T but this time utilising the A_ϕ asymmetry parameter;
- The highest ordered jet in the sorted proto-jet list is retained as an output jet and the 2D region in ϕ and η of all the $(N^2 - 1)$ overlapping jets are vetoed. In a similar manner to the previous filtering stage, the candidate jet list is iterated over and the highest ranked non-vetoed jets are selected, resulting in a p_T -ordered non-overlapping output jet collection.

Following this filtering stage, the resultant jet collection is corrected for pileup using the jet area pileup subtraction method described in Section 4.2.4. The energy of the remaining jets receive (p_T, η) -dependent calibrations, derived from a linear regression of matched offline jets, to correct for the calorimeter response [120].

4.2.3 Development of the upgrade jet algorithm

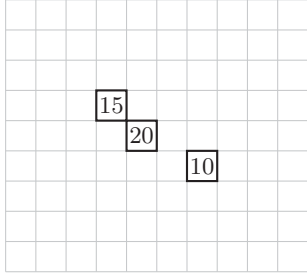
To ensure optimal performance, all aspects of the baseline jet algorithm were studied including: clustering, filtering, pileup correction and jet energy calibrations. The following describes the development of these algorithms, with an evaluation of their performance with Run 1 data selected with a muon trigger and CaloJets reconstructed with a radius parameter of $\Delta R = 0.5$.

4.2.3.1 Level-1 jet clustering

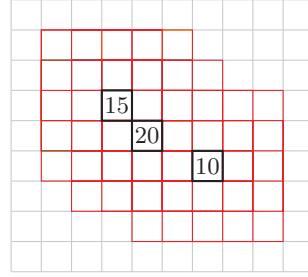
Integral in the design of jet algorithms is the effective and efficient reclustering of energy into jets. In the investigation of the clustering performance of the baseline upgrade algorithm, several improvements to the operation of the algorithm were identified.

An example of the operation of the baseline upgrade jet algorithm over a simple calorimeter input is shown in Figure 4.4, which demonstrates the algorithm for a square (3×3) jet window. This example highlights a problem with the current implementation of the algorithm which, due to the use of two orthogonal asymmetry parameters, can result in problems in the filtering stage. In this example the position of the subleading jet (brown) in Figure 4.4 (d) clustered by the algorithm is offset from the optimal position where the single energy deposit is central in the jet window. Although this preferred jet position does

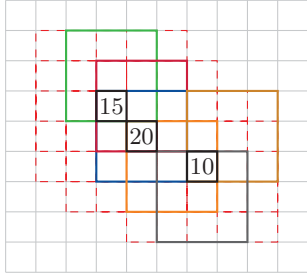
not overlap with the lead jet, it was vetoed in the A_η filtering stage of Figure 4.4 (c), due to an overlapping higher-ranked jet (orange) that was itself later vetoed. The use of two independent filtering stages is not only computationally expensive, but also unstable, with differences occurring in the selection of jets that is dependent on the chosen filtering order. Furthermore, in some configurations it is possible for multiple pseudo-jets to possess both the same energy and asymmetry, leading to a jet selection that is entirely dependent on the choice of sorting algorithm.



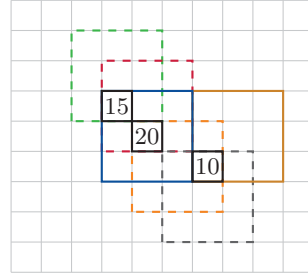
(a) The first stage of the algorithm builds the calorimeter TTs (black) by summing their respective ECAL and HCAL energies; here the magnitude of their energy deposits are represented numerically.



(b) Utilising the TT input of the first stage, the jet algorithm builds all possible (3×3) square jet candidates of non-zero energy (red). This stage is prior to filtering and hence these jets are allowed to overlap.



(c) The candidate jets are A_η filtered, where only the highest ranked non-overlapping jets for each $i\eta$ -strip are kept (solid) and the remaining jets vetoed (dashed).



(d) Finally, the jets are A_ϕ filtered, where the globally highest-ranked jets that are not vetoed are selected as the final jets (solid).

Figure 4.4: A demonstration of the operation of the upgrade jet algorithm utilising a (3×3) square jet shape running over a simple calorimeter input.

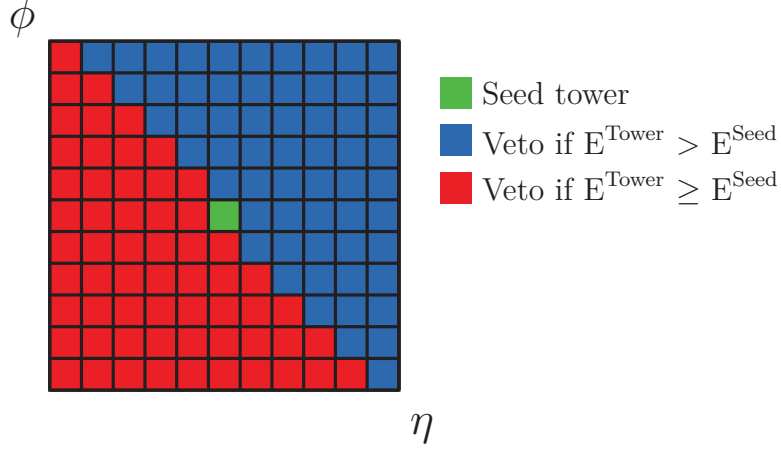


Figure 4.5: A veto mask for an (11×11) square jet illustrating the position of the seed tower and regions of the jet with differing veto conditions.

An alternate clustering algorithm that resolves the issues of asymmetric filtering is the *asymmetric veto mask filter*. Illustrated in Figure 4.5, the algorithm compares the energies of each of the constituent TTs in the jet window with that of the central seed, applying a position-dependent veto condition. If any of the TTs in the jet meet the veto condition, the jet veto bit is set and the jet is discarded, ensuring that no two jets can occupy the same area in the calorimeter. The algorithm is scanned across the calorimeter in single TT increments and the four highest-ranked, non-vetoed jets in each ring of $i\eta$ are retained. At high pseudorapidities, where the jet window extends over the edge of the calorimeter, truncated jets are constructed, with the area exceeding the calorimeter edge removed.

The requirement of a central seed tower is well motivated from the typical energy deposition of jets, where the position of the highest-energy constituent TT has a strong correlation with the centre of the jet itself. This is illustrated in Figure 4.6, which shows the distribution of the constituent calorimeter energy deposits in CaloJets relative to their reconstructed centres. Shown in the left figure, the highest energy constituent is typically close to the reconstructed jet centre, making the highest energy constituent a good proxy for the jet centre. This is shown in the right figure to be characteristic of jets, where in 42% of cases the jet centre is the same position as the highest energy tower and in over 89% of cases within two TTs of the highest energy tower.

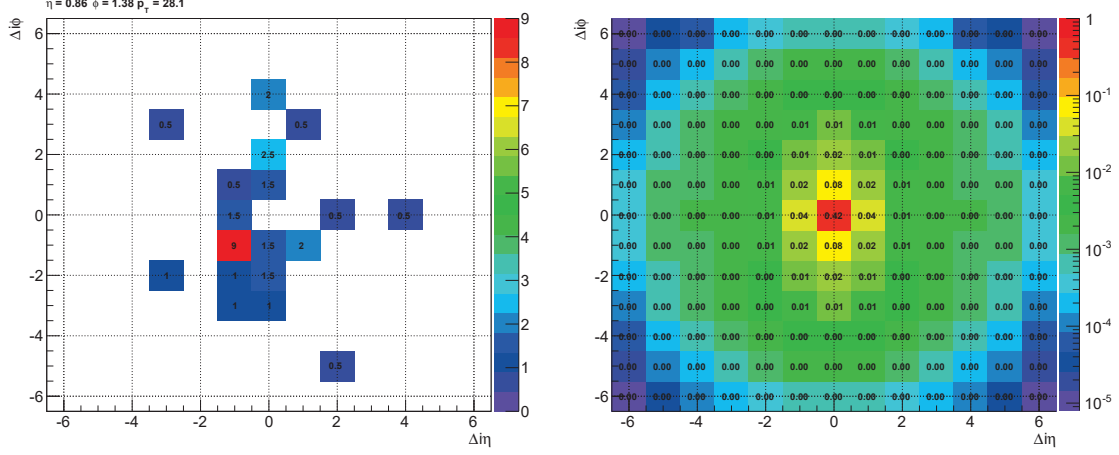


Figure 4.6: Position of constituent TTs within a CaloJet relative to its reconstructed centre where the colour scale represents energy in L1 GeV units (left). Average fractional energy of constituent TTs within a CaloJet relative to its reconstructed centre (right).

To enhance the position resolution of jets, the position of reconstructed jets is calculated from the energy weighted position of its constituent TTs using the relations of Equation 4.1. Utilising the information internal to the jet provides a determination of the jet centre with a position resolution that is finer than the intrinsic tower granularity.

$$\eta^{\text{Weighted}} \equiv \frac{\sum_{i=1}^{N_{\text{TT}}} E_{\text{Ti}} \eta_i}{\sum_{i=1}^{N_{\text{TT}}} E_{\text{Ti}}}, \quad \phi^{\text{Weighted}} \equiv \frac{\sum_{i=1}^{N_{\text{TT}}} E_{\text{Ti}} \phi_i}{\sum_{i=1}^{N_{\text{TT}}} E_{\text{Ti}}} \quad (4.1)$$

The improvement in the position resolution of the upgrade algorithm with respect to the GCT algorithm can be seen in Figure 4.7, which shows the upgrade algorithm possesses superior performance in both η and ϕ dimensions. In isolation, the increase in the input granularity input of the upgrade algorithm provides a factor of 1.9 improvement in the η and ϕ position resolution relative to that of the GCT algorithm. This is further improved with the use of energy weighted position estimates, which yields an increase in position resolution by a factor of 3.3 and 4.3 over the GCT in the η and ϕ dimensions respectively.

This improvement in position resolution of the upgrade trigger could potentially provide a more accurate determination of the calculation of $\cancel{E}_T$ and enable the use of new triggers to be implemented at L1. Novel topological triggers at L1 would be of particular interest in the selection of vector boson fusion events, a distinctive Higgs boson production mode, and in the suppression of dijet QCD events, which are respectively characterised

by dijets with large separations in pseudorapidity and azimuth.

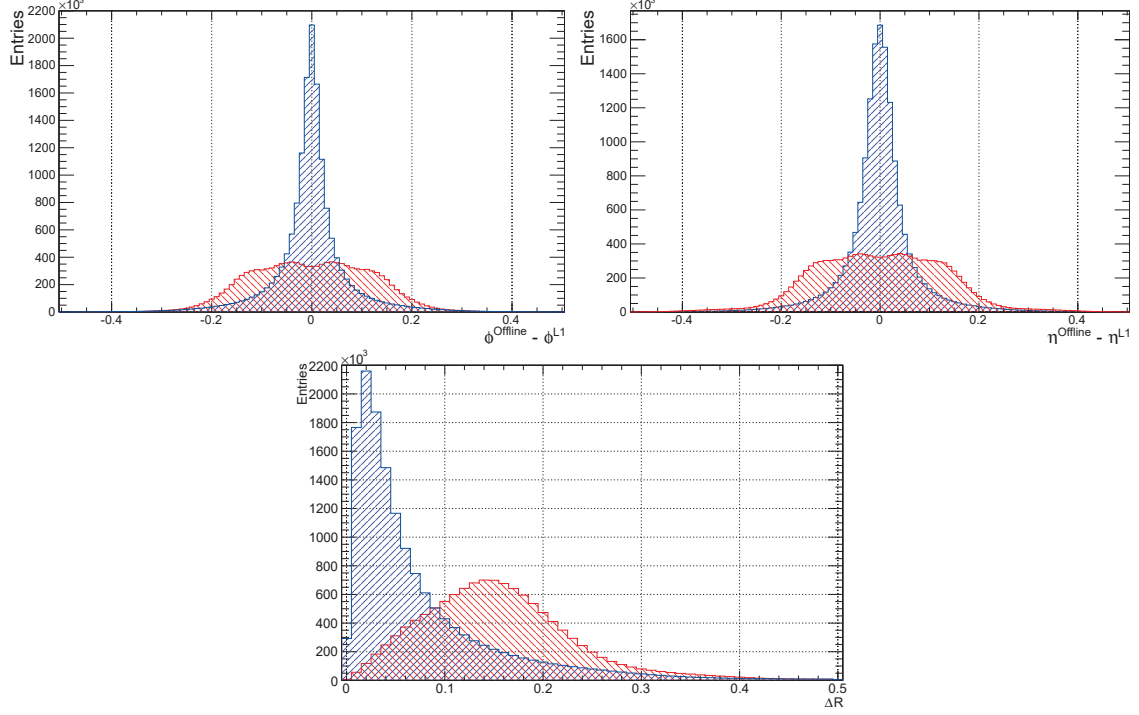


Figure 4.7: Comparison of the ϕ (left), η (right) and ΔR (bottom) position resolutions of the GCT (red) and upgrade L1 jet (blue) algorithms, with respect to offline jets reconstructed with anti- k_T jets with radius parameter $\Delta R = 0.5$ in a 20 pileup single muon data sample.

4.2.4 Pileup subtraction

Particles from pileup provide several challenges in jet selection, inflating the energy and multiplicity of reconstructed jets. Pileup subtraction aims to mitigate these effects by removing additional pileup jets from the event and correcting the energies of the remaining jets. Due to the random nature of pileup, event-by-event estimates of the energy contamination are required, adapting for fluctuations in pileup multiplicity, in addition to changes in detector and beam conditions throughout the run. As the degree of pileup contamination is strongly correlated with the number of reconstructed vertices, offline algorithms typically use tracking information in the determination of corrections for pileup. The lack of tracking information and the low latency requirement of the L1 trigger however make the estimate of pileup contamination challenging, requiring correlations of pileup with observable quantities to determine corrections. Several methods of pileup subtraction are

studied which provide estimates of pileup both *globally*, estimating of the average contamination across the calorimeter, and *locally*, where non-uniformities in the pileup energy density are estimated.

4.2.4.1 Jet area method

Used in offline reconstruction to correct for the energy from pileup in the event, the *jet area method* utilises reconstructed jets themselves to estimate the pileup energy contamination by sampling their energy densities [106]. As the majority of jets in an event are a consequence of pileup, the median jet energy density, $\rho \equiv \text{median}(p_{Tj}/A_j)$, provides an estimate of pileup energy density that is insensitive to the hard jets in the event. Due to the variable η -granularity of the calorimeter for pseudorapidities exceeding $|\eta| > 1.74$, the area of the jet window is computed by the η -dependent relation: $A_j = \Delta\phi\Delta\eta(\eta)$. Assuming a uniform pileup energy density, the pileup energy contamination in jets may be corrected by the relation:

$$(p_{Tj})_{\text{Subtracted}} = (p_{Tj})_{\text{Raw}} - \rho A_j. \quad (4.2)$$

A variant of the jet area method provides an η -dependent estimate of the pileup energy density, $\rho(\eta)$, by computing the median jet energy density for jets local to η -strips in the calorimeter. In the case of low jet multiplicities however, no statistically sensible estimate of the pileup jet energy density can be made and hence no pileup subtraction is performed.

4.2.4.2 Doughnut subtraction

The *doughnut subtraction* method aims to perform a jet-by-jet correction for pileup, sampling the area exterior to each jet to provide an estimate of the local pileup energy density. Illustrated in Figure 4.8, the majority of the jet energy is typically localised within two TTs of the jet centre, with only a small fraction extending to the periphery. As the energy in the ring enclosing the jet is predominantly pileup, it may be used to sample the pileup energy density local to each jet in the event. To ensure this estimate is robust against occurrences where jets in close proximity contaminate the sampling strips of their neighbours, the pileup energy density is estimated from the median energy density of the four exterior strips: $\rho_{\text{Jet}} = \text{median}(p_{T\text{Strip}}/A_{\text{Strip}})$. This localised measure of pileup energy density is utilised to provide a jet-by-jet energy correction using Equation 4.2.

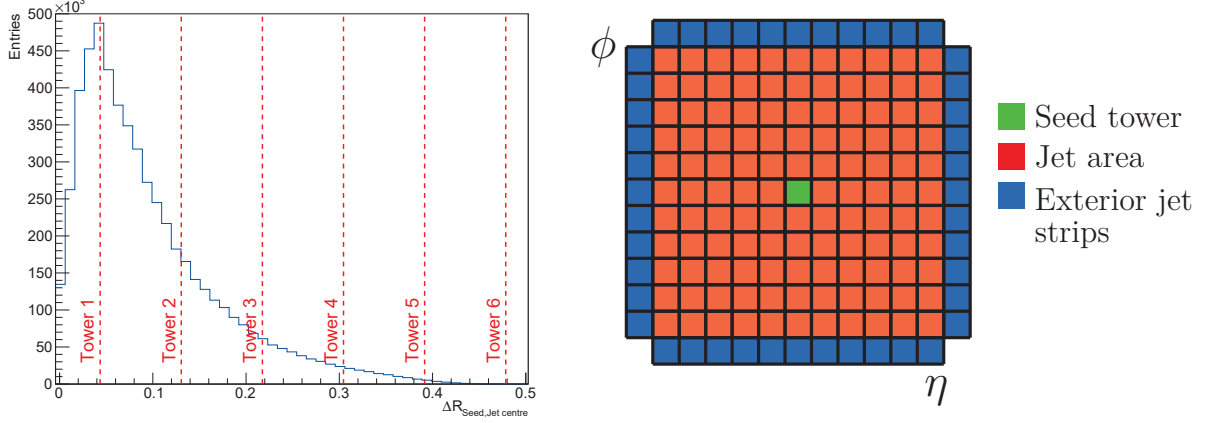


Figure 4.8: ΔR -separation of the jet centre and the constituent TTs weighted by their energies (left), measured in Run 1 data. Schematic of the four exterior strips sampled for doughnut subtraction for an (11×11) square jet (right).

4.2.4.3 Calorimeter area subtraction

The *calorimeter area subtraction* method estimates pileup by partitioning the calorimeter into smaller sections of equal area, with the median energy density of these areas used as an estimate of the pileup energy density. As this method samples more of the calorimeter than the jet area method, more diffuse energy deposits which are characteristic of pileup can be clustered, providing an estimate more similar to the inclusive k_T jet median energy density method used in Run 1. This method can also be used to provide a local energy density estimate by sampling calorimeter areas in η rings to provide an η -dependent pileup energy density estimate.

In addition to directly sampling the energy density of calorimeter areas, the multiplicity of areas above an energy threshold can also be used as an estimator for pileup. Counting the number of TTs below threshold is used as an estimator of online instantaneous luminosity as it exhibits a strong correlation with instantaneous luminosity [121]. Exploiting this correlation, an empirical relation between the area multiplicity and pileup energy density can be determined.

4.2.4.4 Seed threshold

Requiring that the central region of a jet exceeds an energy threshold is an effective method of suppressing pileup jets, which are typically formed of diffuse energy deposits, whilst retaining hard jets that have localised high-energy deposits. This cannot by itself

correct for pileup energy contamination in jets but can be used in conjunction with other pileup subtraction methods.

4.3 Jet energy calibration

To perform an effective selection with reconstructed jets, their energies must be calibrated to compensate for variations in the detector response with energy and pseudorapidity. To achieve this, for each region in η a p_T -dependent calibration factor is applied that is derived from the parameterisation of jet response with L1 p_T by the following fit function [122]:

$$p_T^{\text{L1,corr}} = p_T^{\text{L1}} \cdot \left(p_0 + \frac{p_1}{(\log p_T^{\text{L1}})^2 + p_2} + p_3 \cdot \exp \left(-p_4 \cdot (\log p_T^{\text{L1}} - p_5)^2 \right) \right), \quad (4.3)$$

where p_n are constants that are determined empirically.

As sophisticated calibration techniques have already been developed for the correction of offline reconstructed jets, these jets are utilised as the reference jet collection when calibrating L1 jets. To avoid a mismatch between offline and L1 reconstruction, CaloJets are utilised as the reference jet collection instead of PFJets, which utilise tracker information. The correction factors for L1 jets are derived in a data with a single muon selected sample using the method described below:

- L1 jets are uniquely matched to the offline reference collection by minimising the ΔR separation between the two collections, to a maximum separation of: $\Delta R < 0.3$;
- L1 jets are binned in L1 η and the p_T of their matched offline jet to provide η^{L1} and p_T^{Off} dependent distributions of the L1 jet response and the L1 jet p_T ;
- Gaussian fits of these distributions are used to extract the mean L1 jet response and the L1 jet p_T , which are combined to provide an η -dependent distribution of the mean L1 jet response with respect to the reconstructed L1 p_T ;
- These distributions are fitted using Equation 4.3 to provide a parameterisation of the jet response as a function of L1 from which a (p_T, η) -dependent correction is derived, as shown in Figure 4.9.

The result of the application of the jet energy corrections derived by this method are shown in Figure 4.10. Prior to the application of the jet energy corrections, the relative response of the reconstructed L1 jets is negative with a strong dependence on the reconstructed pseudorapidity and momentum of the offline reconstructed jet. After

applying the corrections, the mean relative response is unbiased, with a flat behaviour as a function of both pseudorapidity and its associated offline p_T , demonstrating the effectiveness of the calibration.

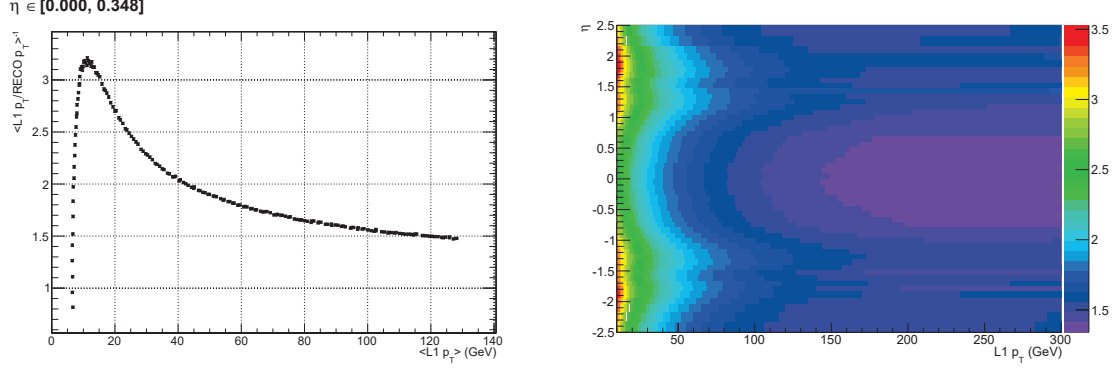


Figure 4.9: Distribution of fitted L1 upgrade jet p_T response and average p_T for jets reconstructed within the pseudorapidity range: $0 < \eta < 0.348$ (left). Derived calibration factor as a function of L1 p_T and η (right).

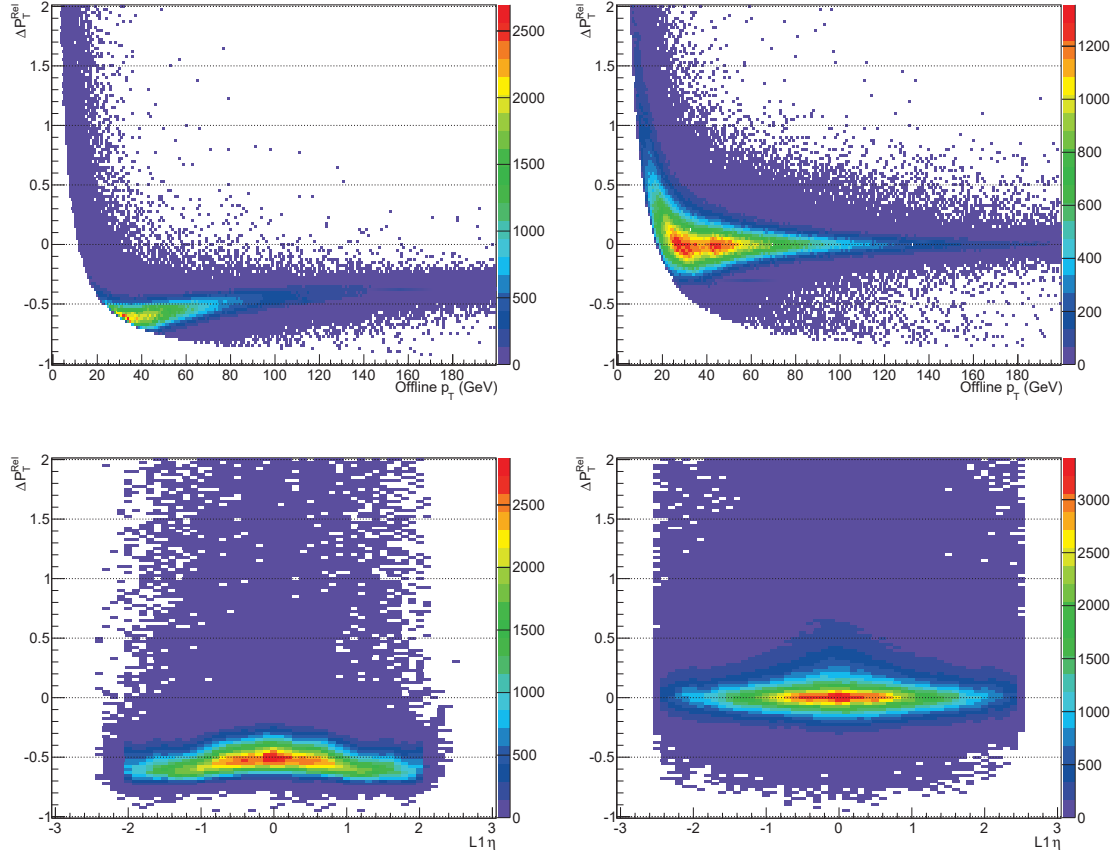


Figure 4.10: p_T resolution of the leading upgrade L1 jet prior to (left) and after (right) calibration as a function of the matched offline jet p_T (top) and L1 jet η (bottom).

4.4 Level-1 performance

To assess the performance of the upgrade algorithm and its various pileup subtraction techniques, single muon enriched and unbiased trigger selected ‘zerobias’ Run 1 data samples with an average of 20 pileup are utilised. The performance of the L1 jets are evaluated with respect to CaloJets reconstructed with a radius parameter of $\Delta R = 0.5$.

4.4.1 Jet energy resolution

The upgrade algorithm exhibits an improved energy resolution with respect to the GCT algorithm, as shown in Figure 4.11, with the upgrade algorithm possessing a smaller variance in jet energy resolution and flatter response with p_T than the GCT algorithm. The upgrade algorithm also shows an improved stability with pileup multiplicity, as seen in Figure 4.12, which shows the jet response of the GCT and upgrade algorithm prior to, and after, pileup subtraction in the low p_T bin which is most susceptible to pileup. Without pileup subtraction, the upgrade exhibits similar behaviour to the GCT algorithm with the jet response increasing with the number of primary vertices, an effect more dominant at high pseudorapidities where pileup is more prevalent. The application of pileup subtraction to the upgrade algorithm is however shown to effectively reduce the pileup contamination in the jets, flattening the jet response with pileup in both the central and the forward region of the detector where pileup is more prevalent.

4.4.2 H_T , $\cancel{H}_T$ resolution

The improved jet energy resolution and pileup subtraction of the upgrade jet algorithm additionally provides improvements in the computation of jet energy sums which are particularly important in hadronic trigger selections. A comparison of the trigger turn on for jet energy sums computed with the GCT and upgrade algorithm can be seen in Figure 4.13, which show a significantly improved resolution, and hence sharper turn on for, for H_T and $\cancel{H}_T$ selections with the upgrade algorithm. The resolution of the upgrade scalar sum of jet energies is also slightly improved with the application of pileup subtraction, however due to the azimuthal symmetry of pileup, leads a smaller improvement in the performance with respect to vectorial jet energy sums.

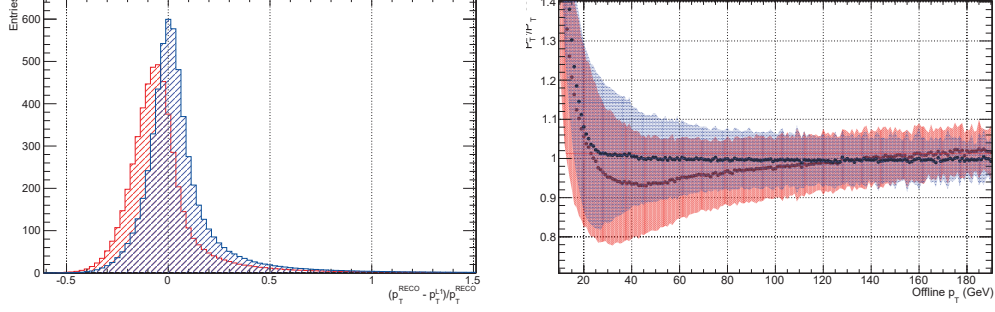


Figure 4.11: Leading L1 jet energy resolution (left) and leading L1 jet energy response as a function of offline p_T (right) for the GCT (red) and upgrade algorithm (blue), measured with respect to offline CaloJets with a radius parameter $\Delta R = 0.5$, for L1 jets reconstructed in the pseudorapidity range: $0 < \eta < 0.348$.

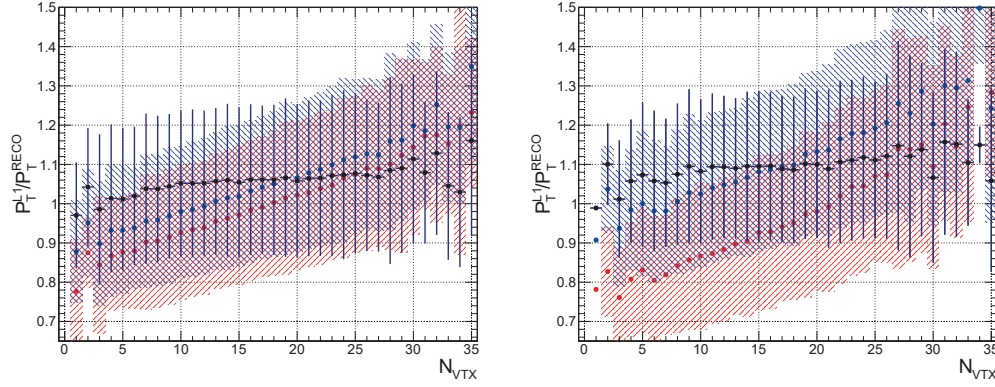


Figure 4.12: Jet energy response for the leading jet as a function of pileup reconstructed in the pseudorapidity regions $0 < \eta < 0.348$ (left) and $-2.172 < \eta < -1.74$ (right), for the GCT (red) and upgrade algorithms, prior to subtraction (blue) and after calorimeter area multiplicity subtraction (black). A $20 < p_T^{\text{L1}} < 40$ GeV selection is applied to the L1 jets.

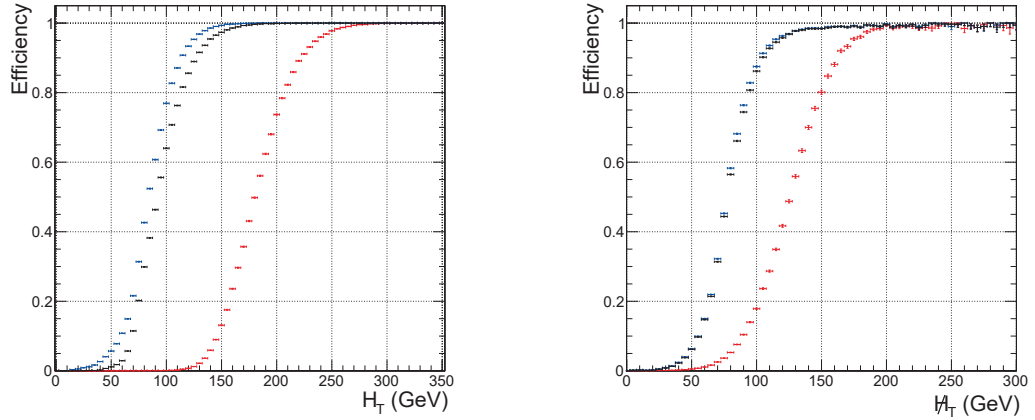


Figure 4.13: H_T (left) and $\#H_T$ (right) turn on curves for the GCT (red), upgrade prior to subtraction (blue) and upgrade after calorimeter multiplicity subtraction (black) for $H_T^{\text{L1}} > 75$ GeV and $\#H_T^{\text{L1}} > 75$ GeV thresholds respectively.

4.4.3 Comparison of pileup subtraction methods

Maintaining a low rate and high efficiency for physics objects is of utmost importance for retaining an effective trigger selection in Run 2 and is therefore an important metric in benchmarking the performance of the different pileup subtraction algorithms. Figure 4.14 shows the trigger rate as a function of signal efficiency for a selected offline signal jet for a variety of jet rank triggers, alongside a representative maximum 5 kHz rate that is allocated to each jet trigger in Run 2.

Without pileup subtraction, the performance of the upgrade algorithm is similar to the GCT algorithm for the single jet trigger, however for the multijet jet triggers the upgrade algorithm performance is worse than GCT, with a significantly higher trigger rate incurred for an equivalent signal efficiency. The application of a central region seed threshold to the upgrade algorithm can reduce the rate for low p_T jets, however at higher p_T the threshold becomes an ineffective method of suppressing rate.

After the application of the pileup subtraction methods however, the upgrade algorithm outperforms the GCT algorithm for all four of the multijet triggers, providing a greater signal efficiency for equivalent trigger rates. Of the three subtraction methods studied, calorimeter area subtraction provides the greatest performance, closely followed by jet area subtraction. The implementation of doughnut subtraction presented however is less efficient at suppressing rate, resulting in a 14% reduction in signal efficiency for the fourth jet trigger at 5 kHz.

4.4.4 Summary

A benchmark algorithm for the upgrade L1 jet trigger has been presented which exhibits improved performance in jet and energy sum triggers over the predecessor GCT algorithm. A suite of pileup subtraction algorithms have been tested which display stability in maintaining performance and reducing rate in a range of pileup regimes. This enables lower trigger thresholds to be employed, providing improvements in the reconstruction efficiency of jets of interest. From these studies it is seen that the use of pileup subtraction provides improvements in performance of the jet trigger with the calorimeter area and jet area methods showing the greatest improvement in performance. In Run 2 the described upgrade algorithm was commissioned in the L1 trigger alongside the existing trigger system,

using a variant of the doughnut subtraction method and was subsequently used to perform the L1 jet trigger selections in 2016 data taking.

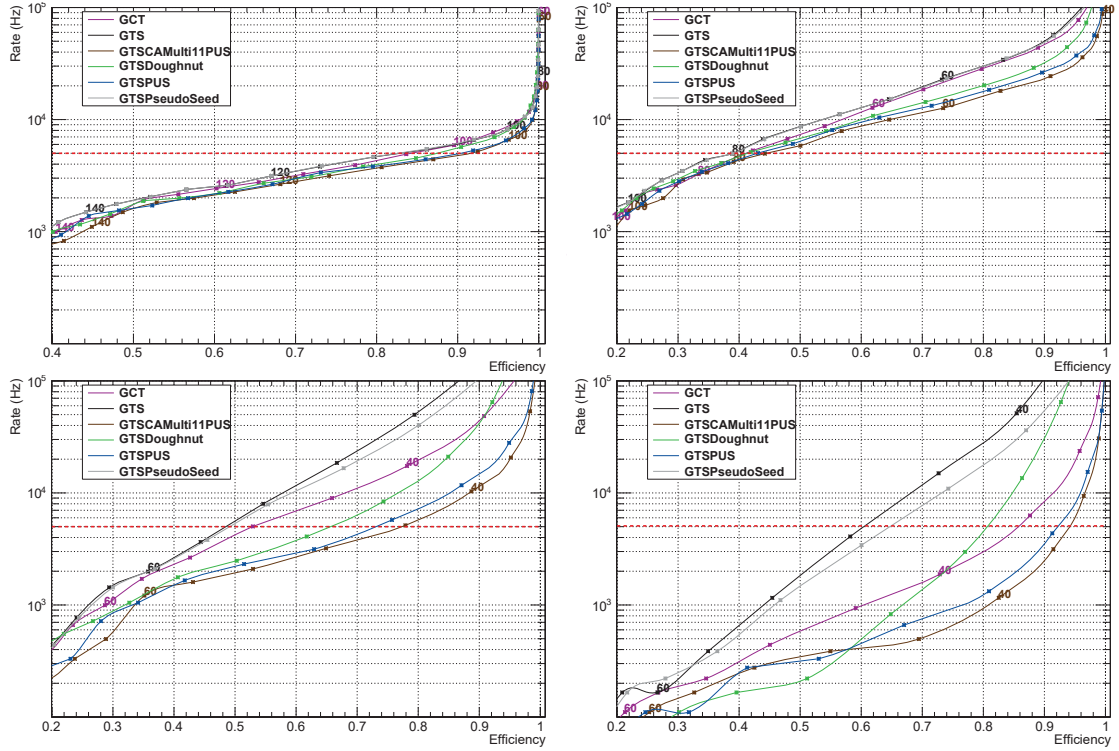


Figure 4.14: Jet trigger rate as a function of the selection efficiency of an offline leading jet with $p_T > 100$ GeV (top left), second leading jet with $p_T > 50$ GeV (top right) and third leading (bottom left) and fourth leading jets with $p_T > 40$ GeV (bottom right). The labels corresponding to the following: No subtraction (GTS), calorimeter area multiplicity subtraction (GTSCAMulti11PUS), jet area subtraction (GTSPUS) and a 5 GeV jet seed threshold (GTSPseudoSeed). The corresponding L1 p_T threshold (GeV) for points in the plane are denoted numerically and a 5 kHz trigger rate is depicted by the red dashed line.

CHAPTER 5

Search for supersymmetry with the α_T variable

Supersymmetry searches with hadronic final states are particularly challenging at the LHC due to the large production cross section of QCD multijets in pp -collisions. Searches for supersymmetry by the ATLAS and CMS experiments in LHC Run 1 failed to find signs of supersymmetry, setting some of the strongest limits on the masses of supersymmetric particles. The increase in centre-of-mass energy to $\sqrt{s} = 13$ TeV in Run 2 however provides a significant enhancement in sensitivity for superpartners, particularly in the production of very massive particles, making the analysis of early data in Run 2 of particular interest to supersymmetry searches.

5.1 Backgrounds for hadronic supersymmetry searches

The jets and missing-energy signature of hadronic SUSY decays are a common event topology for a range of SM processes which constitute backgrounds to the analysis. These backgrounds can be categorised as either arising from SM processes with genuine $\cancel{E}_T$, or as a result of QCD multijet production with $\cancel{E}_T$ arising from detector and acceptance effects. A good understanding of these backgrounds and their characteristics are critical to estimate and mitigate their contributions to searches, in order to maximise the sensitivity for potential signatures of new physics.

5.1.1 The QCD multijet background

As the dominant SM process in pp -collisions at the LHC, QCD multijet production is a challenging background for hadronic searches. Although QCD multijet production itself covers a large range of event topologies, its predominant component is dijet production, pair produced jets in a azimuthally back-to-back configuration. The majority of these QCD multijet events are balanced and in isolation do not possess the $\cancel{E}_T$ signature of the signal. Detector and reconstruction effects however can conspire to introduce a fake momentum imbalance between jets, mimicking the signal missing-energy signature. The mechanisms

by which this fake missing energy arises can be classified into several categories: *detector inefficiency*, *detector effects*, *misreconstruction* and *acceptance effects*, which are described below:

- Detector inefficiencies from regions that are uninstrumented or have reduced response can result in an under-measurement of jet energy, leading to an artificial momentum imbalance in the event. In such circumstances the azimuthal position of the inefficient region is correlated with the resultant missing energy vector.
- Fake additional energy arising from the spontaneous discharge of the calorimeter photodetectors and direct particle interactions electronics can additionally result in an artificial energy imbalance. In addition, secondary particles produced outside the detector from beam interactions, known as *beam halo*, can also leave significant energy deposits in the calorimeter as they traverse the detector.
- Misreconstruction effects such as the under or over-correction of jet energies and tracking failures can also introduce missing energy. Detector noise and misreconstruction of tracker hits can produce fake straight tracks that, due to their small radius of curvature, are falsely ascribed large momenta.
- Selection threshold effects can also introduce imbalance from the under-measurement of energy. Unclustered particles and jets that fall outside of momentum and pseudorapidity acceptances are not included in energy sums, in some cases leading to an artificial energy imbalance.

In addition to events with fake missing energy, QCD multijet production can also result in events with genuine missing energy from the leptonic decay of heavy flavour quarks. In such decays, the lepton is typically confined within the jet and fails isolation selections. The associated neutrino however is typically produced collinear with the emission of the lepton, leading to a signature of a small azimuthal separation between the jet axis and missing energy vector.

5.1.2 SM processes with genuine $\cancel{E}_T$

In addition to the QCD background, there are SM processes that produce jets in association with genuine $\cancel{E}_T$ from neutrinos in leptonic decays, which are collectively referred to as the *electroweak* background. This background itself is comprised of a several different processes, the dominant being top production and vector boson production in association with jets, known as $V + \text{jets}$.

$V + \text{jets}$ production is a major background for hadronic searches which, as a result of the large mass scale and neutrino production in vector boson decay, can result in a signature of significant hadronic energy and missing energy. The $V + \text{jets}$ background itself is admixture of W and Z boson production in association with jets, known as $W + \text{jets}$ and $Z + \text{jets}$ respectively, which emulate the signal topology via different mechanisms.

The $W + \text{jets}$ background can fake the hadronic signal topology via two main mechanisms: misreconstructed leptonic decays and hadronic decays of τ -leptons. In leptonic decays of W bosons, $W \rightarrow l\nu$, the missing-energy signature from the emission of the neutrino is typically associated with an isolated lepton and hence can be effectively suppressed via the application of a lepton veto. Event misreconstruction can however result in the lepton failing to be identified, effects which are collectively known as the *lost-lepton* background, through failures in: reconstruction, identification, isolation or acceptance selections.

In addition, the $W + \text{jets}$ background can fake the hadronic signal topology from hadronic decays of τ leptons, where the τ is misreconstructed as a jet. As approximately 49.5% of hadronic τ decays have final states with one charged pion [33] however, this class of events can be effectively identified by the presence of a single isolated track.

$Z + \text{jets}$ production with the subsequent decay to neutrinos, $Z \rightarrow \nu\bar{\nu}$, results in a pure missing-energy signature which presents an irreducible background for hadronic searches. Decays of Z bosons to charged lepton, $Z \rightarrow ll$, are a sub-dominant background, due to the reduced probability that both leptons fail reconstruction requirements.

The remaining dominant backgrounds arise from decays of top quarks in $t\bar{t}$ production and, more rarely, single top production, which are shown in Figure 5.1. Top quarks decay rapidly after production almost exclusively to bottom quarks via the decay: $t \rightarrow bW$. The resultant decay of the W boson can either be hadronic, producing jets, or leptonic producing a hadronic missing-energy signature when the lepton is misreconstructed. Due to the presence of multiple b -quarks in the final state, top events can be effectively tagged by presence of high multiplicities of b -jets, in addition to large light-jet multiplicities and missing energy from hadronic and leptonic decays of W bosons respectively.

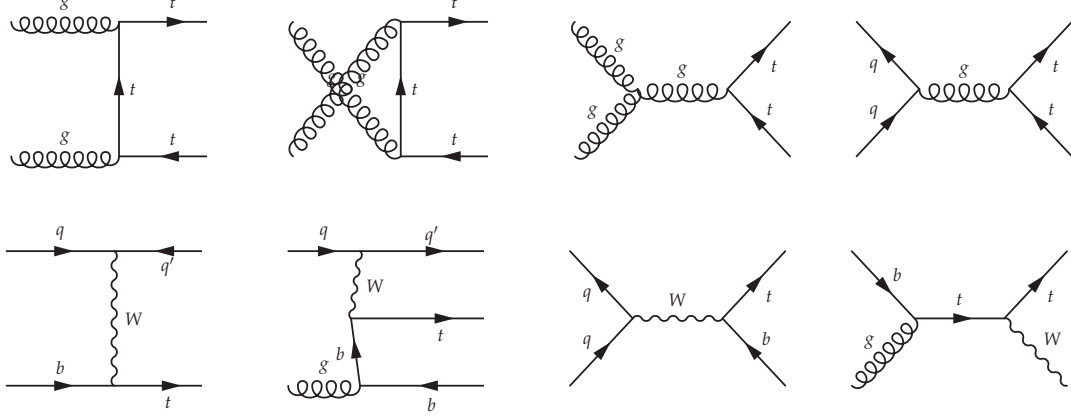


Figure 5.1: Feynman diagrams of LO production of $t\bar{t}$ (top) and t -quarks (bottom).

In addition to the aforementioned backgrounds, there are also residual contributions from the standard model processes: Drell-Yan and diboson production. These however are suppressed due to their smaller cross sections and reduced probability of failing multiple leptonic reconstructions.

The relative contributions of these backgrounds have a strong dependency on event quantities such as the total jet and b -jet multiplicities, n_{jet} and n_b respectively. Events with low n_{jet} and n_b multiplicities are typically dominated by $W \rightarrow l\nu$ decays, where lepton misreconstruction and hadronic decays of τ leptons provide a missing-energy signature, and from $Z \rightarrow \nu\bar{\nu}$ decays, which constitute an irreducible background. The majority of events with high n_{jet} and n_b multiplicities are a result of top physics processes, predominantly $t\bar{t}$ production, with additional contributions from more rare-processes including: single-top production and $t\bar{t}$ associated production of weak vector and Higgs bosons.

5.2 The α_T analysis

The α_T analysis is a hadronic supersymmetric search which uses the dimensionless kinematic α_T variable to effectively suppress the QCD multijet background, whilst maintaining a good acceptance for a range of signal models. The analysis aims to be robust, minimising reliance on MC modelling with the use of data-driven background estimation methods. In addition, the analysis provides an inclusive and model-independent search for new physics with the use of dedicated analysis triggers, providing sensitivity to a large range of signal topologies down to very low hadronic energies. In LHC Run 1 the α_T analysis performed

an extensive search for SUSY, performing analyses of datasets with total integrated luminosity $\mathcal{L} = 4.98 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$ [123, 124, 125] and $\mathcal{L} = 18.5 \text{ fb}^{-1}$ at $\sqrt{s} = 8 \text{ TeV}$ [126], setting strong limits on the masses of supersymmetric particles.

To further increase the scope and sensitivity of supersymmetry signatures in Run 2, the analysis reconstruction techniques, trigger selections and analysis selections have been refined, providing improvements to sensitivity and robustness in a more challenging high-luminosity environment.

Improvements to reconstruction within the analysis have been made with a transition from calorimeter-based reconstruction of jets and $\cancel{E}_T$ to a PF-based reconstruction. The use of PF provides significant improvements to the jet energy resolution, enabling the analysis jet threshold to be reduced to $p_T > 40 \text{ GeV}$ from the $p_T > 50 \text{ GeV}$ threshold used in Run 1, providing increased acceptance to models with softer hadronic signatures. Additionally, a more effective suppression of pileup is achieved with the use of CHS and PF-based jet area pileup corrections, in conjunction with a reduction in the jet clustering radius parameter from $\Delta R = 0.5$ used in Run 1, to $\Delta R = 0.4$.

A greater sensitivity to new physics models is achieved by the use of new signal triggers, which enable the analysis to extend model acceptances in Run 2 in more challenging conditions. In addition, an improvement to the sensitivity of the analysis to new signal topologies is facilitated by the addition of new jet categories and a new analysis $\cancel{H}_T$ dimension, providing increased acceptance to compressed and DM models.

5.3 Suppression of the QCD multijet background

A guiding principle of the α_T analysis is the effective suppression of the QCD multijet background whose contribution, prior to selection, dwarfs the other analysis backgrounds by several orders of magnitude. The analysis utilises three control variables: α_T , $\Delta\phi_{\min}^*$ and $\cancel{H}_T/\cancel{E}_T$, to ensure that the QCD multijet background contribution is sub-dominant with respect to the other backgrounds. These variables exploit the signatures characteristic of QCD multijet background and event misreconstruction to effectively target QCD topologies, whilst maintaining efficiency for signal events.

5.3.1 The α_T variable

Initially proposed as the α variable that utilised the full jet three-momentum [127], a transverse variant more suitable for hadron colliders, α_T , was constructed which provides an effective separation of QCD multijet events with fake- $\cancel{E}_T$ from physics processes containing genuine $\cancel{E}_T$. For a dijet event, α_T is defined as the ratio of the transverse momentum of the subleading jet, $p_T^{j_2}$, and the transverse mass of the dijet system:

$$\alpha_T = \frac{p_T^{j_2}}{M_T^{jj}}. \quad (5.1)$$

Where the dijet transverse mass, M_T^{jj} , is defined:

$$M_T^{jj} = \sqrt{\left(\sum_{i=1}^2 E_T^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_x^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_y^{j_i}\right)^2}. \quad (5.2)$$

In the high energy limit, where jet mass is small with respect to its momentum, the energy of the jet can be approximated as being equivalent to its momentum ($E_T \sim p_T$). This enables the transverse mass to be expressed in terms of the total and missing hadronic energies by the relation:

$$M_T^{jj} = \sqrt{H_T^2 - \cancel{E}_T^2}. \quad (5.3)$$

By Equation 5.3, a simplified form of α_T for a dijet system can be expressed by the relation:

$$\alpha_T = \frac{p_T^{j_2}}{\sqrt{H_T^2 - \cancel{E}_T^2}}. \quad (5.4)$$

The computation of α_T can be generalised to higher jet multiplicities by clustering jets into two *pseudojets*, whose transverse momentum is equivalent to the scalar sum of the constituent jets. In the clustering of pseudojets, all possible combinations are considered, with the configuration that minimises the absolute transverse energy difference between the pseudojets, ΔH_T , being selected. This leads to the general form for the α_T applicable for all jet multiplicities:

$$\alpha_T = \frac{1}{2} \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \cancel{E}_T^2}}. \quad (5.5)$$

An illustration of how the α_T variable can be used to distinguish between events with fake and genuine missing energy is shown in Figure 5.2. For a perfectly reconstructed QCD dijet event with no associated $\cancel{E}_T$, the jets are produced with balanced transverse momenta in a back-to-back configuration, resulting in an α_T value of 0.5. For events with fake missing energy introduced from the mismeasurement of a jet, the imbalance in the momentum in the dijet system acts to decrease the value of α_T below 0.5. In events with jets produced in association with genuine $\cancel{E}_T$, the recoil of jets against the invisible system results in an azimuthal separation between the missing energy vector and the jets, resulting in an α_T value above 0.5. In rare cases of significant jet energy mismeasurement, QCD events can be reconstructed with larger values of α_T , resulting in a residual QCD contamination for $\alpha_T > 0.5$.

The behaviour of α_T measured in data for backgrounds with genuine and fake missing energy is demonstrated in Figure 5.3. For the QCD multijet background, the distribution is strongly peaked for values of α_T below 0.5, which is sharply falling with increasing α_T with some residual leakage above $\alpha_T = 0.55$. SM backgrounds with genuine $\cancel{E}_T$ conversely possess a much broader distribution, with long tails that extend to high values of α_T . This difference in behaviour makes the α_T variable a powerful discriminator between SM processes with genuine missing energy and events with fake- $\cancel{E}_T$, which are characteristic of the QCD multijet background.

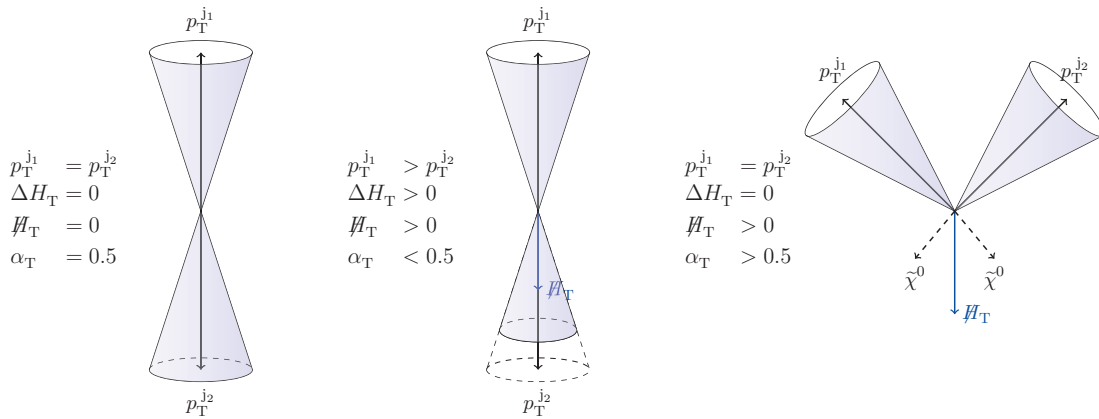


Figure 5.2: Schematic of the behaviour of α_T for a range of different event topologies including: a well-reconstructed QCD dijet event (left), a mismeasured QCD dijet event (middle) and a signal event with genuine $\cancel{E}_T$ (right). The solid arrows represent the direction and magnitude of the true momentum of the jets and the cones their reconstructed momentum.

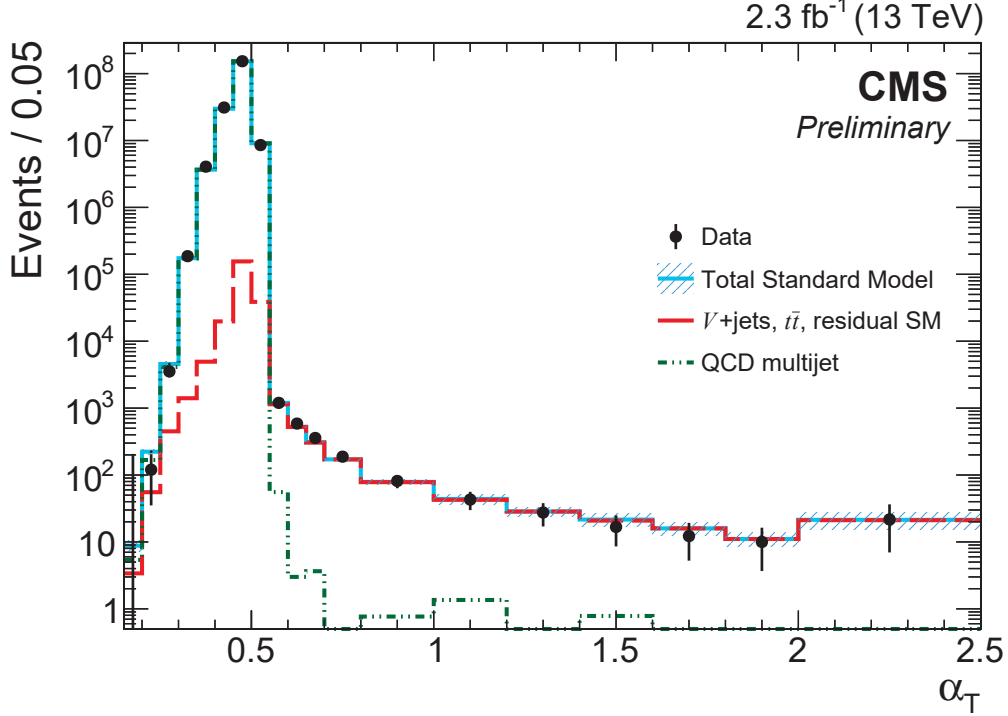


Figure 5.3: α_T distribution measured in data in $\sqrt{s} = 13$ TeV pp -collisions. The individual electroweak (red solid line) and QCD (green dashed line) background components are determined from simulation. Below $\alpha_T = 0.55$ data are collected by unbiased triggers, with a loose preselection applied. Above $\alpha_T = 0.55$ data are collected with signal triggers, with a full analysis selection applied.

5.3.2 The $\Delta\phi_{\min}^*$ variable

Working in conjunction with the α_T variable, the topological ‘biased- $\Delta\phi$ ’ variable, $\Delta\phi_{\min}^*$, is used to suppress residual contamination from QCD. The $\Delta\phi_{\min}^*$ variable is effective in rejecting QCD events with genuine $\cancel{E}_T$ from heavy flavour decays and fake- $\cancel{E}_T$ arising from jet mismeasurement. Illustrated in Figure 5.4, $\Delta\phi_{\min}^*$ is computed as the minimum azimuthal separation between the transverse momentum vector of each jet, $\vec{p}_T^{j_i}$, and the corresponding hadronic missing energy vector when the jet is removed, $\vec{\cancel{H}}_T^{j_i} = \vec{\cancel{H}}_T + \vec{p}_T^{j_i}$:

$$\Delta\phi_{\min}^* = \min \left[\Delta\phi \left(\vec{p}_T^{j_i}, \vec{\cancel{H}}_T^{j_i} \right) \right]. \quad (5.6)$$

Selections on the minimum azimuthal separation between the jet vector and missing energy vector are commonly used in suppressing signatures of mismeasurement in physics searches. These metrics however typically include the highest energy jet in the compu-

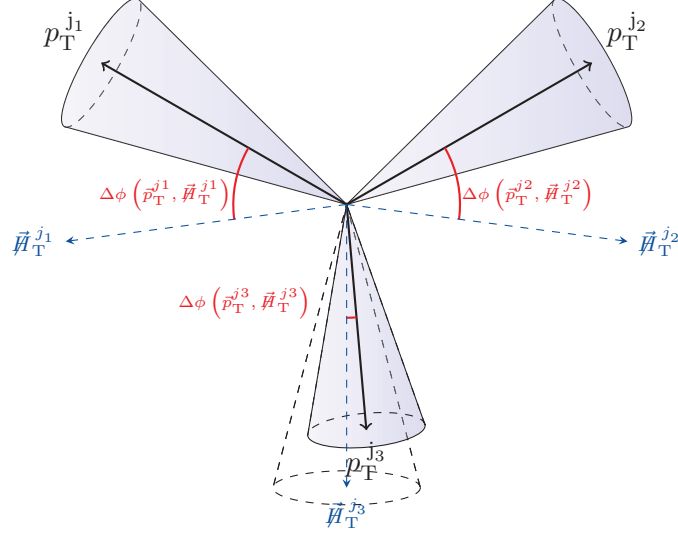


Figure 5.4: Schematic of the computation of $\Delta\phi_{\min}^*$ in a mismeasured three-jet event in a ‘Mercedes’ configuration. The momenta of each jet is represented by the solid black line and the missing energy vector computed for each jet is shown by the dashed blue line, the corresponding angle between the probe jet and the missing energy vector is given by the red solid arc. In this example jet 3 is the jet that minimises $\Delta\phi(\vec{p}_T^{j_i}, \vec{H}_T^{j_i})$.

tation and are therefore susceptible to severe jet mismeasurement. The removal of the ‘probe’ jet in the computation of $\Delta\phi_{\min}^*$ makes the variable more robust against such instances of mismeasurement.

The $\Delta\phi_{\min}^*$ variable is effective in the suppression of detector mismeasurement, where jets are projected in regions of reduced or no response. As the missing hadronic energy vector in such events is typically collinear with the mismeasured jet, they typically possess small values of $\Delta\phi_{\min}^*$ and hence can be suppressed with the application of a $\Delta\phi_{\min}^*$ threshold. Conversely the vector of the $\Delta\phi_{\min}^*$ -jet, the jet responsible for the minimum jet- $\cancel{H}_T$ separation, in events with low values of $\Delta\phi_{\min}^*$ can be exploited to identify regions of inefficiency.

In addition to mismeasurement, $\Delta\phi_{\min}^*$ is effective in suppressing QCD events with genuine $\cancel{H}_T$ from the leptonic decay of heavy flavour quarks. As the neutrino emission is typically collinear with the jet-direction in such decays, the $\cancel{H}_T$ -vector is typically aligned with the axis of the decay jet, resulting in small values of $\Delta\phi_{\min}^*$. This is in contrast to electroweak and signal processes which typically recoil against the jet system, resulting in larger values of $\Delta\phi_{\min}^*$.

The difference in behaviour of $\Delta\phi_{\min}^*$ measured in data for the QCD and electroweak backgrounds is demonstrated in Figure 5.5. As the QCD multijet background typically emulates the signal topology through mismeasurement, the $\Delta\phi_{\min}^*$ distribution for QCD is strongly peaked at $\Delta\phi_{\min}^* = 0$, falling sharply with increasing $\Delta\phi_{\min}^*$. The electroweak backgrounds conversely typically have jets recoiling against the invisible system, resulting in a more gradual reduction for increasing $\Delta\phi_{\min}^*$.

