

Searches for neutral Higgs bosons in the $\tau\tau$ final state with the CMS detector

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Abstract

The Compact Muon Solenoid (CMS) detector is located at the CERN Large Hadron Collider. It is a general purpose detector designed to test predictions of the standard model (SM) and search for the Higgs boson, as well as to look for signatures of new physics beyond the SM. The analyses described in this thesis use proton-proton collision data recorded by CMS during 2011 and 2012. Searches for neutral Higgs bosons decaying into tau pairs are presented. The searches are performed separately for the SM Higgs boson or the neutral Higgs bosons of the minimal supersymmetric standard model (MSSM). The MSSM searches consist of two different analyses. The first is a direct search for any one of the MSSM neutral Higgs bosons in the mass range from 90 GeV to 1 TeV decaying directly into taus. The second searches for the signature from a heavy neutral Higgs boson of the MSSM decaying into two light MSSM Higgs bosons with SM-like properties ($H \rightarrow hh$) in the final state with two b-quarks and two taus. The SM and MSSM $\tau\tau$ analyses use 4.9 fb^{-1} of data collected at 7 TeV and 19.7 fb^{-1} collected at 8 TeV, while the MSSM $H \rightarrow hh$ analysis uses only the 8 TeV data. In the SM analysis, an excess of events in data above the background expectation is observed with an observed (expected) local significance of 3.2 (3.7) standard deviations at 125 GeV. This excess is found to be consistent with the 125 GeV Higgs boson of the SM in mass and coupling strengths. No significant excess is observed in either MSSM search, and so upper limits are set on cross-section times branching ratio for the Higgs production processes at the 95% confidence level. Limits are also set in m_A - $\tan \beta$ parameter space of several interesting MSSM benchmark scenarios.

Declaration

I declare that the work contained in this thesis is my own. Where figures and results are taken from other sources this is indicated by an appropriate reference. All figures labelled “CMS” are sourced directly from CMS publications, including those made by myself, and as such include the relevant reference in the caption. The label “CMS (unpublished)” or “CMS Preliminary” is reserved for figures not directly included in a paper but made public via a public web page or other preliminary public document. Studies conducted and results produced by myself are indicated in the main body of the text. For the analyses in chapters 4 to 6 the work was conducted as part of the CMS $H \rightarrow \tau\tau$ working group. I contributed to measurement of identification and trigger efficiencies and the statistical interpretation for the results in chapters 4 and 5. These results are part of the most recent from Run 1 of the LHC [1, 2], and my work was also included in the preliminary results that predated them with subsets of the Run 1 data available at the time; at the HCP 2012 [3, 4] and Moriond 2013 [5] conferences, as well as for a preliminary result produced in November 2013 [6]. The final analysis in chapter 6 is at the time of writing not yet published. For this analysis, my work included designing event selections, studying background methods and evaluating systematics and further work on statistical interpretation. For this analysis I provided the main result for two out of the three channels included in the final version of the analysis to be published.

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Contents

List of Figures	x
List of Tables	1
1 Theory and motivation	2
1.1 The standard model of particle physics	2
1.1.1 Particles and forces	2
1.1.2 The Higgs mechanism in the standard model	4
1.1.3 Searching for the SM Higgs boson	6
1.2 Higgs boson physics beyond the standard model	10
1.2.1 Motivation for theories beyond the standard model	10
1.2.2 The Higgs sector in the MSSM	12
1.2.3 Searching for a neutral MSSM Higgs boson	14
1.3 MSSM models incorporating the LHC Higgs boson	17
1.3.1 Modification of MSSM models at low $\tan\beta$	21
2 The CMS experiment	27
2.1 The LHC	27
2.2 The CMS experiment	31
2.2.1 Tracker	33
2.2.2 Electromagnetic calorimeter	35
2.2.3 Hadronic calorimeter	36
2.2.4 Muon detector	38
2.2.5 Triggering and data processing	40
3 Event reconstruction	42
3.1 Primary Vertex reconstruction	42
3.2 Electrons	43
3.3 Muons	46

3.4	Lepton isolation	47
3.5	Jets	47
3.5.1	Particle flow	48
3.5.2	Jet identification by clustering	48
3.5.3	Jet energy corrections	49
3.5.4	B-tagged jets	50
3.6	Missing energy	52
3.7	Hadronic taus	54
3.7