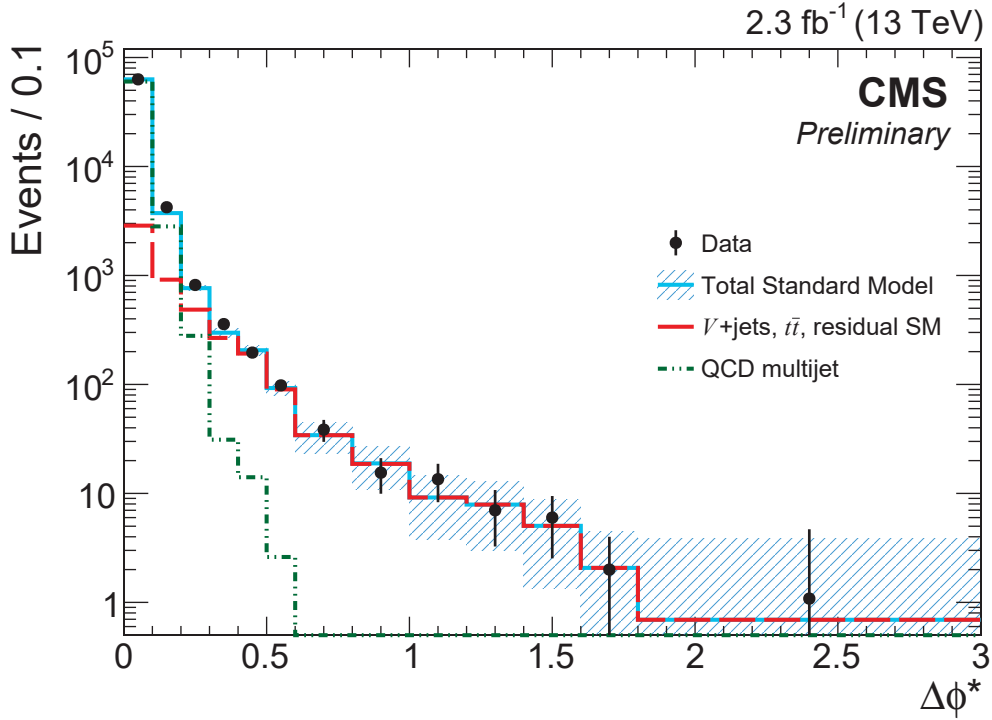


Figure 5.5: $\Delta\phi_{\min}^*$ distribution measured in Run 2 data for a selection $H_T > 800$ GeV. The individual electroweak (red solid line) and QCD (green dashed line) background components are determined from simulation.

5.3.3 $H_T/\cancel{E}_T$

The final control variable used in the control of the QCD background is the ratio $H_T/\cancel{E}_T$, which is effective in the suppression of events with fake missing energy arising from severe mismeasurement and threshold effects. The selection on $H_T/\cancel{E}_T$ ensures agreement between clustered and unclustered energy, reducing the possible contribution to fake- $\cancel{E}_T$ from jets that fail acceptance requirements or fall below threshold.

5.4 Object selection

Event reconstruction within the α_T analysis is performed using the standard CMS reconstruction algorithms described in Chapter 3. Although a fully-hadronic search, the analysis makes use of a large range of physics objects including: jets, leptons, photons and isolated tracks.

Selections are applied to reconstructed objects to maintain high signal efficiency and provide a better control of analysis backgrounds. In the case of leptons and photons, two distinct selections are applied which are categorised as either: *veto*, for objects passing loose selections, or *tight*, when more stringent criteria are met. Veto objects are used to identify contamination from weak decays in the signal and orthogonal control regions, whilst tight objects are utilised in control regions to ensure good reconstruction and a pure sample.

A summary of the algorithms and selections used in the reconstruction of the analysis physics objects are presented below.

5.4.1 Jets

Jets in the analysis are reconstructed with the PF algorithm clustered with a radius parameter of $\Delta R = 0.4$, with additional CHS and jet area corrections applied to compensate for pileup energy contamination. Relative and absolute JECs are applied to calibrate jet energy, with an additional residual correction applied for jets reconstructed in data. All reconstructed jets are required to pass the ‘loose’ PFJet ID WP, which applies requirements on the minimum multiplicity and relative energy of jet constituents to reject jet fakes. The tagging of b -jets is performed using the CSVv2 algorithm with the medium WP, which provides a tagging efficiency of $\sim 80\%$ for a 1% mistag probability [108].

As jets produced in supersymmetric models are typically high-energy and centrally produced, kinematic selections can be applied to ensure good reconstruction and suppress QCD without a large loss in signal efficiency. Analysis jets are required to be centrally produced, $|\eta| < 3$, with a minimum momentum of $p_T > 40$ GeV. A tighter selection is applied on the pseudorapidity and momentum of the leading jet of $|\eta| < 2.5$ and $p_T > 100$ GeV respectively. Jets reconstructed in the forward region, $3 < |\eta| < 5$, are classified as forward jets and have no requirement on PFJet ID.

5.4.2 Photons

Photons are selected using the cut-based ‘tight’ ID WP, which provides a $\sim 71\%$ selection efficiency and $\sim 88\%$ background rejection. Isolation selections, which are categorised according to the detector geometry and background composition, are applied to provide an effective control of fake-prompt photons as shown in Table 5.1. Photon isolation is computed using a PF relative isolation cone of radius $\Delta R = 0.3$ with an EA-correction using grid- ρ .

Kinematic selections are applied to photons passing these requirements, with a loose selection applied on veto photons of: $p_T > 25 \text{ GeV}$ and $|\eta| < 2.5$. A tighter requirement of $p_T > 200 \text{ GeV}$ and $|\eta| < 1.45$ is applied for photons in the photon control region in order to be efficient for trigger selections and be fully contained within the ECAL barrel to ensure a good reconstruction.

Isolation type	Selection	
	Barrel	Endcap
PF charged hadron	0.76	0.56
PF neutral hadron	$0.97 + 0.014 \times p_T^\gamma + 0.000019 \times p_T^{\gamma^2}$	$2.09 + 0.0139 \times p_T^\gamma + 0.000025 \times p_T^{\gamma^2}$
PF photon	$0.08 + 0.0053 \times p_T^\gamma$	$0.16 + 0.0034 \times p_T^\gamma$

Table 5.1: Photon isolation selection requirements according to PF-candidate species for the barrel and endcap.

5.4.3 Muons

Muons in the analysis are selected with the ‘tight’ ID WP which provides a $\sim 95\%$ selection efficiency. Muons are required to be isolated to reject non-prompt muon backgrounds using PF relative isolation with an EA-correction. Muons in the muon control region have a PF relative isolation requirement of $I_{\text{PF}}^{\text{rel}} < 0.12$ computed with a cone size of $\Delta R = 0.4$. Veto muons in the signal and photon control regions are selected by a PF relative mini isolation of $I_{\text{PF}}^{\text{mini}} < 0.2$, with a maximum cone size of $\Delta R = 0.2$. Kinematic selections of $p_T > 10 \text{ GeV}$ and $|\eta| < 2.4$ are applied for the selection of veto muons, with a tighter selection of $p_T > 30 \text{ GeV}$ and $|\eta| < 2.1$ applied in the muon control region to ensure good reconstruction and efficiency with respect to trigger selections.

5.4.4 Electrons

Veto electrons are selected using the ‘loose’ cut-based ID WP, which has a $\sim 90\%$ selection efficiency, with a veto to reject electrons that are a product of photon conversions in the tracking detector. Electrons are required to be isolated with a PF relative mini isolation selection of $I_{\text{PF}}^{\text{mini}} < 0.1$, which is EA-corrected with a maximum cone size of $\Delta R = 0.2$. Additional kinematic selections of $p_{\text{T}} > 10 \text{ GeV}$ and $|\eta| < 2.5$ are applied to ensure good reconstruction.

5.4.5 Isolated tracks

Isolated tracks are selected from all reconstructed charged PF-candidates associated with the primary vertex with $p_{\text{T}} > 10 \text{ GeV}$, with additional selections applied on their track quality. Isolated tracks are required to be isolated with a PF relative isolation requirement of $I_{\text{PF}}^{\text{rel}} < 0.1$, computed from charged PF-candidates associated with the primary vertex.

5.4.6 Energy sums

The total missing energy, $\cancel{E}_{\text{T}}$, is computed from the vector sum of the momentum of all reconstructed PF-candidates with $|\eta| < 5$, with a type-I correction applied using CHS corrected PFJets with $p_{\text{T}} > 15 \text{ GeV}$. In the control regions $\cancel{E}_{\text{T}}$ is computed without the momentum of the corresponding lepton or photon. The total hadronic energy, H_{T} , and hadronic missing energy, $\cancel{H}_{\text{T}}$, are computed from the vectorial and scalar sum of all central analysis jets respectively.

5.4.7 Object selection summary

The selections applied to physics objects used in the analysis are summarised in Table 5.2.

Object		Selections			
		ID	Isolation	Kinematic selection	
Jet	All jets	Loose	N/A	$p_T^j > 40 \text{ GeV}$,	$ \eta < 3$
	Leading jet	Loose	N/A	$p_T^{j_1} > 100 \text{ GeV}$,	$ \eta < 2.5$
	Forward jet (veto)	None	N/A	$p_T^j > 40 \text{ GeV}$,	$3 < \eta < 5$
Photon	γ control region	Tight	See text	$p_T^\gamma > 200 \text{ GeV}$,	$ \eta < 1.45$
	Veto	Tight	See text	$p_T^\gamma > 25 \text{ GeV}$,	$ \eta < 2.5$
Muon	μ control region	Tight	$I_{\text{PF}}^{\text{rel}} < 0.12$	$p_T^\mu > 30 \text{ GeV}$,	$ \eta < 2.1$
	Veto	Loose	$I_{\text{PF}}^{\text{mini}} < 0.2$	$p_T^\mu > 10 \text{ GeV}$,	$ \eta < 2.4$
Electron	Veto	Loose	$I_{\text{PF}}^{\text{mini}} < 0.1$	$p_T^e > 10 \text{ GeV}$,	$ \eta < 2.5$
Isolated track	Veto	N/A	$I_{\text{PF}}^{\text{rel}} < 0.1$	$p_T > 10 \text{ GeV}$,	$ \eta < 2.5$

Table 5.2: A summary of selection of physics objects used in the analysis including: ID, kinematic selection and isolation requirements where applicable.

5.5 Event categorisation

To better separate signal and background topologies, events are categorised by discriminating kinematic variables designed to probe specific event characteristics of backgrounds and target different features of signal models including: mass splittings, production modes and decay modes. For the purpose of categorisation the analysis uses four kinematic variables: total jet multiplicity, n_{jet} ; b -jet multiplicity, n_b ; total hadronic energy, H_T ; and missing hadronic energy, $\cancel{H}_T$.

5.5.1 Jet multiplicity categorisation

The multiplicity of jets in events is a useful discriminator between background event topologies and in the characterisation of signal models. The jet multiplicity for signal models is strongly dependent on the signal production mode, with squark pair production models typically resulting in events with lower jet multiplicities than in gluino pair production. Backgrounds are also discriminated by n_{jet} , with $t\bar{t}$ production typically resulting in events with larger jet multiplicities than in vector boson production.

To distinguish between signal models and backgrounds the analysis utilises three distinct jet categories: *monojet*, *asymmetric* and *symmetric*, which are defined by requirements on the second leading jet. The symmetric selection targets the typical pair produced sparticle signature of at least two hard jets, with a hard second leading jet requirement of $p_T^{j_2} > 100$ GeV, providing an effective suppression of backgrounds whilst maintaining a large acceptance to signal models. In compressed spectrum models, where there is less energy liberated in the decay of the sparticle parents, jets are typically produced with low momentum making them difficult to separate from backgrounds. Sensitivity to such models is typically achieved via ISR recoiling against the decay system, resulting in a signature of a single hard ISR jet and a low- p_T or absent second jet. The asymmetric and monojet categories were introduced in the Run 2 analysis to target this signature, providing a greater acceptance to compressed spectrum and dark matter models, with a relaxed second jet requirement of $40 < p_T^{j_2} < 100$ GeV and a second jet veto for $p_T^{j_2} > 40$ GeV respectively.

In addition to n_{jet} , the multiplicity of reconstructed b -jets, n_b , provides another distinguishing parameter in the separation of signal topologies and backgrounds. For signal models, n_b provides increased sensitivity to the production of third generation squarks which typically produce b -jets in the decay cascade. Background contributions can also be better characterised by the number of b -jets in the event, with top backgrounds typically having a large number of b -jets and vector boson production having few or no b -jets.

To separate different signal and background topologies, events are categorised by their jet and b -jet multiplicities. In Run 2 the analysis utilises a finer granularity n_{jet} binning, transitioning from the two categories of $n_{\text{jet}} = 2 - 3$ and ≥ 4 used in Run 1, to the finer binning: $n_{\text{jet}} = 1, 2, 3, 4$ and ≥ 5 . Similarly, the b -jet dimension is binned to a higher granularity with the bins of $n_b = 0, 1, 2$ and ≥ 3 , where the maximum b -jet multiplicity is bounded by the total jet multiplicity in the event as summarised in Table 5.3.

n_{jet} selection	n_b categorisation
1	0, 1
2	0, 1, 2
3	0, 1, 2, 3
4	0, 1, 2, ≥ 3
≥ 5	0, 1, 2, ≥ 3

Table 5.3: The analysis n_b classifications as a function of the event n_{jet} selection.

5.5.2 Hadronic energy categorisation

In addition to multiplicity, the topology and activity of jets in the event provide useful information on the energy scale of the interaction and a measurement of the momentum of weakly interacting particles. The total hadronic energy in the event, H_T , gives a measure of the mass scale of the interaction and the missing hadronic energy, $\cancel{H}_T$, provides a measure of the mass of the LSP, bounded by the total visible energy in the system.

The analysis has a minimum hadronic energy selection of $H_T > 200$ GeV, with variable width H_T bins driven by trigger selections and predicted statistical power. The nominal H_T binning is chosen to be: $H_T = 200\text{--}250, 250\text{--}300, 300\text{--}350, 350\text{--}400, 400\text{--}500, 500\text{--}600, 600\text{--}800$ GeV, with a final inclusive bin $H_T > 800$ GeV. The threshold of the last H_T bin is selected such that at least ten events are predicted for the corresponding H_T and n_{jet} binning, as summarised in Table 5.4, with a lower threshold used where this requirement is not met.

A minimum missing hadronic energy threshold of $\cancel{H}_T > 130$ GeV is applied to ensure that the event contains a sufficient degree of missing energy and aligns to the minimum α_T selection described in Section 5.7.1. Event yields are measured in bins of $(H_T, n_{\text{jet}}, n_b)$, inclusive of $\cancel{H}_T$, with simulated $\cancel{H}_T$ shapes with bins of width $\cancel{H}_T = 50$ GeV used to predict the distribution of yields in the $\cancel{H}_T$ dimension. The threshold of the final bin of the $\cancel{H}_T$ shape is dictated by the available statistics in simulation and is required to have a sufficiently large predicted SM yield such that the relative statistical uncertainty is smaller than 50%.

Selection	Categorisation														
n_{jet}	2			3				4				≥ 5			
n_{b}	0	1	2	0	1	2	3	0	1	2	≥ 3	0	1	2	≥ 3
Symmetric	800	800	800	800	800	800	500	800	800	800	800	800	800	800	800
Asymmetric	600	600	600	600	600	600	400	600	600	600	500	600	600	600	500

Table 5.4: Threshold of the highest H_T bin as a function of the n_{jet} and n_b category for the symmetric and asymmetric categories.

5.5.3 Event categorisation summary

The nominal choice of event categorisation for the analysis is summarised in Table 5.5.

Selection	Categorisation
Jet multiplicity	Monojet : $n_{\text{jet}} = 1$ Symmetric/Asymmetric : $n_{\text{jet}} = 2, 3, 4, \geq 5$
b -jet multiplicity	$0, 1, 2, \geq 3$ ($n_b \leq n_{\text{jet}}$)
H_T -binning (GeV)	200–250, 250–300, 300–350, 350–400, 400–500, 500–600, 600–800, ≥ 800
$\cancel{H}_T$ -binning (GeV)	> 130

Table 5.5: Summary of the nominal selections in the categorisation of events in the analysis.

5.6 Preselection

To ensure a similar kinematic regime across all analysis regions, common selections are applied to the signal and control regions, reducing reliance on modelling of translation from different regions of phase space. In addition, event filters that are designed to target sources of fake- $\cancel{E}_T$ are applied to ensure good event reconstruction.

5.6.1 Event filters

A range of non-physical instrumental and reconstruction effects can produce a missing-energy signature from the introduction of an artificial momentum imbalance. As the occurrence of these effects is random, the magnitude of these backgrounds cannot be accurately predicted in simulation. Instead, events which exhibit characteristic pathological behaviour are removed using the dedicated event filters described below:

- Beam halo is targeted by the *CSC beam halo filter*, which rejects events with CSC detector hits and calorimeter energy deposits that are consistent with exterior particles traversing the detector.
- Spurious signals in the HCAL and ECAL are tackled by the *HBHE noise and isolation filter* and *EE bad supercluster noise filter*, which reject events with fake-energy deposits from direct particle interactions and anomalous signals in the detector electronics.
- Tracking failures are targeted by the *bad track filter*, which is designed to tackle pathological track reconstruction, and the *primary vertex filter*, which requires at least one good vertex is reconstructed.

The effect of event filters in data can be seen in Figure 5.6, which shows an effective suppression of fake- $\cancel{E}_T$ events that dominate the tail of the $\cancel{E}_T$ distribution with the application of the filters, bringing the measured data back into agreement with simulation.

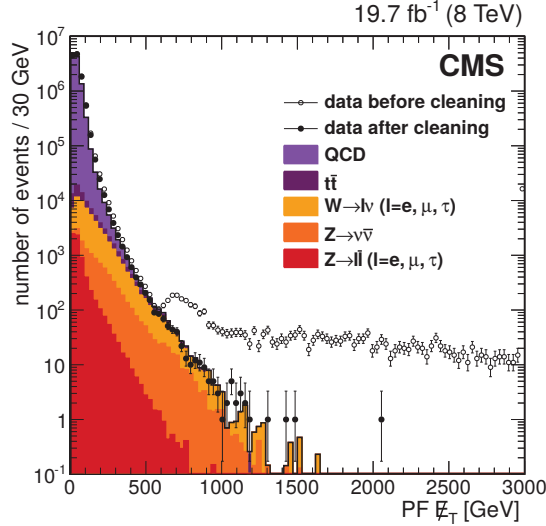


Figure 5.6: Distribution of PF- $\cancel{E}_T$ for a dijet selection measured in $\sqrt{s} = 8$ TeV data without the application of $\cancel{E}_T$ -filters (hollow circles) and with $\cancel{E}_T$ -filters applied (filled circles) and the associated simulated expectation [109].

5.6.2 Event vetoes

In addition to event filters, event vetoes are applied to target specific effects not controlled by the previous selections, particularly during the commissioning of the detector in Run 2. These include:

- A *leading jet veto* is utilised to target residual beam halo, with a veto for leading jets with a PF Charged Hadron Energy Fraction (CHEF) below 10%. This is effective in removing events with fake jets formed from beam halo calorimeter energy deposits.
- Jets failing PFJet ID are typical signatures of fake jets from arising from calorimeter noise or as a result of event misreconstruction. The *odd jet veto* removes events that fail the loose PFJet to suppress this source of fake- $\cancel{E}_T$.
- Particles emitted in the forward region outside the acceptance of the detector can introduce fake- $\cancel{E}_T$. The *forward jet veto* discards events with jets reconstructed with $|\eta| > 3$ and $p_T^j > 40$ GeV, which is effective in suppressing this background with little loss in the acceptance of supersymmetric signal models.

- Lost-lepton events and hadronic tau decays are suppressed with an *Isolated track veto*, which removes events with an isolated track with $p_T > 10 \text{ GeV}$ and $|\eta| < 2.5$. For leptonic samples, a minimum $\Delta R > 0.02$ separation between the reconstructed lepton and isolated track is applied to ensure the isolated track is not attributed to the reconstructed lepton.

5.6.3 Kinematic selections

Kinematic selections are applied with a total hadronic energy and hadronic missing energy selection of $H_T > 200 \text{ GeV}$ and $\cancel{H}_T > 130 \text{ GeV}$, with an additional requirement of at least one jet meeting the selections in Section 5.4.1. This ensures energetic events with a missing-energy signature that are efficient for trigger selections in the signal region.

5.6.4 Preselection summary

A summary of the analysis preselections are shown in Table 5.6.

Selection	Requirement
Event filters	Primary Vertex, CSC Beam Halo, HBHE Noise and Isolation, ECAL Endcap SC Noise, bad track filter
Leading jet veto	Leading jet CHEF > 0.1
Isolated track veto	Veto events with Isolated track with $p_T > 10 \text{ GeV}$, $ \eta < 2.5$
Odd jet veto	Veto events with $p_T > 40 \text{ GeV}$, $ \eta < 3$, failing PFJet ID
Hadronic total energy	$H_T > 200 \text{ GeV}$
Hadronic missing energy	$\cancel{H}_T > 130 \text{ GeV}$

Table 5.6: Summary of the common preselections applied in the analysis.

5.7 Analysis selections

After the application of the preselection criteria, dedicated selections are applied to reduce backgrounds and ensure a purely-hadronic signal region and high-purity control regions. In total four control regions are utilised for the purpose of background estimation: a hadronic control region, which is used in the estimation of the QCD background, a photon control region, $\gamma + \text{jets}$, and two muon control regions, $\mu + \text{jets}$ and $\mu\mu + \text{jets}$, which are used in the estimation of the electroweak backgrounds.

5.7.1 Hadronic signal region

As the signal region is designed to search for fully hadronic signs of new physics, dedicated selections are applied to ensure a pure hadronic topology and to suppress the QCD multijet background.

5.7.1.1 Suppression of the QCD multijet background

After preselection QCD multijet production is the dominant background, with expected yields that are several orders of magnitude larger than other backgrounds. To suppress the QCD multijet background dedicated selections with the α_T , $\Delta\phi_{\min}^*$ and $\cancel{H}_T/\cancel{E}_T$ control variables are applied, reducing its relative contamination with respect to the other backgrounds to the percent-level.

An H_T -dependent α_T selection shown in Table 5.7, which ranges from $0.52 < \alpha_T < 0.65$, is applied to the multijet bins. The scaling of α_T thresholds is driven by trigger selection in the signal region and the evolution of the α_T behaviour of QCD background with H_T . No α_T selection is applied in the high- H_T region, which is seeded by a pure- H_T trigger, due to decreased efficiency of α_T selections with high jet multiplicities. Additionally, no α_T selection is applied for monojet events as the computation of α_T requires a minimum of two jets.

H_T (GeV)	200	250	300	350	400	500	600	800
α_T threshold	0.65	0.60	0.55	0.53	0.52	0.52	0.52	–

Table 5.7: Evolution of the α_T selection as a function of the total hadronic energy selection.

In addition to the α_T requirement, a $\Delta\phi_{\min}^* > 0.5$ selection is applied to provide a suppression of the residual QCD contamination from mismeasurement and heavy flavour QCD. As fake- $\cancel{E}_T$ is often the result of the severe jet mismeasurement, $\Delta\phi_{\min}^*$ is computed from jets with a lower threshold $p_T > 20$ GeV to catch jets that fall below the analysis jet p_T threshold. Finally, a requirement on the agreement in missing energy measurement between clustered and unclustered energies of $\cancel{H}_T/\cancel{E}_T < 1.25$ is applied, which is effective in the suppression of jet threshold and acceptance effects.

5.7.1.2 Lepton and photon veto

Dedicated vetoes on the reconstruction of isolated leptons and photons are utilised in the hadronic signal region to ensure a pure multijet sample and to remove events with poor

reconstruction in the control regions. In the signal and hadronic control regions, a veto is applied for events with leptons or photons passing analysis selections, ensuring a pure hadronic sample. In the lepton and photon control regions, a veto is applied to events with leptons that pass the veto selection but fail the tight selection, to suppress events with poor reconstruction. In addition a veto is applied for objects passing the tight selection that are of a flavour orthogonal to the control region.

5.7.2 Control regions

The α_T analysis aims to be robust through the use of data-driven background estimation from measurements in control regions. For this purpose, $\mu\mu + \text{jets}$ and $\gamma + \text{jets}$ samples are used in the estimation of the irreducible $Z \rightarrow \nu\bar{\nu} + \text{jets}$ background, which are corrected to account for the detector acceptance, and a $\mu + \text{jets}$ data sample is used in the estimation of $W + \text{jets}$ and $t\bar{t}$ backgrounds.

The control regions use the same QCD selections as the signal region to ensure commonality between region phase space, with two exceptions made. No $\Delta\phi_{\text{min}}^*$ selection is applied to the control regions and no α_T requirement is applied in the muon control regions, providing a larger statistical dataset with which to make predictions. Instead, tight selections on topologies consistent with $W \rightarrow \mu\nu$ and $Z \rightarrow \mu\mu$ decays are applied to provide an effective control of the QCD background. All event variables are computed with the respective leptons or photons removed to emulate the signal topology.

5.7.2.1 Hadronic control region

The hadronic control region aims to provide an enriched QCD sample for the estimation of the multijet background in the signal region. To achieve this, the $\Delta\phi_{\text{min}}^*$ and $\cancel{H}_T/\cancel{E}_T$ selections of the signal region are inverted, enriching the QCD composition of the sample.

5.7.2.2 Photon control region

For events in the single photon control region, $\gamma + \text{jets}$, a single tight photon is required to be reconstructed with a minimum total hadronic energy of $H_T > 400 \text{ GeV}$. The photon is additionally required to pass kinematic selections of: $p_T > 200 \text{ GeV}$ and $|\eta| < 1.45$, to ensure efficiency with the trigger selection and good photon reconstruction. A minimum photon-jet separation of $\Delta R_{\text{min}}(\gamma, j) > 1$ is also required to ensure that the photon is

well isolated from any hadronic activity, with α_T and $\cancel{H}_T/\cancel{E}_T$ selections used to reduce contamination from QCD.

5.7.2.3 Muon control regions

The analysis uses two control regions selected by muon multiplicity, $\mu + \text{jets}$ and $\mu\mu + \text{jets}$, which target $W \rightarrow \mu\nu$ and $Z \rightarrow \mu\mu$ decays respectively. Events in the muon control regions require a muon pass the tight selection, in addition to the kinematic selections of: $p_T > 30 \text{ GeV}$ and $|\eta| < 2.1$, to ensure efficiency for trigger selections. In addition, an $\cancel{H}_T/\cancel{E}_T < 1.25$ selection is applied to suppress threshold effects.

The $\mu + \text{jets}$ control region has a single tight muon selection, with a transverse mass requirement of the muon- $\cancel{E}_T$ system of: $30 < M_T(\mu, \cancel{E}_T) < 125 \text{ GeV}$ and a minimum muon-jet separation of: $\Delta R(\mu, j) > 0.5$, to select W boson decays and suppress QCD backgrounds. To provide a sample enriched in $Z \rightarrow \mu\mu$ decays, the $\mu\mu + \text{jets}$ control region requires exactly two oppositely charged tight muons with a dimuon invariant mass compatible with the Z boson mass within a 25 GeV window: $|M_{\mu\mu} - m_Z| < 25 \text{ GeV}$.

5.7.3 Selection summary

The full selection for events in the analysis signal and control regions are summarised in Table 5.8 which are applied in addition to the preselections described in Section 5.6.

Analysis region	Selection	Requirement
Common	Jet acceptance	$p_T > 40 \text{ GeV}$, $ \eta < 3$
	Lead jet acceptance	$p_T > 100 \text{ GeV}$, $ \eta < 2.5$
	Hadronic total energy	$H_T > 200 \text{ GeV}$
	Hadronic missing energy	$\cancel{H}_T > 130 \text{ GeV}$
Signal	α_T selection	H_T -dependent α_T selections
	$\Delta\phi_{\min}^*$ selection	Veto events with $\Delta\phi_{\min}^* < 0.5$
	$\cancel{H}_T/\cancel{E}_T$ selection	Veto events with $\cancel{H}_T/\cancel{E}_T > 1.25$
Hadronic control	Kinematic selections	$\cancel{H}_T/\cancel{E}_T > 1.25$, $\Delta\phi_{\min}^* < 0.5$
Photon control region	Photon selection	Tight ID, $p_T > 200 \text{ GeV}$ and $ \eta < 1.45$
	Kinematic selections	$\cancel{H}_T/\cancel{E}_T < 1.25$, $H_T > 400 \text{ GeV}$, $\alpha_T > 0.52$
	$\gamma + \text{jets}$	Single photon, $\Delta R_{\min}(\gamma, j) > 1$
Muon control region	Muon selection	Tight ID, $p_T > 30 \text{ GeV}$ and $ \eta < 2.1$
	Kinematic selections	$\cancel{H}_T/\cancel{E}_T < 1.25$
	$\mu + \text{jets}$	Single muon, $30 < M_T(\mu, \cancel{E}_T) < 125 \text{ GeV}$, $\Delta R(\mu, j) > 0.5$
	$\mu\mu + \text{jets}$	Two opposite-sign muons, $ M_{\mu\mu} - m_Z < 25 \text{ GeV}$

Table 5.8: Summary of the final selections for the analysis regions.

CHAPTER 6

Development of the α_T Run 2 trigger selection

To perform an inclusive search for signs of new physics, in Run 1 the α_T analysis used a dedicated suite of signal triggers, providing sensitivity for a wide range of event signatures. The conditions in Run 2 however presents major challenges in the selection of events, particularly for hadronic triggers, making the use of these triggers no longer viable. To operate effectively in these new beam conditions the analysis requires new triggers, which are able operate effectively in a high-pileup and maintain sensitivity for events with very low hadronic energies.

In the following the design and characterisation of the α_T triggers for Run 2 is presented, describing improvements in the L1 trigger efficiency and reoptimisation of the HLT selections that enabled an improved control of trigger rate whilst maintaining selection efficiency.

6.1 The α_T triggers

Due to the many signatures that SUSY and DM may exhibit, the α_T analysis aims to be as inclusive as possible, providing sensitivity to a range of energy scales and jet multiplicities. To achieve this, the analysis makes use of dedicated signal triggers which, by utilising α_T selections within the trigger, provide sensitivity to very low hadronic energies.

The selection of events in the analysis signal region in Run 1 was performed by five dedicated CaloJet triggers, referred to as $H_T - \alpha_T$ *cross-triggers*, which performed simultaneous selections on H_T and α_T . The use of an α_T selection in the trigger provides an effective suppression of QCD, enabling a selection of hadronic energies down to $H_T = 200$ GeV. To ensure a sharp turn on offline, the determination of α_T was performed ‘dynamically’, initially calculating α_T for the two leading jets and incrementally adding additional jets until either the α_T requirement has been satisfied, or no further jets above threshold are present.

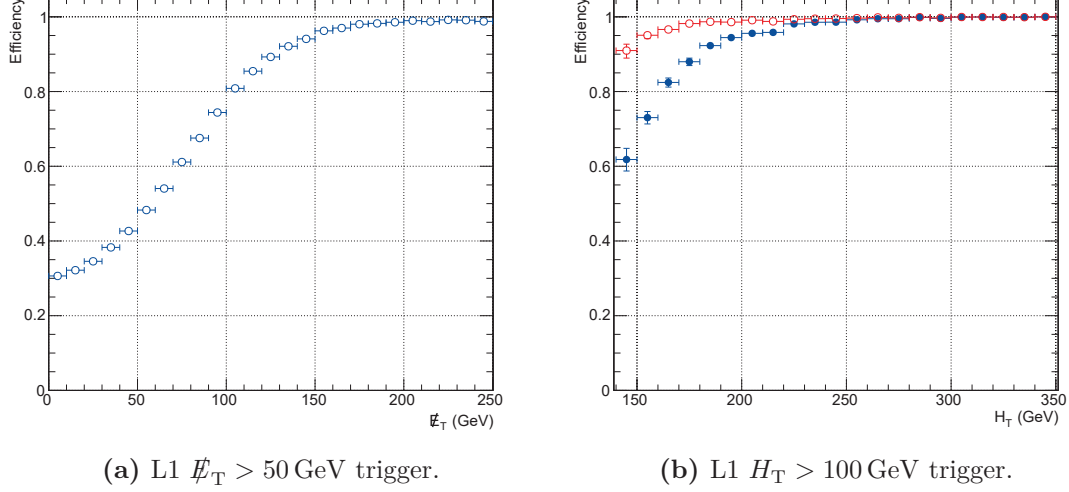


Figure 6.1: Trigger efficiency measured in a muon data sample for the lowest unprescaled L1 $\cancel{E}_T$ (blue hollow circles), H_T (blue filled circles) and their disjunction (red hollow circles). Shown in the $\cancel{E}_T$ (left) and H_T (right) dimension for an offline selection on the leading jet $p_T^{j_1} > 100$ GeV, second jet $p_T^{j_2} > 40$ GeV and the total missing energy $\cancel{E}_T > 130$ GeV.

In Run 2 the analysis aimed to maintain the same analysis acceptance as the first data run, providing sensitivity to low- $\cancel{E}_T$ and hadronic energies in a more challenging environment, in addition to extending acceptance to a wider range of models. To achieve this, improvements in the triggering capabilities of Run 2 trigger system were exploited, utilising the upgraded L1 trigger system and improvements in HLT reconstruction.

In early Run 2 data taking, the upgraded L1 trigger was able to provide unprescaled selections for missing and total hadronic energies down to $\cancel{E}_T > 50$ GeV and $H_T > 100$ GeV respectively. The L1 H_T and $\cancel{E}_T$ selections for these thresholds, shown in Figure 6.1, are fully efficient for offline selections of $\cancel{E}_T > 200$ GeV and $H_T > 250$ GeV respectively. The logical disjunction of these two L1 seeds however is able to restore efficiency at low hadronic energies, increasing from a 95% efficiency to $> 99\%$ for a $H_T > 200$ GeV selection.

Improvements in selection with the HLT were achieved by a transition from calorimeter-based reconstruction to a full-PF reconstruction, which provides superior performance and a greater resilience to pileup. These improvements to trigger capabilities alone however were not sufficient to compensate for the increased rate of hadronic triggers in Run 2. Illustrated in Figure 6.2, although the trigger rate for an H_T - α_T selection is better controlled with the use of PF reconstructed jets, the projected trigger rate for comparable

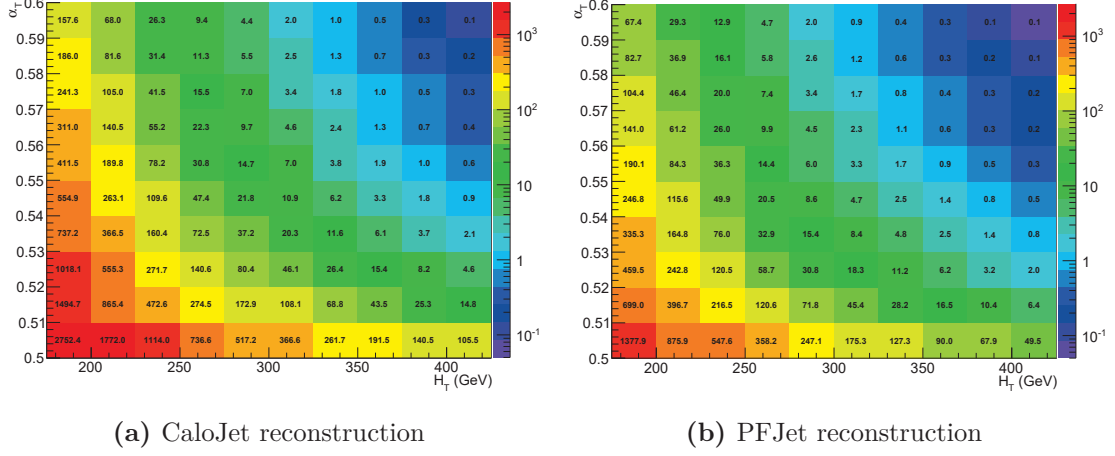


Figure 6.2: Trigger rate as a function of H_T and α_T selections by CaloJet (left) and PFJet (right) reconstruction after a L1 selection, measured in simulation for the 40 pileup with 50 ns bunch spacing.

Run 1 selections exceeds acceptable bounds. The rate of the lowest hadronic energy Run 1 trigger ($H_T > 200$, $\alpha_T > 0.57$) for example, surpasses the rate of the full suite of Run 1 triggers by a factor of two. In order to operate effectively in Run 2 additional selections were required, which are optimised to suppress the QCD background whilst retaining efficiency for potential signatures of new physics.

6.2 Optimisation of trigger thresholds

In the optimisation of trigger performance, selections should be chosen to maximise trigger efficiency within constraints of *trigger rate* and *trigger timing*. Exploiting the difference in characteristics of the QCD background and signal processes enables an effective suppression of rate without significant loss of signal efficiency.

6.2.1 Constraints on trigger selections

Of vital importance in the design of trigger selections is the control of the trigger rate, which for hadronic triggers is predominantly a consequence of inelastic QCD scattering, the highest cross section process at the LHC. To estimate the rates of HLT paths at $\sqrt{s} = 13$ TeV, trigger selections are emulated in $\hat{p}_T$ -binned QCD simulated samples, which are mixed with an admixture of QCD events to simulate the effect of pileup. The rate is

then determined by measuring the efficiency of the selection of the $\hat{p}_T$ QCD samples, scaled by their respective cross sections. It is possible however that in the pileup mixing the $\hat{p}_T$ of the signal QCD event is smaller than that of one of the mixed pileup events, an effect known as *hard-pileup*. In this case it is possible for the more energetic pileup component to cause a trigger to fire, resulting in an overestimate of trigger rate, particularly when scaling the high cross section of low- $\hat{p}_T$ QCD samples. To mitigate the effect of hard-pileup, only $\hat{p}_T$ -binned QCD samples above 30 GeV are utilised and a hard-pileup filter is applied.

In addition, a control of the time taken to perform a reconstruction and selection of events, such that they are within the HLT operating limits, is critical in mitigating trigger dead time. There are two important timing quantities important in the design of trigger selections: the *total time*, the mean processing time of the trigger in isolation, and the *active time*, the mean additional processing time added to a trigger menu by the trigger. As an example, a trigger which takes 10 ms to perform a selection will have total time of 10 ms but, as a consequence of sharing reconstruction steps with other triggers in a menu, may have a significantly smaller active time. To operate within the limits of the HLT, the total time of new triggers are required to be $\lesssim 20$ ms and possess a small ~ 1 ms active time.

A major contributor to the time taken to process a path is performing advanced reconstruction techniques, such as PF reconstruction. To ensure the timing of triggers is controlled, loose selections utilising detectors that can perform fast reconstruction, such as the calorimeters, are used as a *prefilter* to reduce the pass-through rate to more computationally intensive and time-consuming reconstructions.

An estimation of the timing of an HLT trigger path is performed by measuring the trigger reconstruction time of a dataset on a benchmark machine, for which the equivalent timing for the HLT farm at 100 kHz is well known. To enable a sampling of a large number of parameter selections for the optimisation of the calorimeter-prefilter, the measured total and active times are parameterised as a function of the prefilter pass-through rate, as shown in Figure 6.3. From this parameterisation it is determined that a constraint on the prefilter pass-through rate below 1 kHz is required to achieve acceptable trigger path timings.

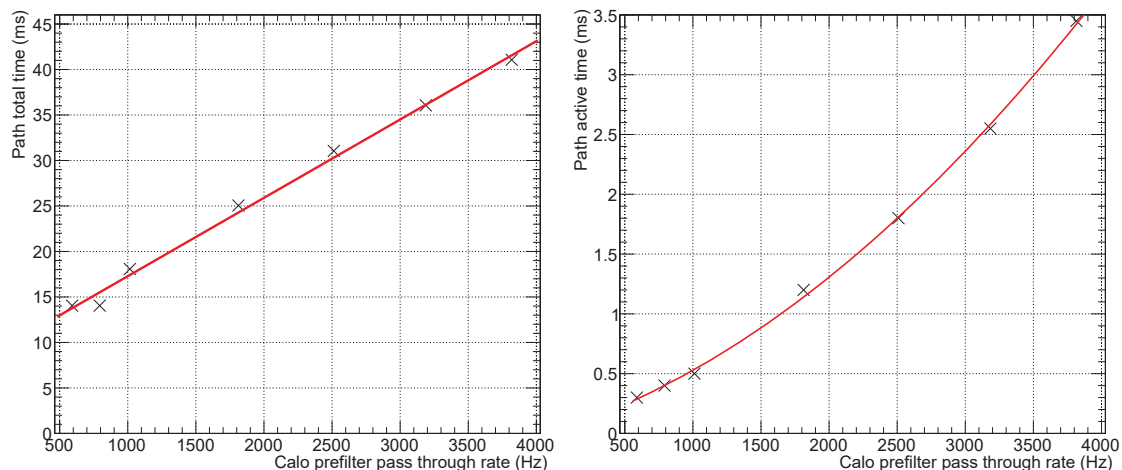


Figure 6.3: Total time (left) measured as a function of the prefilter pass-through rate for the α_T triggers, with the linear parameterisation represented by the solid line. Active time (right) of α_T triggers as a function of prefilter pass-through rate, with the quadratic parameterisation represented by the solid line.

6.2.2 Optimisation variables

To better separate QCD from signal-like topologies, a range of variables that showed efficacy in distinguishing the two are studied. This includes the H_T and α_T variables utilised in Run 1, in addition to new variables and cleaning cuts that show effectiveness in the control of trigger rate whilst maintaining selection efficiency.

6.2.2.1 Variations of α_T

The α_T variable is highly effective in the suppression of QCD, providing a strong reduction in trigger rate which enables the use of low hadronic energy selections. The behaviour of α_T however has a dependency on the multiplicity of the jet system. As illustrated in Figure 6.4, a mismatch in jet multiplicity between trigger and offline reconstructions can result in a decorrelation of α_T , reducing resolution and efficiency of α_T trigger selections. To ensure a good resolution of α_T with respect to offline reconstruction, several alternative computational methods within the trigger are studied, including: *static*, *dynamic* and *prime*.

The static variant mirrors the computation of α_T utilised offline, using all reconstructed trigger jets with $p_T > 40$ GeV. This is effective in controlling rate however, as illustrated

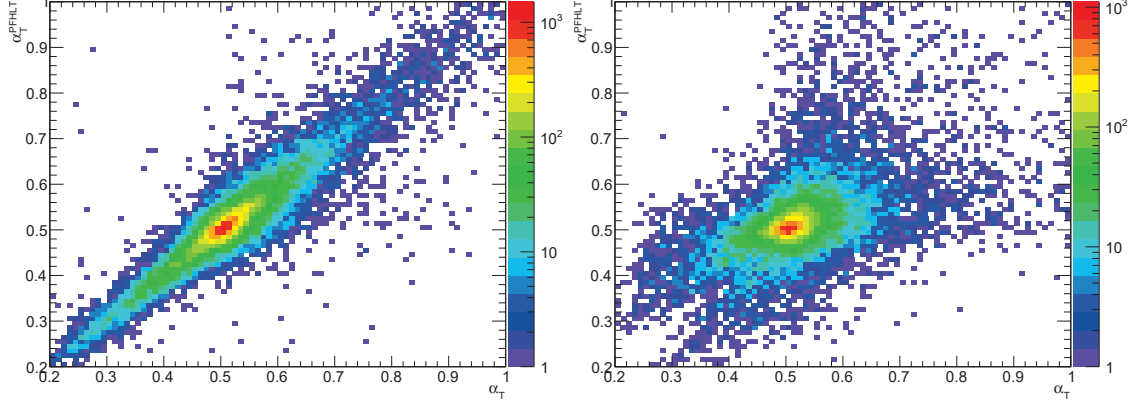


Figure 6.4: Correlation of α_T reconstructed in the trigger and offline for a loose analysis selection, with a requirement of equality (left) and inequality (right) in the reconstructed jet multiplicity in the trigger and offline.

previously, can lead to inefficiencies where there is a mismatch in reconstructed jet multiplicities. Dynamic α_T is designed to counter jet multiplicity mismatching by sequentially computing α_T , starting with the leading two jets, and iteratively including the next hardest jet above threshold until either a combination passes selection or all jets are included. To mitigate instances of under-correction of jets in the trigger, a lower $p_T = 30 \text{ GeV}$ threshold is used in the computation of dynamic α_T . To ensure the jet system is similar between online and offline reconstructions, the corresponding total hadronic energy is also computed from the sum of the jet p_T used in the computation of dynamic α_T . The final quantity, α'_T , also seeks to counter jet multiplicity mismatching by only considering the total and missing hadronic energy, neglecting the hadronic energy difference, ΔH_T , between the two pseudojets in the computation of α_T :

$$\alpha'_T = \frac{1}{2} \frac{H_T}{\sqrt{H_T^2 - \cancel{H}_T^2}}. \quad (6.1)$$

6.2.2.2 Second jet threshold

An additional effective method of suppressing the QCD background is the application of energy threshold requirements on the leading jets. In supersymmetric decays, jets are typically pair produced with large momentum, distinguishing them from the lower energy jets typical of QCD multijet production. A suppression of trigger rate can therefore be achieved by employing a threshold on the second leading jet, $p_T^{j_2}$, whilst maintaining a

high signal efficiency for the majority of supersymmetric models.

In Run 2 the α_T analysis further extends sensitivity to more challenging low hadronic energy topologies with the addition of asymmetric event topologies, the efficiency of which is reduced for a high second jet p_T selection. A compromise to reduce of trigger rate and retain efficiency for this class of events can be achieved with a selection on the average p_T of the leading and second jet, $\langle p_T \rangle^{j_1, j_2}$. This is effective in suppressing events with soft-leading jets, whilst retaining efficiency for supersymmetric signatures with at least one high-momentum jet. Shown in Figure 6.5, the efficiency for signal events with soft subleading jets can be better retained by a $\langle p_T \rangle^{j_1, j_2}$ selection whilst still providing a suppression of QCD.

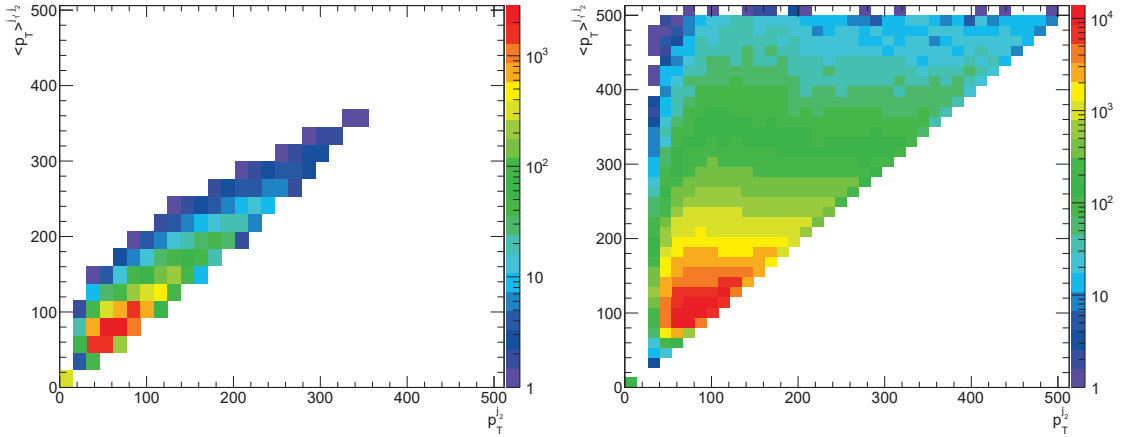


Figure 6.5: Correlation of the average leading dijet transverse momentum, $\langle p_T \rangle^{j_1, j_2}$, and the second leading jet transverse momentum, $p_T^{j_2}$, for QCD (left) and the compressed supersymmetric model T2tt(425,325) (right), for the offline selection: $H_T > 200$ GeV, $p_T^{j_1} > 100$ GeV.

6.2.2.3 Cleaning cuts

From a study of the topology of QCD and signal topologies, additional cleaning selections are identified that are effective in removing pathological effects, reducing rate whilst retaining signal efficiency. Several of these cleaning cuts are found to be effective in this suppression, including the missing energy variables: $\cancel{H}_T$ and $\cancel{E}_T$, and the forward jet p_T .

Variables that are particularly effective in the separation of QCD and signal topologies are the missing energy variables $\cancel{H}_T$ and $\cancel{E}_T$. Shown in Figure 6.6, the bulk of QCD events possess low values of $\cancel{H}_T$ and $\cancel{E}_T$, in addition to having large values of their ratio. Signal events in contrast typically have higher values of $\cancel{E}_T$ and $\cancel{H}_T$, making a selection of $\cancel{H}_T/\cancel{E}_T < 2$ nearly fully efficient for some models.

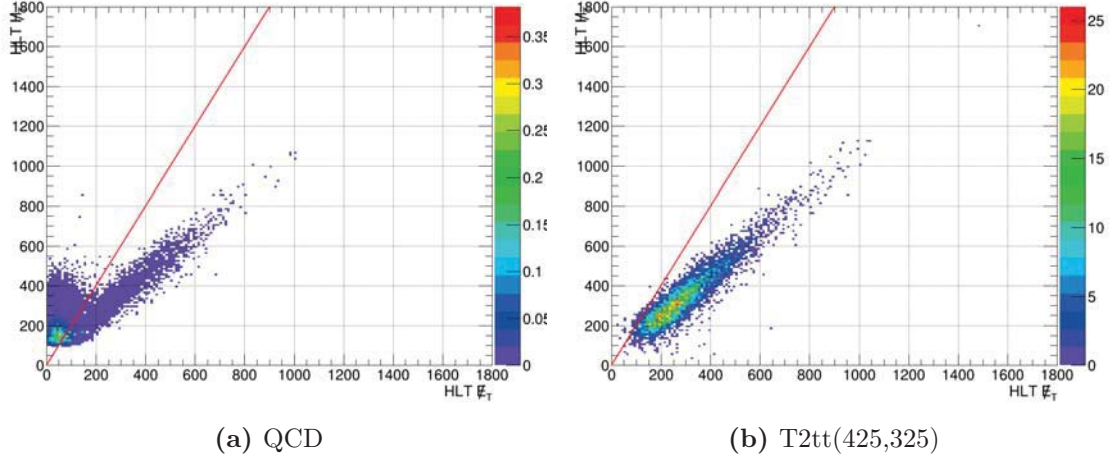


Figure 6.6: Correlation of online reconstructed missing hadronic and missing energy quantities for cross section weighted QCD (left) and a signal model after analysis selections (right). An $H_T/E_T = 2$ selection is indicated by the red line.

6.2.3 Optimisation of trigger selections

Utilising the parameters outlined, an optimisation of selections for the calorimeter and PF filters were performed to maximise efficiency within constraints of trigger rate and timing. Trigger selections were emulated in $\sqrt{s} = 13$ TeV MC and studied for a range of potential Run 2 beam scenarios, with the aim of being robust in the most challenging beam conditions. To ensure the trigger selections are inclusive, selections are not tuned to a specific topology but rather to give the best performance for a range of signal models and SM electroweak backgrounds.

The simulated trigger rates for a H_T - α_T cross-trigger selection, shown in Figure 6.7, far exceed acceptable trigger rates for calorimeter and PF filters to maintain sufficiently low thresholds offline. Selections on additional event variables however enable lower H_T and α_T thresholds to be used, recovering efficiency. Illustrated in Figure 6.8, the application of a second jet threshold can provide a significant suppression of the QCD background, reducing trigger rate. This suppression of QCD enables a reduction in the α_T and H_T thresholds which, illustrated in Figure 6.9, provides improved trigger efficiency for equivalent rate. This improvement in trigger efficiency continues whilst the jet selection is efficient with the offline selection, decreasing when the selection exceeds $p_T > 100$ GeV when the inefficiency in the jet selection becomes dominant.

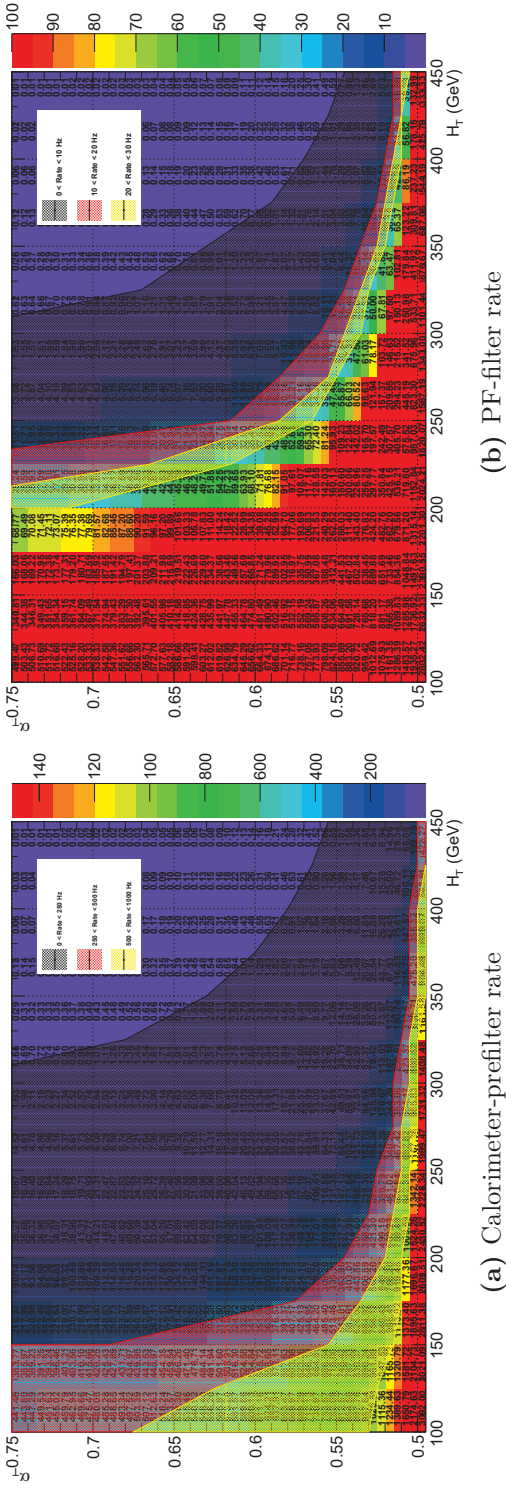


Figure 6.7: Simulated trigger rates for the calorimeter-prefilter (left) and final PF selection (right) measured for a H_T - α_T selection using QCD simulation for the 25 ns scenario. Rate isocontours are represented by the shaded black, red and yellow bands representing increasing poor control of rate.

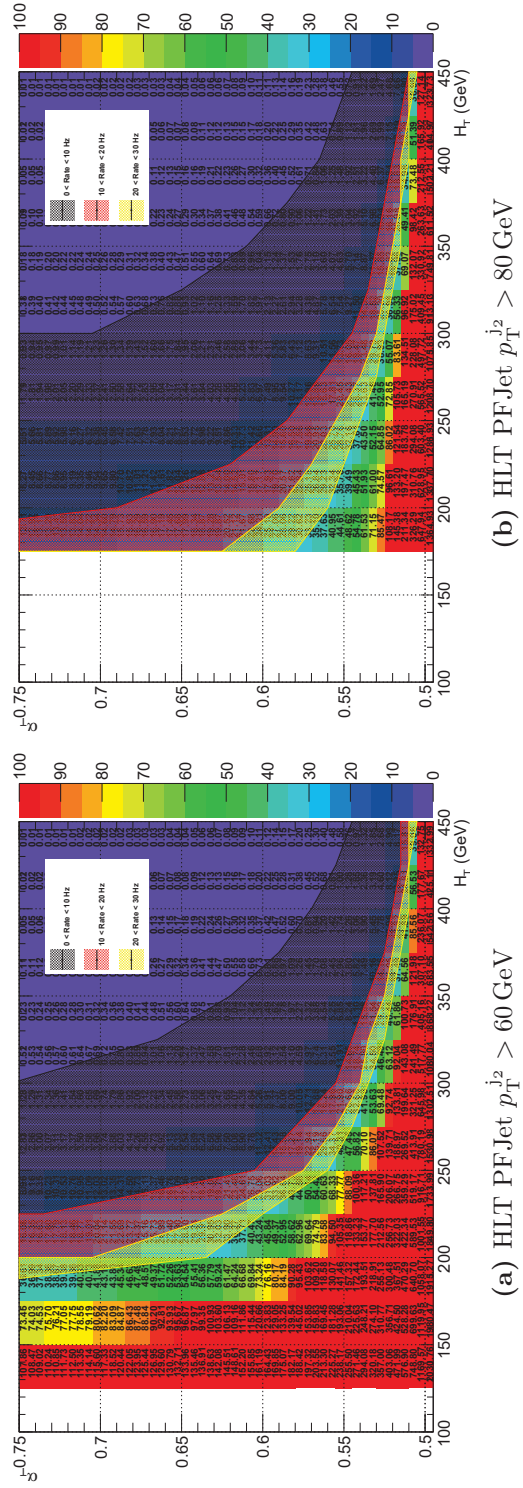


Figure 6.8: Simulated trigger rates for the PF selection with a second jet threshold selections of $p_T^{j2} > 60$ GeV (left) and $p_T^{j2} > 80$ GeV PF selection (right) with rate isocontours for the 25 ns scenario.

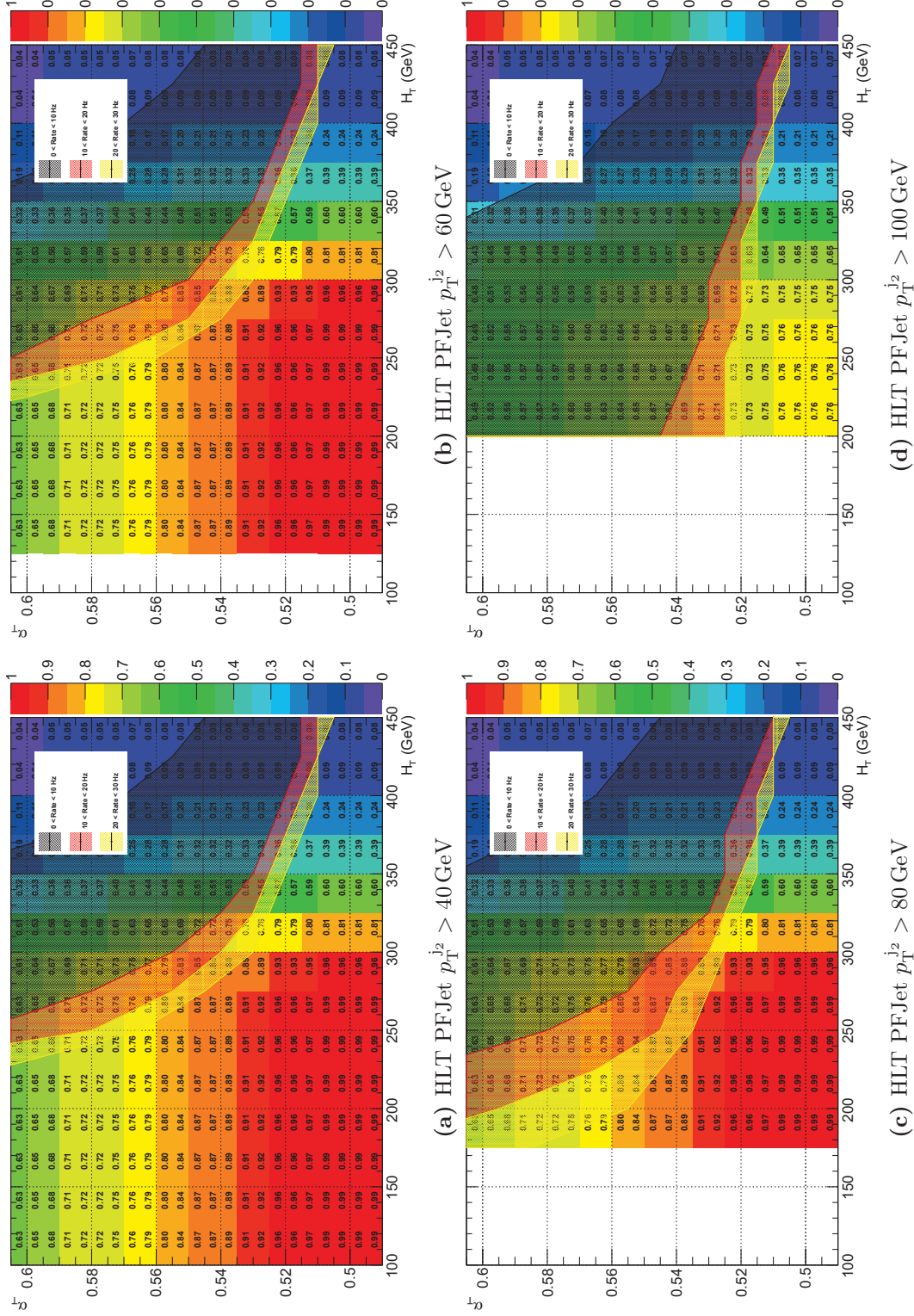


Figure 6.9: Measured trigger efficiency for a simulated $t\bar{t}$ sample with offline selection: $p_T^{j2} > 100$ GeV, $275 < H_T < 325$ GeV, $3 \leq n_{\text{jet}} \leq 4$. Rate isocontours are represented by the coloured bands.

To determine the optimal trigger selection, a simultaneous scan of H_T , α_T and jet thresholds are performed to provide a parameterisation of efficiency as a function of rate. To provide flexibility and robustness during the early operation of the α_T triggers, a selection on the jet threshold was favoured over selections on missing energy variables and forward jets. Optimising across all analysis bins and samples, the second jet threshold selections $p_T^{j2} > 80$ and $p_T^{j2} > 90$ GeV were found to provide optimal efficiencies for the rate allowance. The thresholds for these selections were optimised to provide the highest efficiency, within the constraints of the trigger system, to provide a *primary* and *secondary* trigger menu for the selection of events in the analysis signal region in Run 2.

The primary menu, summarised in Table 6.1, utilises low trigger thresholds to provide nominal performance for the analysis. The simulated rate estimates of this menu however was predicted to only be capable of operating in low-luminosity conditions. An additional secondary menu, which utilises higher trigger thresholds, suppresses the trigger rate by a factor of two with respect to the primary menu, enabling operation at high-luminosity. The utilisation of both menus ensures the analysis is robust against the uncertainty in MC rate predictions and LHC beam conditions, enabling the analysis to fully utilise the available luminosity and provide redundancy if rates had exceeded expectations.

HLT path	L1 trigger (H_T OR $\cancel{E}_T$)	HLT calo-prefilter (H_T , α_T , $p_T^{(j1,j2)}$)	HLT PF-filter (H_T , α_T , $p_T^{(j1,j2)}$)
HLT_PFHT200_PFDijetAve90_AlphaT0p57	100 OR 50	150, 0.540, 70	200, 0.57, 90
HLT_PFHT250_PFDijetAve90_AlphaT0p55	100 OR 50	225, 0.530, 70	250, 0.55, 90
HLT_PFHT300_PFDijetAve90_AlphaT0p53	100 OR 50	275, 0.525, 70	300, 0.53, 90
HLT_PFHT350_PFDijetAve90_AlphaT0p52	100 OR 50	325, 0.515, 70	350, 0.52, 90
HLT_PFHT400_PFDijetAve90_AlphaT0p51	100 OR 50	375, 0.510, 70	400, 0.51, 90

Table 6.1: A summary of the L1, calorimeter prefilter and final PF-trigger selections of the primary α_T hadronic signal triggers.

6.2.4 Commissioning of the α_T triggers in Run 2

The trigger menu designed in simulation was utilised for data collection within the CMS trigger for the 2015 LHC Run 2 period. To ensure the performance of the triggers were comparable to simulation, the rates and efficiencies of triggers were closely monitored during early 50 ns low-luminosity pp -collisions.

The rates of the primary H_T - α_T triggers during 50 ns operation predicted from simulation and low luminosity data, illustrated in Figure 6.10, show the projected data rate is much lower than that predicted by simulation. Summarised in Table 6.2, the predicted rate of all the α_T triggers were found to overestimated in simulation, with the measured rate in data being less than half that predicted by simulation. The cause of this discrepancy was attributed to simulation mismodelling and hard-pileup, which led to a significantly inflated estimate of trigger rate for all hadronic triggers.

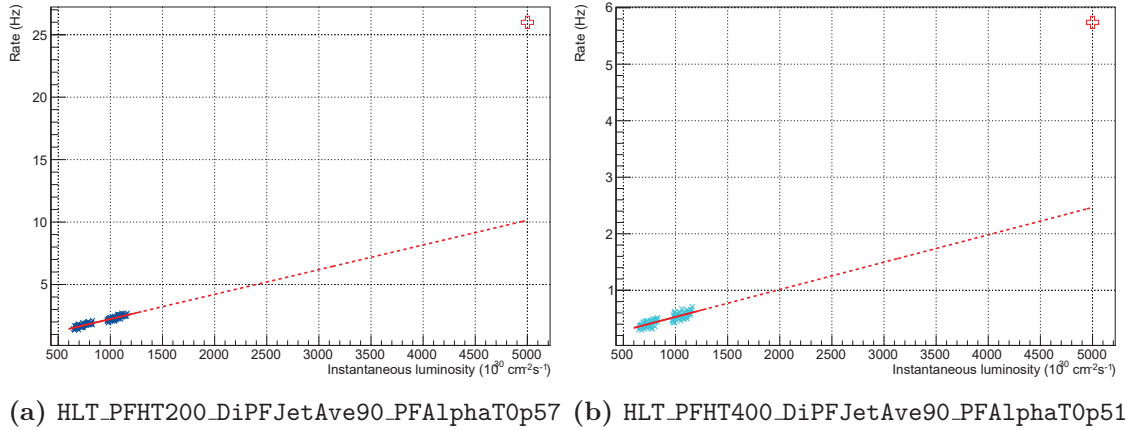


Figure 6.10: Measured trigger rates of α_T primary triggers (crosses) during 50 ns operation with projected and predicted rates for an instantaneous luminosity $\mathcal{L} = 5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ represented by the red dashed line and red cross respectively.

Signal HLT path	Data projected rate (Hz)	Simulation predicted rate (Hz)	Simulation/Data rate
HLT_PFHT200_DiJetAve90_PFA1phaT0p57	10.1 ± 0.07	25.99 ± 0.73	2.6 ± 0.3
HLT_PFHT250_DiJetAve90_PFA1phaT0p55	4.39 ± 0.07	11.72 ± 0.46	2.7 ± 0.1
HLT_PFHT300_DiJetAve90_PFA1phaT0p53	2.56 ± 1.11	6.55 ± 0.34	2.6 ± 1.1
HLT_PFHT350_DiJetAve90_PFA1phaT0p52	2.30 ± 0.05	5.14 ± 0.30	2.2 ± 0.1
HLT_PFHT400_DiJetAve90_PFA1phaT0p51	2.46 ± 0.15	5.74 ± 0.28	2.3 ± 0.2

Table 6.2: Data and simulation projections for the rates of α_T primary triggers for 50 ns at the instantaneous luminosity $\mathcal{L} = 5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

From these measurements it was determined that the primary triggers could operate during the high luminosity 25 ns beam operation and consequently they were utilised as the main triggers throughout the 2015 run. Illustrated in Figure 6.11, an overestimate of trigger rate was also observed in measurements during the high luminosity 25 ns runs, where again the observed rate is approximately half that predicted by simulation.

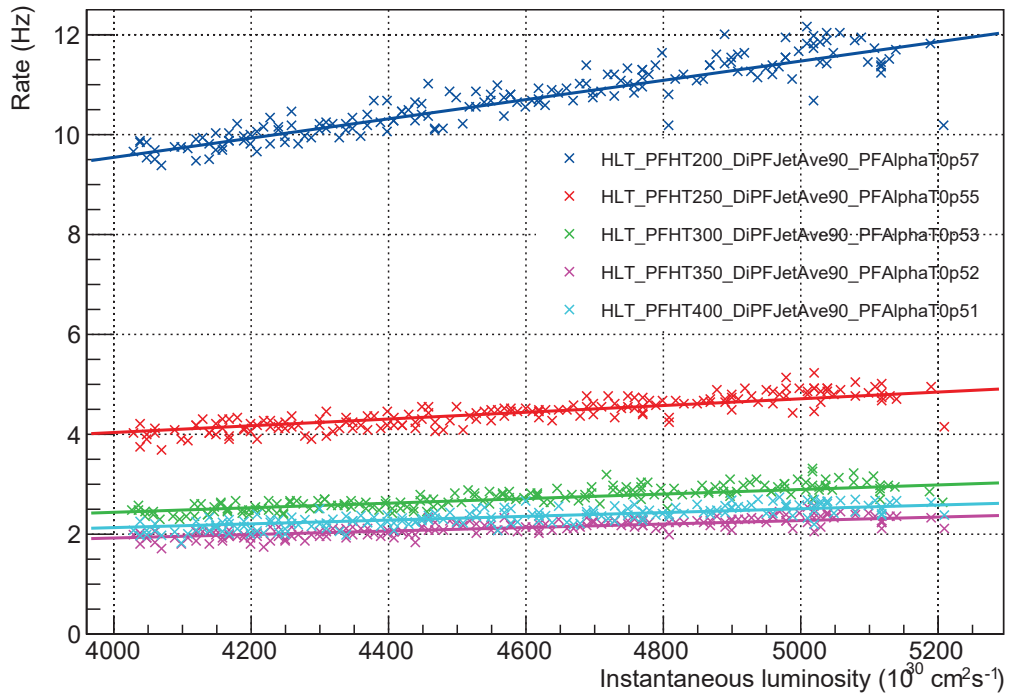


Figure 6.11: Trigger rates of the primary α_T triggers measured in high luminosity 25 ns data. Measured rates for individual triggers are shown by the coloured points, with a linear fit to the data shown by a solid line of the same colour.

6.3 Triggers for the α_T analysis in Run 2

To provide an efficient selection of events in the analysis signal and control regions a suite of signal and control triggers, summarised in Table 6.3, are utilised.

The large range of signatures probed by the analysis requires several different triggers for selection of data in the signal region, which are designed to target specific event topologies. Dedicated analysis H_T - α_T cross-triggers, which provide sensitivity to very low hadronic energies, seed the multijet search region between $H_T = 200$ – 800 GeV, which each have a threshold on the average p_T of the leading dijet pair of $p_T^{\langle j1,j2 \rangle} > 90$ GeV. The triggers use a range of H_T and α_T thresholds between $H_T = 200$ – 400 and $\alpha_T = 0.57$ – 0.51 to effectively select signal events for a manageable trigger rate. In addition to the use of dedicated α_T triggers, the analysis utilises additional signal triggers which provide extended coverage to the large range of signal event topologies targeted by the analysis. Monojet signatures are selected with the $\cancel{H}_T$ - $\cancel{E}_T$ cross-trigger, `HLT_PFMETNoMu90_JetIdCleaned_PFMHTNoMu90_IDTight`, which has thresholds of $\cancel{H}_T > 90$ GeV and $\cancel{E}_T > 90$ GeV and a jet ID selection. Events in the high- H_T region are selected by a pure- H_T trigger, `HLT_PFHT800`, which has a $H_T > 800$ GeV threshold that provides a selection of high- H_T events in the absence of an α_T selection.

The diverse range of control regions of the analysis also require a suite of control triggers specialised in the selection of distinct event signatures. The photon and muon control samples are both selected using the respective lowest-threshold and unrescaled single object trigger, which have thresholds of $E_T^\gamma > 175$ GeV and $p_T^\mu > 20$ GeV respectively. The hadronic control region is seeded by a suite of prescaled hadronic H_T -triggers which share the same hadronic energy thresholds as their α_T signal trigger counterparts. As α_T is highly effective in separating QCD, which typically populate regions of $\alpha_T < 0.5$, an additional $\alpha_T - H_T$ cross-trigger with a threshold of $H_T > 200$ GeV and $\alpha_T > 0.51$ is introduced in Run 2. This provides a better selection of events in the hadronic control region for higher values of α_T .

Analysis region	Trigger	Prescale	Selection
Signal	HLT_PFHT200_DiPFJetAve90_PFA1phaT0p57	1	$p_T^{(j1,j2)} > 90 \text{ GeV}, H_T > 200 \text{ GeV}, \alpha_T > 0.57$
	HLT_PFHT250_DiPFJetAve90_PFA1phaT0p55	1	$p_T^{(j1,j2)} > 90 \text{ GeV}, H_T > 250 \text{ GeV}, \alpha_T > 0.55$
	HLT_PFHT300_DiPFJetAve90_PFA1phaT0p53	1	$p_T^{(j1,j2)} > 90 \text{ GeV}, H_T > 300 \text{ GeV}, \alpha_T > 0.53$
	HLT_PFHT350_DiPFJetAve90_PFA1phaT0p52	1	$p_T^{(j1,j2)} > 90 \text{ GeV}, H_T > 350 \text{ GeV}, \alpha_T > 0.52$
	HLT_PFHT400_DiPFJetAve90_PFA1phaT0p51	1	$p_T^{(j1,j2)} > 90 \text{ GeV}, H_T > 400 \text{ GeV}, \alpha_T > 0.51$
	HLT_PFHT800	1	$H_T > 800 \text{ GeV}$
	HLT_PFMETNoMu90_JetIDCleaned_PFMHTNoMu90_IDTight	1	$\cancel{H}_T > 90 \text{ GeV}, \cancel{E}_T > 90 \text{ GeV}$
	HLT_Photon.175	1	Leading photon, $E_T > 175 \text{ GeV}$
$\gamma + \text{jets}$	HLT_IsoMu20	1	Leading isolated muon, $p_T > 20 \text{ GeV}$
Hadronic control	HLT_PFHT200	3060	$H_T > 200 \text{ GeV}$
	HLT_PFHT250	2040	$H_T > 250 \text{ GeV}$
	HLT_PFHT300	1020	$H_T > 300 \text{ GeV}$
	HLT_PFHT350	180	$H_T > 350 \text{ GeV}$
	HLT_PFHT400	120	$H_T > 400 \text{ GeV}$
	HLT_PFHT200_PFA1phaT0p51	175	$H_T > 200 \text{ GeV}, \alpha_T > 0.51$

Table 6.3: A summary of the triggers used in the α_T analysis to select data for the analysis signal and control regions, in addition to their respective trigger selections and prescales.

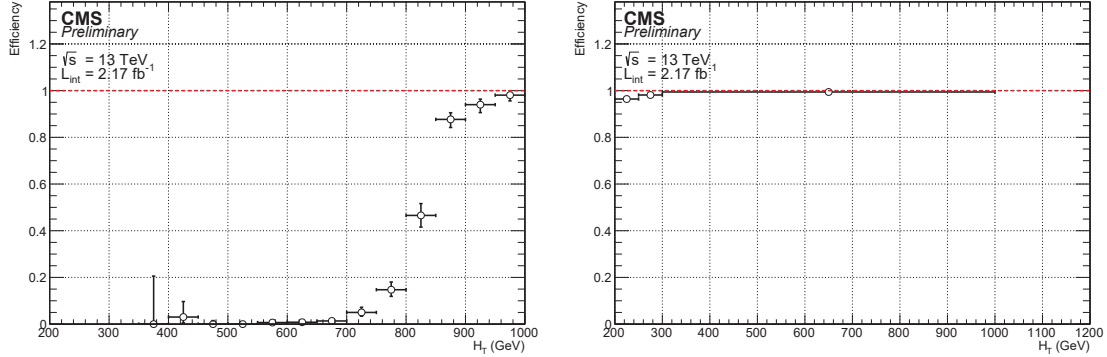


Figure 6.12: Trigger efficiency of the pure- H_T signal trigger as a function of H_T measured in data collected by a hadronic reference trigger for a loose multijet selection (left). Trigger efficiency of the H_T - E_T cross-trigger as a function of H_T measured in data collected by a muon reference trigger for a loose monojet selection (right). It should be noted in the case of a monojet selection that the total hadronic and missing hadronic energies are equivalent.

6.3.1 Measured trigger efficiency

To correct for potential inefficiencies in trigger selections, the efficiency of the analysis signal triggers are measured using electron, muon and hadronic reference triggers. These selections provide unbiased and inclusive samples in which to perform hadronic efficiency measurements. Shown in Figure 6.12, the trigger efficiency of the signal H_T - E_T cross-trigger is measured to provide a near fully-efficient selection for the monojet category, with a greater than 95% efficiency at the lowest hadronic energy $200 < H_T < 250$ GeV. The pure- H_T trigger provides a fully efficient selection of multijets for $H_T \gtrsim 950$ GeV, with inefficiencies at lower hadronic energies as a result of the trigger turn on, resulting in a 46% efficiency in the region $800 < H_T < 850$ GeV. A summary of the efficiency of the α_T triggers, measured in the α_T dimension, are shown in Appendix 1.

Any inefficiencies present in individual signal trigger selections are remedied by performing selections using a combination of complementary triggers. The H_T - E_T cross-trigger is used in conjunction with the H_T - α_T cross-triggers to regain efficiency for very low- H_T asymmetric topologies and the H_T - α_T cross-triggers are used to regain efficiency in the turn on region of the pure- H_T trigger. The efficiency of these combined trigger selections are measured as a function of H_T in bins of hadronic energy and jet multiplicity, which are summarised for symmetric selections in Figure 6.13. These efficiency measurements are utilised in the trigger efficiency correction of MC samples which is described in Section 8.1.3.

6.3 Triggers for the α_T analysis in Run 2

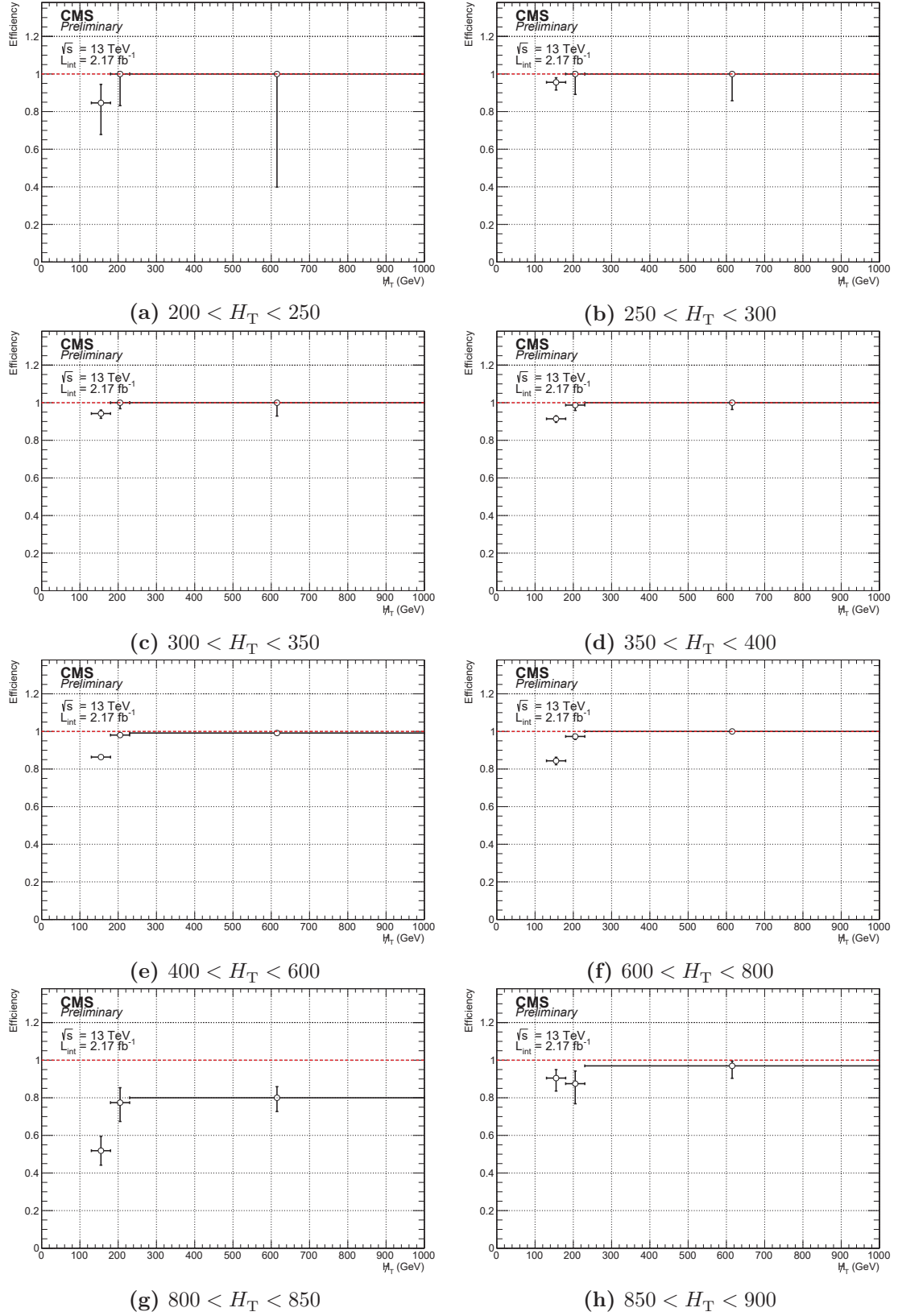


Figure 6.13: Signal trigger efficiency in the H_T dimension for the selection of symmetric jet categories measured in data with an electron sample.

6.4 Efficiency bias in data-driven trigger measurements

An important aspect of the analysis is the accurate determination of the trigger efficiency in the pure-hadronic topology of the signal region. To avoid effects of mismodelling in simulation, this is typically performed by data-driven methods from an unbiased sample, typically a leptonic or a prescaled hadronic sample however both have limitations. The use of prescaled hadronic triggers is limited by their large prescales and thresholds, leading to large statistical uncertainties and limitations in phase space within which to perform measurements. Alternatively lepton triggers may be used which, through the indirect selection of the typical signature of W boson decays. This provides a high statistic sample of the typical $\cancel{E}_T$ and jet signature of the signal region when the lepton is neglected.

In Run 1 trigger efficiency measurements were performed using data collected by prescaled hadronic triggers and a single muon trigger, which exploited the calorimeter reconstruction in both the trigger and offline analysis. As muons are MIPs they deposit very little energy as they traverse the calorimeter, making them almost invisible to the trigger and offline analysis. This leads to an enhancement in the measured missing energy from the combined momenta of the neutrino and muon, enabling a larger area of phase space to be measured.

In Run 2, the transition to a PF reconstruction of jets both online and offline leads to complications in this procedure. As PFJets are reconstructed by clustering all reconstructed PF-candidates in the event, leptons and photons are also clustered into jets. To avoid multiple-counting of energy in the event in the offline analysis, jets are cross-cleaned to remove jets that are associated with isolated leptons and photons. Cross-cleaning is however not performed within the trigger, resulting in a mismatch in event quantities between offline and online reconstruction, leading to a bias in trigger measurements in lepton samples shown in Figure 6.14.

The cause of this bias is illustrated in Figure 6.15, which shows the difference in behaviour between the trigger reconstruction stages for a $t\bar{t}$ event with an isolated electron and muon. The first selection stages are performed by the L1 trigger and HLT calorimeter-prefilter which utilise an entirely calorimeter-based jet reconstruction. Muons are near-invisible to the calorimeter system resulting in little to no energy contamination to reconstructed jet energies. Electrons however are fully reconstructed, providing a large energy contamination to jets. In the final HLT PF reconstruction stage, which includes

information from the tracking and muons systems, the energy of both electrons and muons are fully reconstructed and clustered into jets, which are cross-cleaned from the jet system in the offline analysis.

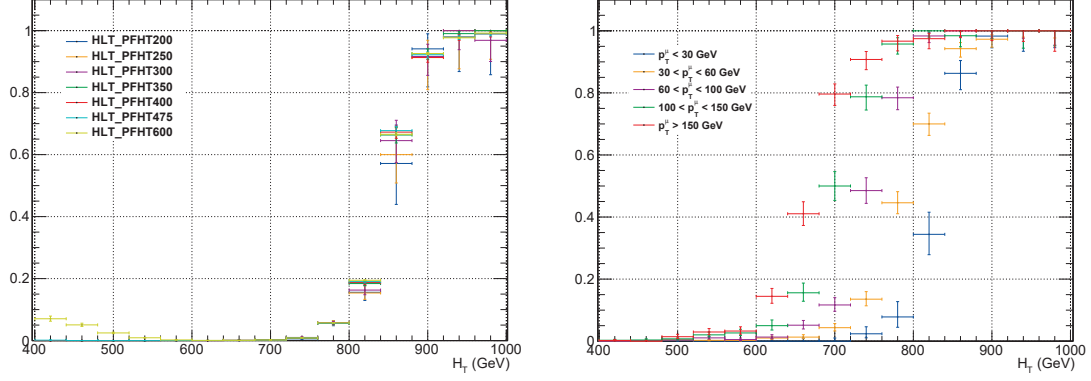


Figure 6.14: A comparison of the measured efficiency of $H_T = 800$ GeV trigger using hadronic reference triggers (left) and using a muon reference trigger (right) with a range of requirements on the muon transverse momentum, p_T^μ .

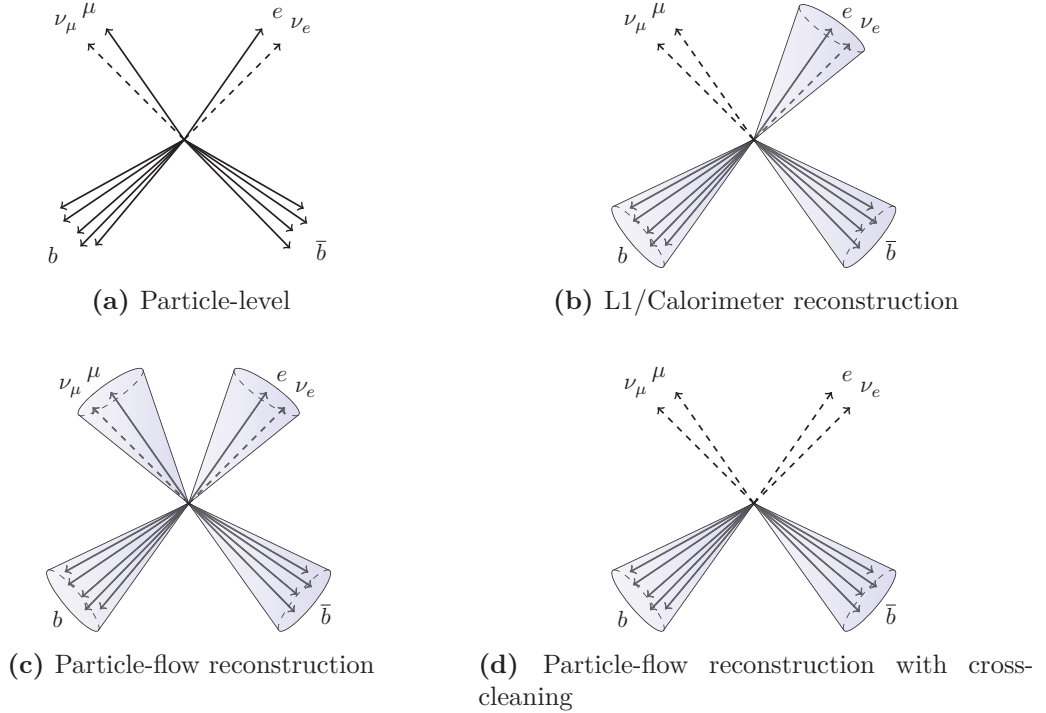


Figure 6.15: Illustration of the different behaviour of jets and isolated electrons and muons produced in fully-leptonic $t\bar{t}$ decay for different reconstructions. Particles clustered in jets are represented by solid cones, whilst particles ‘invisible’ to the jet system are represented by dashed lines.

The inconsistency in treatment of objects between the different reconstruction stages, summarised in Table 6.4, is one cause of bias in trigger measurements. For muons the mismatch occurs between PF reconstruction in the trigger, where muons are clustered as jets, in contrast to the cross-cleaned jets in the offline analysis. Electrons however are treated fully consistently throughout and only differ in the offline reconstruction. This mismatch in reconstruction for muons and electrons can be resolved in different ways.

Object	Level-1	Calo-filter	PF-filter	Offline
Jet	Yes	Yes	Yes	Yes
Muon	No	No	Yes	No
Electron	Yes	Yes	Yes	No

Table 6.4: Summary of the behaviour of different objects between different reconstruction stages, specifying if they are reconstructed as jets.

For muons this problem can be remedied by performing an *online cross-cleaning* of muons from jets in the PF trigger. This requires a method that works efficiently at removing isolated muons from jets within timing constraints and without affecting the efficiency of signal selections. For electrons however no such cross-cleaning can be performed, due to their visibility in both the L1 trigger and HLT-prefilter, and they may only be investigated by disabling offline cross-cleaning.

6.5 Online cross-cleaning

One method of resolving the efficiency bias for muon-jets is to perform a cross-cleaning of online jets to match the behaviour offline, removing jets online that are due to isolated muons. To identify techniques to perform cleaning of muon-jets, a comparison of the behaviour of jets in hadronic and muon samples are studied to enrich and suppress the lepton-jet behaviour. Events are selected to ensure hadronic activity with the following selections applied: $H_T > 200$ GeV, $\cancel{H}_T > 100$ GeV, $n_{\text{jet}} \geq 2$ and jet $p_T > 40$ GeV, $|\eta| < 3$. In addition, the hadronic sample has an additional requirement that no electrons or muons are reconstructed with $p_T > 10$ GeV, and the muon sample has a selection of one muon above 30 GeV and no electrons above 10 GeV. To distinguish between hadronic and muon-jets, two selections are utilised: *Muon matched* jets and *Offline matched* jets, which are jets that are matched within $\Delta R < 0.3$ of offline reconstructed muons and jets respectively.

6.5.1 Identification of muon-jets

An effective separation of fake muon-jets from hadronic jets can be achieved by utilising the reconstructed PF-muon energy of the jet. The correlation of the muon energy and total jet energy, illustrated in Figure 6.16, shows that muon-jets cannot be removed simply by a selection of their muon energy content, as hadronic jets can possess significant muon energy. The muon energy of hadronic jets follows an approximately exponentially falling distribution in energy which, in the hadronic region, is in good agreement with jets that are matched to offline jets. In muon enriched samples there is an enhancement for jets at the diagonal with muon energies above 30 GeV, as a result of real muons being reconstructed as jets. Muon-jets can therefore be effectively distinguished from their hadronic counterparts by a selection on the fractional muon energy of the jet, as muon-jets are typically localised to muon energy fractions above $\mu^{\text{EF}} > 0.6$.

Another potential method to remove muon-jets is to utilise reconstructed muons to filter fake jets. As the primary momentum component of muon-jets is the constituent muon, the ΔR separation of the reconstructed muon and its counterpart muon-jet are typically small. Illustrated in Figure 6.17, the distribution of the separation between muons and jets, $\Delta R(\mu, j)$, is sharply peaked for small separations for jets that have a significant muon energy component, which falls sharply with increasing separations. Real hadronic jets conversely are more prominently distributed with greater separations, making the variable $\Delta R(\mu, j)$ effective in identifying muon-jets.

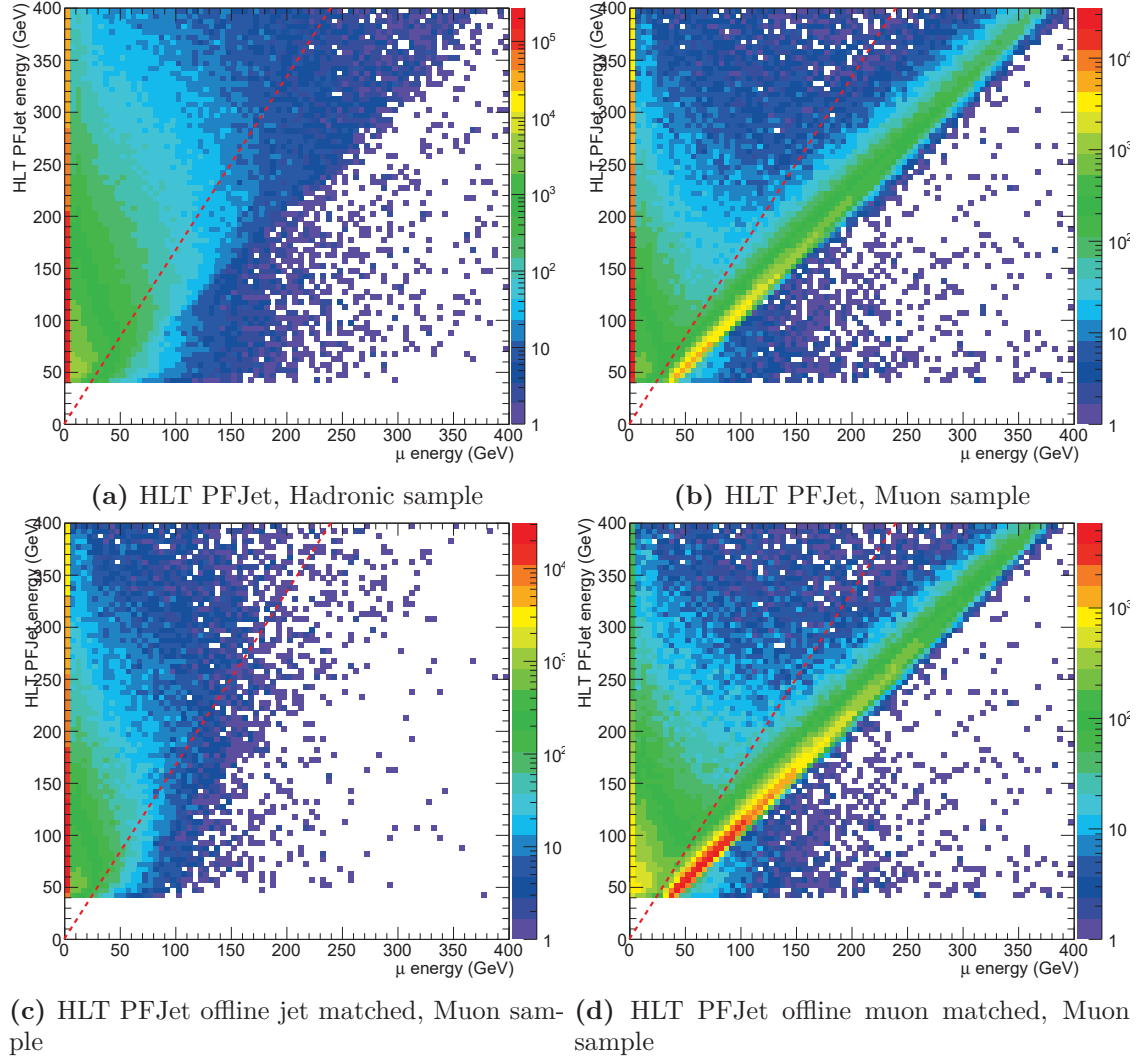


Figure 6.16: Correlation of reconstructed HLT PFJet total energy with its total reconstructed muon energy for all reconstructed jets in a hadronic sample (a) and a muon sample (b-d), with the dashed red line representing a muon energy fraction equivalent to 0.6.

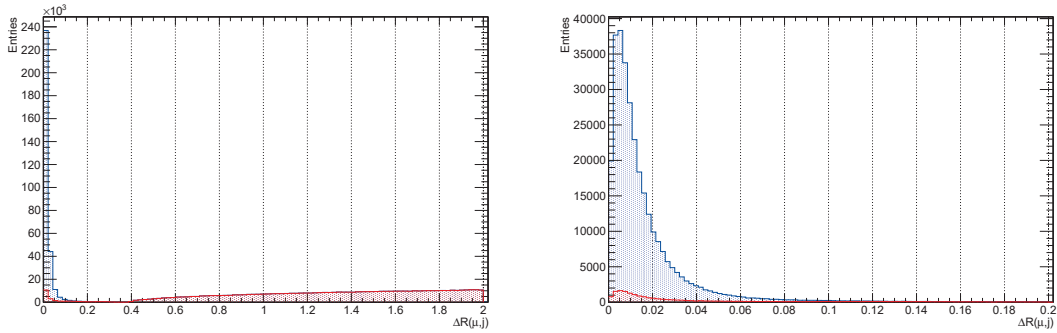


Figure 6.17: Distribution of the ΔR separation of reconstructed muons with all HLT PFJets (blue) and all HLT PFJets with a muon energy fraction < 0.6 (red) for a single muon selection. Shown for a large range (left) and enlarged for small separations (right).

6.5.2 Cross-cleaning methods

In order to correct the bias from additional muon-jets, several methods for removing fake muon-jets are studied:

- *Muon EF selection* - Jets that contain a significant muon energy fraction are likely to be a result of a lepton and can be vetoed. This in effect mimics an isolation requirement from the definition of the relative PF isolation, $I_{\text{PF}}^{\text{rel}}$, of Equation 3.3 which gives the approximate relation:

$$I_{\text{PF}}^{\text{rel}}(p_{\text{T}}^l) \sim \frac{p_{\text{T}}^j - p_{\text{T}}^l}{p_{\text{T}}^l}, \quad (6.2)$$

yielding the relation between fractional energy and isolation:

$$\frac{p_{\text{T}}^l}{p_{\text{T}}^j} \sim \frac{1}{1 + I_{\text{PF}}^{\text{rel}}}. \quad (6.3)$$

For the relative isolation requirement $I_{\text{PF}}^{\text{rel}} < 0.12$ for a $\Delta R = 0.4$ cone, the corresponding jet energy fraction is $\frac{p_{\text{T}}^l}{p_{\text{T}}^j} > 0.89$. For the mini relative isolation requirement $I_{\text{PF}}^{\text{mini}} < 0.2$ with a $\Delta R = 0.2$ cone, the corresponding jet energy fraction is $\frac{p_{\text{T}}^l}{p_{\text{T}}^j} > 0.56$.

- *CaloJet matching* - In the case of genuine jets, the jet hadronic activity should be significant and the jet should in addition be reconstructed as a calorimeter jet. Isolated muon-jets in contrast should not have a corresponding calorimeter jet, making a selection of jets that are ΔR matched to calorimeter reconstructed jets effective in distinguishing hadronic jets.
- *Online lepton veto* - Another method of cleaning can be achieved by a removal of jets that are matched within a specified ΔR of reconstructed leptons. For this purpose muons reconstructed with a single isolated muon trigger with $p_{\text{T}} > 20$ GeV are used to veto jets that can be attributed to muons.

6.5.3 Cross-cleaning resolution

As the behaviour of cross-cleaned quantities in the muon sample should mirror that of the hadronic sample, the performance of the cross-cleaning methods can be evaluated by comparing the measured resolution of event quantities in a muon enriched and hadronic samples. In the absence of a bias, the ratio of the response and resolution in the hadronic and muon samples should yield a flat distribution at unity.

Shown in Figure 6.18 is the ratio of measured H_T and $\cancel{H}_T$ and their respective RMS in a muon enriched and hadronic enriched samples. Without the application of a correction it is evident there is a clear bias, with an overestimate of the true H_T and an overestimate of $\cancel{H}_T$ for events with little true missing energy, falling to an underestimate for events with large missing energy. With the application of an online lepton veto there is a consistent underestimate of the H_T and $\cancel{H}_T$ however the RMS of the distribution grows large for large values of H_T . CaloJet matched jets and jets with a < 0.6 muon energy fraction selection however show a consistent flat behaviour for H_T and $\cancel{H}_T$, with a deviation from flat for the CaloJet matched jets at large $\cancel{H}_T$. These latter methods could therefore potentially be utilised within the trigger to remove muon-jets, mitigating bias in efficiency measurements with muon samples.

6.6 Summary

A suite of dedicated signal triggers for the α_T analysis were developed for the selection of events in the more challenging conditions of LHC Run 2. The performance of these triggers was continually monitored in data during early commissioning in 2015 and were successful in collecting data for the signal region throughout the 2015 data run. The efficiency of the signal triggers are measured using a data-driven method from which a trigger efficiency correction is derived. Sources of bias in the measurement of trigger efficiency using lepton reference triggers are described and bias correction techniques are explored.

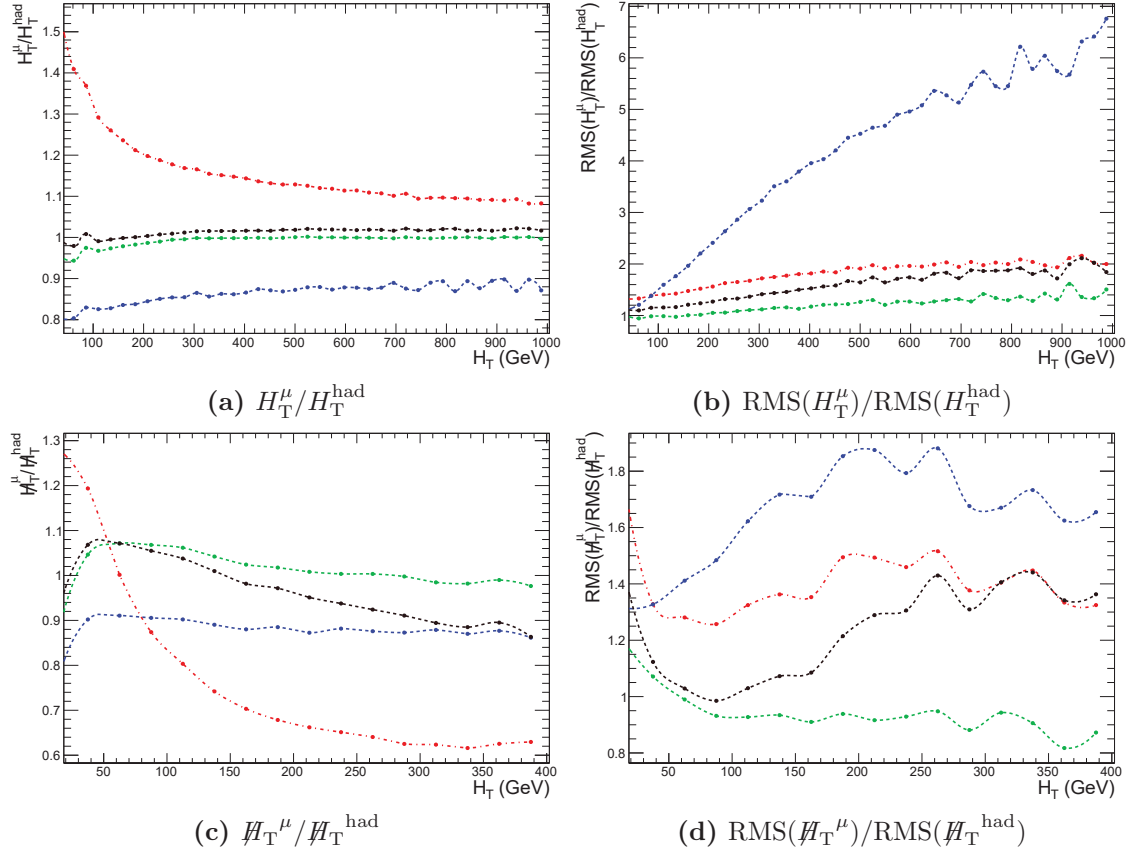


Figure 6.18: Ratio of response variables with their counterpart measured in a simulated hadronic sample for the mean (left) and RMS (right) of the measured for the measured H_T (top) and H_T (bottom), using the standard reconstruction in the hadronic sample and cross-cleaning methods in the muon sample. The lines show the performance in the absence of a correction (red), with an online lepton veto (dark blue), a muon energy fraction < 0.6 selection (green) and a CaloJet matching requirement (brown).

CHAPTER 7

Background estimation

The precise measurement of the SM backgrounds is of critical importance in maximising signal sensitivity in searches for new physics. In the α_T analysis the backgrounds are categorised into two distinct categories: electroweak and QCD multijet. Due to the difference in topology and the effectiveness of which these backgrounds are modelled, dedicated background estimation methods are employed, with the *transfer factor* and *QCD background estimation* methods being utilised in the estimation of the electroweak and QCD multijet backgrounds respectively.

7.1 Estimation of SM processes with genuine $\cancel{E}_T$

To ensure the accurate modelling of the electroweak backgrounds, the analysis uses a combination of simulated MC samples and data-driven corrections to provide predictions of the SM background contamination in the signal region. Although the electroweak background is typically well described in simulation, the exposure to mismodelling is mitigated with the use of electroweak-enriched data control regions which, used in conjunction with *transfer factor* corrections, provide a more accurate estimate of the total electroweak contribution in the signal region. Transfer factors are constructed from the ratio of expected yields in the signal region, $N_{\text{MC}}^{\text{signal}}$, and control region, $N_{\text{MC}}^{\text{control}}$, determined in simulation:

$$\text{TF} = \frac{N_{\text{MC}}^{\text{signal}}(H_T, n_{\text{jet}}, n_b)}{N_{\text{MC}}^{\text{control}}(H_T, n_{\text{jet}}, n_b)}. \quad (7.1)$$

Independent transfer factors are calculated for each of the analysis $(H_T, n_{\text{jet}}, n_b)$ bins in each control region, which are combined with the measured event yields in the data control regions, $N_{\text{obs}}^{\text{control}}$. This provides an extrapolation of the total expected electroweak contribution in the signal region, $N_{\text{pred}}^{\text{signal}}$, by the following relation:

$$N_{\text{pred}}^{\text{signal}}(H_T, n_{\text{jet}}, n_b) = \frac{N_{\text{MC}}^{\text{signal}}(H_T, n_{\text{jet}}, n_b)}{N_{\text{MC}}^{\text{control}}(H_T, n_{\text{jet}}, n_b)} \cdot N_{\text{obs}}^{\text{control}}(H_T, n_{\text{jet}}, n_b). \quad (7.2)$$

Three data control samples are utilised for the purpose of data-driven measurements of the electroweak backgrounds: $\mu\mu + \text{jets}$ and $\gamma + \text{jets}$ samples are used to predict the $Z \rightarrow \nu\bar{\nu}$ background and an $\mu + \text{jets}$ sample is used to predict the $W + \text{jets}$ and $t\bar{t}$ backgrounds. Selections are applied on the quality and kinematic properties of the respective tag-object in the control samples to ensure a well reconstructed sample enriched in $t\bar{t}$ and W/Z bosons, reducing potential contamination from QCD multijet and supersymmetric hadronic signatures. In addition, similar analysis selections as those chosen in the signal region are applied to ensure the control regions have a similar kinematic regime.

The transfer factor method provides an estimate of the total electroweak background yield in the $(H_T, n_{\text{jet}}, n_b)$ analysis bins inclusive of the $\cancel{H}_T$ -dimension. In order to obtain the distribution of background yields in $\cancel{H}_T$ dimension, templates extracted from simulation normalised to the total yield in their respective $(H_T, n_{\text{jet}}, n_b)$ bins are utilised. Constraints are applied on the binning of these templates, driven by the available statistics in simulation, such that each bin in $\cancel{H}_T$ contains a minimum of 10 unweighted simulated events, ensuring the statistical uncertainty is sub-dominant with respect to the estimated systematic uncertainty. Additionally, a minimum bin width of 50 GeV is imposed to reduce the effect of bin migration as a result of limited $\cancel{H}_T$ resolution.

7.1.1 Modelling of the analysis control regions

To ensure the validity of the transfer factor method, the modelling of core analysis variables in the full 2.3 fb^{-1} datasets of the three analysis control regions are studied. A summary of the MC generators used in the creation of the MC samples are described in Section 8.1.2.

The modelling of the H_T , n_{jet} and n_b variables in the $\mu + \text{jets}$, $\mu\mu + \text{jets}$ and $\gamma + \text{jets}$ control regions are summarised in Figure 7.1-7.3. In general there is shown to be a good agreement in the modelling of analysis variables across all the control regions. This is not critical however as any observed mismodelling is corrected through transfer factor method, with any discrepancies observed in the control region used in the correction of modelling in the signal region. A summary of the measured yields in the control region and their corresponding transfer factors are summarised in Appendix 2 and Appendix 3 respectively.

7.1 Estimation of SM processes with genuine $\cancel{E}_T$

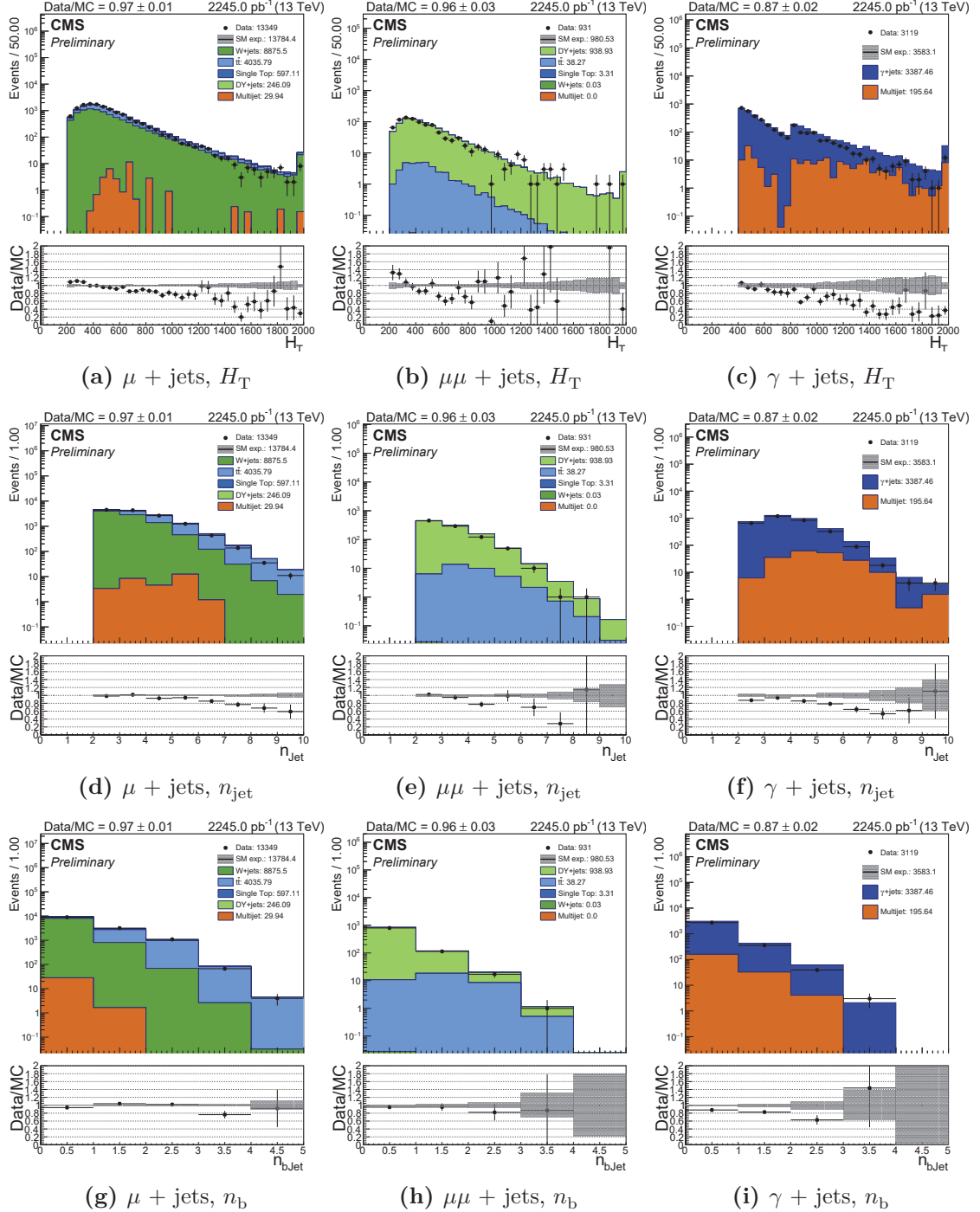


Figure 7.1: Distributions of key analysis variables measured in data (black circles) and simulation (coloured histogram) for the symmetric jet categories in the $\mu + \text{jets}$ control region (left), $\mu\mu + \text{jets}$ control region (middle) and $\gamma + \text{jets}$ control region (right).

7 Background estimation

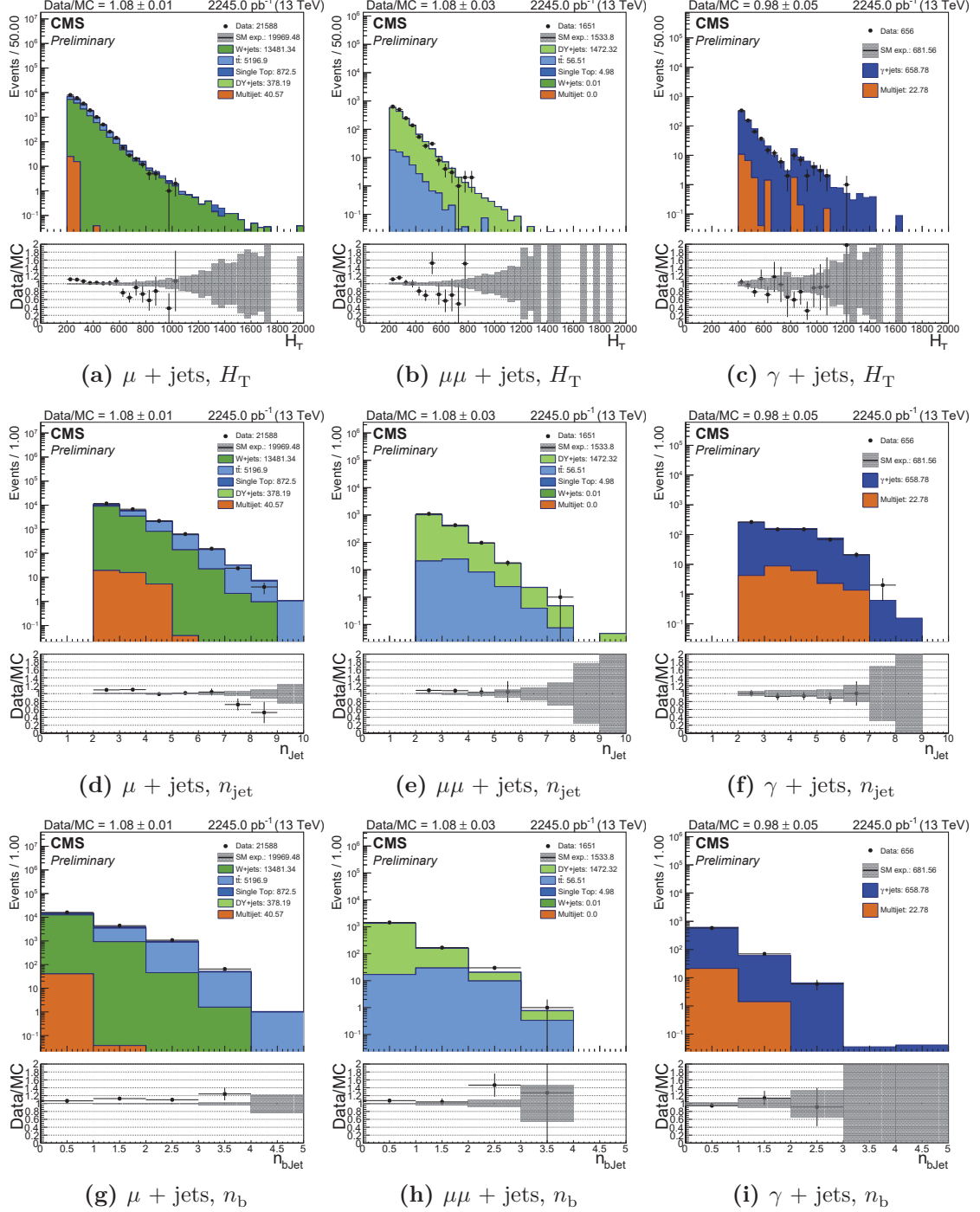


Figure 7.2: Distributions of key analysis variables measured in data (black circles) and simulation (coloured histogram) for the asymmetric jet categories in the $\mu + \text{jets}$ control region (left), $\mu\mu + \text{jets}$ control region (middle) and $\gamma + \text{jets}$ control region (right).

7.1 Estimation of SM processes with genuine $\cancel{E}_T$

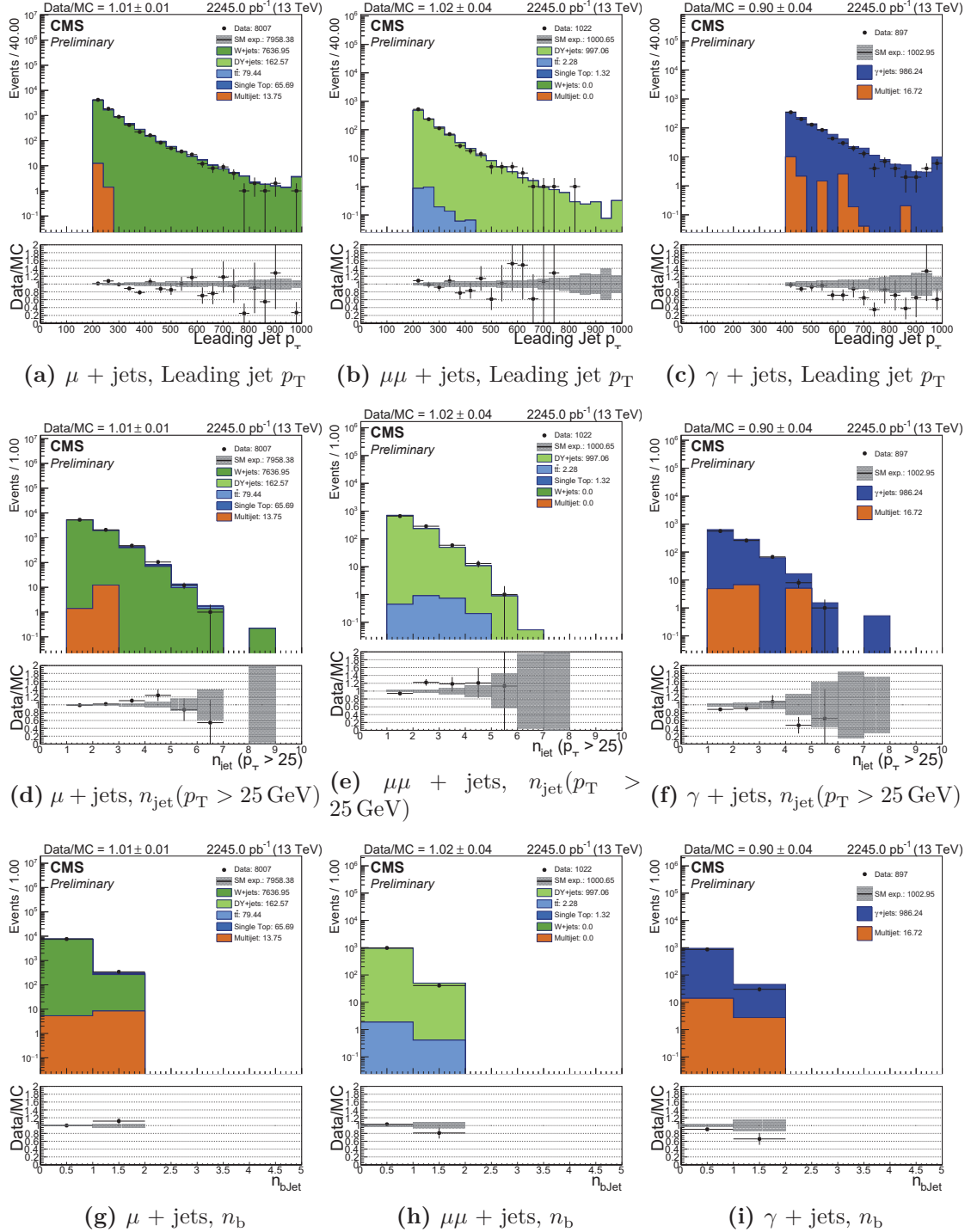


Figure 7.3: Distributions of key analysis variables measured in data (black circles) and simulation (coloured histogram) for the monojet jet categories in the $\mu + \text{jets}$ control region (left), $\mu\mu + \text{jets}$ control region (middle) and $\gamma + \text{jets}$ control region (right).

7.2 QCD multijet background estimation

Hadronic searches for new physics at the LHC are dominated by QCD multijet production which can mimic the jets and missing-energy signature. The estimation of the QCD multijet background however is extremely challenging due to theoretical uncertainties and, as a result of large production cross sections, the limited statistical power of simulated samples, particularly at low- H_T . In addition, it is difficult to accurately model and quantify detector and misreconstruction effects from which QCD enters the signal region. Together these effects result in large uncertainties in predictions from simulation, which can significantly inflate the uncertainty in the total background estimate. To better control the uncertainty and accuracy of the QCD multijet background prediction, a dedicated data-driven background estimation method is utilised, in addition to dedicated studies to suppress events arising from severe mismodelling.

7.2.1 The QCD background estimation method

To provide a reliable measure of the QCD, a dedicated data-driven method is used in the prediction of the QCD background in the signal region. The background estimation method utilises a hadronic control region, which shares the same selections as the signal region except for an inverted $\cancel{H}_T/\cancel{E}_T > 1.25$ requirement. This provides a QCD-enriched sample from which the contamination in the signal region is extrapolated.

The method uses the ratio of QCD multijet background events in the signal region to those in the hadronic control region, R_{QCD} , which is measured for each the analysis (H_T, n_{jet}) bins, inclusive of the n_b and $\cancel{H}_T$ dimensions. The value of R_{QCD} is determined in simulation from the number of QCD events that pass, $N_{\text{Pass}}^{\text{QCD}}$, and fail, $N_{\text{Fail}}^{\text{QCD}}$, the $\cancel{H}_T/\cancel{E}_T < 1.25$ selection respectively:

$$R_{\text{QCD}}(H_T, n_{\text{jet}}) = \frac{N_{\text{Pass}}^{\text{QCD}}(H_T, n_{\text{jet}})}{N_{\text{Fail}}^{\text{QCD}}(H_T, n_{\text{jet}})}. \quad (7.3)$$

With knowledge of R_{QCD} and the QCD yield in the $\cancel{H}_T/\cancel{E}_T$ sideband, the contamination of the QCD multijet background in the signal region can be computed by the relation:

$$N_{\text{Pass}}^{\text{QCD}}(H_T, n_{\text{jet}}) = R_{\text{QCD}}(H_T, n_{\text{jet}}) \cdot N_{\text{Fail}}^{\text{QCD}}(H_T, n_{\text{jet}}). \quad (7.4)$$

In order to determine the number of QCD events failing the $\cancel{E}_T/\cancel{E}_T$ selection a hadronic data sample is utilised, correcting the measured data yield in the $\cancel{E}_T/\cancel{E}_T$ side-band, $N_{\text{Fail}}^{\text{obs}}(H_T, n_{\text{jet}})$, by the electroweak yield computed using the transfer factor method, $N_{\text{Fail}}^{\text{Ewk}}(H_T, n_{\text{jet}})$:

$$N_{\text{Fail}}^{\text{QCD}}(H_T, n_{\text{jet}}) = N_{\text{Fail}}^{\text{obs}}(H_T, n_{\text{jet}}) - N_{\text{Fail}}^{\text{Ewk}}(H_T, n_{\text{jet}}). \quad (7.5)$$

A summary of the measured event yields for the full 2.3 fb^{-1} dataset used in the QCD estimation method are summarised in the following sections. Throughout the uncertainties shown are the statistical uncertainty of the datasets utilised, combined with a 20% systematic uncertainty ascribed to the electroweak prediction where relevant.

7.2.2 Determination of the ratio R_{QCD}

The predicted yield of QCD multijet events passing and failing the $\cancel{E}_T/\cancel{E}_T < 1.25$ selection as a function of the analysis (H_T, n_{jet}) bin are summarised in Figure 7.4. The ratio of these event yields are used to provide a computation of R_{QCD} in the analysis (H_T, n_{jet}) bins, which is shown in Figure 7.5.

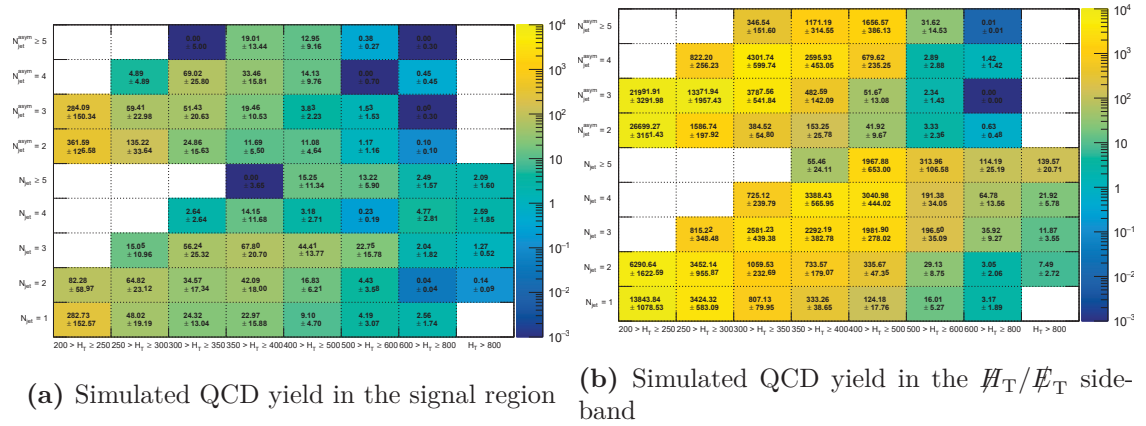
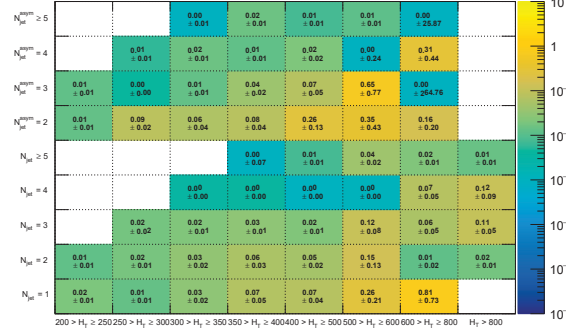


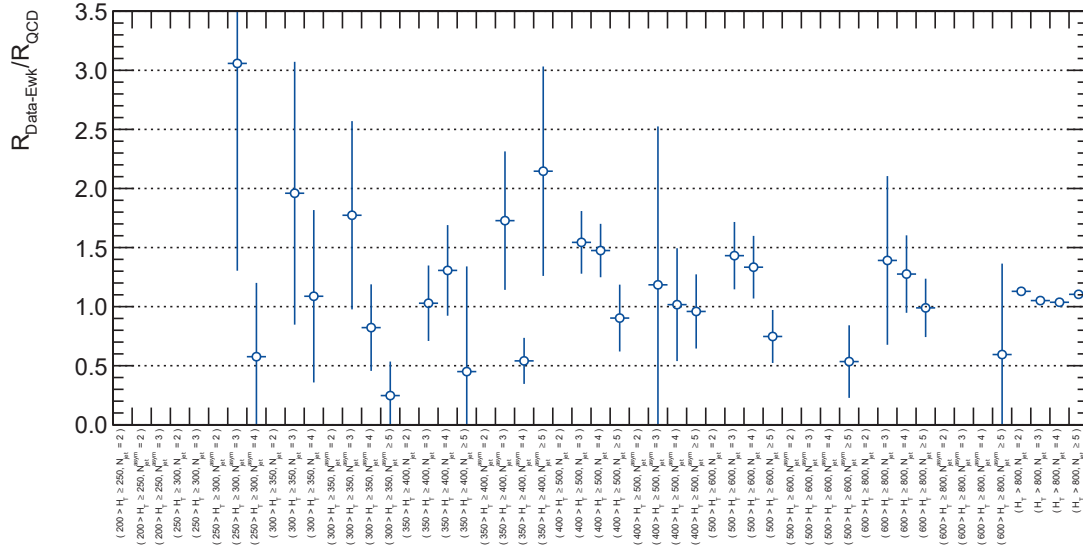
Figure 7.4: Simulated event yields of the QCD multijet background as a function of the analysis H_T and n_{jet} bins for events passing, $N_{\text{Fail}}^{\text{QCD}}$, (left) and failing, $N_{\text{Fail}}^{\text{QCD}}$, (right) the $\cancel{E}_T/\cancel{E}_T < 1.25$ requirement.



(a) Ratio of QCD events in signal region

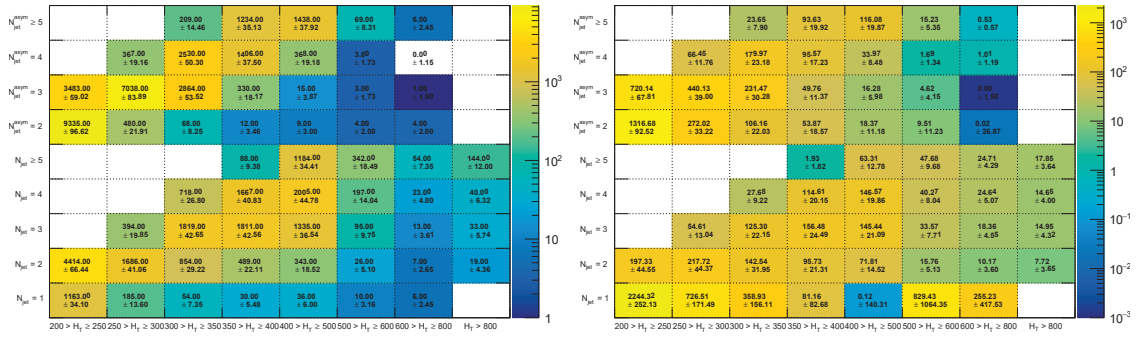
Figure 7.5: Ratio of simulated QCD multijet background event yields as a function of the analysis H_T and n_{jet} bins passing and failing the $\cancel{E}_T/\cancel{E}_T < 1.25$ requirement.

The modelling of R_{QCD} in data and simulation is validated by comparing the ratio computed from electroweak-corrected measurements in data, $R_{\text{Data-Ewk}}$, with that from predicted in simulation, R_{QCD} , in a $\Delta\phi_{\text{min}}^*$ -sideband. Shown in Figure 7.6 the ratio of the measured value of R_{QCD} in data and simulation show no significant deviation from the value of unity expected for agreement between data and simulation.

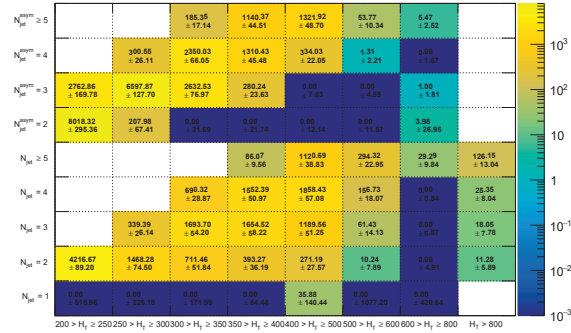

Figure 7.6: Ratio of the computed ratios of QCD multijet background passing and failing the $\cancel{E}_T/\cancel{E}_T < 1.25$ selection in data, $R_{\text{Data-Ewk}}$, and simulation, R_{QCD} , as a function of the analysis (H_T, n_{jet}) bins for a $\Delta\phi_{\text{min}}^* < 0.5$ selection.

7.2.3 Measured QCD multijet yields in data samples

The number of QCD multijet events in the $\cancel{H}_T/\cancel{E}_T$ sideband in data are computed by the correcting the measured data counts by the predicted electroweak background counts, which are shown in (a) and (b) of Figure 7.7 respectively. From the application of Equation 7.5, the predicted QCD multijet yield in the $\cancel{H}_T/\cancel{E}_T$ sideband is obtained, as shown in Figure 7.7 (c).



(a) Binned data counts in $\cancel{H}_T/\cancel{E}_T$ sideband (b) Electroweak events in $\cancel{H}_T/\cancel{E}_T$ sideband



(c) Corrected data counts in $\cancel{H}_T/\cancel{E}_T$ sideband

Figure 7.7: Total event counts measured in data (top left), predicted electroweak contamination (top right) and electroweak-corrected data counts (bottom) in the $\cancel{H}_T/\cancel{E}_T$ sideband.

From the corrected data counts in the $\cancel{H}_T/\cancel{E}_T$ control region of Figure 7.7 and R_{QCD} of Figure 7.5, a prediction of the total QCD multijet, the electroweak background and their ratio is shown in (a), (b) and (c) of Figure 7.8 respectively. The predicted contamination of the QCD multijet background after the full signal selection is shown to be sub-dominant with respect to the predicted electroweak background yield, with the typical contamination of the QCD background predicted to be less than 5% of that from electroweak processes.

7 Background estimation

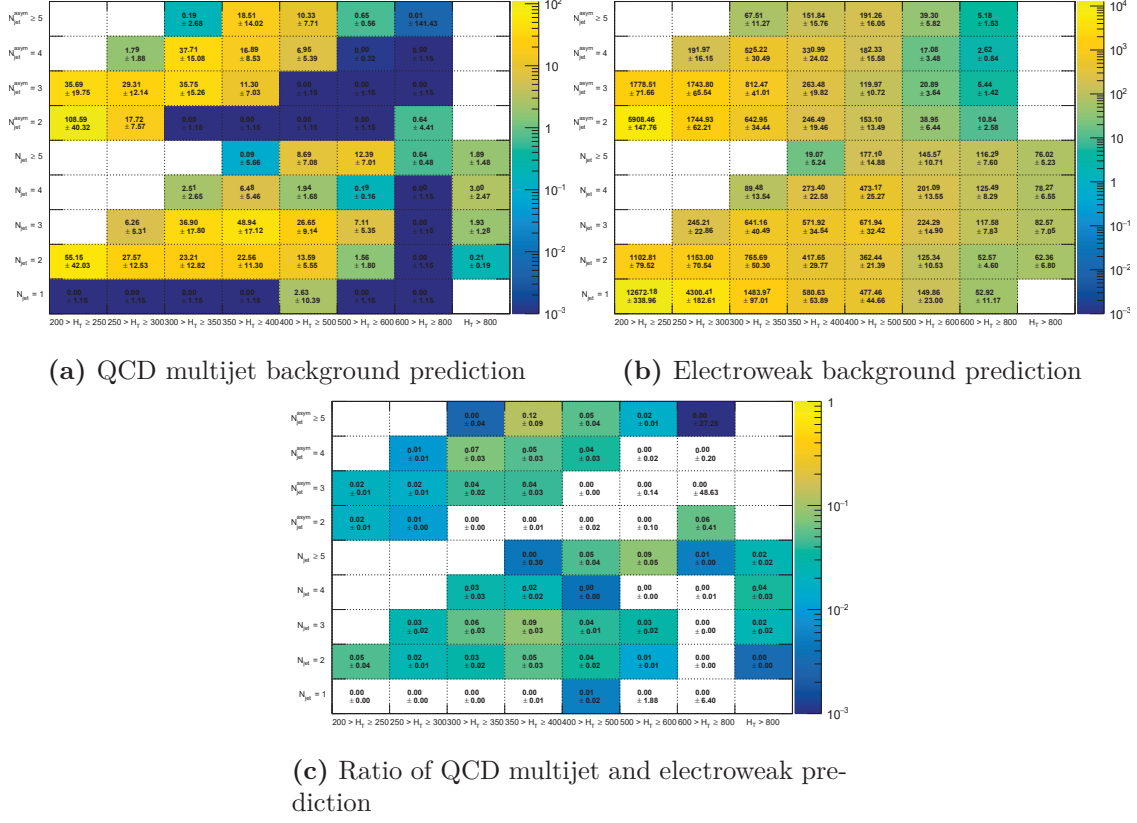


Figure 7.8: Predicted event yield in the signal region as a function of (H_T, n_{jet}) analysis bin for the QCD multijet background (left), the electroweak background (right) and the ratio of the predicted QCD multijet background with respect to the electroweak background yield (bottom).

Due to the limited statistical power of the available data samples, the QCD background prediction is performed per analysis (H_T, n_{jet}) bin, inclusive of n_b and $\cancel{H}_T$ dimensions. In a similar manner to the electroweak background, the prediction of the contamination in these dimensions is determined from their predicted shapes in simulation. However, as there is insufficient statistical power of the simulated QCD samples when divided into these additional dimensions, the n_b and $\cancel{H}_T$ shapes are obtained from the simulated electroweak background, which is expected to be kinetically similar. In order to validate the use of electroweak templates, the ratios of the predicted distribution of the QCD and electroweak backgrounds in the n_b and $\cancel{H}_T$ dimensions are measured. Shown in Figure 7.9, the modelling of the simulated shapes of the QCD and electroweak backgrounds are compatible, with their ratio being flat within the quoted statistical and systematic uncertainties.

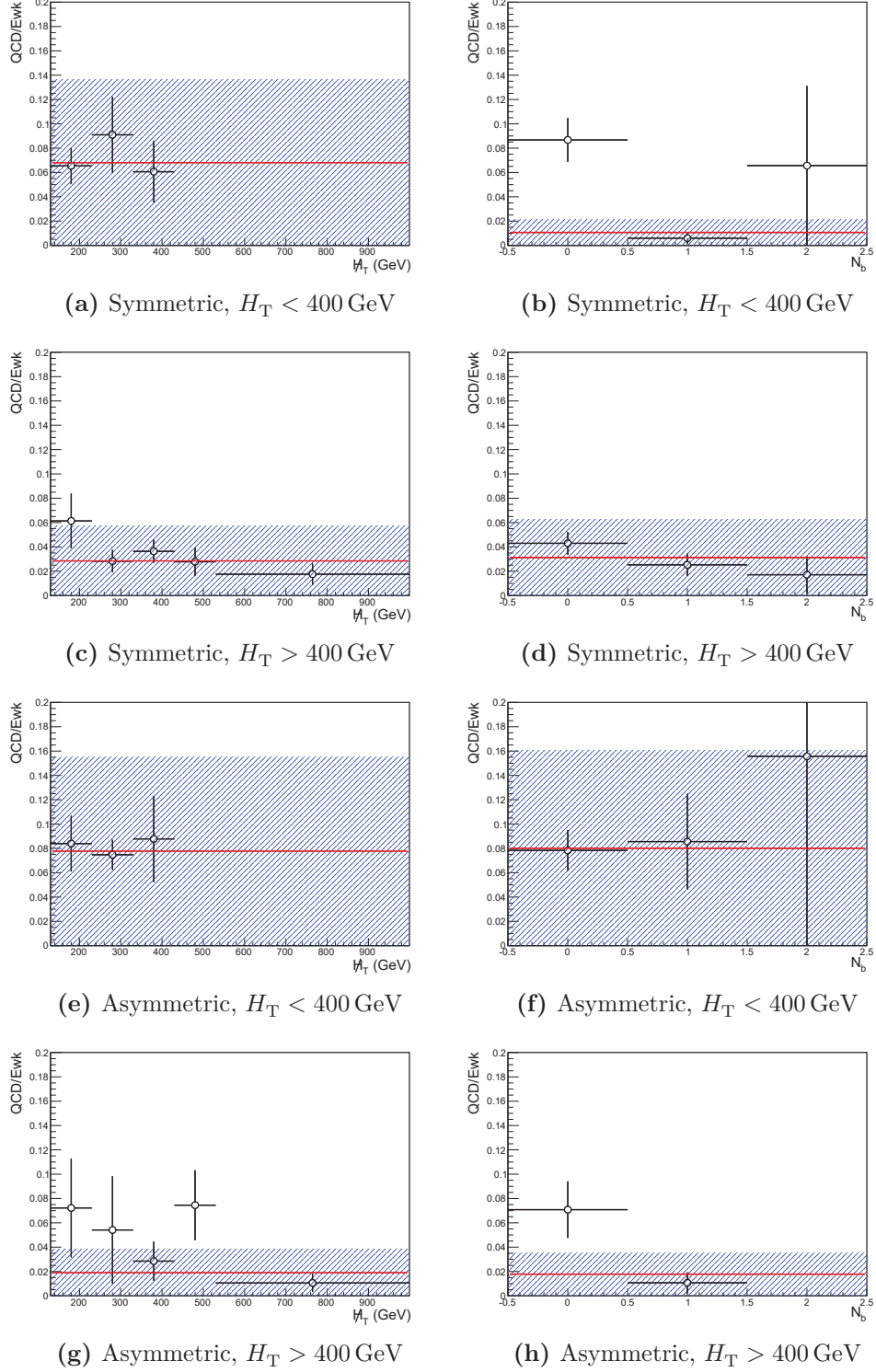


Figure 7.9: Ratio of the QCD to electroweak simulated prediction in the signal region for different H_T selections as a function of $\cancel{H}_T$ (left) and n_b (right) for the symmetric (top) and asymmetric (bottom) jet categories. A constant fit to the data is represented by the red line, with the $\pm 100\%$ uncertainty represented by the blue hashed region.

7.3 Commissioning the α_T analysis in Run 2

In order to validate the modelling of the analysis backgrounds in a new energy regime, an unblinded analysis of the data-MC agreement of early data was performed. This, in combination with a study of the reconstruction of individual events, enabled the operation of the CMS detector and new reconstruction techniques to be commissioned and potential sources of misreconstruction to be identified and mitigated.

7.3.1 Commissioning of early Run 2 data

An important test in the commissioning of the α_T analysis at $\sqrt{s} = 13$ TeV is the validation of the data-MC agreement in early data, to identify and quickly remedy problems in modelling. To achieve this, the first $42 \pm 5 \text{ pb}^{-1}$ of data collected during the 50 ns run were analysed to determine the effectiveness of the modelling of key kinematic distributions in the control and signal regions. Due to the uncertainties in luminosity measurements in early data, simulated distributions are normalised to the integrated data yield.

Shown in Figure 7.10 is the observed data and predicted yields of core analysis distributions for the $\mu + \text{jets}$ control region and unblinded signal regions, for an inclusive n_b and b -jet enriched ($n_b \geq 1$) selection. Due to the limited statistical power of the samples, tighter selections on the minimum hadronic transverse energy of $H_T > 225 \text{ GeV}$ are applied to mitigate any potential mismodelling of trigger efficiencies in early data. The kinematic shapes are shown to be good agreement between data and MC, with an agreement in shape modelling within 20%.

7.3 Commissioning the α_T analysis in Run 2

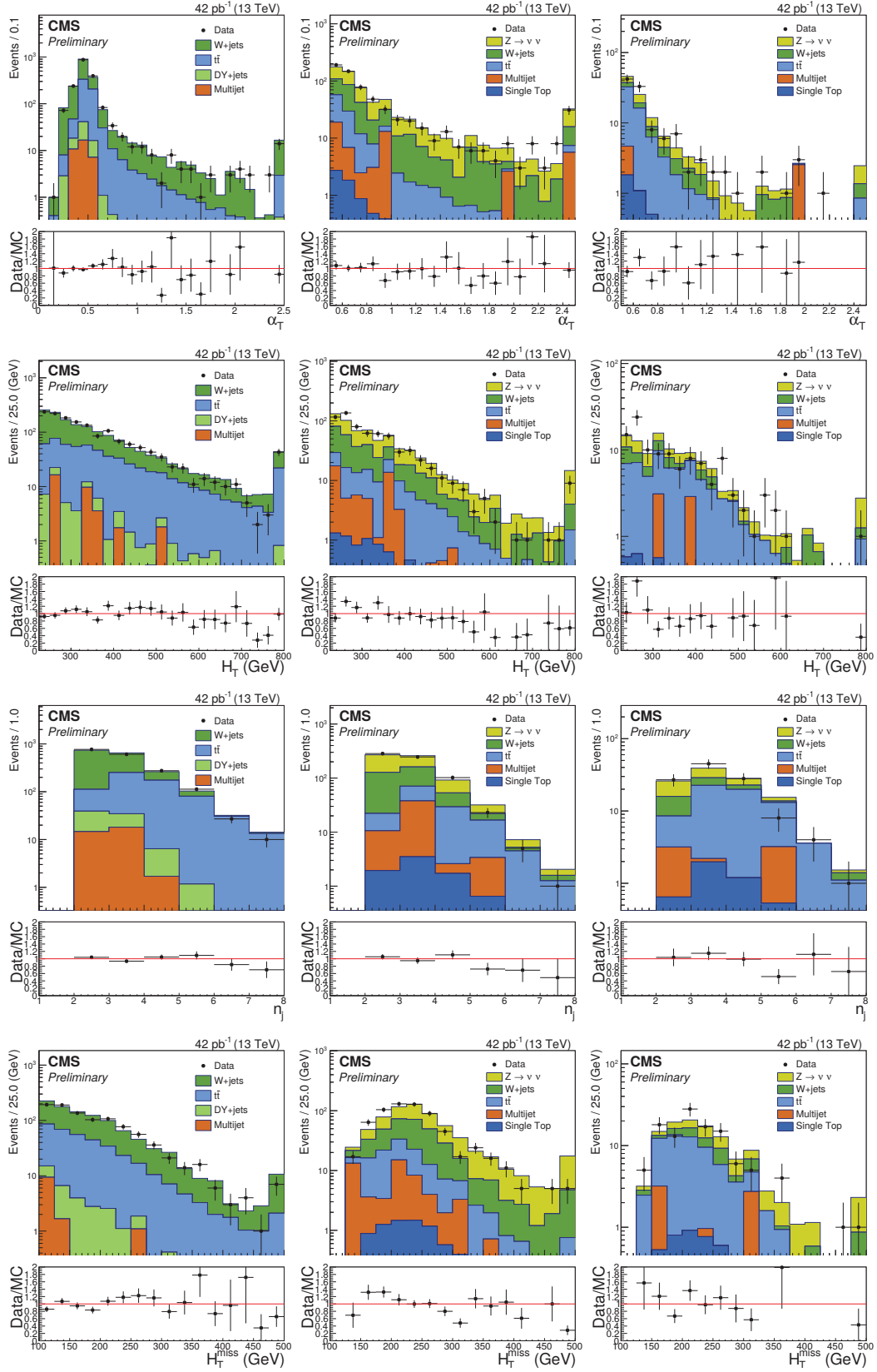


Figure 7.10: Kinematic distributions for the single muon control region (left), signal region (middle) and signal region for a $n_b \geq 1$ selection (right). Errors presented are purely statistical.

7.3.2 Validation of detector reconstruction in Run 2

An additional important area of investigation during commissioning is the validation of event reconstruction in order to mitigate fake events arising from severe misreconstruction and beam effects. In Run 1 $\cancel{E}_T$ -filters were effective in the suppression of such events, however in Run 2, with a change in detector and beam conditions, these filters required a period of commissioning before they could provide similar performance. It is therefore important, particular in early data, to confirm that all spurious signatures are removed and tighter selections applied where this selection is insufficient.

7.3.2.1 Detector misreconstruction

One such source of misreconstruction is an under-measurement of energy as a result of particles traversing areas of the calorimeters with no or reduced response. As the majority of these events pass selections through a jet being projected into regions of inefficiency, the position of these dead regions can be determined from a frequency analysis of the position of the subleading jet. In simulation, this behaviour can be selected by requiring a severe disagreement between the reconstructed and generator-level measurements of missing energy. For a data-driven measurements, an alternative method that exploits the position of the $\Delta\phi_{\min}^*$ -jet, the jet that minimises $\Delta\phi_{\min}^*$, is used. In events with small $\Delta\phi_{\min}^*$, the $\Delta\phi_{\min}^*$ -jet is typically a mismeasured jet and hence provides an effective method for localising dead regions. Figure 7.11 shows that the reconstructed jet position in simulation using the $\cancel{E}_T$ -mismeasurement and $\Delta\phi_{\min}^*$ methods are both effective in localising dead calorimeter regions, with the latter method suffering more from noise.

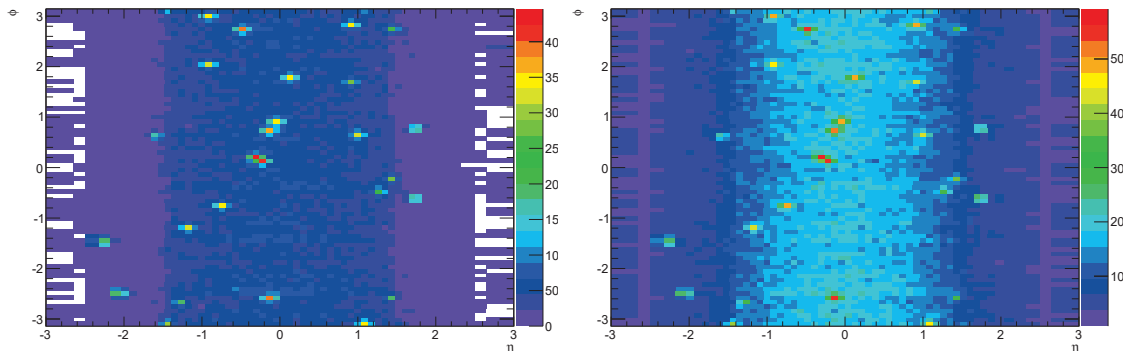


Figure 7.11: η - ϕ position of the subleading jet in events with severe mismeasurement of the missing energy ($\cancel{E}_T^{\text{Gen}}/\cancel{E}_T^{\text{Reco}} > 0.5$) (left) and the $\Delta\phi_{\min}^*$ -jet in events with $\Delta\phi_{\min}^* < 0.5$ (right), measured in a simulated QCD sample with a loose analysis selection.

To validate the modelling of current state of the detector, the $\Delta\phi_{\min}^*$ method is applied to data events in the signal region passing loose analysis selections with an inverted $\Delta\phi_{\min}^* < 0.5$ requirement. To better isolate the position of genuine dead regions from random noise, the significance of each η - ϕ region is computed from the ratio of the number of jets passing the selection $\Delta\phi_{\min}^* < 0.5$, with the square root of the total number of events in the absence of a $\Delta\phi_{\min}^*$ selection: $N(\eta, \phi | \Delta\phi_{\min}^* < 0.5) / \sqrt{N(\eta, \phi)}$. As shown in Figure 7.12, the locality of dead regions identified in data in general are in good agreement with those in simulation, with the use of the signal significance being effective in reducing random noise. This identifies differences between data and simulation, with the apparent addition and loss of dead regions at $(1.8, -2)$ and $(1.7, 1)$ respectively, which are a result of work on the detector during LS1.

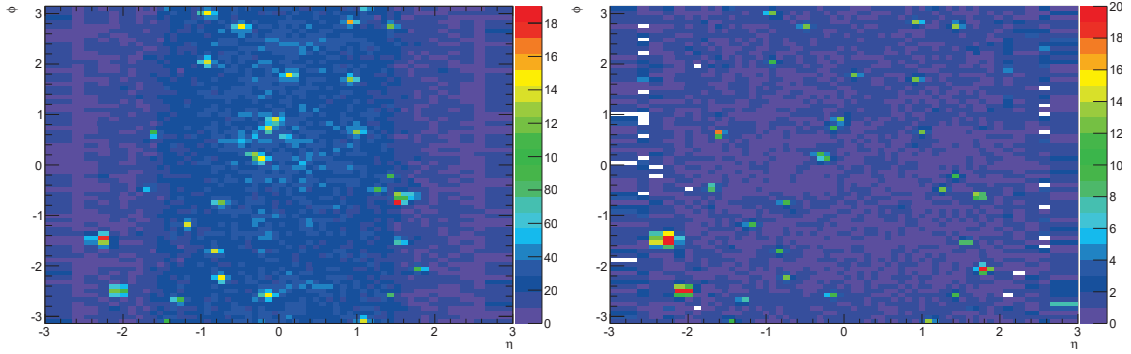


Figure 7.12: Measured frequency (left) and significance (right) of the $\Delta\phi_{\min}^*$ -jet in data events for a $\Delta\phi_{\min}^* < 0.5$ selection as a function of η - ϕ .

To ensure that the analysis selections are effective in suppressing this class of events, it is important to ensure there is no enhancement of events in identified dead regions above what is expected from random jet emission. To achieve this, the same $\Delta\phi_{\min}^*$ method is applied in the signal region with a $\Delta\phi_{\min}^* > 0.5$ selection. In addition, an η -dependent subtraction of the median jet multiplicity is applied to correct for the jet multiplicity background. The significance of the $\Delta\phi_{\min}^*$ -jet frequency as a function of η - ϕ for a loose and full signal selection are shown in Figure 7.13. After the application of a median noise subtraction, the positions of dead regions are shown to be better localised for the loose selection. These known dead regions show no significant correlation in locality with jets after the full analysis selection, demonstrating that this class of mismeasurement is effectively suppressed.

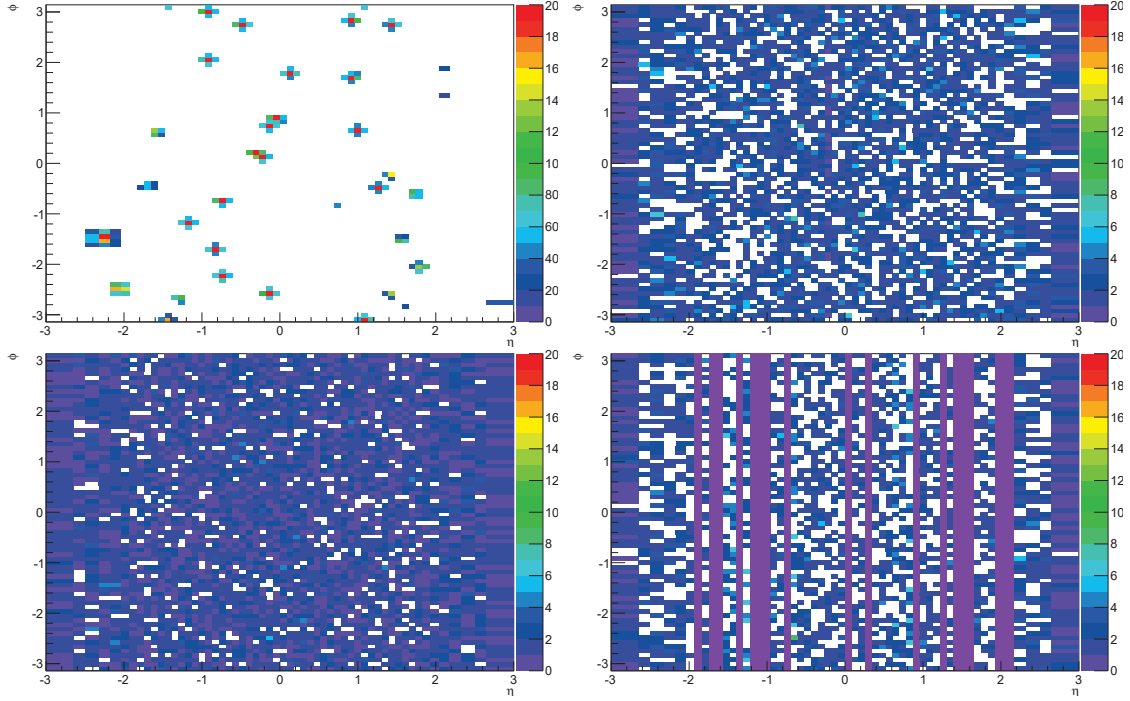


Figure 7.13: Measured significance of the $\Delta\phi_{\min}^*$ -jet multiplicity as a function of η - ϕ after an η -dependent of correction for a loose selection with a $\Delta\phi_{\min}^* < 0.5$ requirement (top left) and the full signal selection for the symmetric (top right) asymmetric (bottom left) and monojet (bottom right) jet categories.

7.3.2.2 Beam halo

In addition to detector mismeasurement, beam effects can also conspire to introduce fake missing energy into the event. Interactions of accelerated protons with the beam gas and collimators can result in the production of particle showers outside the detector. As these particles traverse the detector their interactions can result in fake additional energy deposits, an effect known as beam halo. Beam halo is characterised by strips of energy in the calorimeter at constant azimuth, predominantly in the LHC bending plane ($\phi = 0$ and $\pm\pi$) at high pseudorapidities, with relatively little charged hadronic energy from coincident particles from the pp -collision.

As a consequence of the low fractional energy of charged hadronic activity associated with beam halo, jets arising from halo events can be effectively tagged by a CHEF jet requirement. Figure 7.14 demonstrates that in the absence of beam filters, the application a fractional energy requirement of $\text{CHEF} < 0.1$ on the leading jet is effective in enriching beam halo events.

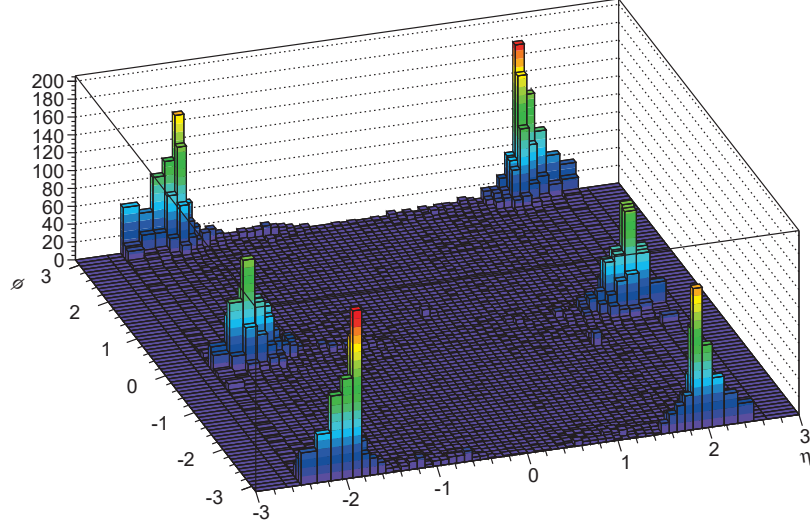


Figure 7.14: Jet η - ϕ distribution for a monojet selection with a $\text{CHEF} < 0.1$ selection measured in data in the absence of cleaning filters.

With the application of these filters however events consistent with beam halo are still present. Shown in Figure 7.15, in early 50 ns data excesses were observed in data for jets with azimuth $\phi = 0$ and $\pm\pi$, which is consistent with beam halo. These excesses are effectively suppressed with the application of a $\text{CHEF} < 0.1$ selection, which enables a good data-MC agreement to be regained.

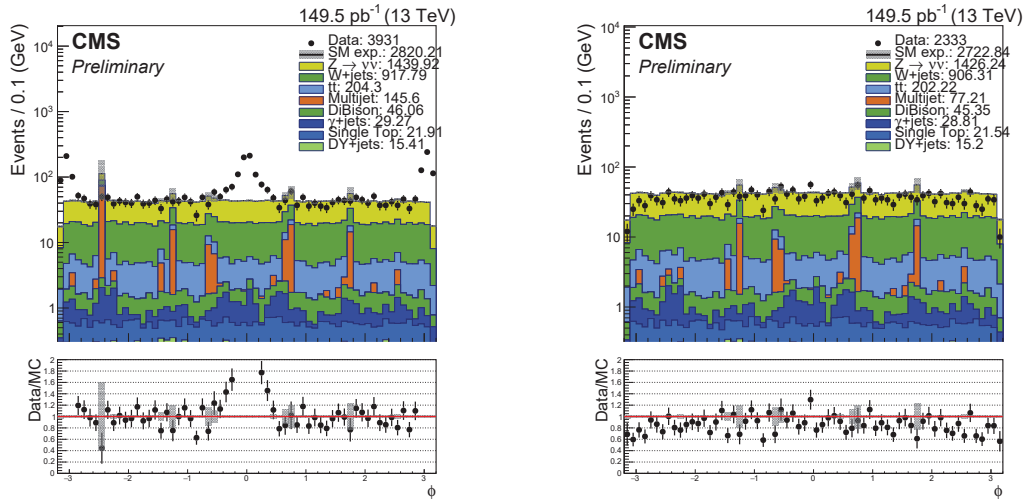


Figure 7.15: Jet azimuthal distribution for monojet in data (black dots) and simulation (histograms) for all events passing signal selections prior to a $\text{CHEF} < 0.1$ selection (left) and after a $\text{CHEF} < 0.1$ selection (right), for the 50 ns dataset.

7.3.2.3 Reconstruction failure

An additional source of fake missing energy is a result of severe event misreconstruction. One such class of events is track misreconstruction of high energy hadrons that ‘punch-through’ the calorimeter into the first layer of the muon system. In this case, the muon energy deposit can be matched to a fake or coincident track and be reconstructed as a PF-candidate muon. As these fake tracks typically have straight trajectories, the reconstructed track momentum is large, significantly inflating the energy of the reconstructed jet it is contained within.

Event misreconstruction can also arise from hard pileup in the generation of simulated samples. Pileup events are randomly sampled from simulated minimum bias QCD events and are overlaid onto the simulated hard scattering. This can however cause problems if the sampled pileup event is more energetic than the generated signal event. This is particularly a problem in the generation of low- $\hat{p}_T$ samples, where there is a greater likelihood that the energy of the pileup event exceeds that of the signal process.

An example of misreconstructed events as a result of hard-pileup and track misreconstruction are shown in Figure 7.16. In the first case, a simulated event with two low- p_T generator jets are correctly reconstructed however several additional hard jets associated with a hard pileup event are also reconstructed. This class of events is vetoed when a severe discrepancy between the lead generator jet p_T and reconstructed jet p_T is identified, which is symptomatic of hard pileup. In the second case, calorimeter punch-through results in the reconstruction of a fake muon track with a very large p_T . To combat such instances, events with large momentum imbalances and uncharacteristic PF energy compositions are scanned in event displays and are vetoed where they are found to exhibit symptoms of misreconstruction.

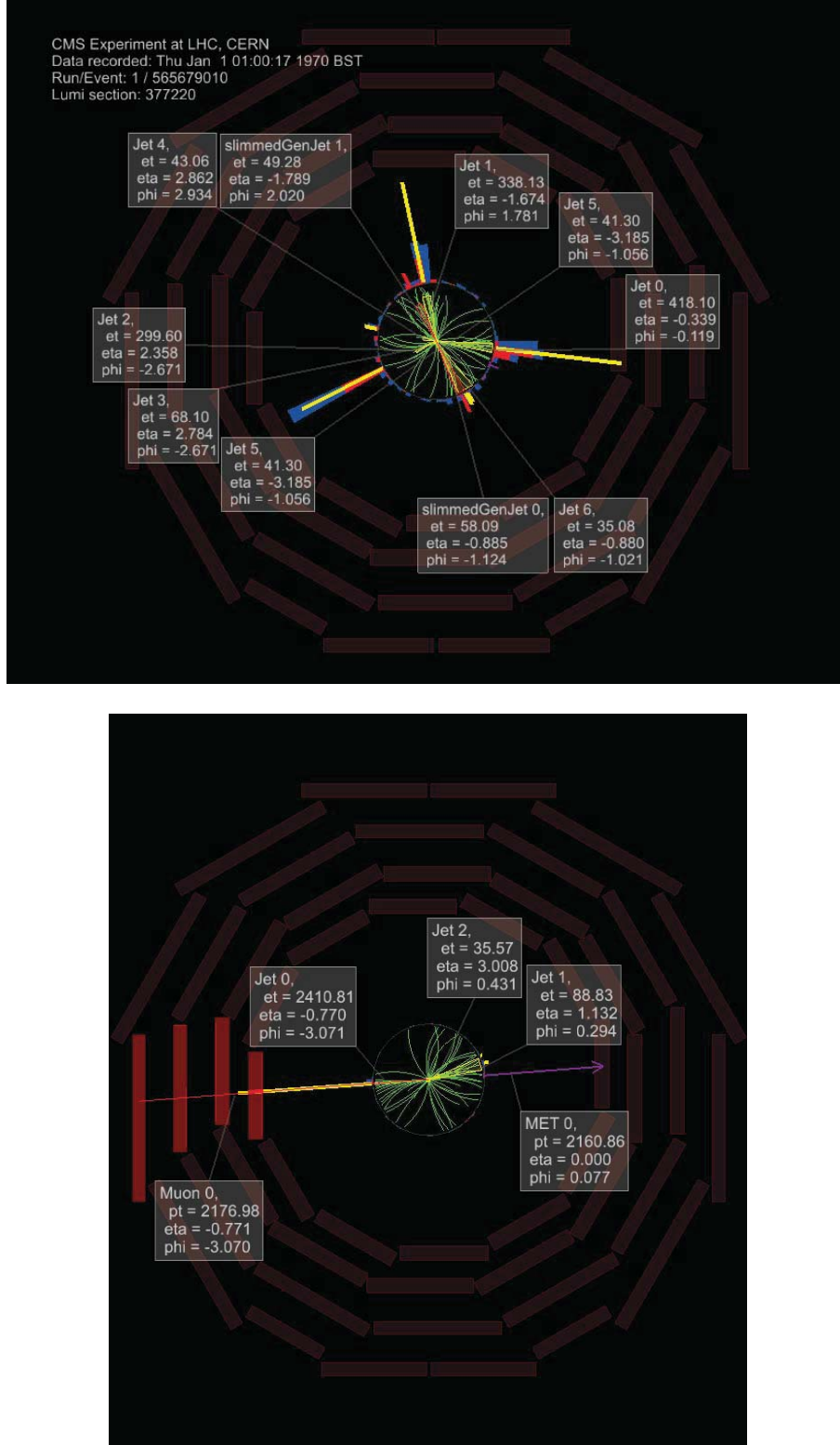


Figure 7.16: Event display of a simulated QCD dijet event (top) with generator jets (red) and reconstructed jets (yellow) for signal QCD event generated with $100 < \hat{p}_T < 200$ GeV and an overlaid pileup event generated with $\hat{p}_T = 466$ GeV. Event display of a data event symptomatic of calorimeter punch-through with track misreconstruction (bottom).

Corrections and systematic uncertainties

To ensure the accurate modelling of the background and signal processes, dedicated methods are used in the determination of corrections and in the estimation of systematic uncertainties, which are described in the following.

8.1 Datasets and Monte Carlo samples

The data utilised in the α_T analysis is a combination of *datasets* collected in $\sqrt{s} = 13$ TeV 25 ns pp -collisions at the LHC during the second data run in 2015 and simulated *Monte Carlo samples* for the modelling of signal and backgrounds.

8.1.1 Datasets

The data selected by the analysis triggers, described in Section 6.3, are collected and stored in the respective *primary dataset* of the trigger that select the event. Data selected by the $H_T\text{-}\alpha_T$, H_T and $\cancel{H}_T\text{-}\cancel{E}_T$ signal triggers are collected into the **HTMHT**, **JetHT** and **MET** primary datasets respectively. Due to overlap between these datasets, an additional trigger veto requirement is applied to ensure that events selected by multiple triggers are only counted once. The data selected by the hadronic, photon and muon control region triggers are collected into the **JetHT**, **SinglePhoton** and **SingleMuon** primary datasets respectively.

A summary of the total integrated luminosity delivered by the LHC and recorded by CMS for the full 2015 data run is shown in Figure 8.1. In 2015 the LHC delivered a total integrated luminosity of $\mathcal{L} = 4.22 \text{ fb}^{-1}$ during the 50 ns and 25 ns data runs, of which $\mathcal{L} = 2.8 \text{ fb}^{-1}$ was recorded by CMS with the magnet operating at the full 3.8 T field strength. Of this data, $\mathcal{L} = 2.3 \text{ fb}^{-1}$ recorded during the 25 ns data run was certified to be during good detector operation, which forms the data sample upon which the analysis is performed.

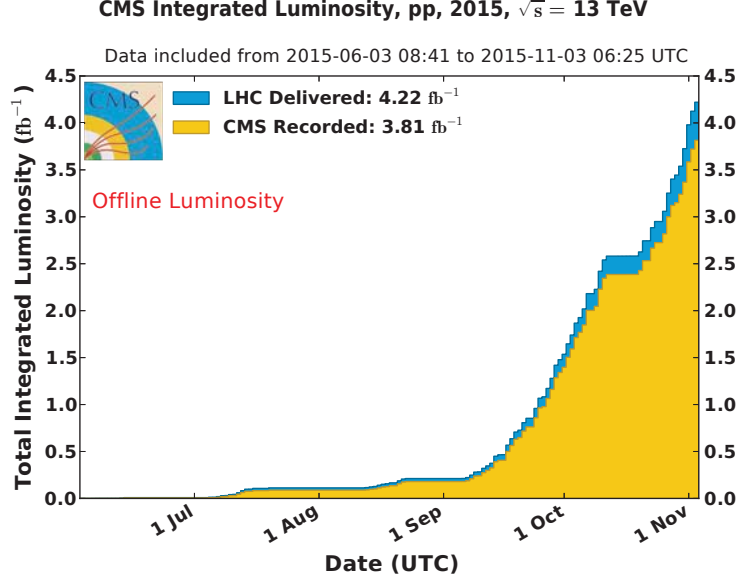


Figure 8.1: The total integrated luminosity of data in pp -collisions at $\sqrt{s} = 13$ TeV during the 2015 data run as a function of day delivered by the LHC (blue) and recorded by CMS during stable collisions (orange) [128].

8.1.2 Monte Carlo samples

In order to perform a precise modelling of the analysis backgrounds and potential signal models a range of MC samples are utilised. In conjunction, specialist corrections are applied to compensate for known sources of misreconstruction to improve the agreement between data and simulation.

The simulated samples used in the analysis are produced with a variety of different MC generators. The signal models and the majority of SM backgrounds are simulated at LO with MADGRAPH5 [111], including: QCD multijets, Drell-Yan + jets, $t\bar{t}$ + jets, W + jets, Z + jets and γ + jets. Single-top samples are produced at NLO with the aMCatNLO and POWHEG MC generators, which simulate the s , t and tW decay channels. The diboson backgrounds: WW , WZ and ZZ are produced with PYTHIA and POWHEG. The sample production cross sections of background samples are computed in most cases to Next-to-next-to-leading order (NNLO) accuracy, with k -factors used to provide additional corrections for samples produced at LO.

The simulation of hadronisation and showering is performed with Pythia8.1 [112], with subsequent decays of τ leptons simulated using the TAUOLA [129] MC generator.

Detector reconstruction for background samples utilise the CMS full detector simulation, which performs a complete simulation of particle interactions with the detector material using GEANT4. Signal samples are reconstructed with CMS fast simulation [130], which performs reconstruction 500-1000 faster than full simulation. This enables the simulation of a larger range of mass splittings and hence a larger region of parameter space to be probed.

Sample	Generator $\hat{H}_T$ selection	Cross section (pb)
QCD	$100 < \hat{H}_T < 200$ GeV	2.785×10^7
	$200 < \hat{H}_T < 300$ GeV	1.717×10^6
	$300 < \hat{H}_T < 500$ GeV	3.513×10^5
	$500 < \hat{H}_T < 700$ GeV	3.163×10^4
	$700 < \hat{H}_T < 1000$ GeV	6.802×10^3
	$1000 < \hat{H}_T < 1500$ GeV	1.206×10^3
	$1500 < \hat{H}_T < 2000$ GeV	1.204×10^2
	$\hat{H}_T > 2000$ GeV	2.525×10^1
$Z/\gamma^* \rightarrow ll + \text{jets}$ ($M_{ll} = 50\text{GeV}$)	$100 < \hat{H}_T < 200$ GeV	1.715×10^2
	$200 < \hat{H}_T < 400$ GeV	5.258×10^1
	$400 < \hat{H}_T < 600$ GeV	6.761×10^0
	$\hat{H}_T > 600$ GeV	2.718×10^0
$\gamma + \text{jets}$	$100 < \hat{H}_T < 200$ GeV	9.226×10^3
	$200 < \hat{H}_T < 400$ GeV	2.300×10^3
	$400 < \hat{H}_T < 600$ GeV	2.774×10^2
	$\hat{H}_T > 600$ GeV	9.338×10^1
$t\bar{t}$	Inclusive	8.318×10^2
$t/\bar{t}$	Inclusive	3.560×10^1
$W \rightarrow l\nu + \text{Jets}$	$100 < \hat{H}_T < 200$ GeV	1.627×10^3
	$200 < \hat{H}_T < 400$ GeV	4.352×10^2
	$400 < \hat{H}_T < 600$ GeV	5.918×10^1
	$600 < \hat{H}_T < 800$ GeV	1.458×10^1
	$800 < \hat{H}_T < 1200$ GeV	6.656×10^0
	$1200 < \hat{H}_T < 2500$ GeV	1.608×10^0
	$\hat{H}_T > 2500$ GeV	3.891×10^{-2}
$Z \rightarrow \nu\nu + \text{Jets}$	$100 < \hat{H}_T < 200$ GeV	3.450×10^2
	$200 < \hat{H}_T < 400$ GeV	9.638×10^1
	$400 < \hat{H}_T < 600$ GeV	1.346×10^1
	$\hat{H}_T > 600$ GeV	5.170×10^0
WW	Inclusive	1.246×10^1
WZ	Inclusive	6.610×10^1
ZZ	Inclusive	3.180×10^1

Table 8.1: A summary of the simulated $\sqrt{s} = 13\text{TeV}$ background samples utilised in the analysis and their generated $\hat{H}_T$ selection and cross section.

A summary of the simulated background samples used in the analysis is shown in Table 8.1. To provide a statistically significant predictive power across the full phase

space, the dominant backgrounds are produced in bins of the hadronic total energy of the scattered partons, $\hat{H}_T$. Signal models are generated in a scan of sparticle and LSP masses, with a coarse granularity used for smaller masses and a finer granularity used close to and beyond limits set in Run 1.

Simulated SMS signal models of gluino and stop pair production were used in the interpretation of the results, each with 100% branching fraction to the specified final state. The production cross sections of signal models are calculated to NLO plus Next-to-leading logarithm (NLL) precision [131].

8.1.3 Monte Carlo corrections

In order to better describe measurements in data, specialised corrections are applied to simulated samples which target a range of sources of mismodelling, including the simulation of the efficiency and resolution of reconstructed physics objects and event variables.

8.1.3.1 Scale factors

In order to correct for small differences in the modelling of the selection efficiency in simulation, ϵ_{MC} , with the efficiency measured in data, ϵ_{Data} , a scale factor correction is used. This scale factor is applied to simulated samples, which is derived from the ratio of the efficiency measurement in data and simulation: $\text{SF} = \epsilon_{\text{Data}}/\epsilon_{\text{MC}}$. Specialised scale factors are used to target specific mismodelling effects, with dedicated scale factors being applied to correct for the modelling the efficiencies for the selections in: object identification, isolation and trigger selections.

Examples of such use of scale factors is the correction of the top-quark p_T spectrum for $t\bar{t}$ events, which is measured to be softer in data than simulation due to the LO generation of $t\bar{t}$ events. To correct the p_T spectrum of $t\bar{t}$ events in simulation, scale factors which are dependent on the top and anti-top p_T are applied. Additionally, scale factor corrections are applied to b -jets and light jets to correct for the simulated tagging efficiency of b -jets, which are dependent on the flavour, p_T and pseudorapidity of the jet.

8.1.3.2 Pileup reweighting

In the generation of simulated samples, a nominal Poisson pileup profile with an average pileup of 20 is utilised for the simulation of both in-time and out-of-time pileup. To

ensure the simulated profile of pileup in simulation matches that recorded in data, simulated events are reweighted such that their pileup distributions are in agreement with that recorded in data. The pileup reweighting procedure uses the pileup profiles from a simulated minimum bias QCD sample and a zerobias data sample to derive pileup-dependent correction factors. The effect of this correction applied to simulated samples is shown in Figure 8.2. This shows that the distribution of the number of reconstructed vertices in simulation prior to the correction are peaked at a higher pileup multiplicity than data which, after the correction, is brought into agreement with the observed distribution in data.

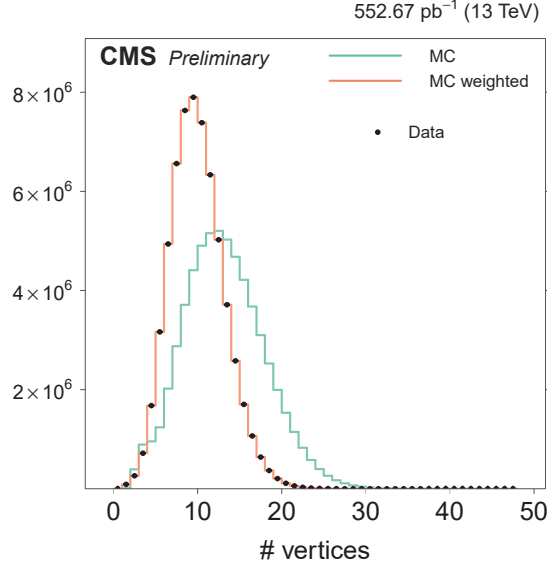


Figure 8.2: Number of reconstructed vertices measured in a zerobias data samples (points) and a minbias MC sample prior to pileup reweighting (green line) and after pileup reweighting (red line).

8.1.3.3 Trigger selection

Inefficiencies in the trigger selection of events in the signal and control regions are compensated for by trigger-dependent corrections. Simulated samples in the muon control regions are corrected by directly emulating the muon trigger selection in simulation, with scale factors applied to correct for residual differences in trigger efficiency between data and simulation. In the signal region, the efficiency of signal triggers are measured in data to provide H_T and $\cancel{H}_T$ -dependent correction factors which are applied to simulated samples.

Finally, in the photon control region the photon trigger selection is measured to be fully efficient with respect to offline selections and therefore no correction is applied.

8.1.3.4 Sideband corrections

Due to uncertainty in the cross section and luminosity of samples, a correction to the normalisation of simulated samples are performed by sideband corrections. These are data-driven corrections to normalisation determined from a comparison of predicted and measured yields in analysis sidebands.

As the cross section of the $\gamma + \text{jets}$ MC sample is only known to LO, a data-driven correction is required for determining the respective k -factor correction. This correction to the cross section is determined by performing a data-driven measurement in α_T sidebands in the single photon control region. For this purpose the kinematic region $H_T < 400 \text{ GeV}$ uses the sideband: $0.5 < \alpha_T < 0.52$ and the region $H_T > 400 \text{ GeV}$ uses the sideband $0.5 < \alpha_T < 0.53$. The correction is taken as the ratio of predicted events in the region, corrected for the QCD multijet background, and the measurement in data. From this procedure a correction of: 1.25 ± 0.05 is obtained, where the error is purely statistical. This in agreement with statistical precision of similar measurements in H_T and $H_T/\cancel{H}_T$ sidebands.

Additional background-specific corrections are derived from data samples that are W , Z and $t\bar{t}$ enriched, as described by the selections in Table 8.2. The yields of these samples in an $\cancel{H}_T$ sideband, $100 < \cancel{H}_T < 130 \text{ GeV}$, are compared with predicted yields from the $t\bar{t} + \text{jets}$, $W + \text{jets}$ and $Z + \text{jets}$ samples. An additional cross-check of these corrections in the $\cancel{H}_T/\cancel{E}_T > 1.25$ sideband is shown to be statistically compatible within uncertainties. A summary of the sideband corrections used in the analysis are presented in Table 8.3.

Sample	Dataset	Selection	Purity
$t\bar{t}$	$\mu + \text{jets}$	$n_{\text{jet}} \geq 2, n_{\text{b}} \geq 2$	84%
W	$\mu + \text{jets}$	$n_{\text{jet}} \leq 3, n_{\text{b}} = 0$	93%
Z	$\mu\mu + \text{jets}$	$n_{\text{b}} = 0$	87%

Table 8.2: Summary of selections for the enrichment of specific backgrounds in data and their purity measured in simulation.

Monte Carlo sample	Sideband correction
$\gamma + \text{jets}$	1.25 ± 0.10
$W + \text{jets}$	1.12 ± 0.03
$Z + \text{jets}$	1.08 ± 0.05
$t\bar{t} + \text{jets}$	0.86 ± 0.03

Table 8.3: Summary of the background-specific sideband corrections applied to MC samples.

8.2 Estimation of systematic uncertainties

There are several sources of systematic uncertainty in the analysis that arise as a result of uncertainties in the theoretical prediction and modelling of physics processes. An estimate of the magnitude of these systematic effects in the normalisation in each of the (H_T , n_{jet} , n_b) analysis bins are provided by the simulation-driven *variation method* and data-driven *closure test method*. Together, these methods are used to provide an estimate of the systematic uncertainty in the transfer factors for the prediction of the total $t\bar{t}$ - W background with the single muon control sample: $\mu + \text{jets} \rightarrow (t\bar{t} + W)$, and the in prediction of the $Z \rightarrow \nu\bar{\nu}$ background from the muon and photon control samples: $\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$, $\mu\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$, $\gamma + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$. The systematic uncertainty in the distribution of events in the missing hadronic energy dimension are estimated independently using the H_T *template uncertainty method*.

8.2.1 Variation method

The variation method seeks to estimate the systematic uncertainty in transfer factors by measuring the relative change in their magnitude, with upwards and downwards variations of the correction within its estimated 1σ uncertainty. The variation method is applied independently to each identified source of uncertainty, providing a fully correlated estimate of systematic uncertainty in each analysis bin. There are several main sources of uncertainty, which can be classified as pertaining to the reconstruction of: jets, leptons and event variables, which are described below:

- *Jet energy scale* – The uncertainty in the JEC is mitigated by identically binning the signal and control regions, which results in a cancellation of the JEC uncertainties when taking the ratio of yields in the transfer factor. Threshold effects however can conspire to migrate events between analysis bins and to alter the selection efficiency. These effects are measured in the $\mu + \text{jets}$, $\mu\mu + \text{jets}$ and $\gamma + \text{jets}$ control regions,

shown in Figures A4.1 - A4.2, where the variation applied is the JEC uncertainty as measured by the Jets and $\cancel{E}_T$ (JetMET) Physics Object Group (POG), which provides an estimate of a 1 – 15% systematic uncertainty in the magnitude of the transfer factor.

- *Heavy flavour jets* – There are several systematic uncertainties associated with jets from the decay of heavy flavour quarks. The uncertainty in the modelling of the: selection, reconstruction and mistag efficiency of jets arising from b -quarks is one such source of uncertainty. The magnitude of this uncertainty is estimated by a variation of the b -tag scale factors within their estimated uncertainty, which are measured to result in an uncertainty in the transfer factors in the range 1 – 5%, as shown in Figures A4.3 - A4.6. In addition, the top p_T correction applied to jets arising from t -quarks is another source of systematic error. For this correction a conservative 100% systematic is estimated, which is measured to produce an uncertainty of 0 – 15%, as shown in Figures A4.7 - A4.10.
- *Pileup* – The reweighting of the simulated pileup distribution to match that in data is reliant on the minimum bias cross section, which is estimated to have a 5% uncertainty. This results in a total variation in the transfer factor of 1 – 5%, as seen in Figures A4.11 - A4.14.
- *Leptons* – The predominant mechanism by which electroweak $t\bar{t}$ and W boson backgrounds enter the signal region is via leptonic decay, with the lepton failing reconstruction. This makes the estimate of the uncertainty in the modelling of lepton reconstruction important in the determination of transfer factors for the $t\bar{t} + W$ background. The uncertainty in the simulation of the lost-lepton background is estimated by simultaneously considering the efficiency of: trigger, identification and isolation selections of leptons.

To estimate the systematic of this background the variable y is utilised, which encodes the total uncertainty propagating to the transfer factors as a function of all the independent sources of uncertainties. y is constructed of the ratio of leptons passing a signal-like selection and control region selection by the relation:

$$y = \frac{\sum_{sample} \left[R_{sample} \times f_{sample} \times N_{sample}^{GEN} \times (1 - \epsilon_{Loose}) + (1 - f_{sample}) \times N_{sample}^{GEN} \right]}{\sum_{sample} N_{sample}^{GEN} \times \epsilon_{Tight} \times R_{sample}}.$$

Where f_{sample} , is a sample-dependent fraction of leptons outside of acceptance measured in simulation, R_{sample} is the cross section reweighting factor for the sample, N_{sample}^{GEN} is the total number of simulated events for the category and ϵ_{Loose} , ϵ_{Tight} are the efficiencies for the selection working points.

The systematic error in the determination of the muon trigger efficiency is measured by the muon POG to be $\sim 2\%$. A 1% systematic uncertainty is estimated for the muon veto and tight WPs selections and a 5% uncertainty for the electron veto working point, which are taken as fully correlated for all signal analysis bins. The uncertainties for each effect are added in quadrature for their respective variation. The total uncertainty in the transfer factor is measured independently for electron and muons to be typically 2 – 5%, as shown in Figure A4.15.

8.2.2 Closure test method

To complement estimates of the systematic uncertainties with variation method, the analysis uses data-driven closure tests to provide a robust estimation of systematic uncertainties. Closure tests are large ensembles of statistically independent tests that determine experimental uncertainties by measuring the agreement of predicted yields using transfer factors, N_{pred} , with the observed yields in data control regions, N_{obs} . The compatibility of predictions are measured by the ratio: $(N_{obs} - N_{pred}) / N_{pred}$, which in the case of perfect agreement will produce a distribution centred on zero, with modelling biases resulting in a displacement of the mean of the distribution. The degree of closure from the statistical compatibility of the ratio with the hypothesis of unity enables a probe of the accuracy of the modelling of specific effects, providing both an estimate of systematic uncertainty and a method to identify modelling bias.

The uncertainty in transfer factors are estimated in bins of H_T , inclusive of n_b , from the quadrature sum of the measure of closure in bins of jet multiplicity, collapsed into symmetric and asymmetric categories. A more coarse H_T binning is utilised for the $\mu\mu +$ jets control region to compensate for reduced statistical power. The resultant systematic estimates are treated as uncorrelated in hadronic energy and jet multiplicity.

There are several sources of potential mismodelling that are probed by closure tests, including the modelling of analysis variables and fractional background compositions, which are described below:

- *Modelling of α_T and $\Delta\phi_{\min}^*$* – An important test is to ensure the correct modelling of events in the α_T and $\Delta\phi_{\min}^*$ dimension between data and simulation. This is tested by using events from the core of the respective distributions, with inverted requirements on α_T and $\Delta\phi_{\min}^*$, to predict events in the tails where the requirement is applied. The inversion of the α_T and $\Delta\phi_{\min}^*$ variables are performed independently in a $\mu + \text{jets}$ sample, to provide an estimate for the systematic uncertainty of hadronic energies $200 < H_T < 800 \text{ GeV}$ and $H_T > 800 \text{ GeV}$ respectively. Shown in Figure A4.16, by this method the systematic uncertainty in the modelling of these parameters is estimated to be 5 – 80%.
- *Modelling of the W/Z ratio* – Validating the modelling of the ratio of W and Z bosons in simulation, with measurements in data, are important in the use of the $\mu + \text{jets}$ and $\mu\mu + \text{jets}$ data control regions for background predictions, which are respectively dominated by the $t\bar{t} + W + \text{jets}$ and $Z + \text{jets}$ processes. To ascertain the accuracy of this modelling, events in the W -enriched $\mu + \text{jets}$ control region are used to predict yields in the Z -enriched $\mu\mu + \text{jets}$ control region. Shown in Figure A4.17, from these tests the systematic uncertainty in the modelling of the W/Z ratio is measured to be 10 – 30%.
- *Modelling of the Z/γ ratio and acceptance* – For the $\gamma + \text{jets}$ control region to be used effectively in the prediction of the $Z \rightarrow \nu\bar{\nu}$ background, corrections for the relative Z/γ production ratio and acceptance are applied. To validate these corrections, the events in the $\gamma + \text{jets}$ control sample are used to predict yields in the Z -enriched $\mu\mu + \text{jets}$ control region, which shown in Figure A4.18, are estimated to have associated systematic uncertainties of 10 – 30%.
- *Modelling of the $W/t\bar{t}$ background composition admixture* – The prediction of the $t\bar{t}$ background is performed by the W -enriched $\mu + \text{jets}$ control region. To validate the modelling of the relative composition of the W and $t\bar{t}$ backgrounds, selections are applied to the $\mu + \text{jets}$ control region to obtain a light flavour enriched region ($n_b = 0$), which is used to predict the yields in a heavy flavour enriched region. The closure tests for this validation is shown in Figure A4.19, which is shown to give an estimate of the systematic uncertainty of 10 – 100%.
- *W/Z acceptance as a consequence of polarisation* – W bosons produced under large boost in pp -collisions are predominantly produced in a left-handed state [132]. In leptonic decays of W^+ bosons, the neutrino and anti-lepton are produced with and

against the boost of the W boson respectively. This results in an enhancement and suppression of their respective transverse momenta, with the converse being true for decays of W^- bosons. As a result there is a lepton p_T asymmetry, with leptons produced in decays of W^+ bosons having lower p_T than those produced in W^- decays, which consequently affects their reconstruction efficiency. To validate the modelling of this asymmetry in acceptance from polarisation effects in the simulation, yields in a W^+ boson enriched sample are used to predict yields in an W^- enriched sample. For this purpose, a closure test is performed for the prediction of yields in the $\mu + \text{jets}$ control region with a μ^+ selection using a μ^- selection which, shown in Figure A4.20, provides an estimate of systematic uncertainty of 5 – 50%.

8.2.3 Systematics summary

A summary of the methods and tests performed in the estimation of systematic uncertainties in the analysis, along with their representative values, are presented in Table 8.4 and Table 8.5.

Systematic	Relative uncertainty on transfer factor			
	$\mu + \text{jets}$ ($Z \rightarrow \nu\bar{\nu}$)	$\mu\mu + \text{jets}$ ($Z \rightarrow \nu\bar{\nu}$)	$\gamma + \text{jets}$ ($Z \rightarrow \nu\bar{\nu}$)	$\mu + \text{jets}$ ($t\bar{t} + W$)
Jet energy scale	< 15%	< 10%	< 15%	< 15%
b -tagging efficiency	< 5%	< 2%	< 2%	< 5%
Pileup weights	< 6%	< 4%	< 3%	< 10%
Top p_T weights	< 20%	< 4%	-	< 5%
Lepton selection	-	-	-	2 – 5%

Table 8.4: Summary of the systematic uncertainties of transfer factors determined by the variation method with representative ranges of uncertainties for the predictions of the $t\bar{t}$, W and $Z \rightarrow \nu\bar{\nu}$ background components.

8.2.4 $\cancel{H}_T$ systematics

In addition to an estimate of the systematic uncertainty in the normalisation of yields in the analysis (H_T , n_{jet} , n_b) bins, the uncertainty of the modelling of their distribution in the $\cancel{H}_T$ -dimension is also considered. For this purpose the data-driven closure test method is utilised, with the level of closure of these tests used to create alternative $\cancel{H}_T$ templates to cover the measured systematic differences.

Systematic	Relative uncertainty on transfer factor			
	$\mu + \text{jets}$ ($Z \rightarrow \nu\bar{\nu}$)	$\mu\mu + \text{jets}$ ($Z \rightarrow \nu\bar{\nu}$)	$\gamma + \text{jets}$ ($Z \rightarrow \nu\bar{\nu}$)	$\mu + \text{jets}$ ($t\bar{t} + W$)
$\alpha_T/\Delta\phi_{\min}^*$ extrapolation	5 – 80%	50 – 80%	-	5 – 80%
W/Z ratio	10 – 30%	-	-	-
Z/γ ratio	-	-	10 – 30%	-
$W/t\bar{t}$ admixture	-	-	-	10 – 100%
W polarisation	5 – 50%	-	-	5 – 50%

Table 8.5: Summary of the systematic uncertainties of transfer factors determined by the closure test method with representative ranges of uncertainties for the predictions of the $t\bar{t}$, W and $Z \rightarrow \nu\bar{\nu}$ background components.

The agreement of the data-simulation ratio of $\mathcal{H}_T$ is parameterised by orthogonal polynomials, which described are the relation:

$$f_n(x) = \sum_{k=0}^n (p_k) \cdot (\bar{x} - x)^k, \quad (8.1)$$

where $\bar{x}$ is the weighted mean of the distribution and p_k are constants. An estimate of the uncertainties for the backgrounds are performed using a combined linear fit of the predictions in all pertinent control regions, where a requirement of $\mathcal{H}_T > 130 \text{ GeV}$ is applied to ensure they are kinematically similar to the signal region. The systematic uncertainty in $\mathcal{H}_T$ is measured from the deviation in closure from the hypothesis of no bias, where the uncertainty on the linear parameter obtained from the fit is used to define the $\pm\sigma$ variation of the nominal template.

Backgrounds events for a given value of $\mathcal{H}_T$ can arise from a range of different effects, leading to uncertainties in the background composition. To mitigate this uncertainty, projections are performed at a chosen H_T scale, ensuring all events of are kinematically similar for a given $\mathcal{H}_T$. In order to ascertain there is no deviation from a flat hypothesis, the pull of the distributions, normalised by their error, are measured in the control regions. As shown in Appendix 5, these distributions show no significant deviation from the flat hypothesis.

The $\mathcal{H}_T$ template closure method is chosen to provide a conservative estimate of the total uncertainty, this is validated by a comparison of the computation of systematic uncertainties through the variation method. Figure 8.3 shows a comparison of the measured systematic uncertainty from the $\mathcal{H}_T$ shape method with the measurement obtained

through $\pm 1\sigma$ variations for the sources of uncertainty in Section 8.2.1. The systematic estimate from the MC based systematic variations are shown to be fully covered by the closure test method. Additional validation is performed in data control regions by the comparison of the predicted systematic uncertainty from a linear extrapolation in $\cancel{H}_T$ with the observed systematic uncertainty. Shown in Figure 8.4, the expected systematic uncertainties for the $t\bar{t} + W + \text{jets}$ and $Z + \text{jets}$ backgrounds are consistent with observed uncertainties in the data control regions.

8 Corrections and systematic uncertainties

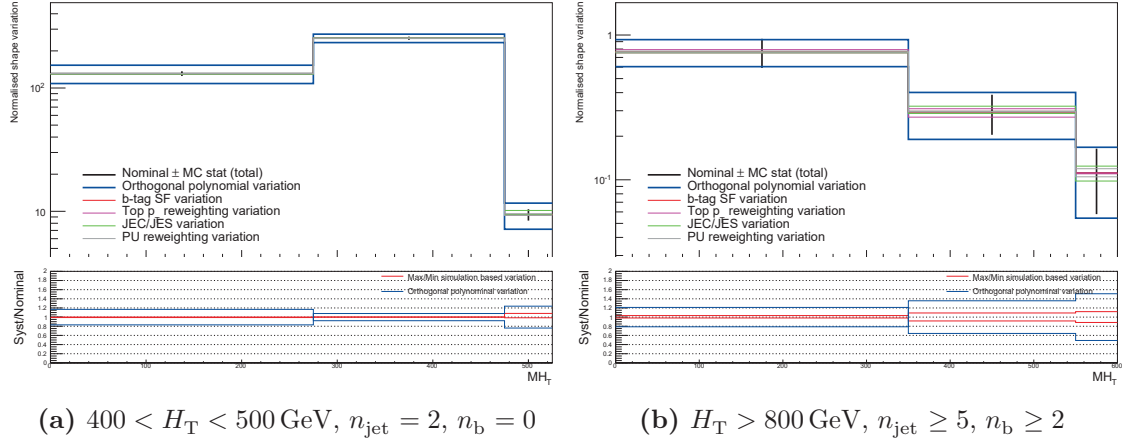


Figure 8.3: Measured systematic uncertainty as a function of H_T for representative low (left) and high (right) hadronic energies and jet multiplicities measured with the data-driven orthogonal polynomial systematic method (blue). The total statistical error (black) is compared with the systematic uncertainty measured through the variation method accounting for uncertainties in the modelling of: b -tagging efficiency (red), top p_T reweighting (magenta), jet energy scale (green) and pileup reweighting (grey).

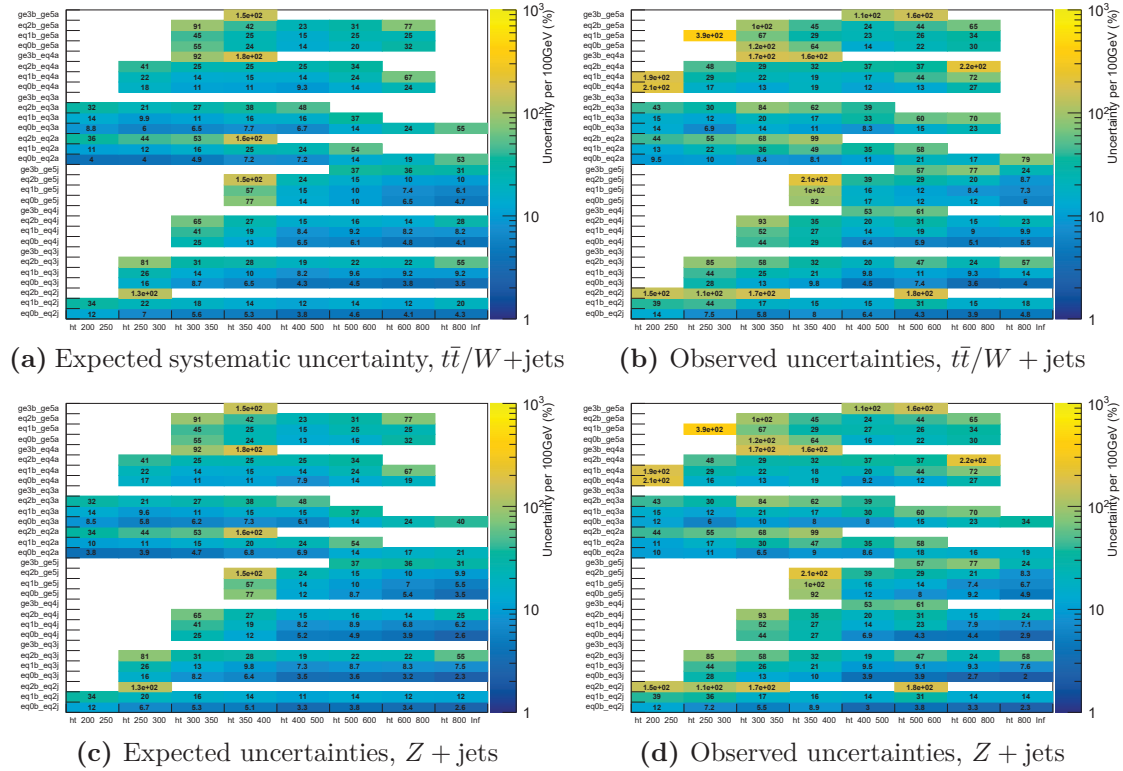


Figure 8.4: Expected (left) and observed (right) relative systematic uncertainties per 100 GeV for the $t\bar{t}/W + \text{jets}$ (top) and $Z + \text{jets}$ (bottom) backgrounds in data control regions.

Results and interpretation

During the 25 ns operation in 2015, a dataset with a total integrated luminosity of 2.3 fb^{-1} was collected and analysed. *Likelihood models* of the compatibility of the results with SM background are constructed and the results interpreted in the context of a range of simplified models.

9.1 Likelihood model

In the interpretation of results, likelihood models for analysis measurements in the signal and control regions are constructed. Events are categorised by their respective $(H_T, n_{\text{jet}}, n_b)$ analysis bin, labelled H_T^{cat} , with an additional index i used in the signal region to represent the corresponding $\cancel{H}_T$ bin. The likelihood function in the hadronic signal region, for each H_T^{cat} and $\cancel{H}_T$ bin, are given as the product of the Poisson distributions of the: observed number events, $n_{\text{had}_i}^{H_T^{\text{cat}}}$, predicted number of background events, $b_{\text{had}_i}^{H_T^{\text{cat}}}$, and predicted number of signal events, $s_{\text{had}_i}^{H_T^{\text{cat}}}$:

$$\mathcal{L}_{\text{had}}^{H_T^{\text{cat}}} = \prod_i \text{Pois} \left(n_{\text{had}_i}^{H_T^{\text{cat}}} | b_{\text{had}_i}^{H_T^{\text{cat}}} + s_{\text{had}_i}^{H_T^{\text{cat}}} \right). \quad (9.1)$$

Likelihood functions are constructed independently for each control region, indexed by j , given the: observed number of events, $n_{\text{CR}_j}^{H_T^{\text{cat}}}$, predicted number of background events, $b_{\text{CR}_j}^{H_T^{\text{cat}}}$, and predicted number of signal events, $s_{\text{CR}_j}^{H_T^{\text{cat}}}$, inclusively in the $\cancel{H}_T$ -dimension:

$$\mathcal{L}_{\text{CR}_j}^{H_T^{\text{cat}}} = \text{Pois} \left(n_{\text{CR}_j}^{H_T^{\text{cat}}} | b_{\text{CR}_j}^{H_T^{\text{cat}}} + s_{\text{CR}_j}^{H_T^{\text{cat}}} \right). \quad (9.2)$$

The total likelihood is constructed from the product of the individual likelihoods over all the H_T^{cat} bins and control regions by the relation:

$$\mathcal{L} = \prod_{H_T^{\text{cat}}} \mathcal{L}_{\text{had}}^{H_T^{\text{cat}}} \times \prod_j \mathcal{L}_{\text{CR}_j}^{H_T^{\text{cat}}}. \quad (9.3)$$

9.1.1 Systematic effects

As the prediction of the background yield in the signal and control regions are connected via transfer factors, a floating parameter is utilised to correlate the expected $Z \rightarrow \nu\bar{\nu}$ and combined $t\bar{t}/W$ background yields between the signal and control regions. Systematic uncertainties in the determination of transfer factors are incorporated in the likelihood through Gaussian nuisance parameters, which act upon the floating parameter. Independent uncertainties are calculated for each of the backgrounds and control regions, which are treated as uncorrelated between each of the H_T^{cat} bins. Additional systematic effects are incorporated through shape uncertainties on the transfer factors that are treated as completely correlated across all bins.

The uncertainties in the product of the signal efficiency and acceptance are taken as shape uncertainties correlated across all H_T^{cat} bins. The uncertainty in the migration of events between bins in the $\cancel{H}_T$ dimension is accounted for by providing alternative templates, corresponding to $\pm\sigma$ variations of each source of uncertainty, which are computed separately for each H_T^{cat} bin. The uncertainty due to the limited statistical power of the MC samples used to populate the template histograms is incorporated as additional nuisance parameters, one per template bin, taken as uncorrelated across all histogram bins.

9.1.2 Fitting

In performing the fit on the likelihood, a two stage approach is taken. First the predicted background yield in the signal region, $b_{\text{had}_i}^{H_T^{\text{cat}}}$, is determined from a control region only likelihood fit as described in Equation 9.2. Following this, a fit using the full likelihood of Equation 9.3 is performed, in which all background correlations in the control regions and signal region are applied. The likelihood is then profiled against all nuisance parameters, to derive the expected exclusion limits and sensitivities shown in Section 9.2.

Due to the increasing computational complexity in fitting with additional categories, only the four jet categories with the highest expected exclusion are utilised in the derivation of exclusion limits, considering all the H_T , n_b and $\cancel{H}_T$ bins within each n_{jet} category. This however does not severely affect the strength of the final limit, as seen in Table 9.2, with the majority of limits being consistent in cases which only consider the top four jet categories and those that consider all jet categories.

9.2 Signal model interpretation

The observed event yields are interpreted in the context of simplified supersymmetric models, which cover a range of: production modes, decay modes and mass spectra. The simplified models considered in this interpretation include the pair production of gluinos, *T1 models*, and the pair production of squarks, *T2 models*, illustrated in the Feynman diagrams of Figure 9.1–9.2. These models may be categorised by their production mechanisms as described below:

- Gluino-mediated production of off mass shell third-generation squarks, with subsequent decays to heavy quarks (T1bbbb, T1tttt, T1ttbb).
- Gluino-mediated and direct production of off mass shell light-flavour squarks, with subsequent decays to light quarks (T1qqqq, T2qq).
- Direct production of third-generation squarks with subsequent decays to heavy quarks (T2tt, T2bb) and kinematically constrained decays where the mass splitting between the stop and LSP is smaller than the W boson mass ($\Delta m = M_{\tilde{t}} - M_{\tilde{\chi}^0} < M_W$) (T2cc).

To characterise the reach of the analysis, a range of benchmark model mass points are selected which encompass both compressed spectra and large mass splittings in regions of mass space beyond the exclusions of Run 1. Summarised in Table 9.1, these benchmark points provide a metric of the sensitivity of the analysis for a range of signal topologies.

Model	Production mode	Decay mode	CMS Run 1 exclusion	Benchmark points ($m_{\text{SUSY}}, m_{\text{LSP}}$)	
				Compressed	Uncompressed
T1tttt	$pp \rightarrow \tilde{g}\tilde{g}^*$	$\tilde{g} \rightarrow \tilde{t}t\chi^0$	$m_{\text{Gluino}} \gtrsim 1320 \text{ GeV}$	(800, 400)	(1300, 100)
T1ttbb	$pp \rightarrow \tilde{g}\tilde{g}^*$	$\tilde{g} \rightarrow \tilde{t}b\chi^\pm, \chi^\pm \rightarrow W^\pm\chi^0$ $\Delta M(\chi^\pm, \chi^0) = 5 \text{ GeV}$	–	(1000, 700)	(1300, 100)
T1bbbb	$pp \rightarrow \tilde{g}\tilde{g}^*$	$\tilde{g} \rightarrow \tilde{b}b\chi^0$	$m_{\text{Gluino}} \gtrsim 1350 \text{ GeV}$	(100, 800)	(1500, 100)
T1qqqq	$pp \rightarrow \tilde{g}\tilde{g}^*$	$\tilde{g} \rightarrow \tilde{q}q\chi^0$	$m_{\text{Gluino}} \gtrsim 1320 \text{ GeV}$	(900, 700)	(1300, 100)
T2tt	$pp \rightarrow \tilde{t}\tilde{t}^*$	$\tilde{t} \rightarrow t\chi^0$	$m_{\text{Stop}} \gtrsim 760 \text{ GeV}$	(350, 100)	(700, 50)
T2bb	$pp \rightarrow \tilde{b}\tilde{b}^*$	$\tilde{b} \rightarrow b\chi^0$	$m_{\text{Sbottom}} \gtrsim 750 \text{ GeV}$	(375, 300)	(800, 50)
T2cc	$pp \rightarrow \tilde{t}\tilde{t}^*$	$\tilde{t} \rightarrow c\chi^0$	$m_{\text{Stop}} \gtrsim 250 \text{ GeV}$	(325, 305)	–
T2qq	$pp \rightarrow \tilde{q}\tilde{q}^*$	$\tilde{q} \rightarrow q\chi^0$	$m_{\text{Stop}} \gtrsim 975 \text{ GeV}$	(500, 400)	(800, 50)

Table 9.1: A summary of the simplified models considered in the interpretation of results, including the best exclusion limits from CMS Run 1 searches and sample benchmark mass points for both compressed and uncompressed mass splittings. In models with squark-pair production with decays to light squarks, both a 1-fold and 8-fold squark mass degeneracy are considered [64].

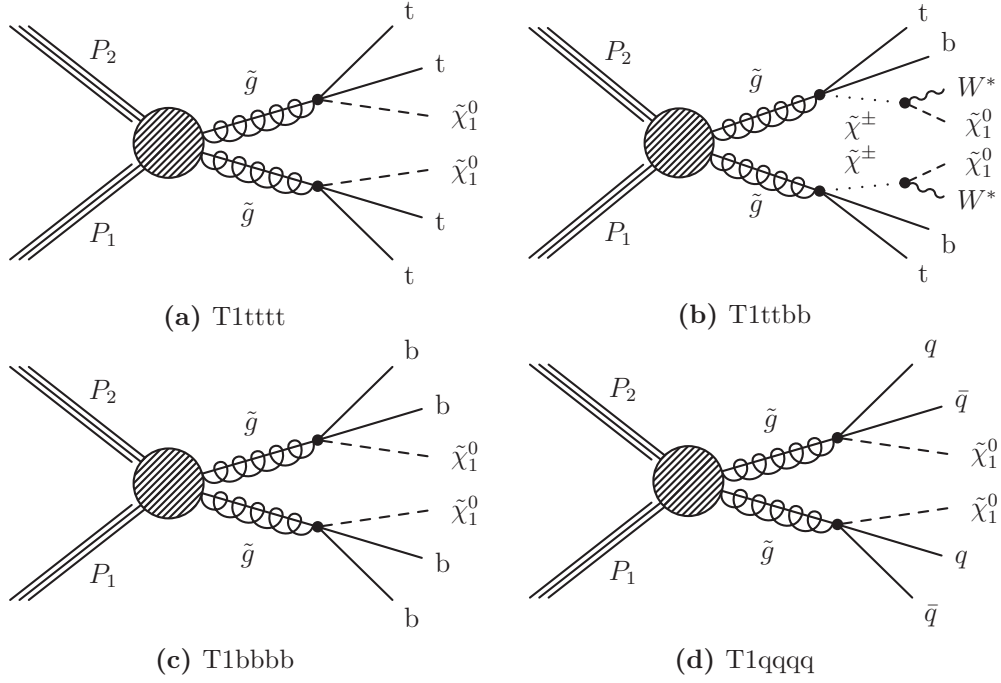


Figure 9.1: Feynman diagrams of gluino pair produced T1 models with subsequent decays to squarks.

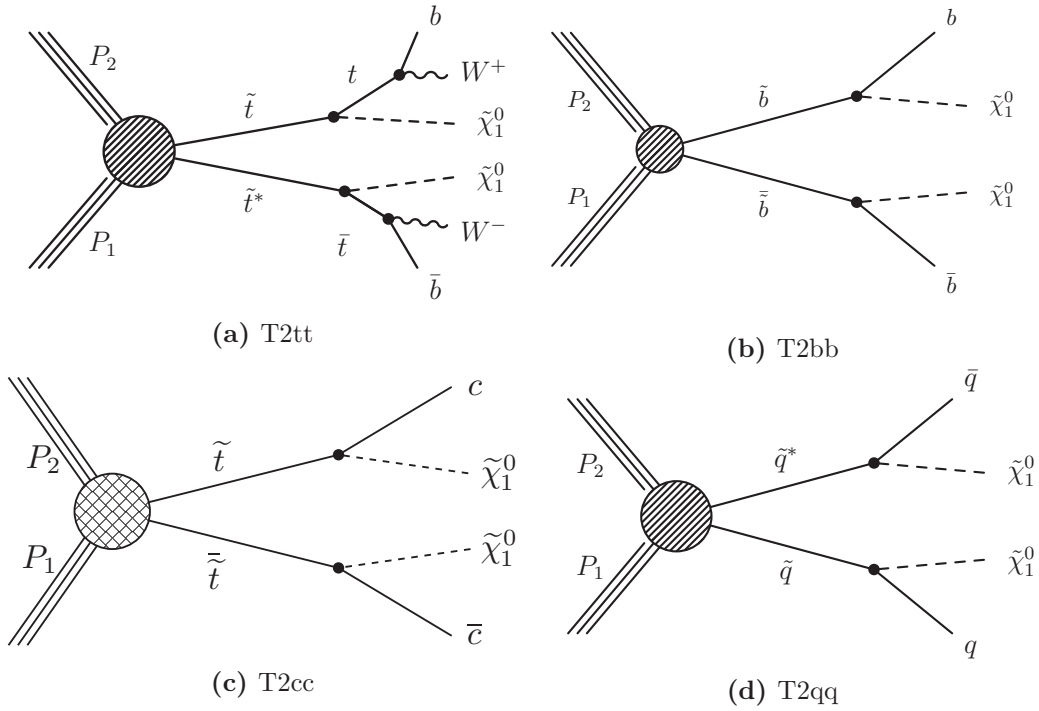


Figure 9.2: Feynman diagrams of squark pair produced T2 models with subsequent decays to squarks.

9.2.1 Signal model efficiencies

An important characterisation of the analysis is the measurement of the selection efficiency of signal models in the signal region, *signal acceptance*, and in the control regions, *signal contamination*.

The measured efficiency for the reference signal model benchmark points for all categories and the four most sensitive categories are shown in Table 9.2. The sensitivity for signal models with large mass-splittings is almost exclusively driven by the highest jet multiplicity symmetric category, leading to near fully efficiency with a selection of the four most sensitive categories. Compressed models typically possess lower jet multiplicities however, due to a larger background component at lower jet multiplicities, are also driven by higher multiplicity jet categories. This diffusion of sensitivity across jet multiplicities for compressed signal models therefore leads to a reduction in efficiency when only the four most sensitive categories are considered. A complete summary of the acceptance of signal models across the $m_{\text{SUSY}} - m_{\text{LSP}}$ mass plane are presented in Appendix 6.

Model	$(m_{\text{SUSY}}, m_{\text{LSP}})$	Efficiency (4 best cat.)	Efficiency (total)	Cat. used for limits
T1tttt	(1300,100)	2.4%	2.4%	$\geq 5j, \geq 5a, 4j, 3j$
	(800,400)	0.6%	0.6%	$\geq 5j, \geq 5a, 4j, 4a$
T1ttbb	(1300,100)	3.8%	3.8%	$\geq 5j, 4j, 3j, \geq 5a$
	(1000,700)	3.4%	4.0%	$\geq 5j, \geq 5a, 4j, 3j$
T1bbbb	(1500,100)	10.1%	10.1%	$\geq 5j, 4j, 3j, 2j$
	(1000,800)	4.9%	7.5%	$\geq 5j, 4j, \geq 5a, 4a$
T1qqqq	(1300,100)	9.4%	9.4%	$\geq 5j, 4j, 3j, 2j$
	(900,700)	5.6%	8.2%	$\geq 5j, \geq 5a, 4j, 4a$
T2tt	(700,50)	8.1%	8.8%	$\geq 5j, 4j, 3j, \geq 5a$
	(350,100)	1.4%	1.9%	$\geq 5j, \geq 5a, 4a, 4j$
T2bb	(800,50)	1.5%	1.6%	$2j, 3j, 4j, \geq 5j$
	(375,300)	0.1%	0.2%	$\geq 5j, 4j, 3a, 3j$
T2cc	(325,305)	0.8%	2.4%	$\geq 5j, 4j, 3j, 2j$
T2qq	(1050,100)	17.9%	18.5%	$\geq 5j, 3j, 2j, 4j$
	(650,550)	2.6%	5.0%	$\geq 5j, 4j, \geq 5a, 4a$

Table 9.2: Signal efficiency utilising all and the top four most excluding jet multiplicity categories for compressed and uncompressed benchmark simplified models.

The contamination from the fully hadronic signal signature in the control regions is strongly suppressed by the requirement of well reconstructed muons and photons. Muons arising from the leptonic decay of heavy quarks, produced in the decay of supersymmetric particles, are further reduced by additional kinematic selections designed to enrich selections of weak vector bosons. The degree of signal contamination is characterised by the

ratio of the sensitivity (the ratio of the expected signal, S , and background, B , yields) in the control region, $S_{\text{CR}}/B_{\text{CR}}$, with that in the signal region, $S_{\text{SR}}/B_{\text{SR}}$. As the selections in the control and signal regions are chosen to be signal-depleted and signal-enriched respectively, the ratio of these sensitivities, $(S_{\text{CR}}/B_{\text{CR}})/(S_{\text{SR}}/B_{\text{SR}})$, is expected to be small.

The signal contamination is heavily suppressed in the $\mu\mu + \text{jets}$ control region due to the tight requirements on the muon pair and is measured to be negligible in the $\gamma + \text{jets}$ control region. There is a measured contamination in the $\mu + \text{jets}$ control region, predominantly in the T1tttt and T2tt signal models which produce top quarks that subsequently decay semi-leptonically. This is particularly enhanced where the mass splitting is comparable to the mass of the top quark ($m_{\text{SUSY}} - m_{\text{LSP}} \sim m_t$), which provides a topological signature similar to $t\bar{t}$ production. The signal contamination across the analysis bins for models with a mass splitting compatible with the top mass are shown in Figure 9.3. Due to the absence of an α_T selection in the control region, the signal yields in the control region for low jet multiplicities are of a similar magnitude to the expected yield in the signal region. The measured signal contamination in the control regions are incorporated into the likelihood model in the interpretation of results.

9.2 Signal model interpretation

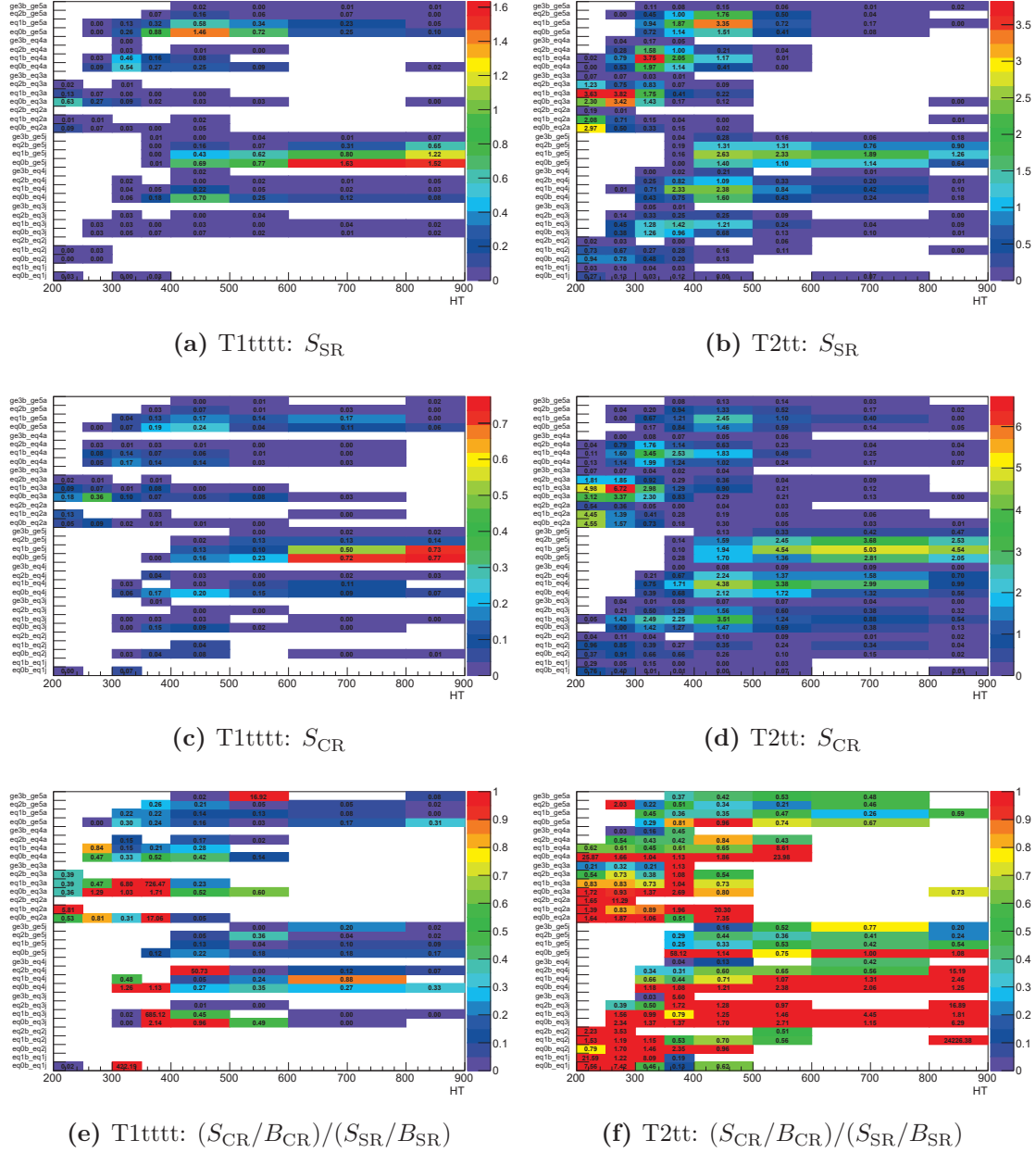


Figure 9.3: Distribution of the signal yield in the signal region S_{SR} (top), signal yield in the $\mu + \text{jets}$ control region S_{CR} (middle) and the ratio of signal significance in $\mu + \text{jets}$ control region to that in signal region $(S_{CR}/B_{CR})/(S_{SR}/B_{SR})$ (bottom), for the T1tttt(800, 575) (left) and T2tt(250,50) (right) simplified models.

9.2.2 Uncertainties in signal model efficiencies

In the same manner as with the SM backgrounds, the following systematic uncertainties for the prediction and correction of the signal yield are utilised:

- A 4.6 % systematic uncertainty is taken on the measurement of the total integrated luminosity, which is treated as correlated across all bins.
- A conservative systematic uncertainty on the trigger efficiency is taken as the magnitude of the trigger inefficiency of the analysis bin.
- A 5% uncertainty is assigned to pileup reweighting procedure as a result of the uncertainty in the minimum bias cross section.
- A 15% and 30% uncertainty are taken for the modelling of ISR for a gluino-gluino system produced with $400 < p_T < 600$ GeV and $p_T > 600$ GeV respectively.
- Uncertainties in the lepton reconstruction efficiency, b-tagging efficiency and JEC are fully propagated and treated as correlated across the analysis bins.

Representative values for range of relative systematic uncertainties for the selection of benchmark models are shown in Table 9.3.

Model	$(m_{\text{SUSY}}, m_{\text{LSP}})$	Luminosity	Trigger	MC statistical	Pileup	ISR	b -tag	JEC
T1tttt	(1300, 100)	4.6%	1-3%	7-16%	1-4%	1-2%	2-12%	2-7%
	(800, 400)	4.6%	1-10%	7-27%	1-13%	1-2%	1-8%	3-45%
T1ttbb	(1300, 100)	4.6%	1-4%	9-32%	1-18%	1-2%	2-19%	3-16%
	(1000, 700)	4.6%	1-14%	9-30%	1-12%	1-9%	1-14%	3-65%
T1bbbb	(1500, 100)	4.6%	1-3%	5-17%	1-4%	1-2%	2-22%	1-12%
	(1000, 800)	4.6%	1-15%	8-31%	1-20%	1-17%	1-14%	1-40%
T1qqqq	(1300, 100)	4.6%	1-3%	7-30%	1-5%	2-2%	2-14%	4-21%
	(900, 700)	4.6%	5-13%	10-33%	1-9%	1-13%	1-10%	1-26%
T2tt	(700, 50)	4.6%	2-11%	8-33%	1-13%	1-4%	1-21%	2-22%
	(350, 100)	4.6%	5-9%	7-31%	1-10%	1-1%	1-7%	1-28%
T2bb	(800, 50)	4.6%	2-12%	5-31%	1-16%	2-6%	1-23%	1-21%
	(375, 300)	4.6%	3-3%	8-33%	1-11%	1-10%	1-7%	3-25%
T2cc	(325, 305)	4.6%	5-16%	3-32%	1-26%	1-27%	1-12%	1-27%
T2qq	(1050, 100)	4.6%	1-6%	7-33%	1-10%	2-5%	1-11%	3-16%
	(650, 550)	4.6%	3-12%	10-28%	1-15%	3-9%	1-6%	2-28%

Table 9.3: Range of the measured relative uncertainties for each of the systematic sources for a selection of benchmark simplified models.

9.3 Results

A blind analysis is performed on the complete data sample in the 2015 25 ns data run, from which a total integrated luminosity of 2.3 fb^{-1} was collected. A prediction of the total background yields in each of the $(H_T, n_{\text{jet}}, n_b)$ analysis bins are obtained from a fit of corrected simulated samples with yields in data control regions, excluding the signal region. The uncertainty in this prediction is obtained from the quadrature sum of the statistical and the pre-fit systematic errors for each analysis bin. The nuisance parameters for the fit, shown in Appendix 7, show no significant pulls post-fit for any of the observed parameters. The modelling of the key analysis variables in the signal region are verified by a comparison of their simulated and observed distributions which, shown in Appendix 8, are in good agreement.

A comparison of the observed event yields and the predicted background yields, both pre-fit and post-fit, in the signal region for each of the $(H_T, n_{\text{jet}}, n_b)$ analysis bin in the monojet, symmetric and asymmetric jet categories are shown in Figures 9.4–9.6. The background yields, shown as a decomposition of their constituent processes, are shown in addition to the expected event yields of selected benchmark signal models. A comprehensive summary of the predicted and observed yields in the signal region for all three jet categories are summarised in Appendix 9.

Across the majority of the analysis signal bins the observed yields are compatible with the SM prediction, with the exception of bins of high H_T , n_{jet} and n_b for symmetric categories, where excesses in the observed event yields are seen. The observed and predicted distribution of events in the H_T dimension of the background and some benchmark signals in these analysis bins is shown in Figure 9.7. There is shown to be good shape agreement for high jet multiplicity symmetric categories, both for events with high hadronic energy and low b -jet multiplicity ($H_T > 800 \text{ GeV}$, $n_{\text{jet}} \geq 5$, $n_b = 1$) and moderate hadronic energy and high b -jet multiplicity ($600 < H_T < 800 \text{ GeV}$, $n_{\text{jet}} \geq 5$, $n_b \geq 3$). For extreme jet multiplicities and hadronic energies however there is an observed excess, predominantly in the analysis bins ($H_T > 800$, $n_{\text{jet}} \geq 5$, $n_b = 2$) and ($H_T > 800$, $n_{\text{jet}} \geq 5$, $n_b \geq 3$).

The results of this search are interpreted in the context of simplified models.

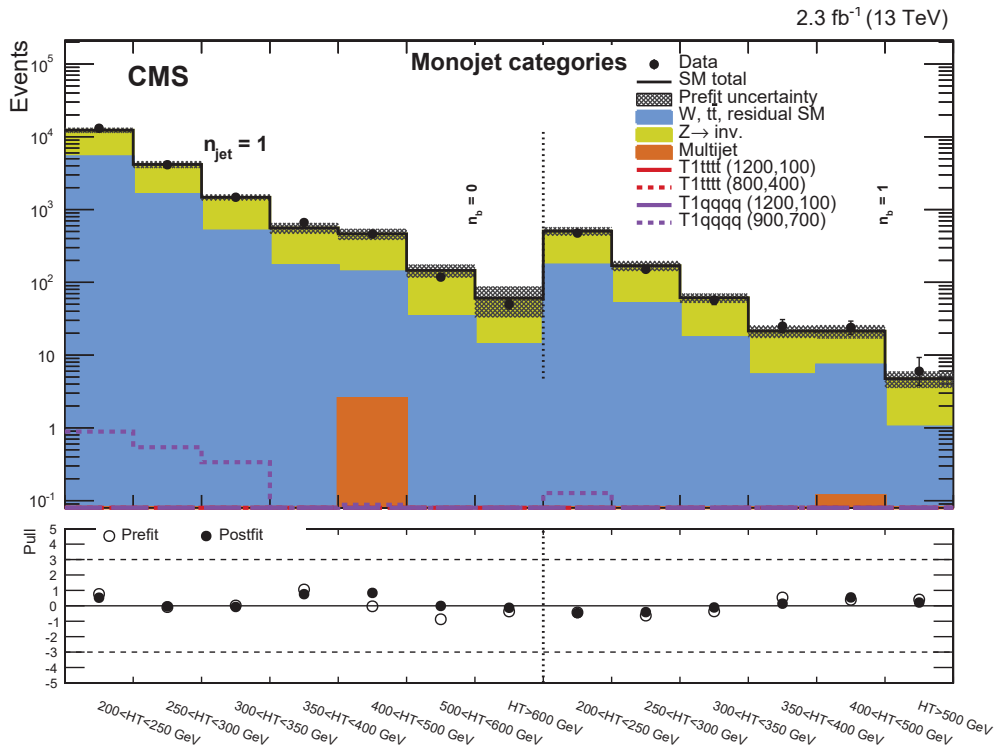
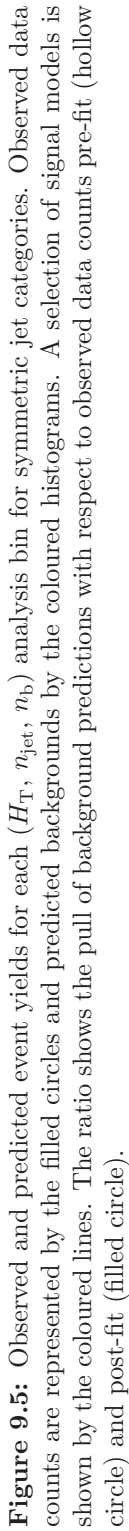


Figure 9.4: Observed and predicted event yields for each $(H_T, n_{\text{jet}}, n_b)$ analysis bin for monojet jet categories. Observed data counts are represented by the filled circles and predicted backgrounds by the coloured histograms. A selection of signal models is shown by the coloured lines. The ratio shows the pull of background predictions with respect to observed data counts pre-fit (hollow circle) and post-fit (filled circle).



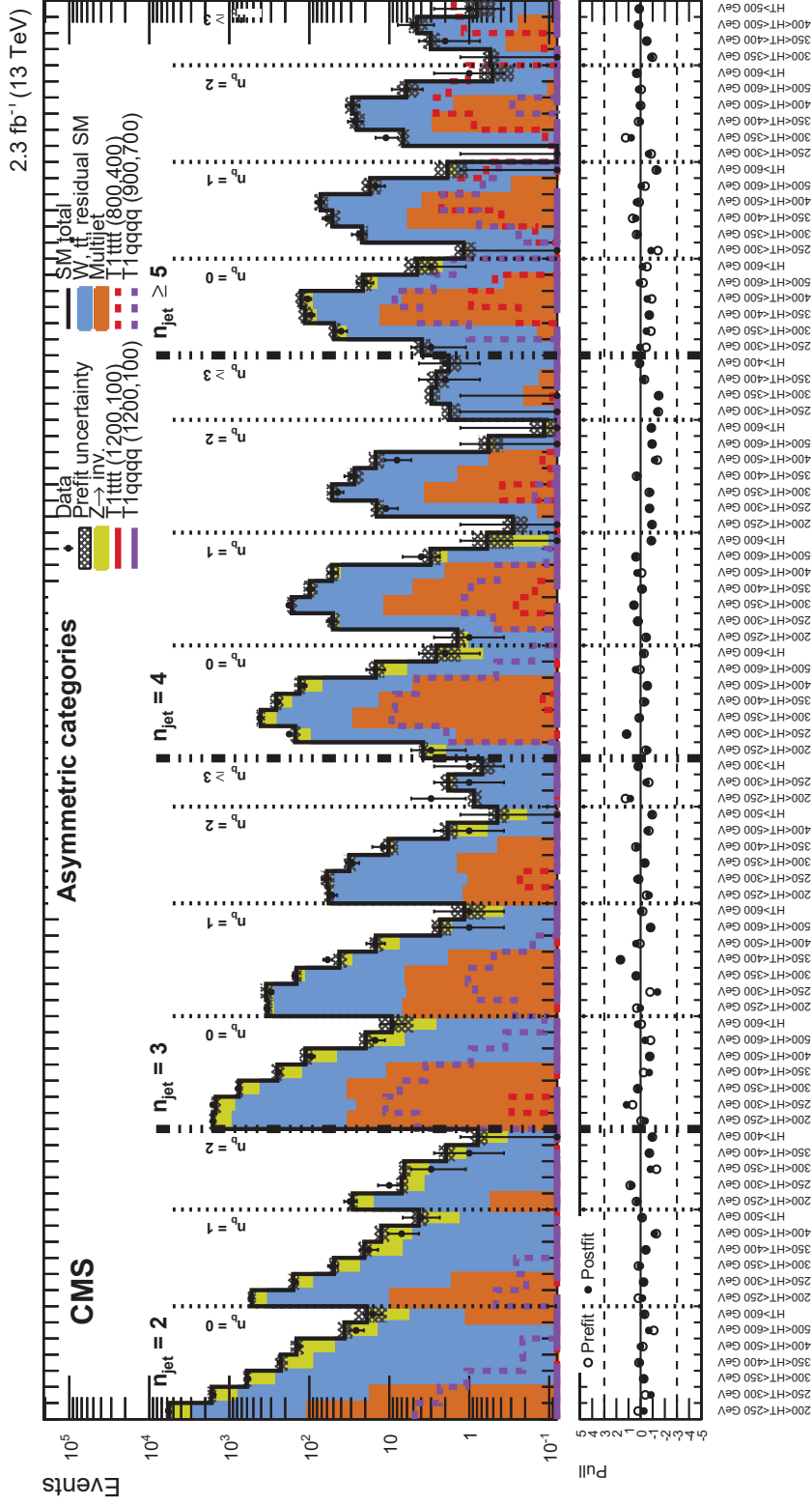


Figure 9.6: Observed and predicted event yields for each (H_T , n_{jet} , n_b) analysis bin for asymmetric jet categories. Observed data counts are represented by the filled circles and predicted backgrounds by the coloured histograms. A selection of signal models is shown by the coloured lines. The ratio shows the pull of background predictions with respect to observed data counts pre-fit (hollow circle) and post-fit (filled circle).

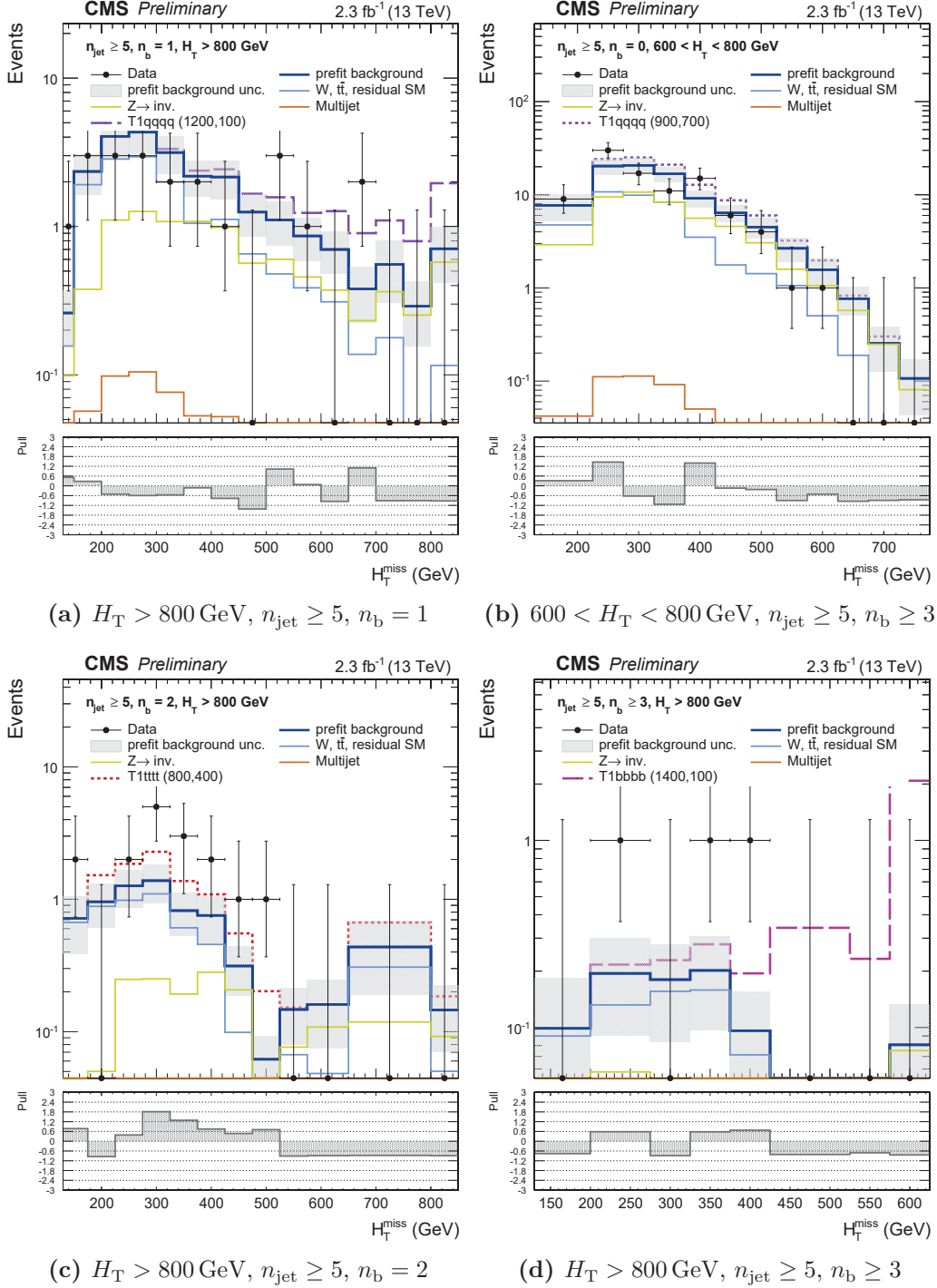


Figure 9.7: Observed and predicted event yields for events in the symmetric jet categories in the specified $(H_T, n_{\text{jet}}, n_b)$ analysis bin in the H_T dimension. Observed data counts are represented by the filled circles and predicted backgrounds by the solid coloured histograms. A selection of signal models are shown by the dashed coloured lines. The ratio shows the pull of background predictions with respect to observed data counts.

9.4 Interpretation of results

A full scan of the $m_{\text{SUSY}} - m_{\text{LSP}}$ mass plane is performed for each of the considered simplified models, utilising the four most sensitive jet categories. For each mass point a 95% C.L. upper limit is set on the production cross section, using the CL_s method [133], with the asymptotic formulae [134] used to model the test statistic distribution.

The results for a full scan of the gluino and squark pair produced models using the full 2.3 fb^{-1} dataset collected at $\sqrt{s} = 13 \text{ TeV}$ are summarised in Figure 9.8 and Figure 9.9 respectively. The colour scale of these distributions show the 95% C.L. upper limit on the production cross section for each pair of mass points, assuming a 100% branching fraction to the respective final state. The dashed and solid lines represent the expected and observed 95% C.L. upper limits on the signal production cross section respectively. In the determination of the exclusion contour, next-to-leading order with next-to-leading logarithmic (NLO+ NLL) corrections are utilised in the computation of the production cross section of each mass point and the 95% C.L. upper limit on production cross section. Each contour is shown with a $\pm 1\sigma$ band of uncertainty corresponding to the experimental uncertainty for the expected limit and the theoretical uncertainty on the signal model cross section for the observed limit.

The total exclusion for simplified models with common production modes are summarised in Figure 9.10. For gluino-mediated models with decays to heavy and light quarks, gluino masses up to $\sim 1550 \text{ GeV}$ and $\sim 1350 \text{ GeV}$ are excluded respectively for small LSP masses, with weaker limits observed for increasing LSP mass. For squark-mediated models with decays to light quarks, squark masses are excluded up to $\sim 1150 \text{ GeV}$ for models with an 8-fold light quark degeneracy, with a weaker $\sim 600 \text{ GeV}$ limit when considering models with a single light squark. Models with direct production of third-generation squarks exclude sbottoms and stops with masses below $\sim 800 \text{ GeV}$ and $\sim 660 \text{ GeV}$ respectively for large mass splittings. For compressed models limits are weaker, with stop masses being excluded up to $\sim 370 \text{ GeV}$ for small mass splittings.

The excesses observed in analysis bins with $n_{\text{jet}} \geq 5$, $n_{\text{b}} \geq 2$ and $H_{\text{T}} > 800 \text{ GeV}$ result in a weaker than expected observed limit for some models. This predominantly effects gluino-mediated models with decays to third-generation quarks, which are most sensitive in the high hadronic energy and jet multiplicity region, resulting in observed limits in some regions of mass space that are weaker than the expected limit by $\sim 2\sigma$. The events in these

regions of excess were studied with event displays and were observed to exhibit behaviour consistent with genuine physics processes and not to be the result of misreconstruction or detector effects.

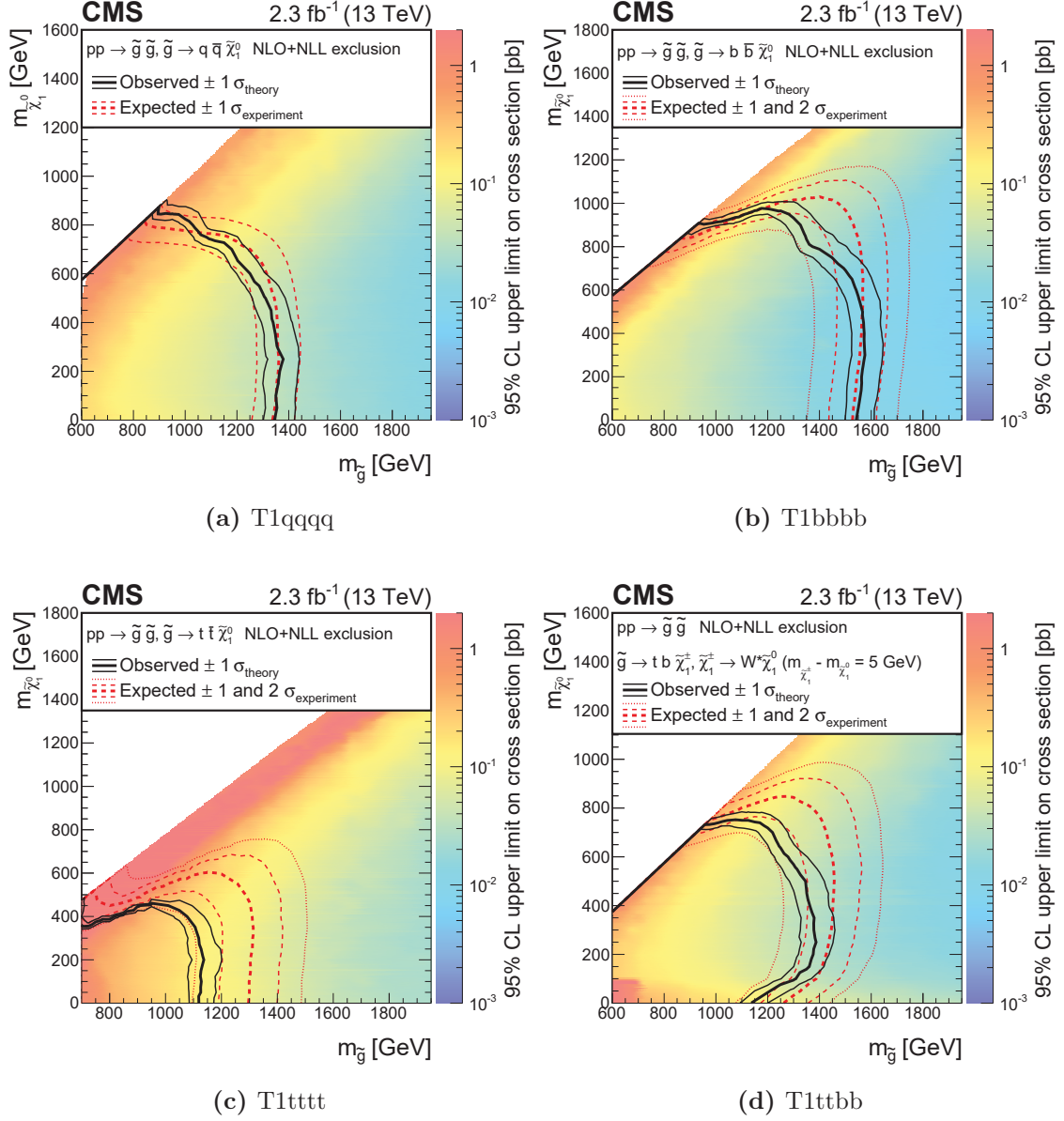


Figure 9.8: Upper limit on the production cross section for the: T1qqqq (top left), T1bbbb (top right), T1tttt (bottom left) and T1ttbb (bottom right) T1 simplified models in the $(m_{\text{Gluino}}, m_{\text{SUSY}})$ mass plane. The observed and expected exclusions are represented by the solid black line and dashed red line respectively, with the banded uncertainty represented by thinner contours.

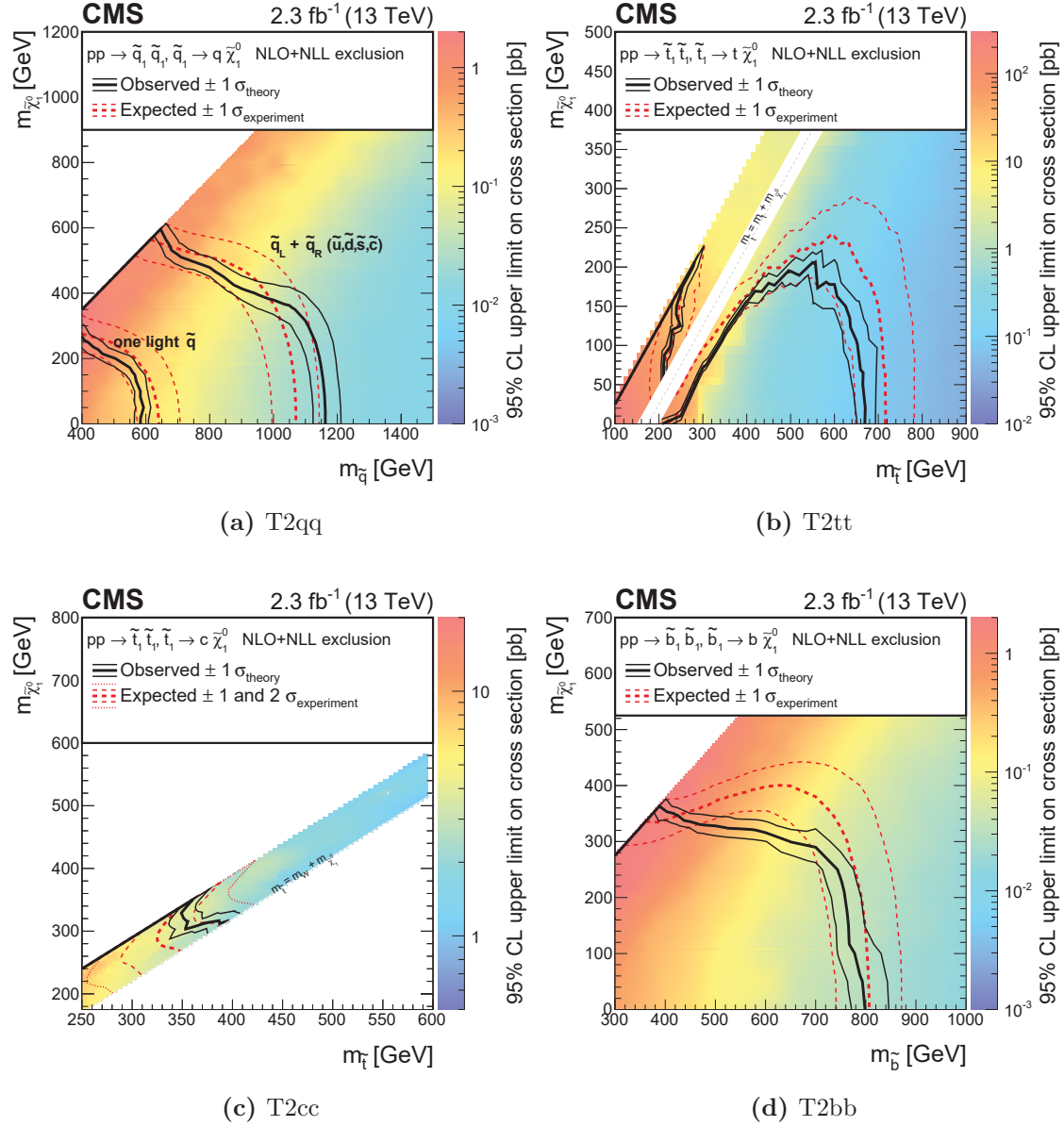


Figure 9.9: Upper limit on the production cross section for the: T2qq (top left), T2tt (top right), T2cc (bottom left) and T2bb (bottom right) T2 simplified models in the $(m_{\text{Squark}}, m_{\text{SUSY}})$ mass plane. The observed and expected exclusions are represented by the solid black line and dashed red line respectively, with the banded uncertainty represented by thinner contours.

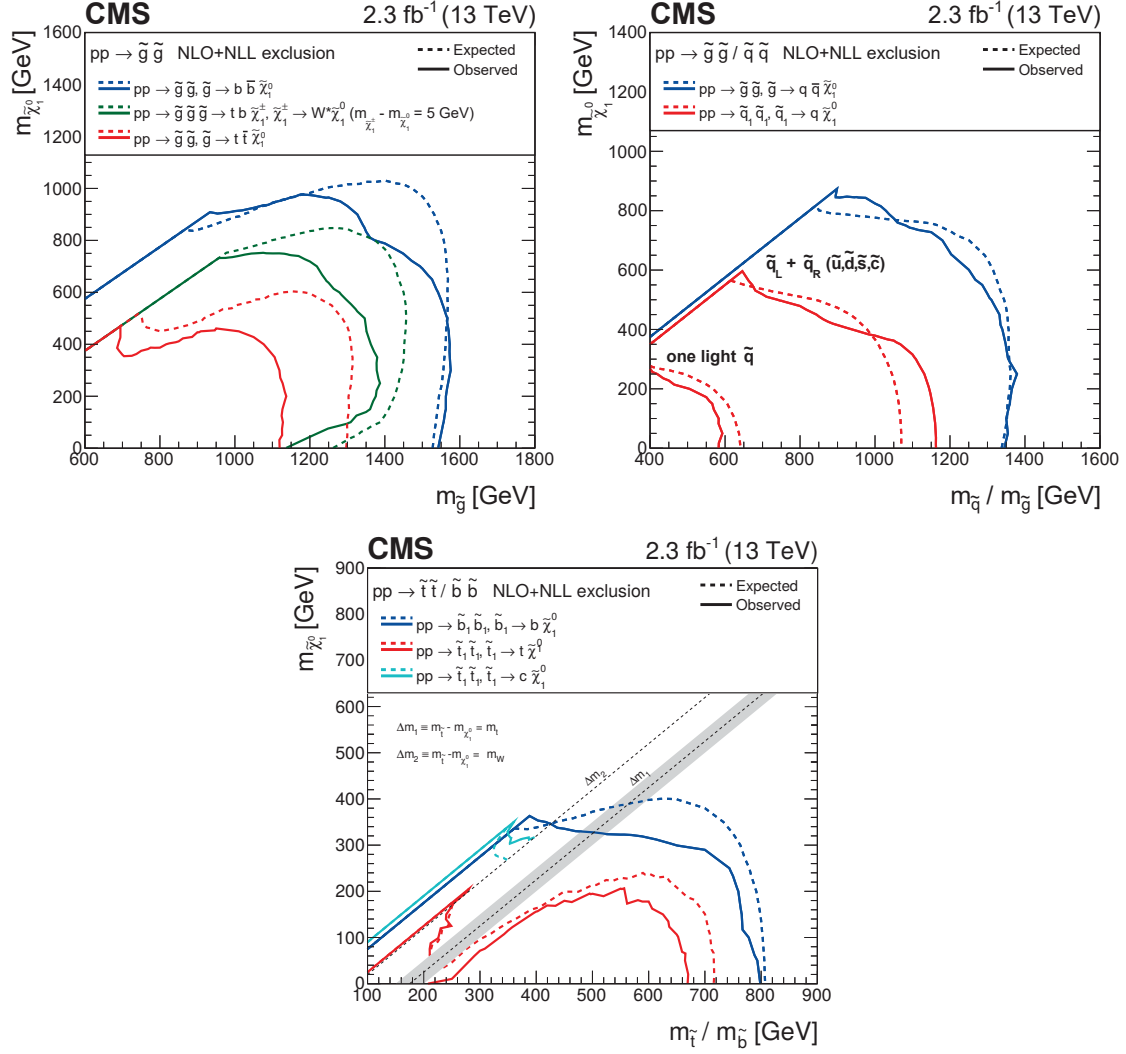


Figure 9.10: Summary of the observed (solid line) and expected (dashed line) exclusions of the simplified models in the $(m_{\text{SUSY}}, m_{\text{LSP}})$ mass plane categorised by their production mechanism. Gluino-mediated production of off mass shell third-generation squarks (T1bbbb, T1tttt, T1ttbb) (left), Gluino-mediated and direct production of off mass shell light-flavour squarks for both 1-fold and 8-fold mass degeneracy (T1qqqq, T2qq) (right) and direct production of third-generation squarks (T2tt, T2bb, T2cc) (bottom).

CHAPTER 10

Conclusions

With the LHC operating at new frontiers in energy and luminosity, the coming years will be of particular interest in the searches for signatures of BSM theories. The more extreme beam environments at the LHC will however make it challenging to maintain the low thresholds required to perform an inclusive search of the remaining parameter space.

The efficient selection of hadronic events in the more challenging environment at the LHC were maintained by an upgrade to the calorimeter trigger system and its algorithms. From the study of the operation of baseline L1 upgrade jet algorithm, a refined algorithm was developed, providing improvements in the performance of the clustering, calibration and pileup correction of jets. An analysis of the performance of the upgrade jet algorithm demonstrated a marked improvement in the selection of hadronic events and a greater stability in high-luminosity environments. This research was further expanded upon and was successfully commissioned in the upgrade trigger system in the 2015 data run [135] and is currently in operation in the L1 calorimeter trigger.

Improvements in the search sensitivity for SUSY of the α_T analysis were made in preparation of the increase in collision centre-of-mass energy of the LHC. Through a study of trigger selections in the high luminosity environment of Run 2, a new trigger strategy for the α_T analysis was developed. Using improved reconstruction and an optimisation of trigger selections, the analysis was able to effectively select events in the signal region throughout the 2015 data run. The performance of these triggers were closely monitored during commissioning and were found to provide an effective control of trigger rate, whilst maintaining acceptance for a diverse range of signal topologies.

Additionally, the design of the α_T analysis and its background estimation methods were refined, with the addition of new search categories and dimensions to improve sensitivity to a greater range of signatures. The analysis was successfully commissioned during early data taking, with extensive studies of data modelling successful in identifying and suppressing new sources of fake missing energy. The α_T analysis performed an inclusive search for SUSY in the first pp -collisions at $\sqrt{s} = 13$ TeV, on a data sample corresponding to an integrated luminosity of 2.3 fb^{-1} . No significant excess was observed above the SM

background expectation and the results were interpreted in the context of SMS models, setting stringent limits on the masses of sparticles. The limits achieved by the search are comparable or greater than exclusions achieved by CMS SUSY searches with the full LHC Run 1 dataset. Achieving an improvement on the exclusion of gluino masses in models with large mass splittings by ~ 200 GeV and stop masses, in more in challenging compressed spectrum models, by ~ 120 GeV.

Although no evidence of signatures of BSM have yet been identified, the increased sensitivity of direct DM searches [136] and indirect searches at a high-luminosity LHC promise that future searches will have the best chance of detecting natural SUSY. A failure to identify SUSY at the LHC however will put significant constraints on the remaining parameter space, leading to models that are increasingly less tenable from arguments of naturalness. Having experienced the last major leap in collision energy for the foreseeable future, the continued search for SUSY at the LHC will become increasingly more challenging. With future searches needing to better exploit the capabilities of the trigger system and novel analysis techniques, to hunt for SUSY in the remaining vestiges of parameter space.

APPENDIX 1

Trigger efficiencies

Trigger efficiency of the individual H_T - α_T triggers in the α_T dimension measured in data collected using a reference electron trigger.

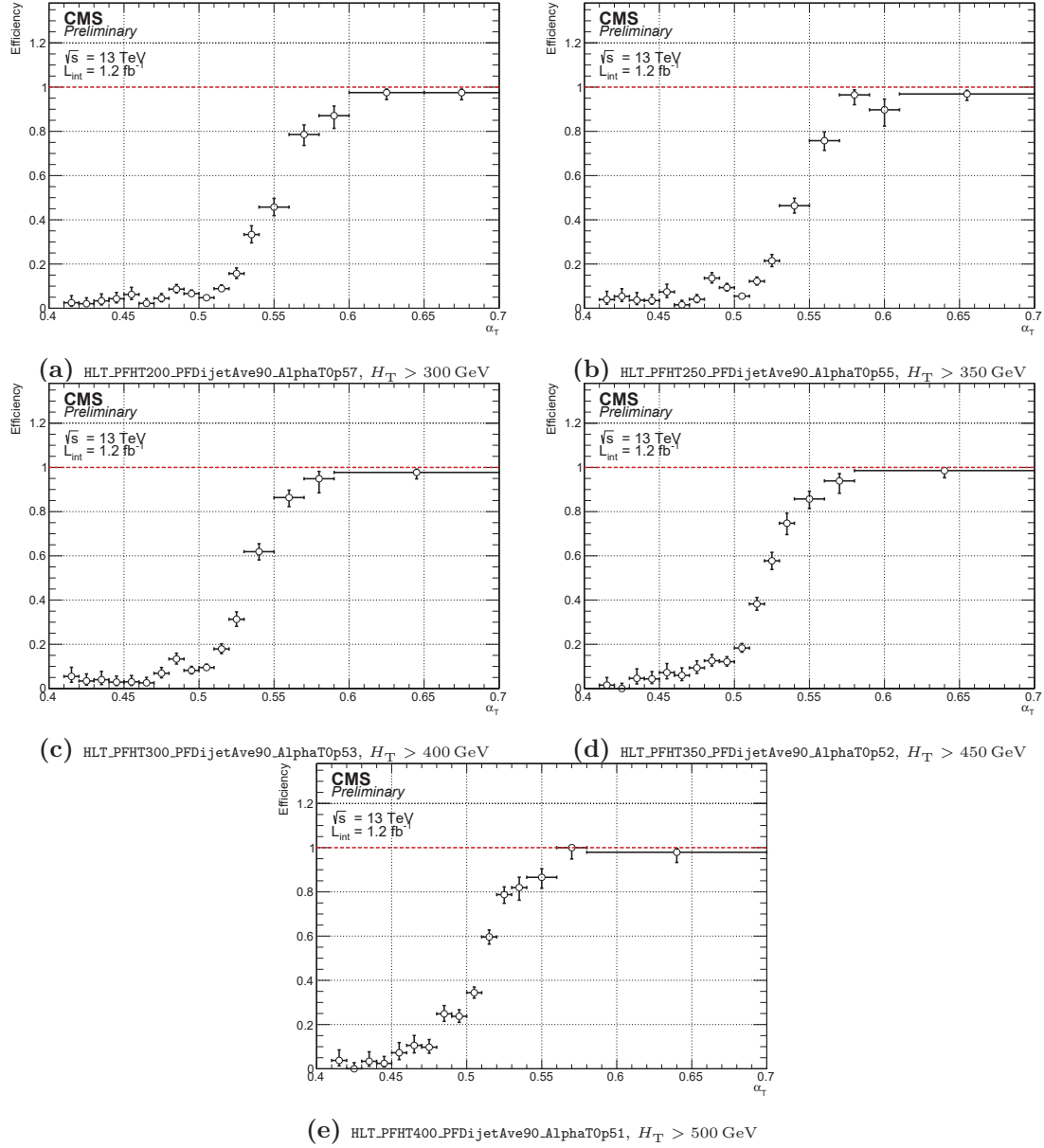


Figure A1.1: The trigger efficiency of the signal H_T - α_T triggers measured in the data as a function of α_T , an offline H_T selection applied to ensure efficiency for the H_T trigger selection is also specified.

APPENDIX 2

Control region yields

A summary of the yields in the $\mu + \text{jets}$, $\mu\mu + \text{jets}$ and $\gamma + \text{jets}$ control regions are presented in Table A2.1-A2.3

$(n_{\text{jet}}, n_{\text{b}})$	H_{T} (GeV)							
	200-250	250-300	300-350	350-400	400-500	500-600	600-800	800- ∞
(1, 0)	4575	1711	686	303	260	89	35	–
(1, 1)	216	73	27	14	11	1	–	–
(2, 0)	516	775	709	566	709	331	250	132
(2, 1)	91	94	63	56	93	53	31	12
(2, 2)	4	4	7	1	6	5	2	–
(3, 0)	1	244	498	470	754	419	354	190
(3, 1)	–	94	201	229	287	118	112	39
(3, 2)	–	28	65	68	76	35	20	11
(3, ≥ 3)	–	1	–	–	–	–	–	–
(4, 0)	–	–	45	161	407	287	309	176
(4, 1)	–	–	46	140	297	183	146	53
(4, 2)	–	–	18	57	149	70	54	27
(4, ≥ 3)	–	–	1	5	8	6	2	3
(≥ 5 , 0)	–	–	–	19	116	157	225	176
(≥ 5 , 1)	–	–	–	9	150	184	242	162
(≥ 5 , 2)	–	–	–	7	63	107	128	82
(≥ 5 , ≥ 3)	–	–	–	–	3	11	15	12
(2a, 0)	5204	2722	1255	529	365	91	32	–
(2a, 1)	793	376	149	66	36	10	–	–
(2a, 2)	52	20	15	8	2	–	–	–
(3a, 0)	1244	1537	854	424	326	77	26	–
(3a, 1)	530	731	324	124	84	23	4	–
(3a, 2)	150	198	89	37	15	4	–	–
(3a, ≥ 3)	4	6	3	–	–	–	–	–
(4a, 0)	15	189	362	236	171	41	10	–
(4a, 1)	11	164	318	187	124	20	9	–
(4a, 2)	3	74	124	70	52	7	4	–
(4a, ≥ 3)	–	6	8	8	5	–	–	–
(≥ 5 a, 0)	–	2	40	92	124	39	10	–
(≥ 5 a, 1)	–	3	35	83	141	55	15	–
(≥ 5 a, 2)	–	1	13	42	61	30	5	–
(≥ 5 a, ≥ 3)	–	–	2	7	9	4	–	–

Table A2.1: Observed yields in data for the $\mu + \text{jets}$ control region in the analysis (H_{T} , n_{jet} , n_{b}) bins.

2 Control region yields

$(n_{\text{jet}}, n_{\text{b}})$	H_{T} (GeV)							
	200-250	250-300	300-350	350-400	400-500	500-600	600-800	800- ∞
(1, 0)	4575	1711	686	303	260	89	35	–
(1, 1)	216	73	27	14	11	1	–	–
(2, 0)	516	775	709	566	709	331	250	132
(2, 1)	91	94	63	56	93	53	31	12
(2, 2)	4	4	7	1	6	5	2	–
(3, 0)	1	244	498	470	754	419	354	190
(3, 1)	–	94	201	229	287	118	112	39
(3, 2)	–	28	65	68	76	35	20	11
(3, ≥ 3)	–	1	–	–	–	–	–	–
(4, 0)	–	–	45	161	407	287	309	176
(4, 1)	–	–	46	140	297	183	146	53
(4, 2)	–	–	18	57	149	70	54	27
(4, ≥ 3)	–	–	1	5	8	6	2	3
(≥ 5 , 0)	–	–	–	19	116	157	225	176
(≥ 5 , 1)	–	–	–	9	150	184	242	162
(≥ 5 , 2)	–	–	–	7	63	107	128	82
(≥ 5 , ≥ 3)	–	–	–	–	3	11	15	12
(2a, 0)	5204	2722	1255	529	365	91	32	–
(2a, 1)	793	376	149	66	36	10	–	–
(2a, 2)	52	20	15	8	2	–	–	–
(3a, 0)	1244	1537	854	424	326	77	26	–
(3a, 1)	530	731	324	124	84	23	4	–
(3a, 2)	150	198	89	37	15	4	–	–
(3a, ≥ 3)	4	6	3	–	–	–	–	–
(4a, 0)	15	189	362	236	171	41	10	–
(4a, 1)	11	164	318	187	124	20	9	–
(4a, 2)	3	74	124	70	52	7	4	–
(4a, ≥ 3)	–	6	8	8	5	–	–	–
(≥ 5 a, 0)	–	2	40	92	124	39	10	–
(≥ 5 a, 1)	–	3	35	83	141	55	15	–
(≥ 5 a, 2)	–	1	13	42	61	30	5	–
(≥ 5 a, ≥ 3)	–	–	2	7	9	4	–	–

Table A2.2: Observed yields in data for the $\mu\mu$ + jets control region in the analysis (H_{T} , n_{jet} , n_{b}) bins.

$(n_{\text{jet}}, n_{\text{b}})$	H_{T} (GeV)			
	400-500	500-600	600-800	800- ∞
(1, 0)	593	183	73	–
(1, 1)	23	6	–	–
(2, 0)	333	108	55	133
(2, 1)	17	2	2	8
(2, 2)	0	0	0	–
(3, 0)	499	214	115	224
(3, 1)	47	23	16	35
(3, 2)	6	1	2	4
(3, ≥ 3)	–	–	–	–
(4, 0)	256	161	120	157
(4, 1)	47	37	10	38
(4, 2)	3	2	1	3
(4, ≥ 3)	0	1	1	0
(≥ 5 , 0)	54	77	93	122
(≥ 5 , 1)	13	13	20	28
(≥ 5 , 2)	3	3	3	8
(≥ 5 , ≥ 3)	0	0	0	0
(2a, 0)	164	44	17	–
(2a, 1)	16	2	–	–
(2a, 2)	1	–	–	–
(3a, 0)	105	17	8	–
(3a, 1)	7	2	2	–
(3a, 2)	1	0	–	–
(3a, ≥ 3)	–	–	–	–
(4a, 0)	112	13	3	–
(4a, 1)	16	5	0	–
(4a, 2)	1	0	0	–
(4a, ≥ 3)	0	–	–	–
(≥ 5 a, 0)	55	12	4	–
(≥ 5 a, 1)	10	6	0	–
(≥ 5 a, 2)	3	0	0	–
(≥ 5 a, ≥ 3)	0	0	–	–

Table A2.3: Observed yields in data for the $\gamma + \text{jets}$ control region in the analysis (H_{T} , n_{jet} , n_{b}) bins.

APPENDIX 3

Transfer factors

The transfer factors measured in the control regions are summarised in Table A3.1–A3.4.

(n_{jet}, n_b)	H_T (GeV)							
	200 – 250	250 – 300	300 – 350	350 – 400	400 – 500	500 – 600	600 – 800	800 – ∞
(1, 0)	1.15 ± 0.02	0.95 ± 0.02	0.72 ± 0.03	0.56 ± 0.03	0.52 ± 0.03	0.39 ± 0.03	0.33 ± 0.03	–
(1, 1)	0.84 ± 0.07	0.71 ± 0.09	0.65 ± 0.13	0.42 ± 0.10	0.72 ± 0.16	0.38 ± 0.15	–	–
(2, 0)	1.00 ± 0.04	0.67 ± 0.03	0.46 ± 0.02	0.28 ± 0.01	0.18 ± 0.01	0.12 ± 0.01	0.06 ± 0.00	0.14 ± 0.01
(2, 1)	0.75 ± 0.06	0.50 ± 0.05	0.38 ± 0.05	0.21 ± 0.03	0.11 ± 0.02	0.09 ± 0.02	0.04 ± 0.01	0.12 ± 0.01
(2, 2)	0.70 ± 0.20	0.43 ± 0.14	0.61 ± 0.20	0.17 ± 0.07	0.10 ± 0.05	0.22 ± 0.11	0.01 ± 0.01	–
(3, 0)	0.57 ± 0.39	0.43 ± 0.03	0.61 ± 0.03	0.50 ± 0.02	0.34 ± 0.01	0.19 ± 0.01	0.10 ± 0.00	0.12 ± 0.00
(3, 1)	–	0.37 ± 0.03	0.36 ± 0.02	0.33 ± 0.02	0.25 ± 0.01	0.14 ± 0.01	0.07 ± 0.01	0.09 ± 0.01
(3, 2)	–	0.18 ± 0.03	0.26 ± 0.03	0.27 ± 0.03	0.15 ± 0.01	0.09 ± 0.02	0.02 ± 0.00	0.04 ± 0.01
(3, ≥ 3)	–	0.15 ± 0.10	–	–	–	–	–	–
(4, 0)	–	–	0.75 ± 0.09	0.66 ± 0.04	0.47 ± 0.02	0.25 ± 0.01	0.14 ± 0.01	0.14 ± 0.00
(4, 1)	–	–	0.52 ± 0.05	0.49 ± 0.03	0.29 ± 0.01	0.17 ± 0.01	0.09 ± 0.01	0.10 ± 0.01
(4, 2)	–	–	0.35 ± 0.04	0.35 ± 0.03	0.25 ± 0.02	0.12 ± 0.01	0.04 ± 0.01	0.06 ± 0.01
(4, ≥ 3)	–	–	0.32 ± 0.14	0.32 ± 0.08	0.32 ± 0.06	0.12 ± 0.05	0.02 ± 0.01	0.03 ± 0.02
(≥ 5 , 0)	–	–	–	0.62 ± 0.15	0.58 ± 0.04	0.31 ± 0.02	0.19 ± 0.01	0.13 ± 0.00
(≥ 5 , 1)	–	–	–	0.35 ± 0.06	0.39 ± 0.02	0.22 ± 0.01	0.11 ± 0.01	0.09 ± 0.00
(≥ 5 , 2)	–	–	–	0.35 ± 0.08	0.34 ± 0.02	0.17 ± 0.01	0.07 ± 0.01	0.06 ± 0.01
(≥ 5 , ≥ 3)	–	–	–	–	0.33 ± 0.06	0.24 ± 0.04	0.08 ± 0.02	0.06 ± 0.01
(2a, 0)	0.52 ± 0.01	0.27 ± 0.01	0.20 ± 0.01	0.16 ± 0.01	0.12 ± 0.01	0.14 ± 0.02	0.09 ± 0.02	–
(2a, 1)	0.39 ± 0.01	0.22 ± 0.02	0.15 ± 0.02	0.10 ± 0.02	0.12 ± 0.03	0.11 ± 0.05	–	–
(2a, 2)	0.28 ± 0.04	0.15 ± 0.04	0.16 ± 0.08	0.13 ± 0.09	0.08 ± 0.06	–	–	–
(3a, 0)	0.68 ± 0.02	0.50 ± 0.01	0.42 ± 0.02	0.24 ± 0.02	0.13 ± 0.01	0.08 ± 0.01	0.05 ± 0.01	–
(3a, 1)	0.47 ± 0.02	0.36 ± 0.01	0.31 ± 0.02	0.21 ± 0.02	0.09 ± 0.02	0.07 ± 0.02	0.03 ± 0.01	–
(3a, 2)	0.31 ± 0.02	0.24 ± 0.02	0.27 ± 0.02	0.20 ± 0.03	0.04 ± 0.02	0.07 ± 0.06	–	–
(3a, ≥ 3)	0.19 ± 0.06	0.25 ± 0.06	0.17 ± 0.07	–	–	–	–	–
(4a, 0)	0.13 ± 0.06	0.46 ± 0.03	0.58 ± 0.03	0.59 ± 0.03	0.35 ± 0.02	0.14 ± 0.02	0.05 ± 0.01	–
(4a, 1)	0.09 ± 0.03	0.23 ± 0.01	0.42 ± 0.02	0.40 ± 0.02	0.29 ± 0.02	0.08 ± 0.02	0.01 ± 0.01	–
(4a, 2)	0.09 ± 0.05	0.16 ± 0.02	0.35 ± 0.02	0.34 ± 0.02	0.24 ± 0.02	0.06 ± 0.02	0.01 ± 0.01	–
(4a, ≥ 3)	–	0.27 ± 0.09	0.31 ± 0.06	0.27 ± 0.07	0.24 ± 0.08	–	–	–
($\geq 5a$, 0)	–	1.81 ± 1.14	0.79 ± 0.11	0.69 ± 0.06	0.64 ± 0.04	0.32 ± 0.04	0.18 ± 0.04	–
($\geq 5a$, 1)	–	0.32 ± 0.13	0.56 ± 0.05	0.51 ± 0.03	0.43 ± 0.02	0.25 ± 0.03	0.08 ± 0.02	–
($\geq 5a$, 2)	–	0.03 ± 0.03	0.49 ± 0.06	0.52 ± 0.04	0.42 ± 0.02	0.18 ± 0.02	0.10 ± 0.03	–
($\geq 5a$, ≥ 3)	–	–	0.27 ± 0.09	0.39 ± 0.08	0.45 ± 0.07	0.19 ± 0.06	–	–

Table A3.1: Transfer factors from the $\mu + \text{jets}$ control region for the prediction of the $t\bar{t}/W + \text{jets}$ background per analysis bin, where asymmetric categories are represented by the suffix a .

(n_{jet}, n_b)	H_T (GeV)							
	200 – 250	250 – 300	300 – 350	350 – 400	400 – 500	500 – 600	600 – 800	800 – ∞
(1, 0)	1.54 ± 0.02	1.50 ± 0.03	1.39 ± 0.04	1.29 ± 0.05	1.26 ± 0.04	1.27 ± 0.06	1.15 ± 0.05	–
(1, 1)	1.63 ± 0.09	1.63 ± 0.15	1.66 ± 0.21	1.25 ± 0.20	1.41 ± 0.22	1.33 ± 0.30	–	–
(2, 0)	1.03 ± 0.04	0.79 ± 0.02	0.58 ± 0.02	0.42 ± 0.01	0.30 ± 0.01	0.23 ± 0.01	0.14 ± 0.00	0.30 ± 0.01
(2, 1)	0.42 ± 0.03	0.43 ± 0.03	0.41 ± 0.04	0.33 ± 0.03	0.21 ± 0.02	0.17 ± 0.02	0.12 ± 0.01	0.28 ± 0.03
(2, 2)	0.70 ± 0.19	0.57 ± 0.13	0.46 ± 0.13	0.22 ± 0.07	0.18 ± 0.05	0.11 ± 0.04	0.06 ± 0.02	–
(3, 0)	0.37 ± 0.21	0.46 ± 0.03	0.60 ± 0.02	0.53 ± 0.02	0.44 ± 0.01	0.30 ± 0.01	0.20 ± 0.00	0.27 ± 0.01
(3, 1)	–	0.12 ± 0.01	0.15 ± 0.01	0.17 ± 0.01	0.18 ± 0.01	0.14 ± 0.01	0.11 ± 0.01	0.19 ± 0.01
(3, 2)	–	0.06 ± 0.02	0.06 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	0.06 ± 0.01	0.04 ± 0.01	0.08 ± 0.02
(3, ≥ 3)	–	–	–	–	–	–	–	–
(4, 0)	–	–	0.57 ± 0.05	0.55 ± 0.03	0.45 ± 0.01	0.34 ± 0.01	0.24 ± 0.01	0.26 ± 0.01
(4, 1)	–	–	0.10 ± 0.02	0.12 ± 0.01	0.10 ± 0.01	0.10 ± 0.01	0.09 ± 0.01	0.15 ± 0.01
(4, 2)	–	–	0.06 ± 0.02	0.03 ± 0.01	0.04 ± 0.00	0.03 ± 0.01	0.03 ± 0.00	0.07 ± 0.01
(4, ≥ 3)	–	–	–	0.07 ± 0.04	0.03 ± 0.02	0.03 ± 0.02	0.01 ± 0.01	0.00 ± 0.00
(≥ 5 , 0)	–	–	–	0.33 ± 0.07	0.36 ± 0.02	0.29 ± 0.01	0.22 ± 0.01	0.20 ± 0.01
(≥ 5 , 1)	–	–	–	0.05 ± 0.02	0.06 ± 0.01	0.05 ± 0.00	0.04 ± 0.00	0.06 ± 0.00
(≥ 5 , 2)	–	–	–	0.03 ± 0.02	0.02 ± 0.00	0.02 ± 0.00	0.01 ± 0.00	0.02 ± 0.00
(≥ 5 , ≥ 3)	–	–	–	–	0.02 ± 0.01	0.01 ± 0.01	0.02 ± 0.01	0.02 ± 0.01
(2a, 0)	0.55 ± 0.01	0.34 ± 0.01	0.28 ± 0.01	0.27 ± 0.01	0.27 ± 0.01	0.26 ± 0.02	0.23 ± 0.01	–
(2a, 1)	0.26 ± 0.01	0.20 ± 0.01	0.18 ± 0.02	0.21 ± 0.02	0.19 ± 0.02	0.28 ± 0.06	–	–
(2a, 2)	0.29 ± 0.03	0.16 ± 0.03	0.19 ± 0.05	0.12 ± 0.05	0.10 ± 0.06	–	–	–
(3a, 0)	0.59 ± 0.01	0.45 ± 0.01	0.43 ± 0.01	0.32 ± 0.01	0.22 ± 0.01	0.18 ± 0.02	0.17 ± 0.02	–
(3a, 1)	0.13 ± 0.01	0.11 ± 0.01	0.12 ± 0.01	0.12 ± 0.01	0.10 ± 0.01	0.04 ± 0.01	0.10 ± 0.02	–
(3a, 2)	0.06 ± 0.01	0.06 ± 0.01	0.07 ± 0.01	0.05 ± 0.01	0.10 ± 0.03	0.09 ± 0.04	–	–
(3a, ≥ 3)	0.03 ± 0.03	0.07 ± 0.04	–	–	–	–	–	–
(4a, 0)	0.14 ± 0.04	0.31 ± 0.02	0.45 ± 0.02	0.45 ± 0.02	0.40 ± 0.02	0.23 ± 0.02	0.14 ± 0.02	–
(4a, 1)	0.04 ± 0.02	0.07 ± 0.01	0.08 ± 0.01	0.09 ± 0.01	0.12 ± 0.01	0.06 ± 0.02	0.04 ± 0.01	–
(4a, 2)	–	0.03 ± 0.01	0.03 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.02 ± 0.01	0.00 ± 0.00	–
(4a, ≥ 3)	–	0.02 ± 0.02	0.05 ± 0.03	0.04 ± 0.03	0.00 ± 0.00	–	–	–
($\geq 5a$, 0)	–	0.14 ± 0.14	0.43 ± 0.05	0.41 ± 0.03	0.35 ± 0.02	0.21 ± 0.02	0.21 ± 0.03	–
($\geq 5a$, 1)	–	0.07 ± 0.08	0.07 ± 0.02	0.05 ± 0.01	0.05 ± 0.01	0.06 ± 0.01	0.03 ± 0.01	–
($\geq 5a$, 2)	–	–	0.03 ± 0.01	0.03 ± 0.01	0.02 ± 0.01	0.03 ± 0.01	0.00 ± 0.00	–
($\geq 5a$, ≥ 3)	–	–	–	0.00 ± 0.00	0.02 ± 0.01	0.03 ± 0.03	–	–

Table A3.2: Transfer factors from the $\mu + \text{jets}$ control region for the prediction of the $Z \rightarrow \nu\bar{\nu}$ background per analysis bin, where asymmetric categories are represented by the suffix a .

3 Transfer factors

(n_{jet}, n_b)	H_T (GeV)							
	200 – 250	250 – 300	300 – 350	350 – 400	400 – 500	500 – 600	600 – 800	800 – ∞
(1, 0)	12.89 $\pm$ 0.32	10.96 $\pm$ 0.41	10.41 $\pm$ 0.56	9.98 $\pm$ 0.68	9.13 $\pm$ 0.46	9.13 $\pm$ 0.53	8.57 $\pm$ 0.53	–
(1, 1)	10.34 $\pm$ 1.14	8.83 $\pm$ 1.43	6.71 $\pm$ 1.43	7.00 $\pm$ 1.79	10.04 $\pm$ 2.61	9.92 $\pm$ 2.73	–	–
(2, 0)	10.39 $\pm$ 0.85	8.02 $\pm$ 0.54	5.29 $\pm$ 0.34	4.16 $\pm$ 0.24	3.23 $\pm$ 0.11	2.18 $\pm$ 0.09	1.27 $\pm$ 0.05	2.94 $\pm$ 0.11
(2, 1)	9.67 $\pm$ 2.64	5.30 $\pm$ 1.06	3.60 $\pm$ 0.69	2.89 $\pm$ 0.54	2.58 $\pm$ 0.24	2.12 $\pm$ 0.29	1.63 $\pm$ 0.19	2.73 $\pm$ 0.32
(2, 2)	12.95 $\pm$ 10.34	3.43 $\pm$ 1.77	5.47 $\pm$ 3.05	1.69 $\pm$ 0.94	3.54 $\pm$ 1.48	4.38 $\pm$ 2.12	1.32 $\pm$ 0.61	–
(3, 0)	15.27 $\pm$ 15.92	7.66 $\pm$ 1.16	7.38 $\pm$ 0.66	6.49 $\pm$ 0.43	4.97 $\pm$ 0.18	3.24 $\pm$ 0.11	1.98 $\pm$ 0.06	2.67 $\pm$ 0.09
(3, 1)	–	6.10 $\pm$ 2.23	4.42 $\pm$ 0.87	6.64 $\pm$ 1.16	3.60 $\pm$ 0.36	2.39 $\pm$ 0.25	1.63 $\pm$ 0.14	2.57 $\pm$ 0.24
(3, 2)	–	1.40 $\pm$ 0.75	2.76 $\pm$ 1.06	2.79 $\pm$ 0.89	2.88 $\pm$ 0.63	1.64 $\pm$ 0.46	0.87 $\pm$ 0.27	1.39 $\pm$ 0.53
(3, $\geq$ 3)	–	–	–	–	–	–	–	–
(4, 0)	–	–	5.34 $\pm$ 1.19	8.10 $\pm$ 1.13	6.27 $\pm$ 0.35	4.48 $\pm$ 0.21	2.75 $\pm$ 0.10	2.76 $\pm$ 0.10
(4, 1)	–	–	6.58 $\pm$ 4.07	9.77 $\pm$ 2.08	4.12 $\pm$ 0.49	2.74 $\pm$ 0.30	2.09 $\pm$ 0.19	2.44 $\pm$ 0.22
(4, 2)	–	–	5.27 $\pm$ 3.43	1.67 $\pm$ 0.72	3.04 $\pm$ 0.85	2.32 $\pm$ 0.57	1.15 $\pm$ 0.28	2.43 $\pm$ 0.49
(4, $\geq$ 3)	–	–	–	5.35 $\pm$ 6.10	4.16 $\pm$ 3.94	6.87 $\pm$ 6.61	1.87 $\pm$ 1.67	0.11 $\pm$ 0.08
($\geq$ 5, 0)	–	–	–	20.33 $\pm$ 7.31	7.08 $\pm$ 1.02	5.46 $\pm$ 0.48	3.43 $\pm$ 0.19	2.69 $\pm$ 0.10
($\geq$ 5, 1)	–	–	–	12.37 $\pm$ 12.20	4.94 $\pm$ 1.29	4.15 $\pm$ 0.85	2.48 $\pm$ 0.26	2.02 $\pm$ 0.16
($\geq$ 5, 2)	–	–	–	3.16 $\pm$ 3.96	1.73 $\pm$ 0.60	1.69 $\pm$ 0.44	1.61 $\pm$ 0.36	1.43 $\pm$ 0.24
($\geq$ 5, $\geq$ 3)	–	–	–	–	0.98 $\pm$ 0.94	4.97 $\pm$ 5.75	3.27 $\pm$ 2.20	1.63 $\pm$ 0.84
(2a, 0)	5.88 $\pm$ 0.16	3.31 $\pm$ 0.12	2.63 $\pm$ 0.13	2.12 $\pm$ 0.13	2.47 $\pm$ 0.13	1.86 $\pm$ 0.14	1.84 $\pm$ 0.16	–
(2a, 1)	3.99 $\pm$ 0.33	2.47 $\pm$ 0.28	1.69 $\pm$ 0.26	2.42 $\pm$ 0.49	2.07 $\pm$ 0.32	1.98 $\pm$ 0.58	–	–
(2a, 2)	3.04 $\pm$ 0.63	1.63 $\pm$ 0.51	7.30 $\pm$ 3.08	9.91 $\pm$ 10.07	1.17 $\pm$ 0.81	–	–	–
(3a, 0)	7.86 $\pm$ 0.49	5.31 $\pm$ 0.27	5.61 $\pm$ 0.39	3.47 $\pm$ 0.27	2.14 $\pm$ 0.13	1.48 $\pm$ 0.16	1.34 $\pm$ 0.15	–
(3a, 1)	5.56 $\pm$ 0.83	3.78 $\pm$ 0.46	3.22 $\pm$ 0.47	2.17 $\pm$ 0.39	1.52 $\pm$ 0.24	0.43 $\pm$ 0.15	1.18 $\pm$ 0.35	–
(3a, 2)	3.08 $\pm$ 0.86	2.15 $\pm$ 0.53	3.05 $\pm$ 0.79	3.05 $\pm$ 1.13	1.75 $\pm$ 0.59	1.46 $\pm$ 0.85	–	–
(3a, $\geq$ 3)	1.06 $\pm$ 1.33	1.10 $\pm$ 1.25	–	–	–	–	–	–
(4a, 0)	1.89 $\pm$ 1.31	4.34 $\pm$ 0.65	7.32 $\pm$ 0.83	7.17 $\pm$ 0.82	5.18 $\pm$ 0.46	2.49 $\pm$ 0.38	1.19 $\pm$ 0.25	–
(4a, 1)	1.30 $\pm$ 1.43	5.14 $\pm$ 1.89	3.84 $\pm$ 0.83	4.93 $\pm$ 1.18	4.14 $\pm$ 0.62	2.03 $\pm$ 0.64	0.79 $\pm$ 0.34	–
(4a, 2)	–	10.86 $\pm$ 5.46	3.25 $\pm$ 1.38	6.05 $\pm$ 2.19	3.70 $\pm$ 1.28	0.46 $\pm$ 0.32	0.06 $\pm$ 0.05	–
(4a, $\geq$ 3)	–	1332.61 $\pm$ 1844.69	3.00 $\pm$ 2.92	–	–	–	–	–
($\geq$ 5a, 0)	–	–	6.17 $\pm$ 2.52	11.59 $\pm$ 3.27	7.60 $\pm$ 1.32	3.83 $\pm$ 0.60	2.83 $\pm$ 0.57	–
($\geq$ 5a, 1)	–	–	6.88 $\pm$ 3.75	2.83 $\pm$ 1.04	3.25 $\pm$ 0.79	4.80 $\pm$ 1.65	1.43 $\pm$ 0.66	–
($\geq$ 5a, 2)	–	–	12.08 $\pm$ 12.96	9.24 $\pm$ 6.67	3.89 $\pm$ 1.52	2.68 $\pm$ 1.42	0.37 $\pm$ 0.39	–
($\geq$ 5a, $\geq$ 3)	–	–	–	–	6.04 $\pm$ 5.54	49.96 $\pm$ 67.51	–	–

Table A3.3: Transfer factors from the $\mu\mu$ + jets control region for the prediction of the $Z \rightarrow \nu\bar{\nu}$ background per analysis bin, where asymmetric categories are represented by the suffix a .

(n_{jet}, n_b)	H_T (GeV)							
	200 – 250	250 – 300	300 – 350	350 – 400	400 – 500	500 – 600	600 – 800	800 – ∞
(1, 0)	–	–	–	–	0.55 $\pm$ 0.02	0.52 $\pm$ 0.03	0.51 $\pm$ 0.03	–
(1, 1)	–	–	–	–	0.56 $\pm$ 0.10	0.56 $\pm$ 0.16	–	–
(2, 0)	–	–	–	–	0.78 $\pm$ 0.04	0.72 $\pm$ 0.06	0.54 $\pm$ 0.04	0.28 $\pm$ 0.01
(2, 1)	–	–	–	–	0.82 $\pm$ 0.16	0.71 $\pm$ 0.20	0.78 $\pm$ 0.18	0.24 $\pm$ 0.03
(2, 2)	–	–	–	–	0.64 $\pm$ 0.42	1.93 $\pm$ 1.63	0.52 $\pm$ 0.55	–
(3, 0)	–	–	–	–	0.72 $\pm$ 0.04	0.64 $\pm$ 0.04	0.67 $\pm$ 0.03	0.26 $\pm$ 0.01
(3, 1)	–	–	–	–	0.78 $\pm$ 0.10	0.68 $\pm$ 0.11	1.02 $\pm$ 0.17	0.26 $\pm$ 0.03
(3, 2)	–	–	–	–	0.71 $\pm$ 0.28	0.89 $\pm$ 0.55	0.63 $\pm$ 0.28	0.21 $\pm$ 0.07
(3, $\geq$ 3)	–	–	–	–	–	–	–	–
(4, 0)	–	–	–	–	0.83 $\pm$ 0.05	0.73 $\pm$ 0.05	0.58 $\pm$ 0.03	0.27 $\pm$ 0.01
(4, 1)	–	–	–	–	0.72 $\pm$ 0.11	0.85 $\pm$ 0.15	0.69 $\pm$ 0.09	0.29 $\pm$ 0.03
(4, 2)	–	–	–	–	0.75 $\pm$ 0.25	0.70 $\pm$ 0.30	0.31 $\pm$ 0.10	0.27 $\pm$ 0.06
(4, $\geq$ 3)	–	–	–	–	577.40 $\pm$ 664.02	0.38 $\pm$ 0.44	0.26 $\pm$ 0.31	0.04 $\pm$ 0.05
($\geq$ 5, 0)	–	–	–	–	0.89 $\pm$ 0.13	0.71 $\pm$ 0.08	0.57 $\pm$ 0.04	0.30 $\pm$ 0.01
($\geq$ 5, 1)	–	–	–	–	0.79 $\pm$ 0.22	0.57 $\pm$ 0.12	0.48 $\pm$ 0.07	0.26 $\pm$ 0.02
($\geq$ 5, 2)	–	–	–	–	0.85 $\pm$ 0.54	0.40 $\pm$ 0.16	0.43 $\pm$ 0.15	0.22 $\pm$ 0.04
($\geq$ 5, $\geq$ 3)	–	–	–	–	–	–	1.40 $\pm$ 1.47	0.52 $\pm$ 0.33
(2a, 0)	–	–	–	–	0.65 $\pm$ 0.05	0.55 $\pm$ 0.07	0.55 $\pm$ 0.07	–
(2a, 1)	–	–	–	–	1.08 $\pm$ 0.36	0.54 $\pm$ 0.24	–	–
(2a, 2)	–	–	–	–	–	–	–	–
(3a, 0)	–	–	–	–	0.67 $\pm$ 0.07	0.61 $\pm$ 0.12	0.80 $\pm$ 0.18	–
(3a, 1)	–	–	–	–	0.70 $\pm$ 0.21	0.26 $\pm$ 0.13	0.66 $\pm$ 0.43	–
(3a, 2)	–	–	–	–	0.72 $\pm$ 0.46	1.27 $\pm$ 1.39	–	–
(3a, $\geq$ 3)	–	–	–	–	–	–	–	–
(4a, 0)	–	–	–	–	0.74 $\pm$ 0.07	0.67 $\pm$ 0.14	0.42 $\pm$ 0.12	–
(4a, 1)	–	–	–	–	0.85 $\pm$ 0.20	0.34 $\pm$ 0.16	0.51 $\pm$ 0.35	–
(4a, 2)	–	–	–	–	1.01 $\pm$ 0.65	–	–	–
(4a, $\geq$ 3)	–	–	–	–	0.00 $\pm$ 0.00	–	–	–
($\geq$ 5a, 0)	–	–	–	–	0.69 $\pm$ 0.09	0.65 $\pm$ 0.17	0.87 $\pm$ 0.28	–
($\geq$ 5a, 1)	–	–	–	–	1.00 $\pm$ 0.38	0.52 $\pm$ 0.23	1.99 $\pm$ 1.90	–
($\geq$ 5a, 2)	–	–	–	–	0.75 $\pm$ 0.54	6.79 $\pm$ 6.43	–	–
($\geq$ 5a, $\geq$ 3)	–	–	–	–	–	–	–	–

Table A3.4: Transfer factors from the γ + jets control region for the prediction of the $Z \rightarrow \nu\bar{\nu}$ background per analysis bin, where asymmetric categories are represented by the suffix a .

Systematic uncertainties

The systematic uncertainties measured in the analysis bins for the variation and closure test methods are summarised in Figure A4.1–A4.15 and Figure A4.16–A4.20 respectively.

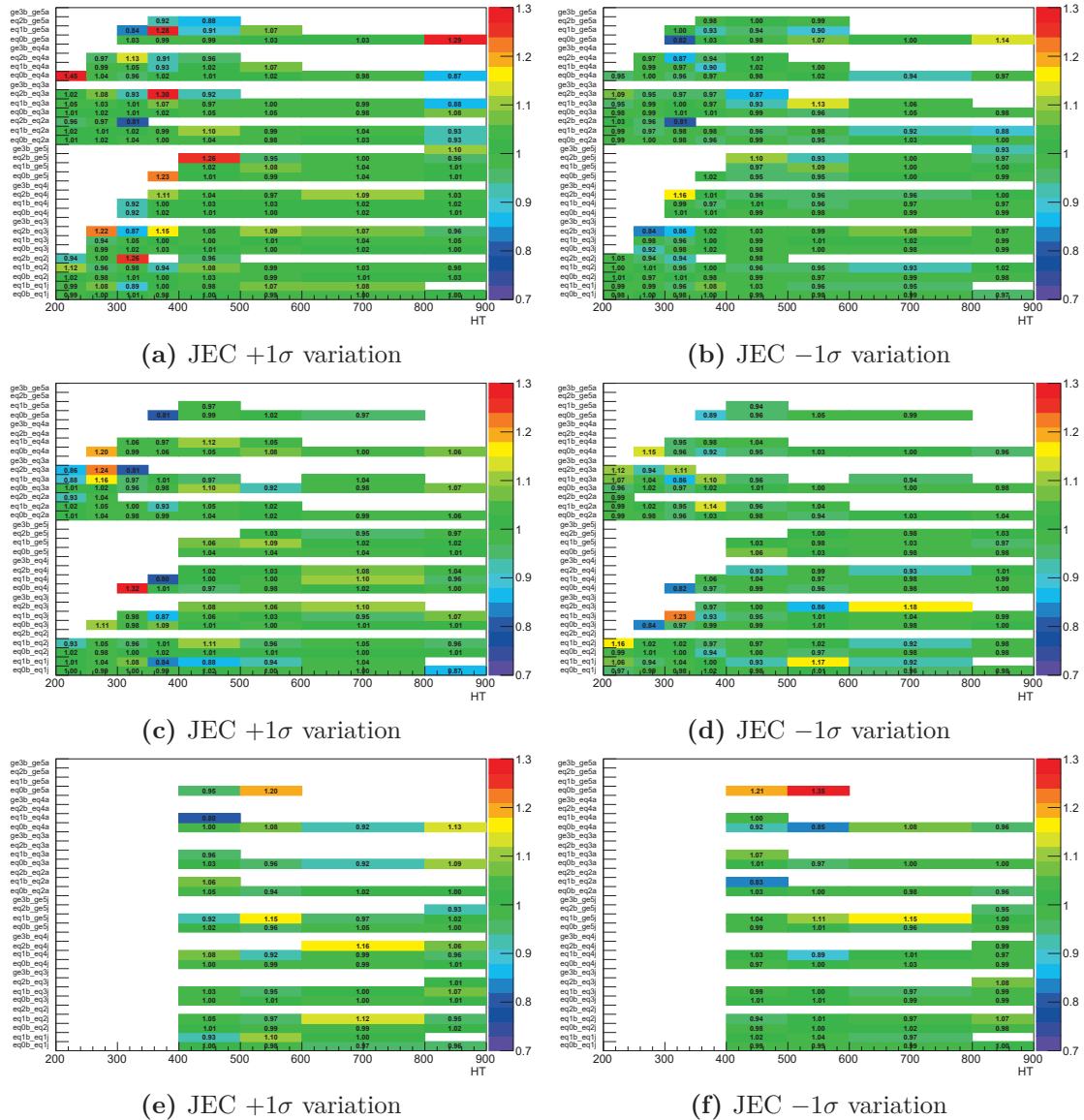


Figure A4.1: The relative change in $\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ (top), $\mu\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ (middle) and $\gamma + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ (bottom) transfer factors with respect to the nominal jet energy correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.

4 Systematic uncertainties

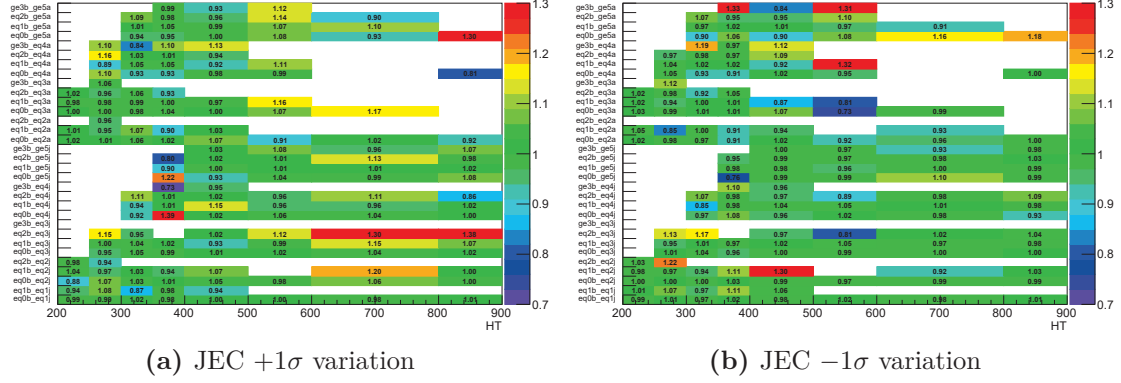


Figure A4.2: The relative change in $\mu + \text{jets} \rightarrow (t\bar{t} + W)$ transfer factors with respect to the nominal jet energy correction for a +1 σ (left) and -1 σ (right) variation as a function of total hadronic energy and jet category.

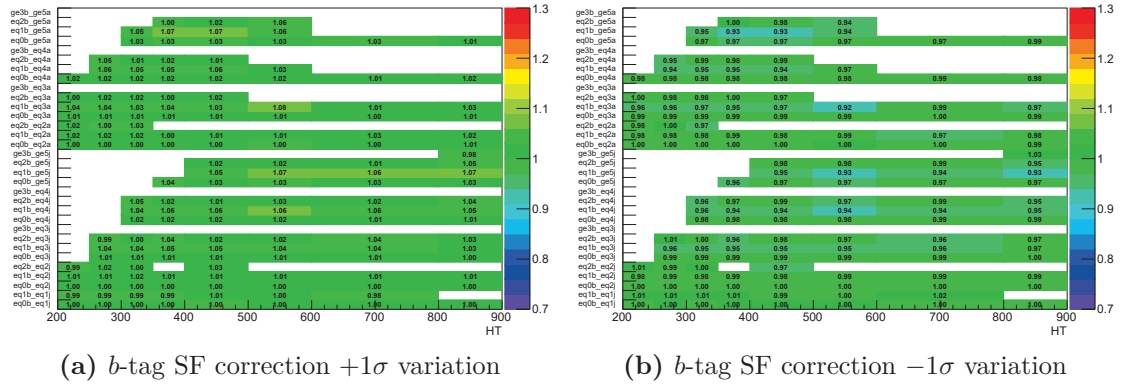


Figure A4.3: The relative change in $\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ transfer factors with respect to the nominal b -tag scale factor correction for a +1 σ (left) and -1 σ (right) variation as a function of total hadronic energy and jet category.

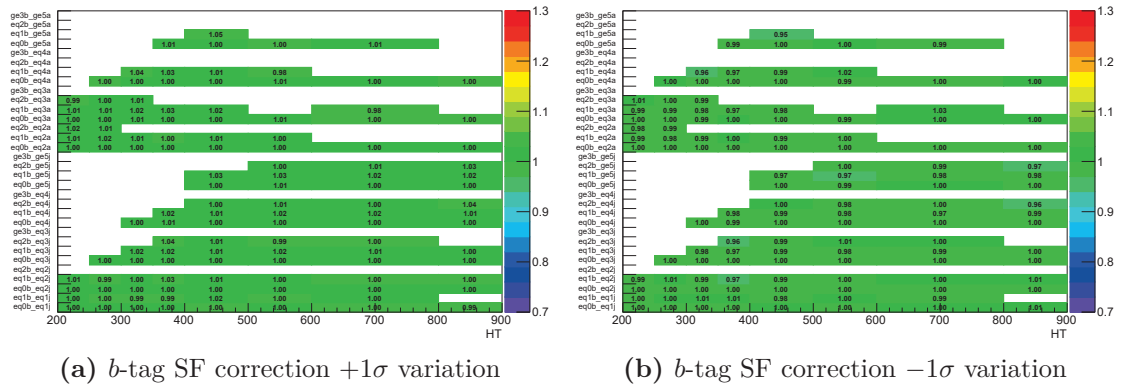


Figure A4.4: The relative change in $\mu\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ transfer factors with respect to the nominal b -tag scale factor correction for a +1 σ (left) and -1 σ (right) variation as a function of total hadronic energy and jet category.

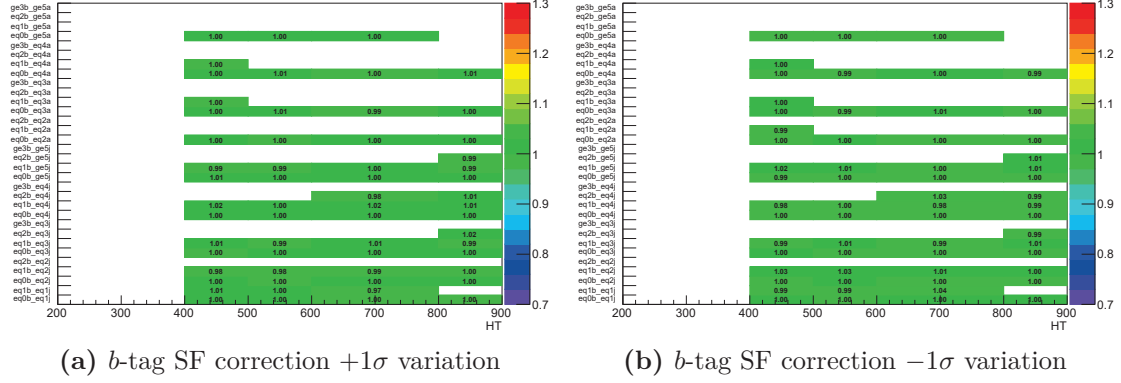


Figure A4.5: The relative change in $\gamma + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ transfer factors with respect to the nominal b -tag scale factor correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.

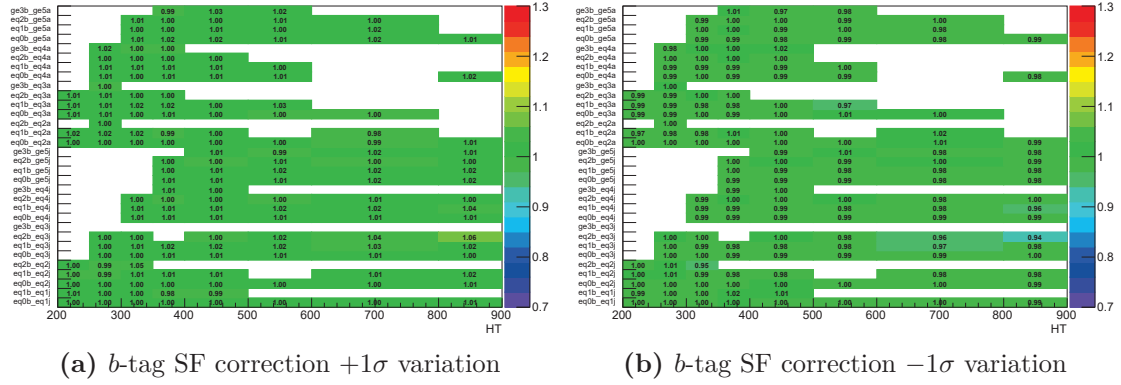


Figure A4.6: The relative change in $\mu + \text{jets} \rightarrow (t\bar{t} + W)$ transfer factors with respect to the nominal b -tag scale factor correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.

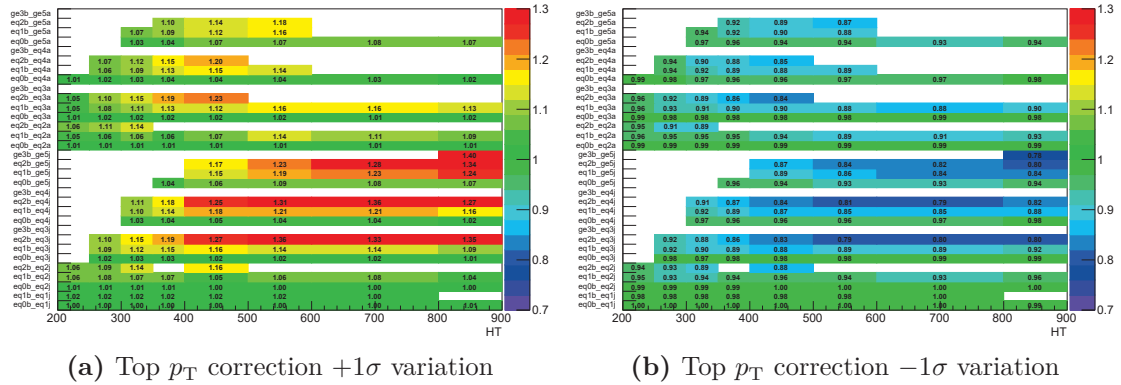


Figure A4.7: The relative change in $\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ transfer factors with respect to the nominal top p_T correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.

4 Systematic uncertainties

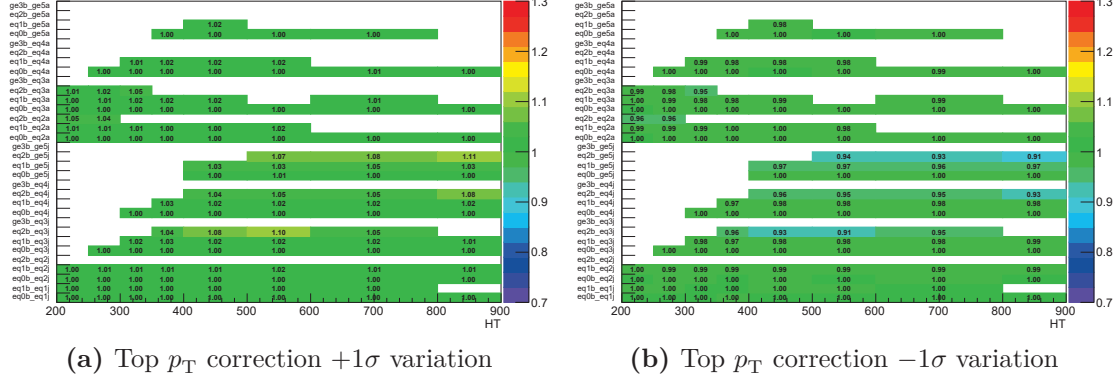


Figure A4.8: The relative change in $\mu\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ transfer factors with respect to the nominal top p_T correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.

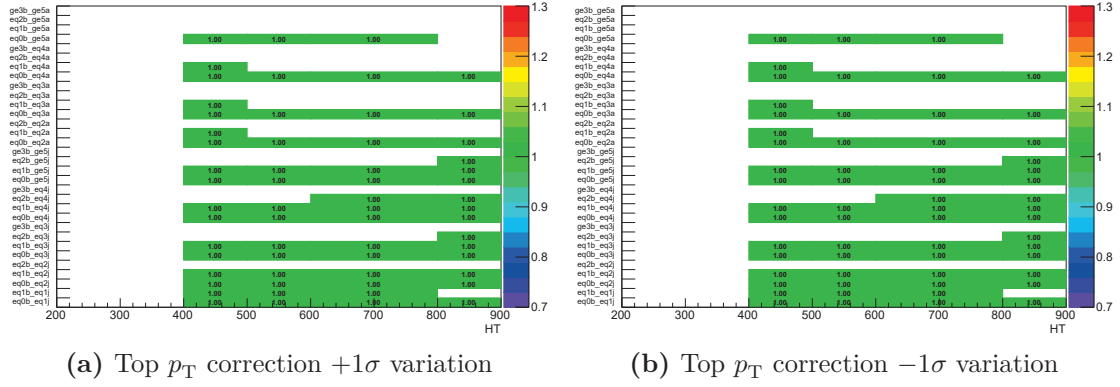


Figure A4.9: The relative change in $\gamma + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ transfer factors with respect to the nominal top p_T correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.

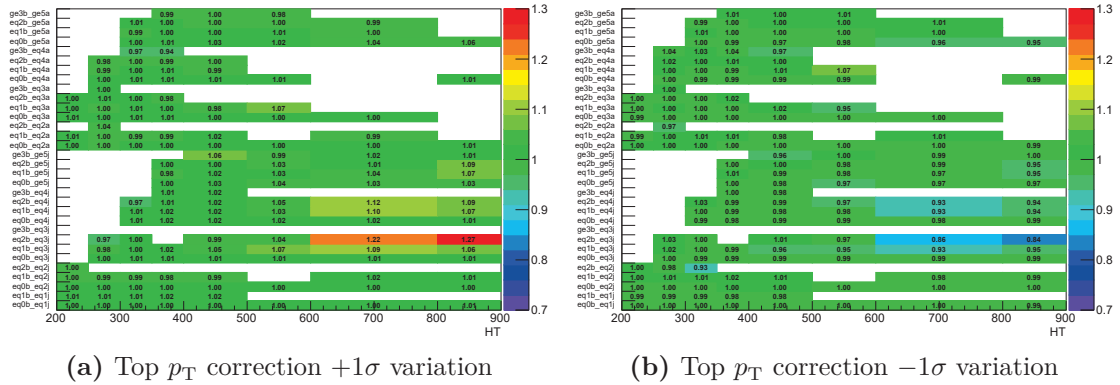


Figure A4.10: The relative change in $\gamma + \text{jets} \rightarrow (t\bar{t} + W)$ transfer factors with respect to the nominal top p_T correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.

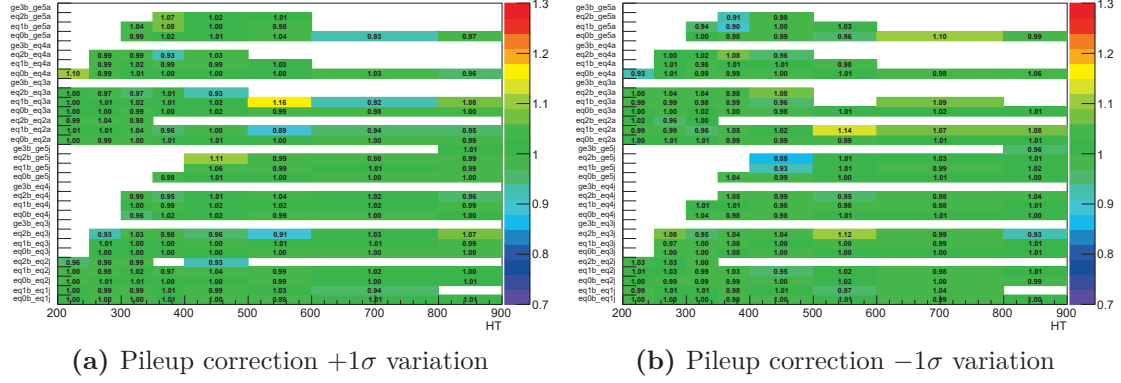


Figure A4.11: The relative change in $\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ transfer factors with respect to the nominal pileup correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.

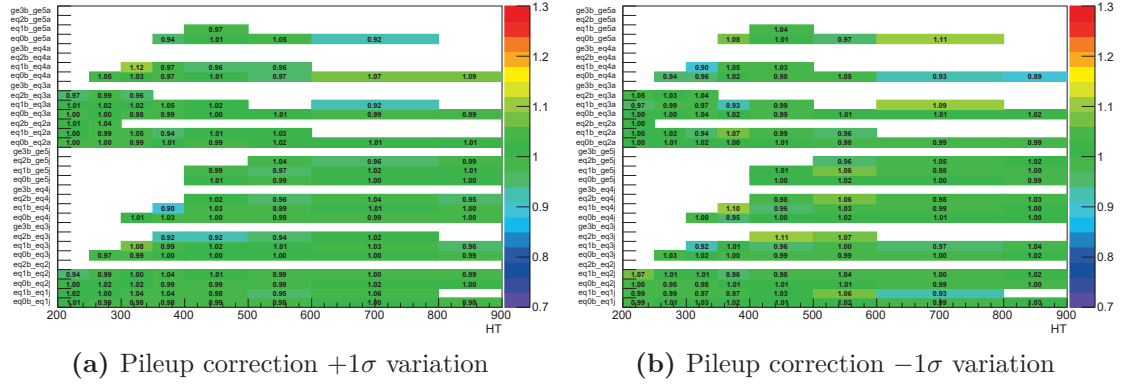


Figure A4.12: The relative change in $\mu\mu + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ transfer factors with respect to the nominal pileup correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.

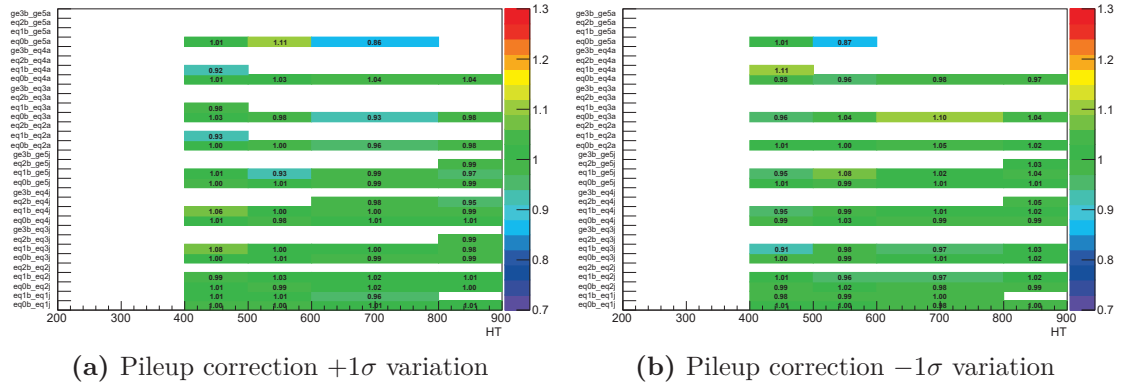
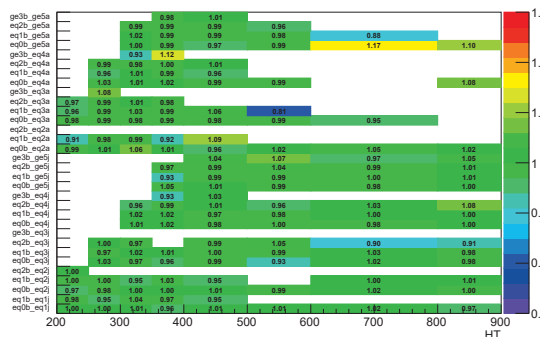
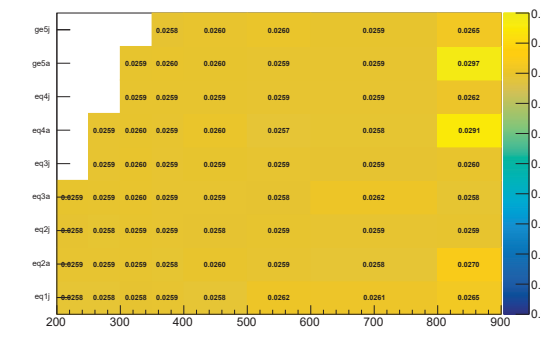


Figure A4.13: The relative change in $\gamma + \text{jets} \rightarrow (Z \rightarrow \nu\bar{\nu})$ transfer factors with respect to the nominal pileup correction for a $+1\sigma$ (left) and -1σ (right) variation as a function of total hadronic energy and jet category.



(b) Pileup correction -1σ variation



(d) Electron SF correction -1 σ variation

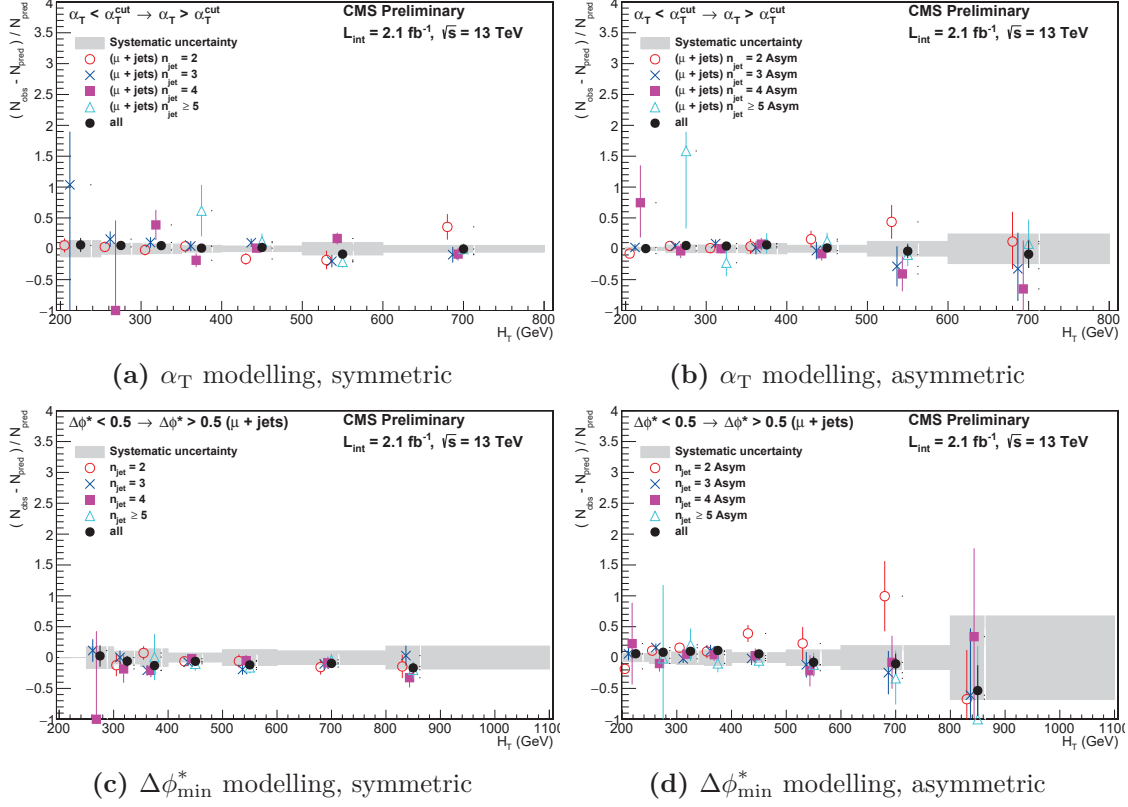


Figure A4.16: The measure of closure in the modelling of the α_T (top) and $\Delta\phi_{\text{min}}^*$ (bottom) variables for the symmetric (left) and asymmetric (right) jet categories as a function of H_T . The closure for each jet multiplicity and their quadrature sum are shown by the coloured and solid black points respectively, with the estimated total systematic uncertainty shown by the shaded bands.

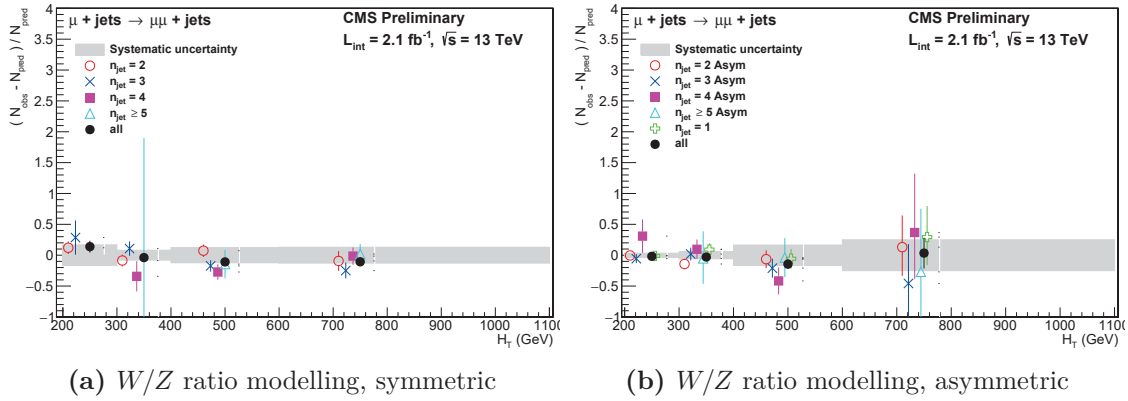


Figure A4.17: The measure of closure in the modelling of the W/Z ratio for the symmetric (left) and asymmetric (right) jet categories as a function of H_T . The closure for each jet multiplicity and their quadrature sum are shown by the coloured and solid black points respectively, with the estimated total systematic uncertainty shown by the shaded bands.

4 Systematic uncertainties

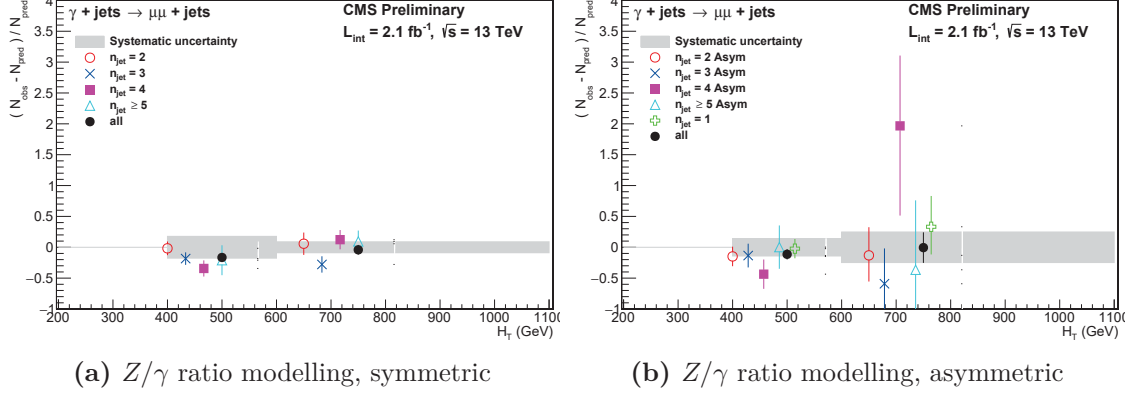


Figure A4.18: The measure of closure in the modelling of the Z/γ ratio for the symmetric (left) and asymmetric (right) jet categories as a function of H_T . The closure for each jet multiplicity and their quadrature sum are shown by the coloured and solid black points respectively, with the estimated total systematic uncertainty shown by the shaded bands.

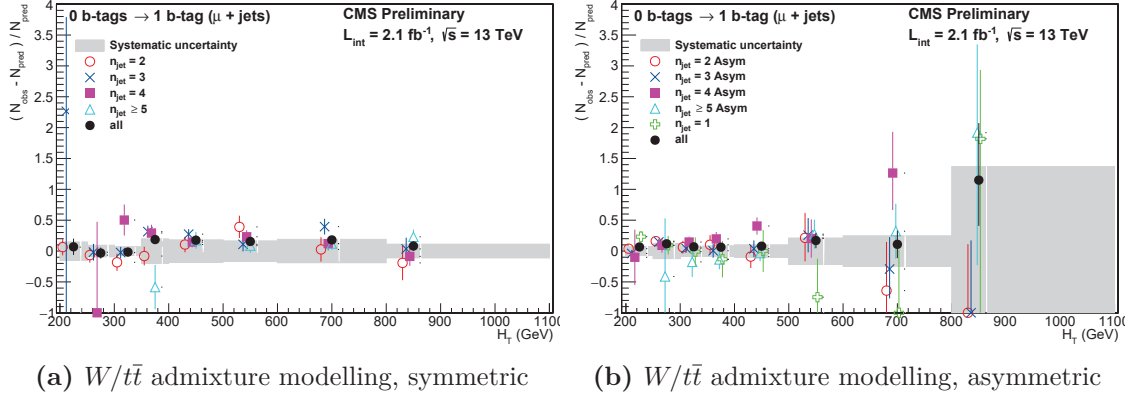


Figure A4.19: The measure of closure in the modelling of the $W/t\bar{t}$ admixture for the symmetric (left) and asymmetric (right) jet categories as a function of H_T . The closure for each jet multiplicity and their quadrature sum are shown by the coloured and solid black points respectively, with the estimated total systematic uncertainty shown by the shaded bands.

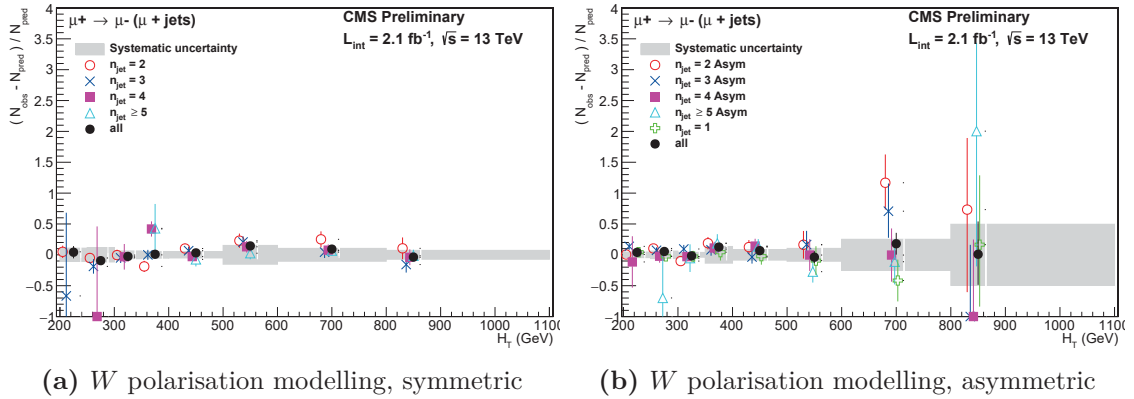


Figure A4.20: The measure of closure in the modelling of the W polarisation for the symmetric (left) and asymmetric (right) jet categories as a function of H_T . The closure for each jet multiplicity and their quadrature sum are shown by the coloured and solid black points respectively, with the estimated total systematic uncertainty shown by the shaded bands.

APPENDIX 5

$\mathcal{H}_T$ linear fit compatibility

The measured pull distributions of the $\mathcal{H}_T$ template fit in data control regions are shown in Figure A5.1.

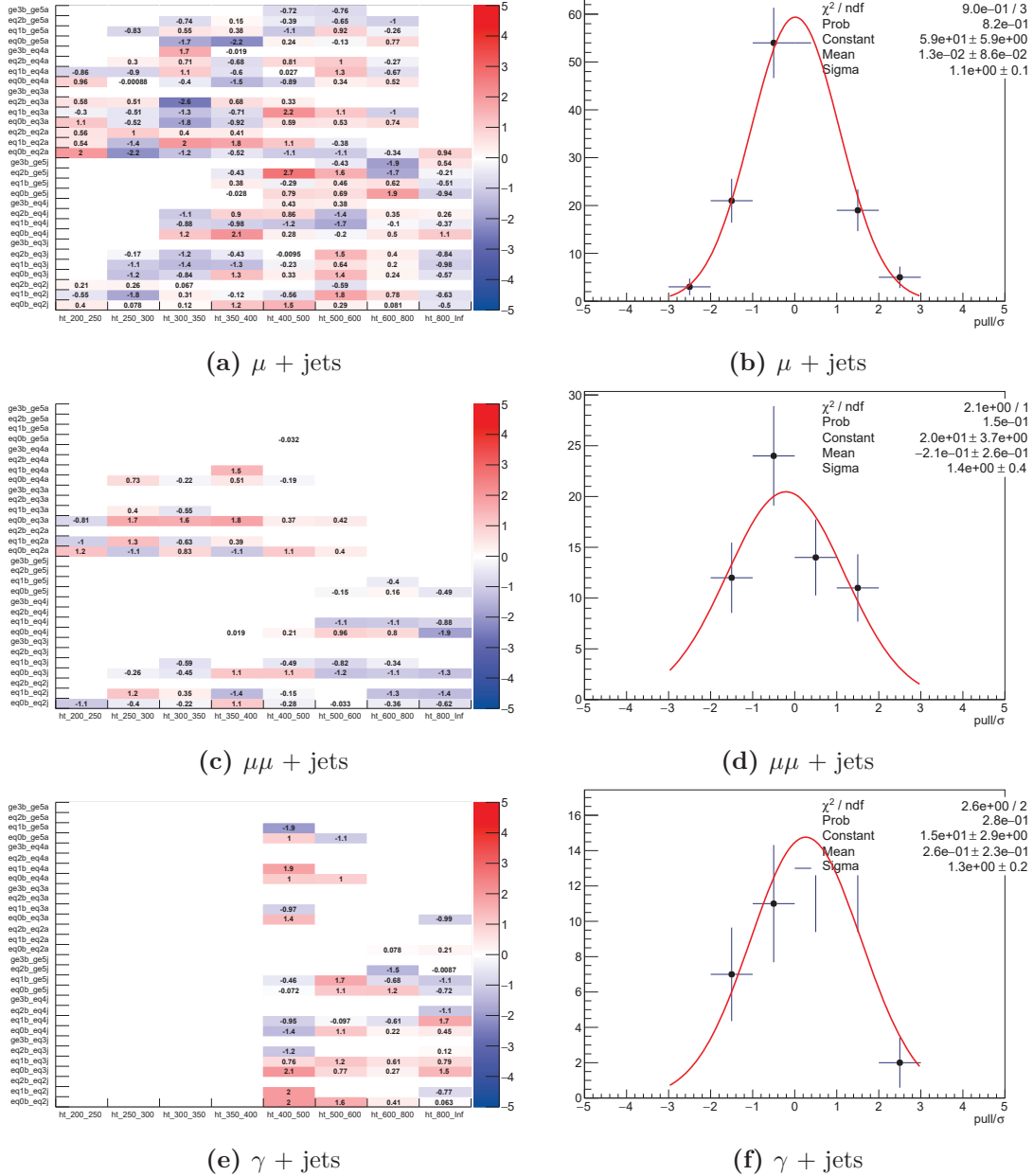


Figure A5.1: Measured pull of the linear parameter from the flat hypothesis as a function of (H_T, n_{jet}) bin (left) and inclusive of analysis binning (right) for the $\mu + \text{jets}$ (top), $\mu\mu + \text{jets}$ (middle) and $\gamma + \text{jets}$ (bottom) data control regions.

APPENDIX 6

Acceptance of signal models

The total signal acceptance from a selection of the four most sensitive categories, $\epsilon_{\text{sig}}^{4\text{cat}}$, and the ratio of acceptances for a selection for the four most sensitive categories to the acceptance using all categories, $\epsilon_{\text{sig}}^{\text{tot}}$, across the parameterised simplified model space are shown in Figure A6.2-A6.4.

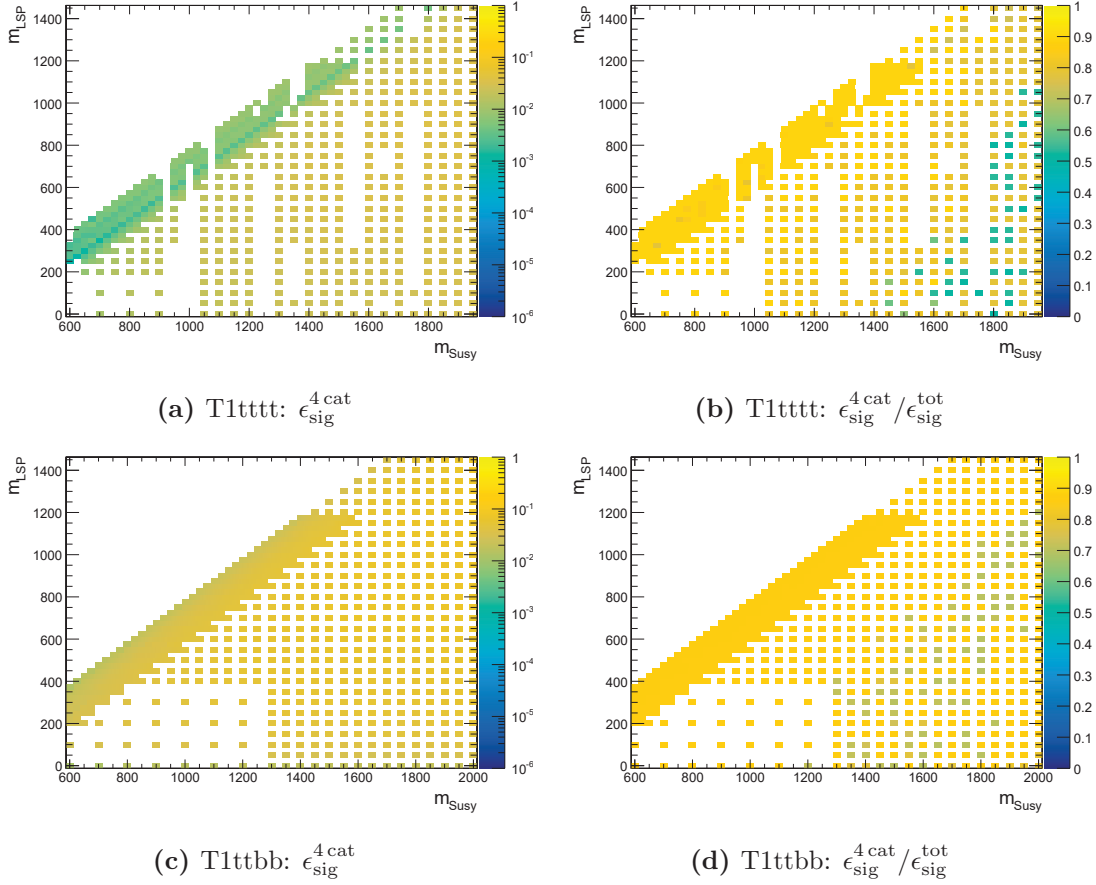


Figure A6.1: Signal acceptance in the $(m_{\text{SUSY}}, m_{\text{LSP}})$ plane for T1 simplified models. Signal acceptance considering only the four most sensitive categories (left) and the ratio of signal acceptance for the four most sensitive categories to the total signal acceptance (right).

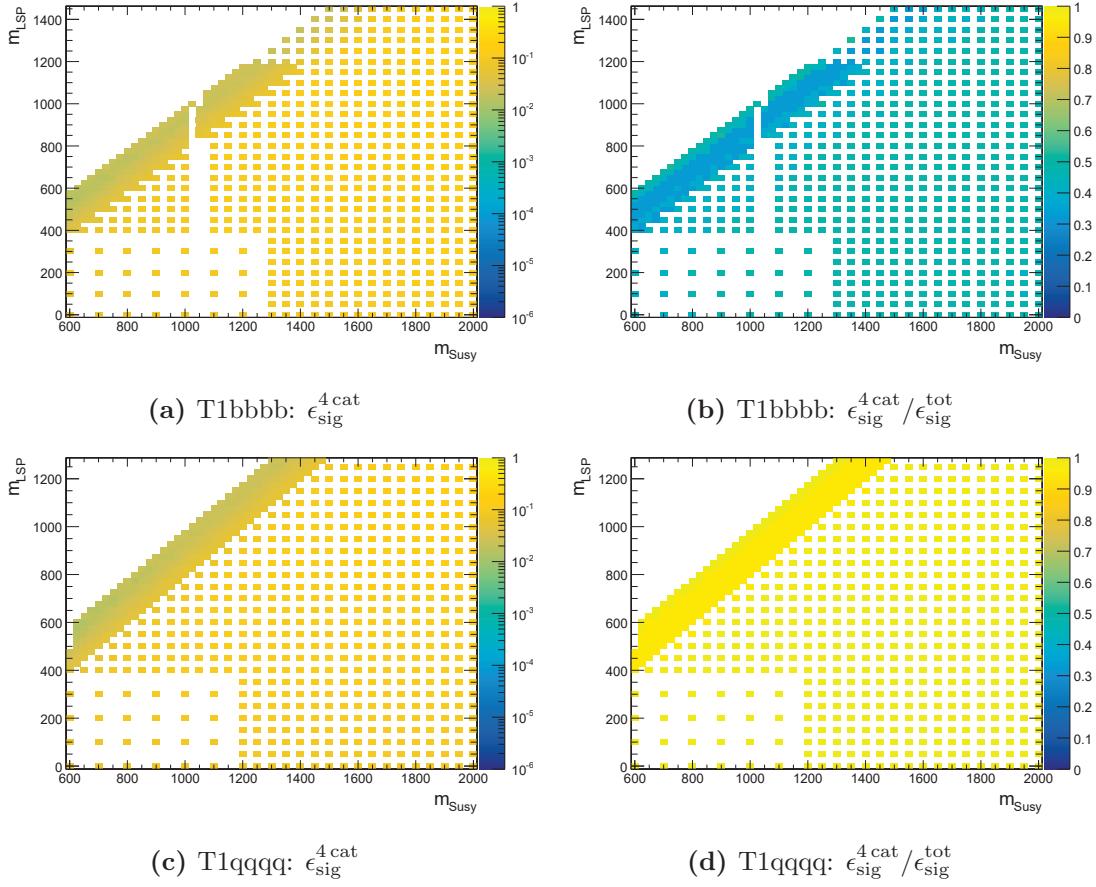


Figure A6.2: Signal acceptance in the $(m_{\text{SUSY}}, m_{\text{LSP}})$ plane for T1 simplified models. Signal acceptance considering only the four most sensitive categories (left) and the ratio of signal acceptance for the four most sensitive categories to the total signal acceptance (right).

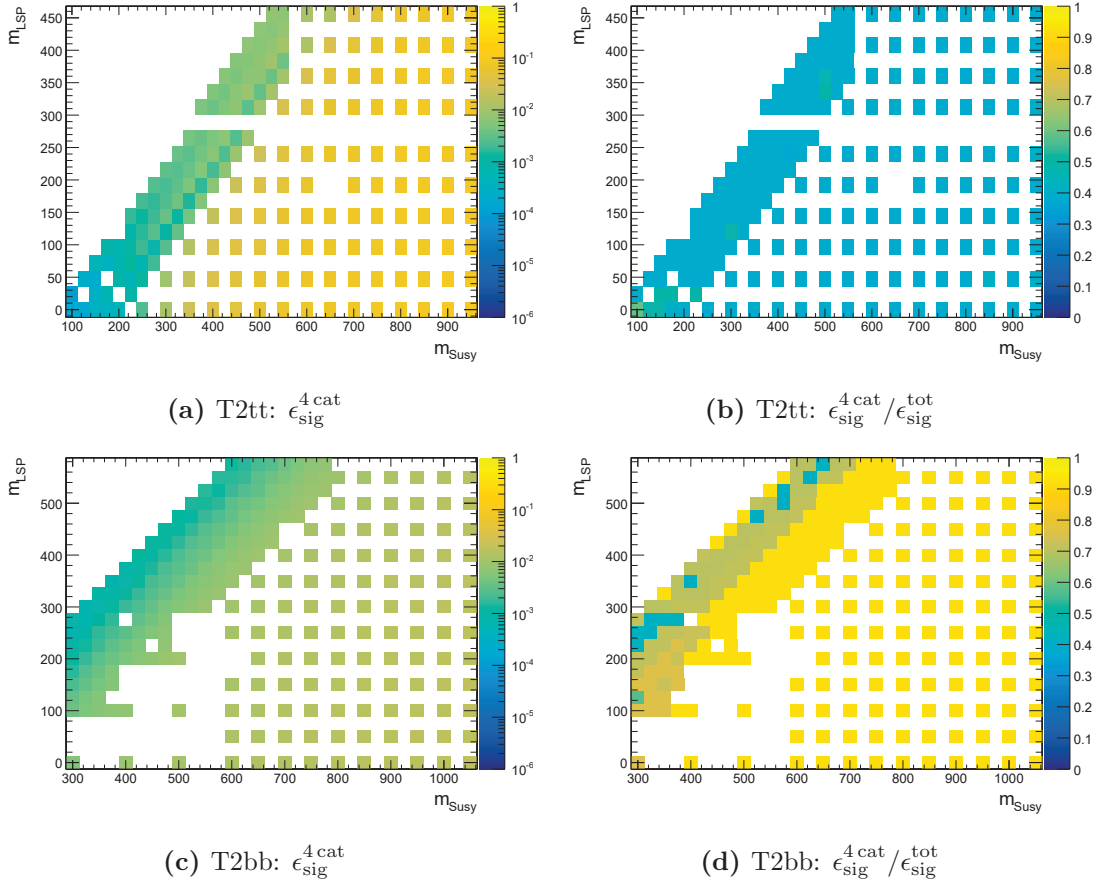


Figure A6.3: Signal acceptance in the $(m_{\text{SUSY}}, m_{\text{LSP}})$ plane for T2 simplified models. Signal acceptance considering only the four most sensitive categories (left) and the ratio of signal acceptance for the four most sensitive categories to the total signal acceptance (right).

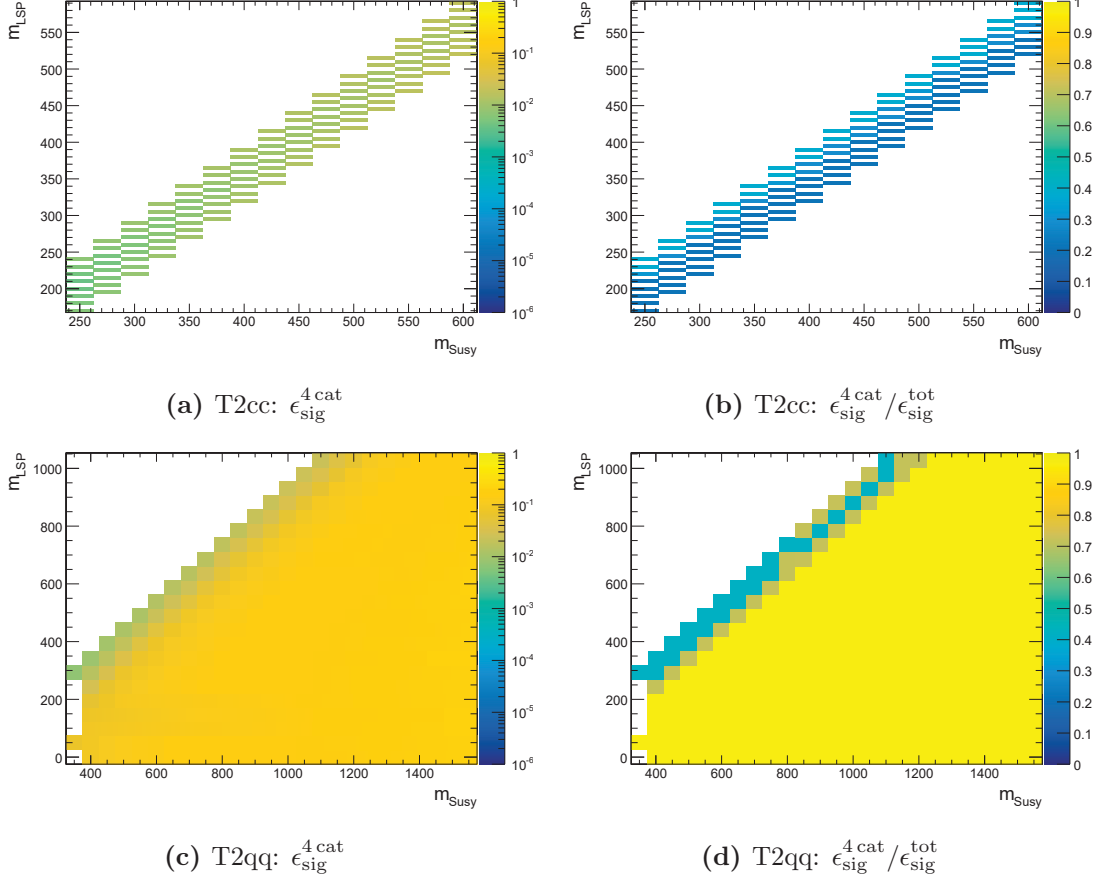


Figure A6.4: Signal acceptance in the $(m_{\text{SUSY}}, m_{\text{LSP}})$ plane for T2 simplified models. Signal acceptance considering only the four most sensitive categories (left) and the ratio of signal acceptance for the four most sensitive categories to the total signal acceptance (right).

APPENDIX 7

Nuisance parameters

The pull of the parameters with respect to the pre-fit value are shown in Figures A7.1–A7.9, where the nuisance are group by type and, where pertinent, as symmetric or asymmetric topologies, where the later also includes monojet topologies.

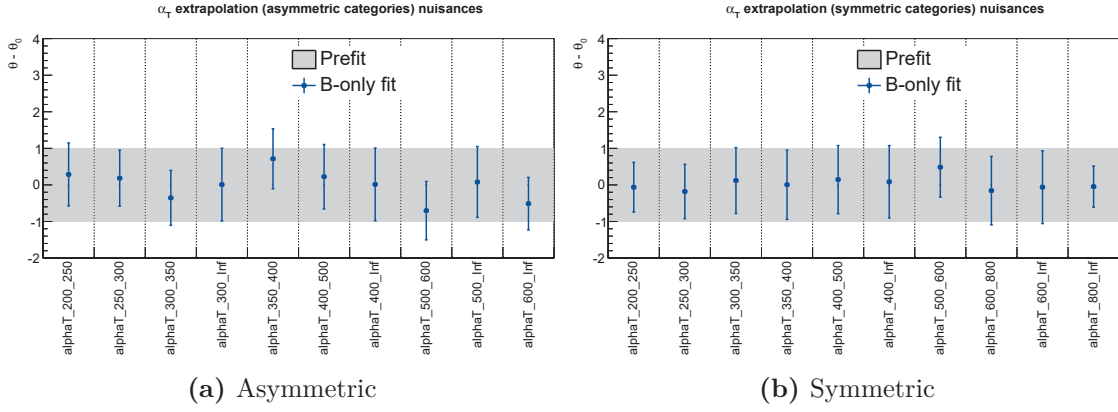


Figure A7.1: Pull of the nuisance parameters associated to the α_T -extrapolation systematic uncertainty, for the asymmetric (left) and symmetric (right) jet categories.

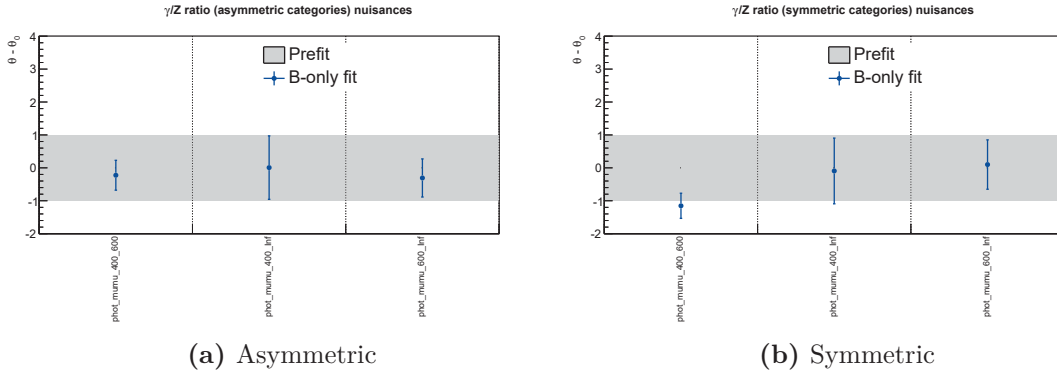


Figure A7.2: Pull of the nuisance parameters associated to the γ/Z ratio systematic uncertainty, for the asymmetric (left) and symmetric (right) jet categories.

7 Nuisance parameters

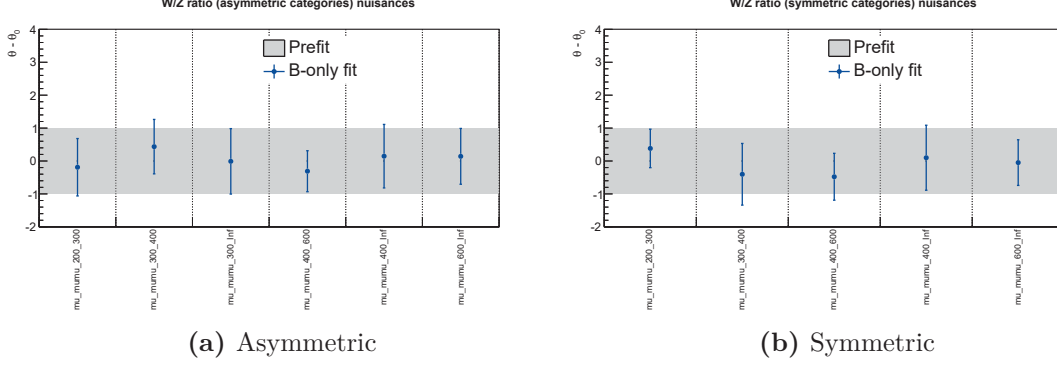


Figure A7.3: Pull of the nuisance parameters associated to the W/Z ratio systematic uncertainty, for the asymmetric (left) and symmetric (right) jet categories.

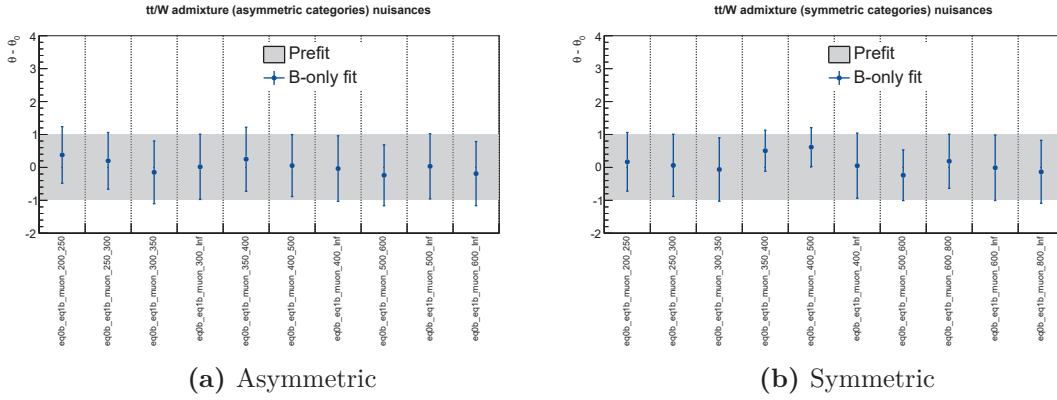


Figure A7.4: Pull of the nuisance parameters associated to the $t\bar{t} + W$ admixture systematic uncertainty, for the asymmetric (left) and symmetric (right) jet categories.

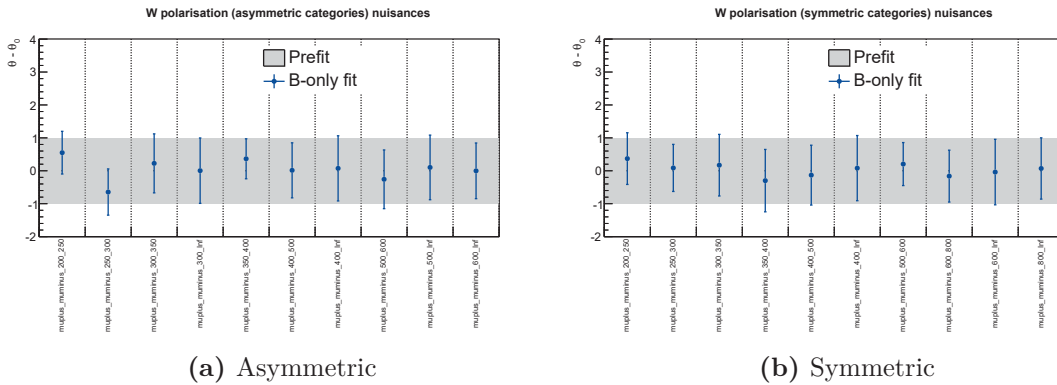
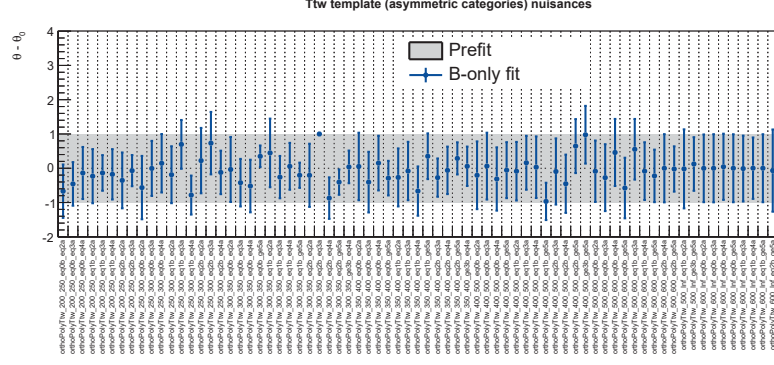
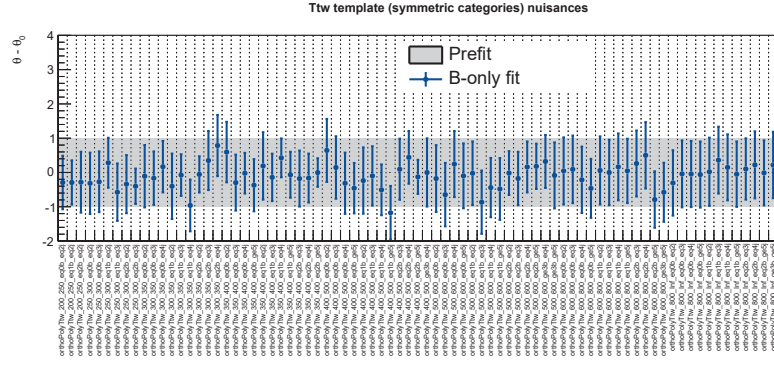


Figure A7.5: Pull of the nuisance parameters associated to the W polarisation systematic uncertainty, for the asymmetric (left) and symmetric (right) jet categories.

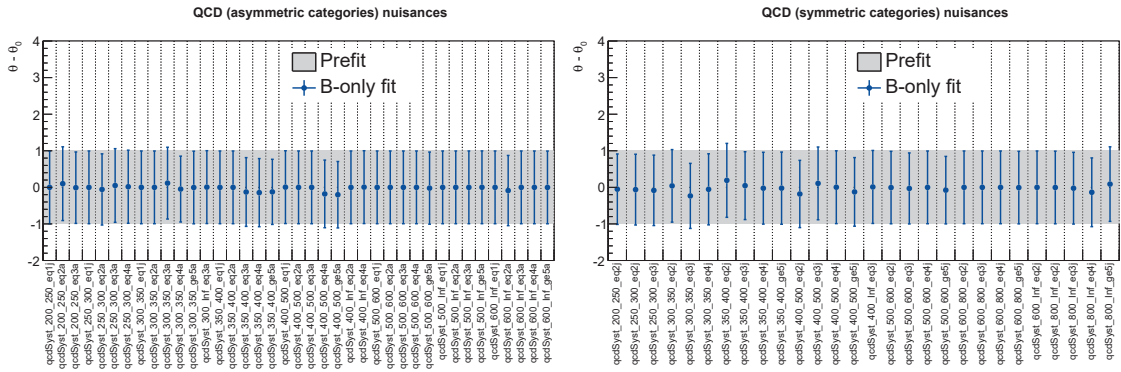


(a) Asymmetric

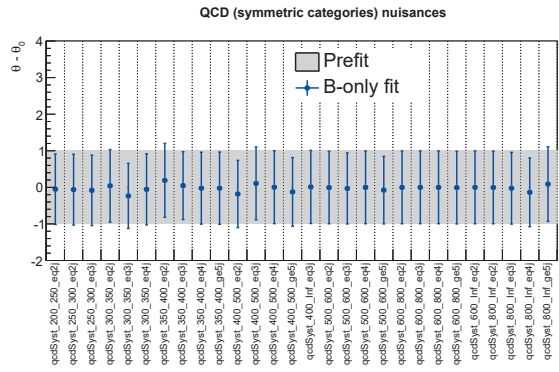


(b) Symmetric

Figure A7.6: Pull of the nuisance parameters associated to the $t\bar{t} + W$ template systematic uncertainty, for the asymmetric (top) and symmetric (bottom) jet categories.



(a) Asymmetric



(b) Symmetric

Figure A7.7: Pull of the nuisance parameters associated to the QCD systematic uncertainty, for the asymmetric (left) and symmetric (right) jet categories.

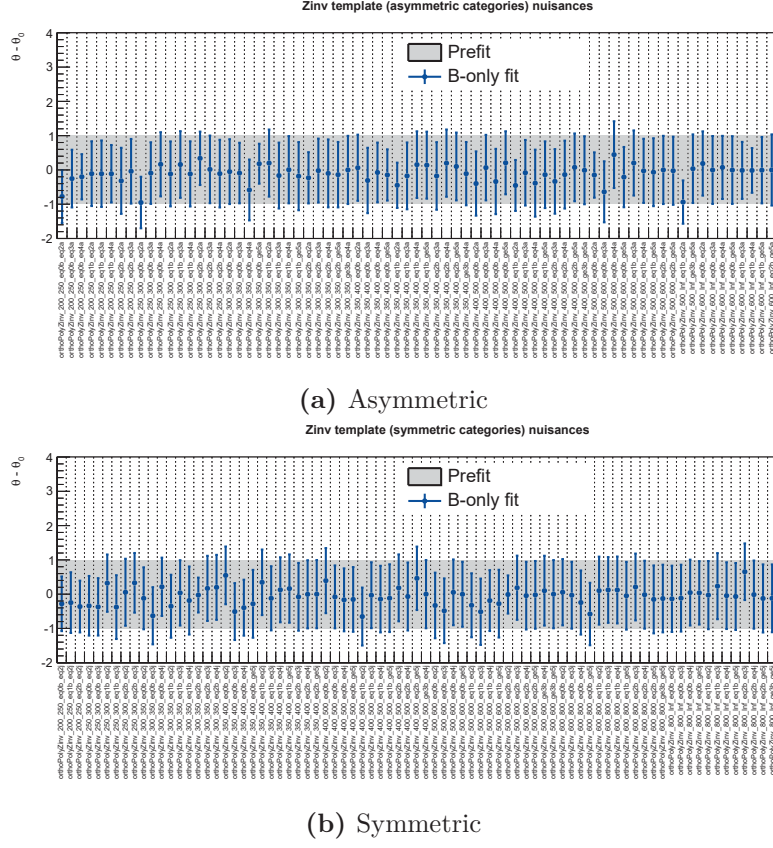


Figure A7.8: Pull of the nuisance parameters associated to the $t\bar{t} + W$ template systematic uncertainty, for the asymmetric (top) and symmetric (bottom) jet categories.

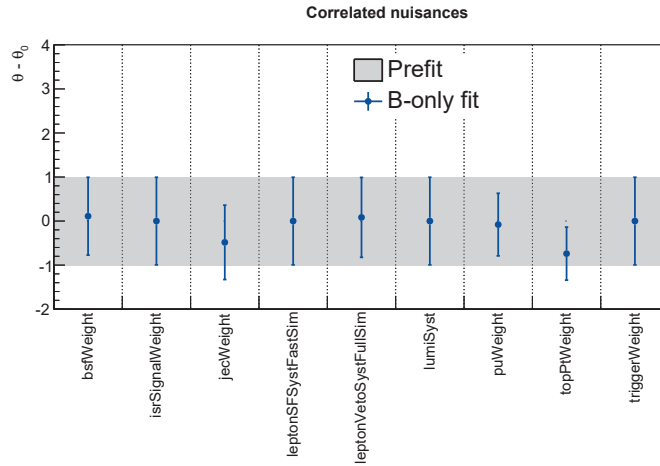


Figure A7.9: Pull of the nuisance parameters associated to the correlated systematic uncertainties.

APPENDIX 8

Signal region modelling

A comparison of the modelling of the key analysis variables for the analysis backgrounds with observed data yields in the hadronic signal region are summarised in Figures A8.2–A8.4.

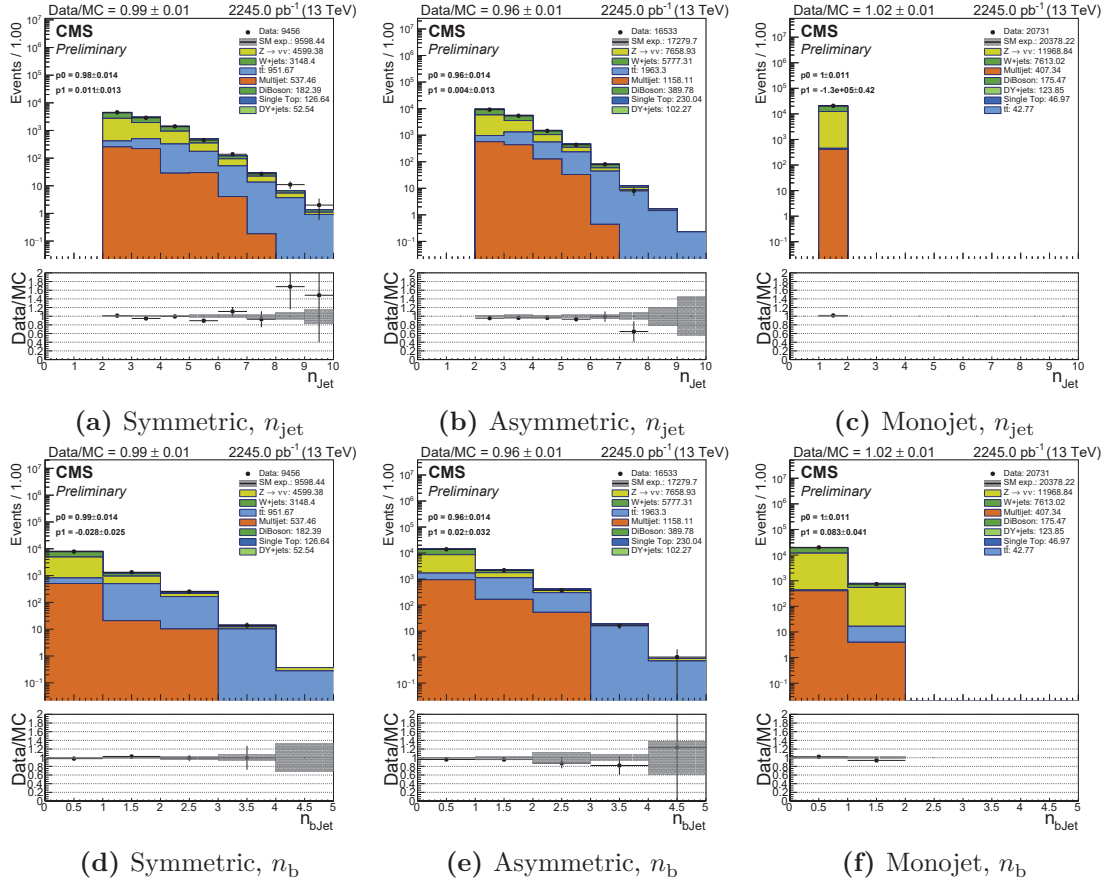


Figure A8.1: Distributions of reconstructed jet multiplicities in the signal region following all analysis selections from simulation after the application of analysis corrections (coloured histograms) and yields measured in data (black circles) for the symmetric (left), asymmetric (middle) and monojet (right) jet categories.

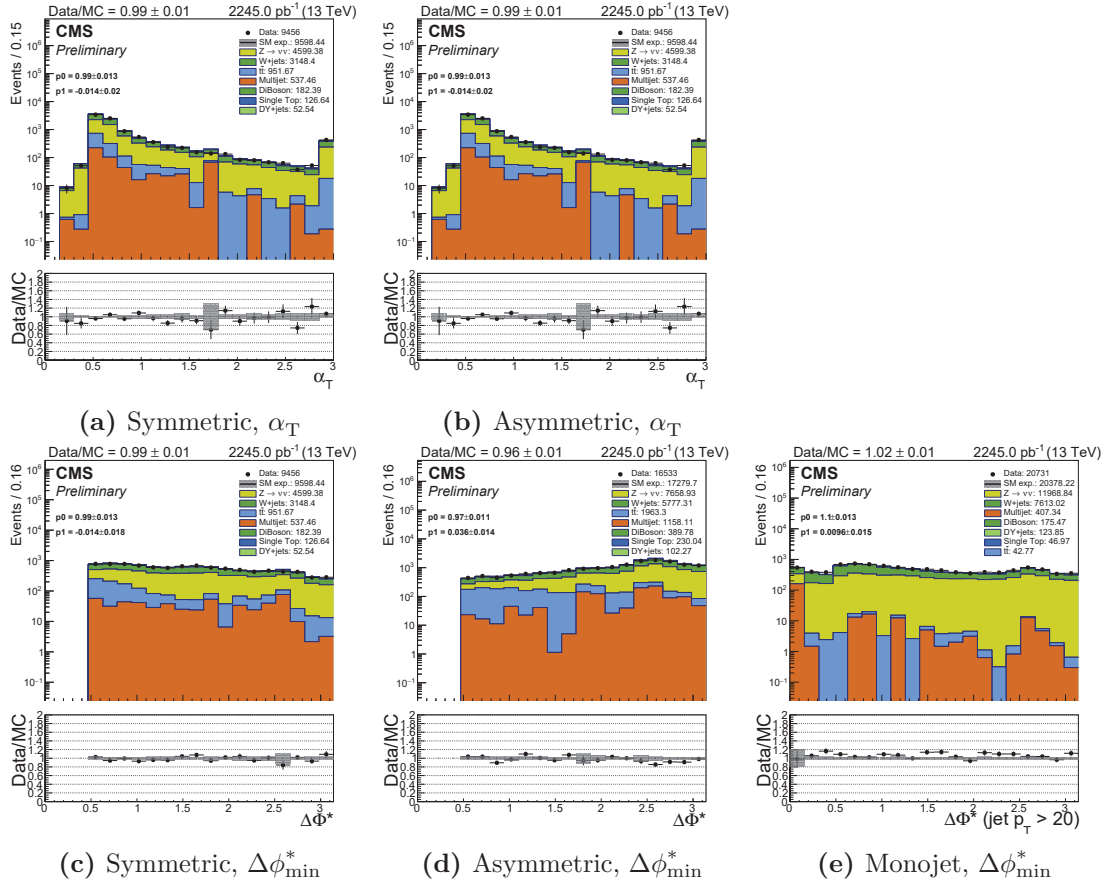


Figure A8.2: Distributions of the analysis QCD control variables in the signal region following all analysis selections from simulation after the application of analysis corrections (coloured histograms) and yields measured in data (black circles) for the symmetric (left), asymmetric (middle) and monojet (right) jet categories. No α_T distribution is shown for the monojet category as the computation requires a minimum of two jets.

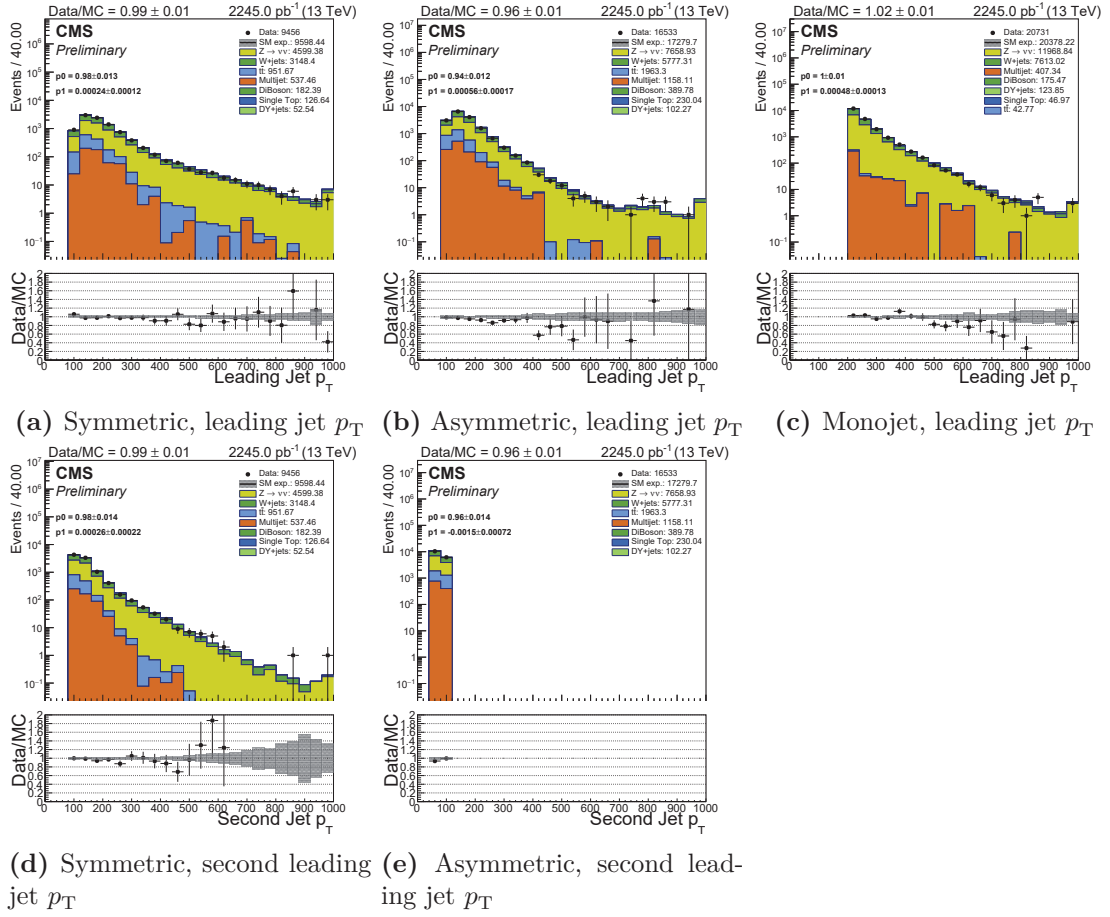


Figure A8.3: Distributions of reconstructed jet momenta in the signal region following all analysis selections from simulation after the application of analysis corrections (coloured histograms) and yields measured in data (black circles) for the symmetric (left), asymmetric (middle) and monojet (right) jet categories.

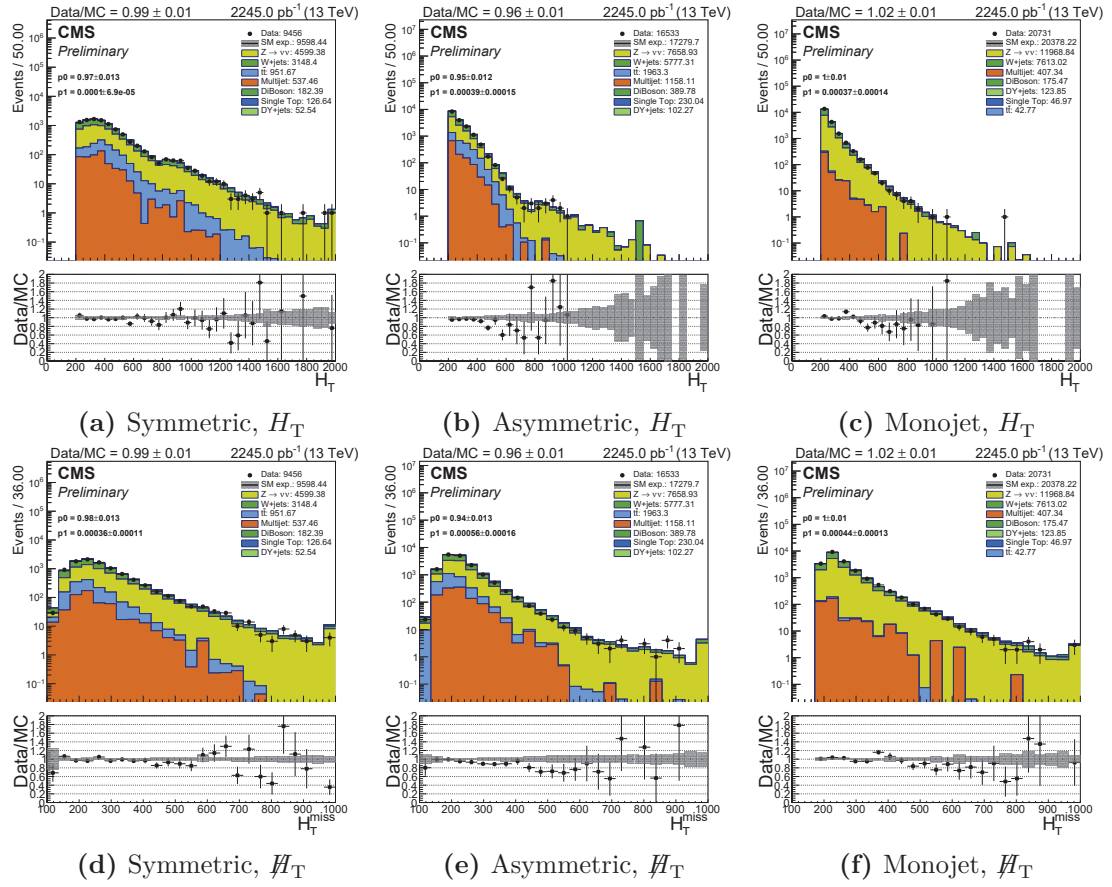


Figure A8.4: Distributions of reconstructed energy variables in the signal region following all analysis selections from simulation after the application of analysis corrections (coloured histograms) and yields measured in data (black circles) for the symmetric (left), asymmetric (middle) and monojet (right) jet categories.

APPENDIX 9

Event yields

A summary of the predicted background yield and the observed data yields in the signal region corresponding to an integrated luminosity of 2.3 fb^{-1} are summarised in Table A9.1–A9.6. The background components are split into: $t\bar{t} + W$, $Z \rightarrow \nu\bar{\nu}$ and QCD components, where $t\bar{t} + W$ is inclusive of residual contributions from sub-dominant processes such as diboson production. The numerical yields for the prefit and postfit predictions are further grouped by jet category which are shown for monojet, symmetric and asymmetric jet categories in Table A9.1–A9.2, Table A9.3–A9.4 and Table A9.5–A9.6 respectively.

		H_T (GeV)							
(n_{jet}, n_b)		200-250	250-300	300-350	350-400	400-500	500-600	600-800	800- ∞
Data	(1, 0)	13094	4130	1477	663	461	118	50	–
SM	(1, 0)	12319.3 ± 1003.0	4167.9 ± 450.4	1474.0 ± 136.6	560.1 ± 94.4	463.7 ± 79.9	146.0 ± 29.8	60.4 ± 27.4	–
Ttw	(1, 0)	5275.2 ± 546.4	1615.9 ± 247.3	504.4 ± 53.8	169.1 ± 32.2	135.8 ± 20.4	33.9 ± 9.0	13.9 ± 6.1	–
Zinv	(1, 0)	7044.1 ± 552.7	2552.0 ± 258.2	969.6 ± 100.7	391.0 ± 66.2	325.4 ± 67.8	112.1 ± 25.4	46.5 ± 23.2	–
QCD	(1, 0)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.5 ± 2.9	0.0 ± 0.0	0.0 ± 0.0	–
Data	(1, 1)	475	151	57	25	24	6	–	–
SM	(1, 1)	505.3 ± 66.8	169.6 ± 26.3	61.3 ± 9.0	21.4 ± 4.1	21.3 ± 4.4	4.8 ± 1.2	–	–
Ttw	(1, 1)	172.2 ± 27.2	51.2 ± 10.6	17.3 ± 3.0	5.4 ± 1.1	7.2 ± 1.4	1.0 ± 0.4	–	–
Zinv	(1, 1)	333.2 ± 41.8	118.4 ± 17.3	44.0 ± 6.5	16.0 ± 3.1	14.0 ± 3.4	3.7 ± 1.0	–	–
QCD	(1, 1)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	–	–

Table A9.1: Pre-fit predicted and observed data yield of monojet categories in the signal region for the full 2.3 fb^{-1} dataset.

		H_T (GeV)							
(n_{jet}, n_b)		200-250	250-300	300-350	350-400	400-500	500-600	600-800	800- ∞
Data	(1, 0)	13094	4130	1477	663	461	118	50	–
SM	(1, 0)	13011.4 ± 108.0	4133.6 ± 55.7	1480.8 ± 31.9	638.0 ± 21.4	439.5 ± 14.9	118.1 ± 7.3	51.2 ± 6.7	–
Ttw	(1, 0)	5564.7 ± 186.9	1574.9 ± 88.4	514.7 ± 27.5	190.7 ± 12.1	129.4 ± 10.1	27.8 ± 4.7	10.2 ± 3.4	–
Zinv	(1, 0)	7446.8 ± 201.3	2558.6 ± 99.3	966.0 ± 35.1	447.3 ± 19.3	307.4 ± 14.1	90.3 ± 6.0	41.1 ± 6.1	–
QCD	(1, 0)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	2.7 ± 2.7	0.0 ± 0.0	0.0 ± 0.0	–
Data	(1, 1)	475	151	57	25	24	6	–	–
SM	(1, 1)	488.4 ± 17.9	157.9 ± 11.2	58.1 ± 6.4	24.1 ± 3.9	20.8 ± 2.6	5.3 ± 1.4	–	–
Ttw	(1, 1)	167.0 ± 8.7	49.0 ± 4.6	16.1 ± 2.0	6.1 ± 1.0	7.1 ± 1.0	1.2 ± 0.4	–	–
Zinv	(1, 1)	321.3 ± 13.7	108.9 ± 8.4	42.0 ± 4.7	17.9 ± 3.0	13.6 ± 1.8	4.2 ± 1.1	–	–
QCD	(1, 1)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1	0.0 ± 0.0	–	–

Table A9.2: Post-fit predicted and observed data yield of monojet categories in the signal region for the full 2.3 fb^{-1} dataset.

9 Event yields

		H_T (GeV)							
(n_{jet}, n_b)		200-250	250-300	300-350	350-400	400-500	500-600	600-800	800- ∞
Data	(2, 0)	1167	1155	760	442	335	119	58	57
SM	(2, 0)	1104.5 ± 248.2	1156.7 ± 196.1	756.9 ± 92.7	417.8 ± 50.2	354.8 ± 47.2	117.5 ± 21.8	48.5 ± 8.1	57.8 ± 13.8
Ttw	(2, 0)	516.4 ± 127.7	519.3 ± 87.2	325.2 ± 42.4	158.8 ± 33.7	127.8 ± 26.9	39.7 ± 8.4	14.8 ± 3.3	18.2 ± 4.5
Zinv	(2, 0)	535.4 ± 131.8	610.4 ± 133.9	409.5 ± 55.3	237.5 ± 26.9	214.2 ± 31.0	76.4 ± 15.7	33.7 ± 6.1	39.5 ± 10.1
QCD	(2, 0)	52.6 ± 60.1	27.0 ± 26.1	22.3 ± 23.3	21.4 ± 23.5	12.8 ± 12.8	1.4 ± 1.4	0.0 ± 0.0	0.2 ± 0.2
Data	(2, 1)	137	115	76	40	39	5	4	2
SM	(2, 1)	112.7 ± 25.7	91.0 ± 15.8	53.3 ± 8.2	31.6 ± 4.8	31.3 ± 4.6	12.0 ± 2.4	4.9 ± 0.9	4.4 ± 1.3
Ttw	(2, 1)	69.0 ± 17.3	47.7 ± 8.9	24.6 ± 4.4	11.5 ± 2.8	10.5 ± 2.3	4.0 ± 0.9	1.3 ± 0.3	1.3 ± 0.4
Zinv	(2, 1)	38.3 ± 9.6	41.2 ± 9.1	27.1 ± 4.4	18.5 ± 2.6	19.6 ± 3.0	7.8 ± 1.7	3.6 ± 0.7	3.1 ± 0.9
QCD	(2, 1)	5.4 ± 6.1	2.1 ± 2.1	1.6 ± 1.6	1.6 ± 1.8	1.1 ± 1.1	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Data	(2, 2)	8	6	3	5	3	0	0	–
SM	(2, 2)	5.6 ± 1.3	3.5 ± 0.7	7.1 ± 1.3	1.1 ± 0.2	1.3 ± 0.2	1.5 ± 0.5	0.3 ± 0.1	–
Ttw	(2, 2)	2.7 ± 0.7	1.5 ± 0.3	3.9 ± 0.9	0.4 ± 0.1	0.5 ± 0.1	1.0 ± 0.4	0.1 ± 0.0	–
Zinv	(2, 2)	2.7 ± 0.7	2.0 ± 0.5	3.0 ± 0.5	0.6 ± 0.1	0.8 ± 0.2	0.5 ± 0.2	0.2 ± 0.1	–
QCD	(2, 2)	0.3 ± 0.3	0.1 ± 0.1	0.2 ± 0.2	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–
Data	(3, 0)	4	205	592	577	624	215	97	79
SM	(3, 0)	0.9 ± 0.3	225.8 ± 39.6	639.8 ± 82.5	535.5 ± 81.8	614.1 ± 79.1	213.5 ± 38.9	103.5 ± 17.8	78.0 ± 18.5
Ttw	(3, 0)	0.6 ± 0.2	105.4 ± 18.0	305.5 ± 42.6	238.5 ± 50.8	257.9 ± 52.4	80.8 ± 17.1	34.2 ± 7.5	23.8 ± 6.0
Zinv	(3, 0)	0.4 ± 0.2	114.8 ± 26.5	299.5 ± 43.2	254.8 ± 32.3	332.8 ± 48.6	126.2 ± 25.8	69.3 ± 12.9	52.4 ± 13.3
QCD	(3, 0)	0.0 ± 0.0	5.6 ± 6.5	34.8 ± 29.0	42.2 ± 42.8	23.4 ± 20.3	6.6 ± 7.1	0.0 ± 0.0	1.8 ± 1.7
Data	(3, 1)	–	46	114	114	93	32	18	10
SM	(3, 1)	–	47.2 ± 8.3	107.8 ± 17.2	123.1 ± 22.6	125.2 ± 18.7	33.8 ± 6.6	20.8 ± 3.7	11.7 ± 3.1
Ttw	(3, 1)	–	34.9 ± 6.6	72.8 ± 13.8	75.1 ± 18.2	70.2 ± 15.4	16.7 ± 3.9	8.1 ± 1.9	3.8 ± 1.1
Zinv	(3, 1)	–	11.2 ± 2.6	29.2 ± 4.6	38.3 ± 5.4	50.2 ± 7.5	16.1 ± 3.4	12.8 ± 2.5	7.7 ± 2.2
QCD	(3, 1)	–	1.2 ± 1.4	5.9 ± 4.9	9.7 ± 9.8	4.8 ± 4.1	1.0 ± 1.1	0.0 ± 0.0	0.3 ± 0.3
Data	(3, 2)	–	11	12	14	16	5	1	1
SM	(3, 2)	–	7.1 ± 1.3	23.0 ± 4.4	24.4 ± 5.6	16.1 ± 3.6	5.1 ± 1.3	1.2 ± 0.3	1.3 ± 0.4
Ttw	(3, 2)	–	5.1 ± 1.1	17.5 ± 3.9	18.4 ± 4.9	11.2 ± 3.3	2.9 ± 1.0	0.3 ± 0.1	0.5 ± 0.2
Zinv	(3, 2)	–	1.8 ± 0.4	4.2 ± 0.7	4.1 ± 0.7	4.3 ± 0.7	2.0 ± 0.5	0.9 ± 0.2	0.8 ± 0.3
QCD	(3, 2)	–	0.2 ± 0.2	1.3 ± 1.0	1.9 ± 1.9	0.6 ± 0.5	0.2 ± 0.2	0.0 ± 0.0	0.0 ± 0.0
Data	(3, ≥ 3)	–	1	–	–	–	–	–	–
SM	(3, ≥ 3)	–	1.1 ± 0.3	–	–	–	–	–	–
Ttw	(3, ≥ 3)	–	0.8 ± 0.2	–	–	–	–	–	–
Zinv	(3, ≥ 3)	–	0.2 ± 0.0	–	–	–	–	–	–
QCD	(3, ≥ 3)	–	0.0 ± 0.0	–	–	–	–	–	–
Data	(4, 0)	–	–	77	181	369	175	120	68
SM	(4, 0)	–	–	60.0 ± 8.1	192.5 ± 30.8	373.7 ± 55.7	169.6 ± 32.2	117.6 ± 20.9	71.2 ± 16.6
Ttw	(4, 0)	–	–	33.2 ± 5.5	102.9 ± 24.6	190.0 ± 40.9	70.7 ± 15.3	44.0 ± 9.6	24.0 ± 6.0
Zinv	(4, 0)	–	–	25.2 ± 3.5	85.1 ± 11.9	182.1 ± 27.6	98.8 ± 20.6	73.7 ± 14.3	44.6 ± 11.4
QCD	(4, 0)	–	–	1.6 ± 2.0	4.5 ± 4.2	1.5 ± 2.6	0.2 ± 0.1	0.0 ± 0.0	2.6 ± 3.0
Data	(4, 1)	–	–	19	93	134	39	18	10
SM	(4, 1)	–	–	31.5 ± 5.2	86.1 ± 18.1	114.4 ± 21.3	49.2 ± 10.5	25.7 ± 4.9	14.5 ± 3.8
Ttw	(4, 1)	–	–	25.8 ± 4.9	67.8 ± 17.4	84.5 ± 20.0	30.6 ± 8.0	13.2 ± 3.3	5.5 ± 1.5
Zinv	(4, 1)	–	–	4.9 ± 0.7	16.3 ± 2.4	29.4 ± 4.4	18.6 ± 4.0	12.5 ± 2.5	8.4 ± 2.4
QCD	(4, 1)	–	–	0.9 ± 1.0	2.0 ± 1.9	0.5 ± 0.8	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.6
Data	(4, 2)	–	–	8	30	39	12	7	2
SM	(4, 2)	–	–	7.4 ± 1.5	21.9 ± 5.6	42.4 ± 10.1	10.8 ± 2.9	3.6 ± 0.8	3.4 ± 1.1
Ttw	(4, 2)	–	–	6.2 ± 1.4	19.9 ± 5.5	36.5 ± 9.9	8.6 ± 2.7	2.2 ± 0.7	1.6 ± 0.6
Zinv	(4, 2)	–	–	1.0 ± 0.2	1.5 ± 0.3	5.8 ± 0.9	2.1 ± 0.5	1.4 ± 0.3	1.7 ± 0.5
QCD	(4, 2)	–	–	0.2 ± 0.2	0.5 ± 0.5	0.2 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1
Data	(4, ≥ 3)	–	–	0	3	0	2	0	0
SM	(4, ≥ 3)	–	–	0.3 ± 0.1	2.0 ± 0.5	2.8 ± 0.9	1.0 ± 0.3	0.1 ± 0.0	0.1 ± 0.0
Ttw	(4, ≥ 3)	–	–	0.3 ± 0.1	1.6 ± 0.5	2.5 ± 0.8	0.7 ± 0.3	0.0 ± 0.0	0.1 ± 0.0
Zinv	(4, ≥ 3)	–	–	0.0 ± 0.0	0.3 ± 0.1	0.2 ± 0.0	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
QCD	(4, ≥ 3)	–	–	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Data	($\geq 5, 0$)	–	–	–	8	109	100	94	64
SM	($\geq 5, 0$)	–	–	–	18.7 ± 4.7	114.9 ± 19.0	103.3 ± 19.6	91.8 ± 17.6	62.9 ± 15.7
Ttw	($\geq 5, 0$)	–	–	–	12.1 ± 3.6	68.0 ± 14.5	49.1 ± 11.5	42.6 ± 10.0	24.5 ± 6.5
Zinv	($\geq 5, 0$)	–	–	–	6.5 ± 1.7	41.5 ± 7.4	46.1 ± 9.7	48.7 ± 10.1	37.0 ± 9.7
QCD	($\geq 5, 0$)	–	–	–	0.1 ± 0.1	5.4 ± 5.0	8.1 ± 7.4	0.5 ± 0.5	1.5 ± 2.2
Data	($\geq 5, 1$)	–	–	–	6	62	48	35	21
SM	($\geq 5, 1$)	–	–	–	3.6 ± 1.0	71.1 ± 14.0	54.0 ± 12.3	37.9 ± 8.9	24.3 ± 6.7
Ttw	($\geq 5, 1$)	–	–	–	3.1 ± 1.0	58.8 ± 13.2	40.3 ± 10.8	27.0 ± 7.8	14.3 ± 4.5
Zinv	($\geq 5, 1$)	–	–	–	0.4 ± 0.1	8.9 ± 1.6	9.4 ± 2.0	10.7 ± 2.2	9.4 ± 2.6
QCD	($\geq 5, 1$)	–	–	–	0.0 ± 0.0	3.3 ± 3.1	4.2 ± 3.9	0.2 ± 0.2	0.6 ± 0.9
Data	($\geq 5, 2$)	–	–	–	0	27	18	10	16
SM	($\geq 5, 2$)	–	–	–	2.7 ± 0.8	24.6 ± 5.5	21.7 ± 5.8	10.9 ± 3.1	7.2 ± 2.3
Ttw	($\geq 5, 2$)	–	–	–	2.4 ± 0.8	22.1 ± 5.3	17.9 ± 5.4	8.9 ± 2.9	5.3 ± 1.9
Zinv	($\geq 5, 2$)	–	–	–	0.2 ± 0.1	1.3 ± 0.3	2.1 ± 0.5	1.9 ± 0.4	1.7 ± 0.5
QCD	($\geq 5, 2$)	–	–	–	0.0 ± 0.0	1.1 ± 1.1	1.7 ± 1.5	0.1 ± 0.1	0.2 ± 0.3
Data	($\geq 5, \geq 3$)	–	–	–	–	1	1	1	3
SM	($\geq 5, \geq 3$)	–	–	–	–	1.4 ± 0.3	3.0 ± 0.9	1.5 ± 0.4	0.9 ± 0.4
Ttw	($\geq 5, \geq 3$)	–	–	–	–	1.3 ± 0.3	2.6 ± 0.8	1.1 ± 0.4	0.6 ± 0.3
Zinv	($\geq 5, \geq 3$)	–	–	–	–	0.1 ± 0.0	0.2 ± 0.0	0.3 ± 0.1	0.2 ± 0.1
QCD	($\geq 5, \geq 3$)	–	–	–	–	0.1 ± 0.1	0.2 ± 0.2	0.0 ± 0.0	0.0 ± 0.0

Table A9.3: Pre-fit predicted and observed data yield of symmetric categories in the signal region for the full 2.3 fb^{-1} dataset.

		H_T (GeV)							
(n_{jet}, n_b)		200-250	250-300	300-350	350-400	400-500	500-600	600-800	800- ∞
Data	(2, 0)	1167	1155	760	442	335	119	58	57
SM	(2, 0)	1177.7 ± 41.2	1166.3 ± 35.9	760.4 ± 29.8	441.6 ± 23.7	351.0 ± 13.2	113.5 ± 6.0	48.4 ± 2.9	56.7 ± 3.7
Ttw	(2, 0)	540.4 ± 51.7	503.4 ± 38.2	318.8 ± 19.7	169.1 ± 13.9	127.1 ± 8.0	38.5 ± 3.9	15.0 ± 1.6	18.2 ± 1.9
Zinv	(2, 0)	587.1 ± 49.2	635.0 ± 42.5	416.6 ± 20.8	245.8 ± 17.3	212.6 ± 11.4	73.6 ± 5.0	33.4 ± 2.3	38.3 ± 2.9
QCD	(2, 0)	50.2 ± 47.0	27.9 ± 29.5	25.0 ± 29.5	26.7 ± 27.1	11.4 ± 9.4	1.4 ± 1.1	0.0 ± 0.0	0.2 ± 0.2
Data	(2, 1)	137	115	76	40	39	5	4	2
SM	(2, 1)	128.9 ± 9.0	100.9 ± 6.6	63.3 ± 5.5	34.3 ± 3.5	31.9 ± 2.8	9.5 ± 1.2	4.6 ± 0.8	3.7 ± 0.8
Ttw	(2, 1)	79.7 ± 8.1	54.0 ± 4.7	30.4 ± 3.2	12.9 ± 1.7	11.3 ± 1.2	3.2 ± 0.5	1.2 ± 0.2	1.2 ± 0.3
Zinv	(2, 1)	44.1 ± 5.1	44.8 ± 4.5	31.2 ± 3.1	19.3 ± 2.2	19.6 ± 1.9	6.1 ± 0.8	3.4 ± 0.6	2.5 ± 0.5
QCD	(2, 1)	5.1 ± 4.8	2.2 ± 2.3	1.8 ± 2.1	2.0 ± 2.1	1.0 ± 0.8	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
Data	(2, 2)	8	6	3	5	3	0	0	—
SM	(2, 2)	7.0 ± 2.0	4.5 ± 1.3	5.0 ± 1.5	2.1 ± 0.8	1.3 ± 0.5	1.2 ± 0.6	0.2 ± 0.1	—
Ttw	(2, 2)	3.5 ± 1.1	1.8 ± 0.6	2.8 ± 0.9	0.9 ± 0.4	0.5 ± 0.2	0.7 ± 0.4	0.1 ± 0.0	—
Zinv	(2, 2)	3.3 ± 1.0	2.6 ± 0.8	2.0 ± 0.6	1.1 ± 0.4	0.8 ± 0.3	0.5 ± 0.2	0.2 ± 0.1	—
QCD	(2, 2)	0.3 ± 0.2	0.1 ± 0.1	0.2 ± 0.3	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	—
Data	(3, 0)	4	205	592	577	624	215	97	79
SM	(3, 0)	2.8 ± 1.2	217.4 ± 13.3	606.8 ± 20.4	564.1 ± 21.9	606.5 ± 21.2	210.0 ± 10.4	100.8 ± 5.4	81.4 ± 4.7
Ttw	(3, 0)	1.7 ± 0.8	101.1 ± 9.2	292.7 ± 17.8	255.6 ± 21.2	260.4 ± 15.6	79.2 ± 7.3	34.2 ± 3.6	26.0 ± 2.5
Zinv	(3, 0)	1.1 ± 0.5	111.2 ± 9.6	288.4 ± 15.9	269.0 ± 18.0	322.5 ± 18.0	123.4 ± 8.2	66.6 ± 4.1	53.7 ± 3.5
QCD	(3, 0)	0.0 ± 0.0	5.0 ± 3.6	25.7 ± 17.0	39.5 ± 25.9	23.6 ± 19.2	7.4 ± 6.4	0.0 ± 0.0	1.7 ± 1.8
Data	(3, 1)	—	46	114	114	93	32	18	10
SM	(3, 1)	—	46.7 ± 4.2	105.2 ± 6.1	119.6 ± 7.9	108.2 ± 5.9	30.9 ± 2.6	19.2 ± 1.7	11.7 ± 1.4
Ttw	(3, 1)	—	34.9 ± 3.6	72.9 ± 5.3	75.4 ± 6.8	62.7 ± 4.5	15.4 ± 1.8	7.7 ± 0.9	4.0 ± 0.6
Zinv	(3, 1)	—	10.8 ± 1.3	28.0 ± 2.4	35.1 ± 3.2	40.7 ± 3.2	14.3 ± 1.3	11.5 ± 1.1	7.4 ± 0.9
QCD	(3, 1)	—	1.1 ± 0.8	4.3 ± 2.9	9.1 ± 6.0	4.8 ± 3.9	1.2 ± 1.0	0.0 ± 0.0	0.3 ± 0.3
Data	(3, 2)	—	11	12	14	16	5	1	1
SM	(3, 2)	—	7.7 ± 1.2	20.1 ± 2.2	21.2 ± 2.3	15.6 ± 1.6	4.4 ± 0.7	1.1 ± 0.2	1.2 ± 0.3
Ttw	(3, 2)	—	5.8 ± 1.0	15.7 ± 1.8	16.2 ± 2.0	11.6 ± 1.3	2.7 ± 0.5	0.4 ± 0.1	0.5 ± 0.1
Zinv	(3, 2)	—	1.8 ± 0.3	3.6 ± 0.4	3.2 ± 0.4	3.5 ± 0.5	1.4 ± 0.3	0.7 ± 0.2	0.7 ± 0.2
QCD	(3, 2)	—	0.2 ± 0.1	0.9 ± 0.6	1.8 ± 1.2	0.6 ± 0.5	0.2 ± 0.2	0.0 ± 0.0	0.0 ± 0.0
Data	(3, ≥ 3)	—	1	—	—	—	—	—	—
SM	(3, ≥ 3)	—	1.1 ± 0.5	—	—	—	—	—	—
Ttw	(3, ≥ 3)	—	0.9 ± 0.4	—	—	—	—	—	—
Zinv	(3, ≥ 3)	—	0.2 ± 0.1	—	—	—	—	—	—
QCD	(3, ≥ 3)	—	0.0 ± 0.0	—	—	—	—	—	—
Data	(4, 0)	—	—	77	181	369	175	120	68
SM	(4, 0)	—	—	67.6 ± 5.9	189.5 ± 10.7	372.2 ± 13.6	167.4 ± 7.9	116.2 ± 6.5	69.1 ± 4.3
Ttw	(4, 0)	—	—	37.7 ± 3.6	102.5 ± 8.6	192.5 ± 11.6	71.4 ± 6.7	45.6 ± 4.9	23.9 ± 2.4
Zinv	(4, 0)	—	—	28.3 ± 2.9	82.6 ± 6.5	178.1 ± 10.4	95.8 ± 6.5	70.6 ± 4.1	42.8 ± 3.1
QCD	(4, 0)	—	—	1.6 ± 1.9	4.5 ± 3.6	1.6 ± 1.7	0.2 ± 0.1	0.0 ± 0.0	2.4 ± 1.9
Data	(4, 1)	—	—	19	93	134	39	18	10
SM	(4, 1)	—	—	25.9 ± 3.3	89.0 ± 7.3	118.4 ± 6.7	46.7 ± 3.8	22.8 ± 2.1	14.2 ± 1.7
Ttw	(4, 1)	—	—	21.1 ± 2.7	71.6 ± 6.6	90.5 ± 6.2	30.2 ± 3.3	12.4 ± 1.5	5.8 ± 0.9
Zinv	(4, 1)	—	—	4.0 ± 0.6	15.4 ± 1.7	27.5 ± 2.2	16.5 ± 1.5	10.4 ± 1.0	7.9 ± 0.9
QCD	(4, 1)	—	—	0.9 ± 1.0	2.0 ± 1.6	0.5 ± 0.5	0.0 ± 0.0	0.0 ± 0.0	0.5 ± 0.4
Data	(4, 2)	—	—	8	30	39	12	7	2
SM	(4, 2)	—	—	7.8 ± 1.6	25.0 ± 2.9	40.2 ± 3.3	10.6 ± 1.4	3.5 ± 0.5	2.9 ± 0.5
Ttw	(4, 2)	—	—	6.6 ± 1.4	23.1 ± 2.9	35.1 ± 3.1	8.7 ± 1.2	2.2 ± 0.3	1.5 ± 0.3
Zinv	(4, 2)	—	—	0.9 ± 0.2	1.4 ± 0.2	4.9 ± 0.5	1.8 ± 0.3	1.2 ± 0.2	1.3 ± 0.2
QCD	(4, 2)	—	—	0.2 ± 0.2	0.5 ± 0.4	0.2 ± 0.2	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.1
Data	(4, ≥ 3)	—	—	0	3	0	2	0	0
SM	(4, ≥ 3)	—	—	0.2 ± 0.2	2.4 ± 0.9	2.0 ± 0.7	1.0 ± 0.4	0.1 ± 0.1	0.1 ± 0.0
Ttw	(4, ≥ 3)	—	—	0.2 ± 0.2	2.0 ± 0.8	1.8 ± 0.6	0.8 ± 0.3	0.1 ± 0.0	0.1 ± 0.0
Zinv	(4, ≥ 3)	—	—	0.0 ± 0.0	0.3 ± 0.1	0.2 ± 0.1	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
QCD	(4, ≥ 3)	—	—	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
Data	($\geq 5, 0$)	—	—	—	8	109	100	94	64
SM	($\geq 5, 0$)	—	—	—	13.1 ± 2.4	110.6 ± 7.2	99.2 ± 6.7	91.1 ± 5.3	63.2 ± 4.3
Ttw	($\geq 5, 0$)	—	—	—	8.3 ± 1.6	66.7 ± 5.3	48.4 ± 4.9	44.4 ± 4.2	25.6 ± 2.7
Zinv	($\geq 5, 0$)	—	—	—	4.7 ± 0.9	39.1 ± 3.4	43.9 ± 3.7	46.2 ± 3.2	35.9 ± 2.7
QCD	($\geq 5, 0$)	—	—	—	0.1 ± 0.1	4.8 ± 4.4	6.9 ± 4.6	0.5 ± 0.5	1.7 ± 2.1
Data	($\geq 5, 1$)	—	—	—	6	62	48	35	21
SM	($\geq 5, 1$)	—	—	—	4.5 ± 1.1	67.6 ± 5.3	49.7 ± 4.4	36.7 ± 2.8	22.6 ± 1.8
Ttw	($\geq 5, 1$)	—	—	—	3.9 ± 0.9	56.5 ± 4.8	38.3 ± 3.9	27.5 ± 2.7	14.2 ± 1.5
Zinv	($\geq 5, 1$)	—	—	—	0.6 ± 0.2	8.1 ± 0.8	7.9 ± 0.8	9.1 ± 0.8	7.8 ± 0.7
QCD	($\geq 5, 1$)	—	—	—	0.0 ± 0.0	2.9 ± 2.7	3.6 ± 2.4	0.2 ± 0.2	0.7 ± 0.8
Data	($\geq 5, 2$)	—	—	—	0	27	18	10	16
SM	($\geq 5, 2$)	—	—	—	1.9 ± 0.8	25.2 ± 2.7	20.1 ± 2.2	10.8 ± 1.1	7.5 ± 0.8
Ttw	($\geq 5, 2$)	—	—	—	1.7 ± 0.7	22.9 ± 2.6	16.9 ± 2.0	9.2 ± 1.0	5.8 ± 0.7
Zinv	($\geq 5, 2$)	—	—	—	0.1 ± 0.1	1.3 ± 0.2	1.7 ± 0.2	1.5 ± 0.2	1.5 ± 0.2
QCD	($\geq 5, 2$)	—	—	—	0.0 ± 0.0	1.0 ± 0.9	1.4 ± 1.0	0.1 ± 0.1	0.2 ± 0.2
Data	($\geq 5, \geq 3$)	—	—	—	—	1	1	1	3
SM	($\geq 5, \geq 3$)	—	—	—	—	1.2 ± 0.5	2.3 ± 0.7	1.4 ± 0.4	1.0 ± 0.3
Ttw	($\geq 5, \geq 3$)	—	—	—	—	1.1 ± 0.5	2.1 ± 0.6	1.2 ± 0.3	0.7 ± 0.2
Zinv	($\geq 5, \geq 3$)	—	—	—	—	0.1 ± 0.0	0.1 ± 0.0	0.3 ± 0.1	0.2 ± 0.1
QCD	($\geq 5, \geq 3$)	—	—	—	—	0.1 ± 0.1	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0

Table A9.4: Post-fit predicted and observed data yield of symmetric categories in the signal region for the full 2.3 fb^{-1} dataset.

9 Event yields

	(n_{jet}, n_b)	200-250	250-300	300-350	H_T (GeV) 350-400	400-500	500-600	600-800	800- ∞
Data	(2a, 0)	5788	1585	584	232	139	26	16	–
SM	(2a, 0)	5681.6 ± 512.7	1662.2 ± 195.7	601.4 ± 63.5	226.2 ± 39.7	144.3 ± 26.5	36.3 ± 7.3	19.0 ± 8.2	–
Ttw	(2a, 0)	2705.4 ± 292.2	725.3 ± 115.2	250.8 ± 30.8	83.2 ± 16.6	44.7 ± 7.9	13.0 ± 3.5	4.2 ± 1.8	–
Zinv	(2a, 0)	2873.7 ± 251.3	920.2 ± 100.9	350.6 ± 39.9	143.0 ± 24.8	99.6 ± 21.6	23.3 ± 5.4	13.8 ± 6.9	–
QCD	(2a, 0)	102.5 ± 98.8	16.7 ± 19.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.1 ± 1.1	–
Data	(2a, 1)	536	152	51	18	7	4	–	–
SM	(2a, 1)	524.5 ± 57.4	158.5 ± 23.5	49.3 ± 6.7	20.5 ± 3.7	12.6 ± 2.5	4.3 ± 1.0	–	–
Ttw	(2a, 1)	306.7 ± 39.4	81.9 ± 15.9	21.8 ± 3.6	6.3 ± 1.3	4.8 ± 1.0	1.2 ± 0.4	–	–
Zinv	(2a, 1)	208.3 ± 21.9	75.1 ± 9.9	27.5 ± 3.8	14.2 ± 2.7	7.8 ± 1.8	3.0 ± 0.8	–	–
QCD	(2a, 1)	9.5 ± 9.1	1.6 ± 1.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–	–
Data	(2a, 2)	31	10	3	1	0	–	–	–
SM	(2a, 2)	28.6 ± 3.6	7.0 ± 1.2	6.5 ± 1.0	2.0 ± 0.4	0.8 ± 0.2	–	–	–
Ttw	(2a, 2)	14.0 ± 2.0	3.3 ± 0.7	2.9 ± 0.5	1.0 ± 0.3	0.3 ± 0.1	–	–	–
Zinv	(2a, 2)	14.1 ± 1.8	3.6 ± 0.5	3.6 ± 0.6	0.9 ± 0.2	0.5 ± 0.1	–	–	–
QCD	(2a, 2)	0.5 ± 0.5	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–	–	–
Data	(3a, 0)	1599	1609	777	239	95	15	9	–
SM	(3a, 0)	1605.7 ± 160.4	1477.9 ± 193.8	757.0 ± 80.3	250.6 ± 43.6	111.7 ± 19.5	19.7 ± 4.0	9.3 ± 4.2	–
Ttw	(3a, 0)	847.9 ± 97.3	764.3 ± 128.5	361.3 ± 39.2	104.5 ± 20.9	42.2 ± 6.5	6.0 ± 1.7	2.4 ± 1.1	–
Zinv	(3a, 0)	726.3 ± 71.7	689.2 ± 78.7	363.7 ± 41.7	135.8 ± 24.1	69.5 ± 15.3	13.8 ± 3.1	6.8 ± 3.5	–
QCD	(3a, 0)	31.6 ± 25.7	24.4 ± 23.9	31.9 ± 32.1	10.3 ± 12.2	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–
Data	(3a, 1)	340	299	152	59	15	1	1	–
SM	(3a, 1)	327.0 ± 36.9	346.4 ± 57.8	143.9 ± 18.8	42.0 ± 7.9	14.7 ± 2.8	2.3 ± 0.6	1.2 ± 0.5	–
Ttw	(3a, 1)	250.7 ± 30.9	259.7 ± 50.2	99.7 ± 15.1	25.3 ± 5.6	6.9 ± 1.5	1.5 ± 0.5	0.3 ± 0.2	–
Zinv	(3a, 1)	69.9 ± 7.5	81.0 ± 10.1	38.1 ± 4.7	15.0 ± 2.7	7.8 ± 1.8	0.8 ± 0.2	0.8 ± 0.4	–
QCD	(3a, 1)	6.4 ± 5.2	5.7 ± 5.6	6.1 ± 6.1	1.7 ± 2.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–
Data	(3a, 2)	52	62	29	12	1	0	–	–
SM	(3a, 2)	57.2 ± 7.3	59.8 ± 11.2	31.6 ± 5.1	10.2 ± 2.5	1.9 ± 0.5	0.4 ± 0.1	–	–
Ttw	(3a, 2)	46.6 ± 6.5	47.9 ± 10.0	24.1 ± 4.4	7.8 ± 2.1	0.6 ± 0.2	0.2 ± 0.1	–	–
Zinv	(3a, 2)	9.4 ± 1.0	11.0 ± 1.5	6.2 ± 0.9	2.1 ± 0.4	1.3 ± 0.3	0.3 ± 0.1	–	–
QCD	(3a, 2)	1.1 ± 0.9	1.0 ± 1.0	1.3 ± 1.3	0.4 ± 0.5	0.0 ± 0.0	0.0 ± 0.0	–	–
Data	(3a, ≥ 3)	3	1	1	–	–	–	–	–
SM	(3a, ≥ 3)	0.9 ± 0.2	1.8 ± 0.4	0.7 ± 0.2	–	–	–	–	–
Ttw	(3a, ≥ 3)	0.7 ± 0.2	1.4 ± 0.4	0.7 ± 0.2	–	–	–	–	–
Zinv	(3a, ≥ 3)	0.1 ± 0.0	0.4 ± 0.1	0.0 ± 0.0	–	–	–	–	–
QCD	(3a, ≥ 3)	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–	–	–	–	–
Data	(4a, 0)	3	178	412	246	119	15	2	–
SM	(4a, 0)	3.8 ± 0.5	150.4 ± 20.7	406.0 ± 48.5	259.6 ± 47.5	132.3 ± 21.3	14.7 ± 3.2	2.6 ± 1.3	–
Ttw	(4a, 0)	1.8 ± 0.6	88.7 ± 15.0	212.1 ± 25.8	140.4 ± 29.2	59.3 ± 9.4	5.6 ± 1.6	0.6 ± 0.4	–
Zinv	(4a, 0)	2.0 ± 0.4	60.3 ± 7.5	166.7 ± 20.8	106.5 ± 18.9	68.1 ± 14.9	9.1 ± 2.2	2.0 ± 1.0	–
QCD	(4a, 0)	0.0 ± 0.0	1.4 ± 1.6	27.2 ± 30.4	12.6 ± 10.6	4.9 ± 3.8	0.0 ± 0.0	0.0 ± 0.0	–
Data	(4a, 1)	1	53	180	96	51	4	0	–
SM	(4a, 1)	1.4 ± 0.3	50.5 ± 8.3	165.7 ± 22.6	98.3 ± 19.4	52.0 ± 9.4	3.1 ± 0.8	0.6 ± 0.3	–
Ttw	(4a, 1)	1.0 ± 0.3	39.0 ± 7.3	130.4 ± 18.6	75.5 ± 16.6	35.5 ± 7.6	1.7 ± 0.6	0.1 ± 0.1	–
Zinv	(4a, 1)	0.4 ± 0.1	11.1 ± 1.5	24.2 ± 3.2	18.0 ± 3.2	14.7 ± 3.3	1.3 ± 0.3	0.5 ± 0.3	–
QCD	(4a, 1)	0.0 ± 0.0	0.5 ± 0.5	11.1 ± 12.4	4.8 ± 4.0	1.9 ± 1.5	0.0 ± 0.0	0.0 ± 0.0	–
Data	(4a, 2)	0	11	44	30	8	0	0	–
SM	(4a, 2)	0.3 ± 0.1	14.4 ± 2.6	51.9 ± 8.4	27.2 ± 6.1	14.8 ± 3.2	0.6 ± 0.2	0.1 ± 0.1	–
Ttw	(4a, 2)	0.3 ± 0.1	11.7 ± 2.4	44.2 ± 7.5	23.3 ± 5.7	12.3 ± 2.9	0.4 ± 0.2	0.0 ± 0.0	–
Zinv	(4a, 2)	0.0 ± 0.0	2.5 ± 0.4	4.2 ± 0.6	2.5 ± 0.5	1.9 ± 0.5	0.1 ± 0.0	0.1 ± 0.0	–
QCD	(4a, 2)	0.0 ± 0.0	0.1 ± 0.2	3.5 ± 3.9	1.3 ± 1.1	0.5 ± 0.4	0.0 ± 0.0	0.0 ± 0.0	–
Data	(4a, ≥ 3)	–	0	0	2	–	–	–	–
SM	(4a, ≥ 3)	–	1.8 ± 0.4	3.0 ± 0.6	2.6 ± 0.8	1.8 ± 0.5	–	–	–
Ttw	(4a, ≥ 3)	–	1.6 ± 0.4	2.4 ± 0.6	2.1 ± 0.7	1.7 ± 0.5	–	–	–
Zinv	(4a, ≥ 3)	–	0.1 ± 0.0	0.4 ± 0.1	0.3 ± 0.1	0.0 ± 0.0	–	–	–
QCD	(4a, ≥ 3)	–	0.0 ± 0.0	0.2 ± 0.2	0.1 ± 0.1	0.1 ± 0.1	–	–	–
Data	($\geq 5a, 0$)	–	3	40	96	105	20	3	–
SM	($\geq 5a, 0$)	–	3.9 ± 1.0	49.0 ± 7.9	113.6 ± 22.1	127.0 ± 21.2	21.4 ± 4.9	4.5 ± 2.0	–
Ttw	($\geq 5a, 0$)	–	3.6 ± 1.4	31.6 ± 4.8	63.7 ± 13.2	77.8 ± 14.1	12.8 ± 3.7	2.0 ± 0.9	–
Zinv	($\geq 5a, 0$)	–	0.3 ± 0.6	17.2 ± 3.6	37.6 ± 7.3	42.7 ± 9.3	8.3 ± 2.0	2.5 ± 1.3	–
QCD	($\geq 5a, 0$)	–	0.0 ± 0.0	0.1 ± 0.1	12.3 ± 9.5	6.5 ± 6.7	0.3 ± 0.5	0.0 ± 0.0	–
Data	($\geq 5a, 1$)	–	0	24	60	74	15	0	–
SM	($\geq 5a, 1$)	–	1.2 ± 0.3	21.9 ± 3.4	51.6 ± 10.5	72.2 ± 13.7	17.3 ± 4.8	1.9 ± 0.8	–
Ttw	($\geq 5a, 1$)	–	1.0 ± 0.4	19.5 ± 3.0	41.8 ± 8.7	61.0 ± 12.4	14.0 ± 4.4	1.3 ± 0.6	–
Zinv	($\geq 5a, 1$)	–	0.2 ± 0.5	2.4 ± 0.5	4.2 ± 0.9	7.5 ± 1.7	3.0 ± 0.7	0.5 ± 0.3	–
QCD	($\geq 5a, 1$)	–	0.0 ± 0.0	0.1 ± 0.1	5.6 ± 4.3	3.7 ± 3.8	0.3 ± 0.4	0.0 ± 0.0	–
Data	($\geq 5a, 2$)	–	0	11	27	29	6	1	–
SM	($\geq 5a, 2$)	–	0.0 ± 0.0	6.7 ± 1.1	25.6 ± 5.4	29.1 ± 6.1	6.1 ± 1.8	0.5 ± 0.2	–
Ttw	($\geq 5a, 2$)	–	0.0 ± 0.0	6.4 ± 1.0	21.8 ± 4.7	26.0 ± 5.8	5.2 ± 1.7	0.5 ± 0.2	–
Zinv	($\geq 5a, 2$)	–	0.0 ± 0.0	0.3 ± 0.1	1.1 ± 0.2	1.5 ± 0.3	0.8 ± 0.2	0.0 ± 0.0	–
QCD	($\geq 5a, 2$)	–	0.0 ± 0.0	0.0 ± 0.0	2.8 ± 2.1	1.5 ± 1.5	0.1 ± 0.1	0.0 ± 0.0	–
Data	($\geq 5a, \geq 3$)	–	–	0	2	5	1	–	–
SM	($\geq 5a, \geq 3$)	–	–	0.5 ± 0.1	3.0 ± 0.7	4.5 ± 1.2	0.8 ± 0.3	–	–
Ttw	($\geq 5a, \geq 3$)	–	–	0.5 ± 0.1	2.7 ± 0.7	4.0 ± 1.1	0.7 ± 0.3	–	–
Zinv	($\geq 5a, \geq 3$)	–	–	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.1	0.1 ± 0.0	–	–
QCD	($\geq 5a, \geq 3$)	–	–	0.0 ± 0.0	0.3 ± 0.3	0.2 ± 0.2	0.0 ± 0.0	–	–

Table A9.5: Pre-fit predicted and observed data yield of asymmetric categories in the signal region for the full 2.3 fb^{-1} dataset.

		H_T (GeV)							
	(n_{jet}, n_b)	200-250	250-300	300-350	350-400	400-500	500-600	600-800	800- ∞
Data	(2a, 0)	5788	1585	584	232	139	26	16	–
SM	(2a, 0)	5816.6 ± 72.6	1628.1 ± 30.2	590.1 ± 15.6	231.5 ± 9.6	138.8 ± 6.7	30.2 ± 2.9	17.2 ± 2.5	–
Ttw	(2a, 0)	2803.2 ± 95.9	702.4 ± 38.7	245.8 ± 13.7	84.4 ± 5.4	43.9 ± 3.5	10.3 ± 1.9	3.1 ± 1.1	–
Zinv	(2a, 0)	2930.7 ± 83.8	911.7 ± 39.5	344.3 ± 13.7	147.1 ± 7.7	94.9 ± 5.8	19.8 ± 1.9	13.0 ± 2.3	–
QCD	(2a, 0)	82.7 ± 63.2	13.9 ± 14.8	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	1.0 ± 1.0	–
Data	(2a, 1)	536	152	51	18	7	4	–	–
SM	(2a, 1)	540.3 ± 16.5	155.2 ± 7.4	50.8 ± 4.0	20.1 ± 2.2	10.9 ± 1.4	4.1 ± 1.0	–	–
Ttw	(2a, 1)	325.0 ± 14.1	81.5 ± 5.8	23.4 ± 2.1	7.0 ± 0.8	4.1 ± 0.6	1.3 ± 0.4	–	–
Zinv	(2a, 1)	207.7 ± 8.4	72.4 ± 4.4	27.5 ± 2.4	13.0 ± 1.5	6.8 ± 0.9	2.8 ± 0.7	–	–
QCD	(2a, 1)	7.6 ± 5.8	1.3 ± 1.4	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–	–
Data	(2a, 2)	31	10	3	1	0	–	–	–
SM	(2a, 2)	29.5 ± 3.1	7.5 ± 1.3	5.0 ± 1.1	1.9 ± 0.6	0.6 ± 0.3	–	–	–
Ttw	(2a, 2)	14.9 ± 1.7	3.5 ± 0.6	2.3 ± 0.5	1.1 ± 0.4	0.3 ± 0.1	–	–	–
Zinv	(2a, 2)	14.2 ± 1.6	3.9 ± 0.7	2.8 ± 0.6	0.8 ± 0.2	0.3 ± 0.2	–	–	–
QCD	(2a, 2)	0.4 ± 0.3	0.1 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–	–	–
Data	(3a, 0)	1599	1609	777	239	95	15	9	–
SM	(3a, 0)	1617.9 ± 31.4	1538.7 ± 46.2	770.3 ± 33.1	254.1 ± 14.0	102.8 ± 5.1	16.6 ± 1.6	8.1 ± 1.5	–
Ttw	(3a, 0)	863.9 ± 29.7	784.1 ± 45.0	373.8 ± 21.9	106.3 ± 6.6	39.0 ± 3.0	5.2 ± 0.9	1.9 ± 0.7	–
Zinv	(3a, 0)	727.8 ± 25.9	716.9 ± 33.4	355.3 ± 16.3	138.0 ± 7.6	63.8 ± 4.1	11.4 ± 1.2	6.2 ± 1.3	–
QCD	(3a, 0)	26.3 ± 18.6	37.6 ± 52.4	41.2 ± 38.2	9.8 ± 11.6	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–
Data	(3a, 1)	340	299	152	59	15	1	1	–
SM	(3a, 1)	339.5 ± 12.1	331.9 ± 15.1	146.8 ± 9.1	46.5 ± 3.4	13.3 ± 1.2	2.1 ± 0.4	1.0 ± 0.4	–
Ttw	(3a, 1)	264.9 ± 11.3	248.8 ± 14.2	102.2 ± 7.0	29.1 ± 2.5	6.4 ± 0.7	1.4 ± 0.3	0.3 ± 0.1	–
Zinv	(3a, 1)	69.2 ± 3.5	74.3 ± 4.7	36.7 ± 2.7	15.7 ± 1.4	6.9 ± 0.7	0.7 ± 0.1	0.7 ± 0.3	–
QCD	(3a, 1)	5.4 ± 3.8	8.8 ± 12.3	7.8 ± 7.3	1.6 ± 1.9	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	–
Data	(3a, 2)	52	62	29	12	1	0	–	–
SM	(3a, 2)	58.0 ± 4.0	59.3 ± 4.0	30.9 ± 2.9	11.0 ± 1.5	1.6 ± 0.4	0.4 ± 0.2	–	–
Ttw	(3a, 2)	48.1 ± 3.4	47.7 ± 3.7	23.9 ± 2.3	8.6 ± 1.2	0.6 ± 0.2	0.1 ± 0.1	–	–
Zinv	(3a, 2)	9.0 ± 0.7	10.1 ± 0.8	5.3 ± 0.6	2.0 ± 0.3	0.9 ± 0.2	0.2 ± 0.1	–	–
QCD	(3a, 2)	0.9 ± 0.7	1.5 ± 2.1	1.7 ± 1.6	0.4 ± 0.5	0.0 ± 0.0	0.0 ± 0.0	–	–
Data	(3a, ≥ 3)	3	1	1	–	–	–	–	–
SM	(3a, ≥ 3)	1.3 ± 0.5	1.5 ± 0.5	0.8 ± 0.4	–	–	–	–	–
Ttw	(3a, ≥ 3)	1.2 ± 0.5	1.2 ± 0.4	0.8 ± 0.4	–	–	–	–	–
Zinv	(3a, ≥ 3)	0.1 ± 0.1	0.3 ± 0.1	0.0 ± 0.0	–	–	–	–	–
QCD	(3a, ≥ 3)	0.0 ± 0.0	0.0 ± 0.1	0.0 ± 0.0	–	–	–	–	–
Data	(4a, 0)	3	178	412	246	119	15	2	–
SM	(4a, 0)	4.2 ± 1.0	159.4 ± 8.8	411.1 ± 19.3	254.2 ± 11.8	126.1 ± 7.0	13.1 ± 1.8	2.3 ± 0.6	–
Ttw	(4a, 0)	2.2 ± 0.5	93.3 ± 6.9	219.3 ± 14.2	139.3 ± 8.6	58.1 ± 4.5	5.0 ± 1.0	0.5 ± 0.2	–
Zinv	(4a, 0)	2.0 ± 0.5	64.7 ± 4.6	164.0 ± 9.5	104.5 ± 7.2	63.9 ± 4.3	8.1 ± 1.1	1.8 ± 0.5	–
QCD	(4a, 0)	0.0 ± 0.0	1.5 ± 1.4	27.8 ± 18.3	10.4 ± 7.9	4.2 ± 3.7	0.0 ± 0.0	0.0 ± 0.0	–
Data	(4a, 1)	1	53	180	96	51	4	0	–
SM	(4a, 1)	1.6 ± 0.5	51.1 ± 3.7	170.0 ± 9.9	98.5 ± 6.0	48.6 ± 4.3	2.9 ± 0.6	0.5 ± 0.2	–
Ttw	(4a, 1)	1.1 ± 0.4	40.0 ± 3.3	135.1 ± 9.1	78.1 ± 5.5	34.9 ± 3.5	1.8 ± 0.4	0.1 ± 0.0	–
Zinv	(4a, 1)	0.5 ± 0.1	10.5 ± 0.9	23.6 ± 1.8	16.5 ± 1.4	12.0 ± 1.2	1.2 ± 0.2	0.4 ± 0.1	–
QCD	(4a, 1)	0.0 ± 0.0	0.5 ± 0.5	11.3 ± 7.5	3.9 ± 3.0	1.6 ± 1.5	0.0 ± 0.0	0.0 ± 0.0	–
Data	(4a, 2)	0	11	44	30	8	0	0	–
SM	(4a, 2)	0.3 ± 0.2	14.0 ± 1.5	50.9 ± 4.4	28.5 ± 3.1	12.7 ± 2.0	0.6 ± 0.2	0.1 ± 0.0	–
Ttw	(4a, 2)	0.3 ± 0.2	11.6 ± 1.3	43.8 ± 4.3	25.3 ± 2.8	10.7 ± 1.7	0.5 ± 0.2	0.0 ± 0.0	–
Zinv	(4a, 2)	0.0 ± 0.0	2.3 ± 0.2	3.6 ± 0.4	2.2 ± 0.3	1.5 ± 0.2	0.1 ± 0.0	0.0 ± 0.0	–
QCD	(4a, 2)	0.0 ± 0.0	0.1 ± 0.1	3.6 ± 2.3	1.1 ± 0.8	0.5 ± 0.4	0.0 ± 0.0	0.0 ± 0.0	–
Data	(4a, ≥ 3)	–	0	0	2	2	–	–	–
SM	(4a, ≥ 3)	–	1.3 ± 0.5	2.4 ± 0.8	2.3 ± 0.7	2.0 ± 0.6	–	–	–
Ttw	(4a, ≥ 3)	–	1.2 ± 0.5	2.0 ± 0.7	1.9 ± 0.7	1.9 ± 0.6	–	–	–
Zinv	(4a, ≥ 3)	–	0.1 ± 0.0	0.2 ± 0.1	0.3 ± 0.1	0.0 ± 0.0	–	–	–
QCD	(4a, ≥ 3)	–	0.0 ± 0.0	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	–	–	–
Data	($\geq 5a$, 0)	–	3	40	96	105	20	3	–
SM	($\geq 5a$, 0)	–	2.9 ± 1.3	44.0 ± 4.9	105.6 ± 7.5	112.2 ± 7.8	19.4 ± 2.8	3.3 ± 0.9	–
Ttw	($\geq 5a$, 0)	–	2.4 ± 1.2	29.2 ± 3.5	61.6 ± 5.5	69.6 ± 6.5	11.4 ± 2.1	1.3 ± 0.5	–
Zinv	($\geq 5a$, 0)	–	0.4 ± 0.3	14.6 ± 1.8	34.9 ± 3.2	36.6 ± 2.9	7.7 ± 1.1	2.0 ± 0.5	–
QCD	($\geq 5a$, 0)	–	0.0 ± 0.0	0.1 ± 0.1	9.1 ± 5.0	6.0 ± 4.3	0.3 ± 0.4	0.0 ± 0.0	–
Data	($\geq 5a$, 1)	–	0	24	60	74	15	0	–
SM	($\geq 5a$, 1)	–	0.8 ± 0.4	22.7 ± 3.0	56.4 ± 4.7	70.6 ± 5.1	15.3 ± 2.2	1.5 ± 0.5	–
Ttw	($\geq 5a$, 1)	–	0.6 ± 0.4	20.3 ± 2.8	47.5 ± 4.5	60.7 ± 5.0	12.7 ± 2.1	1.1 ± 0.4	–
Zinv	($\geq 5a$, 1)	–	0.1 ± 0.1	2.3 ± 0.3	4.7 ± 0.6	6.6 ± 0.6	2.3 ± 0.3	0.4 ± 0.1	–
QCD	($\geq 5a$, 1)	–	0.0 ± 0.0	0.1 ± 0.1	4.1 ± 2.3	3.4 ± 2.4	0.3 ± 0.3	0.0 ± 0.0	–
Data	($\geq 5a$, 2)	–	0	11	27	29	6	1	–
SM	($\geq 5a$, 2)	–	0.0 ± 0.0	8.1 ± 1.6	26.9 ± 3.2	28.4 ± 2.9	5.5 ± 1.1	0.4 ± 0.2	–
Ttw	($\geq 5a$, 2)	–	0.0 ± 0.0	7.8 ± 1.5	23.6 ± 3.1	25.7 ± 2.7	4.7 ± 1.0	0.4 ± 0.2	–
Zinv	($\geq 5a$, 2)	–	0.0 ± 0.0	0.3 ± 0.1	1.2 ± 0.2	1.3 ± 0.2	0.6 ± 0.1	0.0 ± 0.0	–
QCD	($\geq 5a$, 2)	–	0.0 ± 0.0	0.0 ± 0.0	2.1 ± 1.1	1.4 ± 1.0	0.1 ± 0.1	0.0 ± 0.0	–
Data	($\geq 5a$, ≥ 3)	–	–	0	2	5	1	–	–
SM	($\geq 5a$, ≥ 3)	–	–	0.5 ± 0.3	2.9 ± 0.9	4.5 ± 1.2	0.9 ± 0.4	–	–
Ttw	($\geq 5a$, ≥ 3)	–	–	0.5 ± 0.3	2.7 ± 0.9	4.1 ± 1.2	0.8 ± 0.4	–	–
Zinv	($\geq 5a$, ≥ 3)	–	–	0.0 ± 0.0	0.0 ± 0.0	0.2 ± 0.1	0.1 ± 0.0	–	–
QCD	($\geq 5a$, ≥ 3)	–	–	0.0 ± 0.0	0.2 ± 0.1	0.2 ± 0.2	0.0 ± 0.0	–	–

Table A9.6: Post-fit predicted and observed data yield of asymmetric categories in the signal region for the full 2.3 fb^{-1} dataset.

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Acronyms

ALICE A Large Ion Collider Experiment.

APD Avalanche Photodiode.

ATLAS A Toroidal LHC Apparatus.

BPIX Barrel Pixel detector.

BSM Beyond the Standard Model.

CaloJet Calorimeter jet.

CERN European Organisation for Nuclear Research.

CHEF Charged Hadron Energy Fraction.

CHS Charged Hadron Subtraction.

CKM Cabibbo-Kobayashi-Maskawa.

CMB Cosmic Microwave Background.

CMS Compact Muon Solenoid.

CMSSM Constrained Minimal Supersymmetric Standard Model.

CSC Cathode Strip Chamber.

CSVv2 Combined Secondary Vertex version 2.

CTF Combinatorial Track Finder.

DM Dark matter.

DT Drift Tube.

EA Effective Area.

EB ECAL Barrel.

ECAL Electromagnetic Calorimeter.

EE ECAL Endcap.

ES Preshower.

FCNC Flavour Changing Neutral Current.

FED Front End Driver.

FPGA Field Programmable Gate Array.

FPIX Forward Pixel detector.

FSR Final State Radiation.

GCT Global Calorimeter Trigger.

GenJet Generator jet.

GSF Gaussian Sum Filter.

GUT Grand Unified Theory.

HB HCAL Barrel.

HCAL Hadronic Calorimeter.

HE HCAL Endcap.

HF Hadron Forward Calorimeter.

HLT High Level Trigger.

HO Hadron Outer Calorimeter.

HPD Hybrid Photodiode.

IP Interaction Point.

ISR Initial State Radiation.

JEC Jet Energy Correction.

JES Jet Energy Scale.

JetMET Jets and $\cancel{E}_T$.

L1 Level-1.

L1Jet Level-1 jet.

LEP Large Electron-Positron Collider.

LHC Large Hadron Collider.

LHCb LHC-beauty.

LO Leading order.

LS1 Long Shutdown 1.

LSP Lightest Supersymmetric Particle.

MC Monte Carlo.

MIP Minimally Ionising Particle.

MP7 Imperial Master Processor Virtex-7.

MSSM Minimal Supersymmetric Standard Model.

NLL Next-to-leading logarithm.

NLO Next-to-leading order.

NNLO Next-to-next-to-leading order.

OOTPU Out-of-time pileup.

PDF Patron distribution function.

PF Particle-Flow.

PFJet Particle-Flow jet.

PMNS Pontecorvo-Maki-Nakagawa-Sakata.

PMT Photomultiplier Tube.

POG Physics Object Group.

PU Pileup.

PUPPI Pileup Per Particle Identification.

QCD Quantum Chromodynamics.

QED Quantum Electrodynamics.

QFT Quantum Field Theory.

Acronyms

RCT Regional Calorimeter Trigger.

RF Radio Frequency.

RPC Resistive Plate Chamber.

SIPM Silicon Photomultiplier.

SM Standard Model.

SMS Simplified Model Spectra.

SPS Super Proton Synchrotron.

SSB Spontaneous symmetry breaking.

SUSY Supersymmetry.

TEC Tracker Endcap.

TF Transfer Factor.

TIB Tracker Inner Barrel.

TID Tracker Inner disk.

TMT Time-Multiplexed Trigger.

TOB Tracker Outer Barrel.

TOE Theory of Everything.

TPG Trigger Primitive Generator.

TT Trigger Tower.

VPT Vacuum Phototriode.

WP Working Point.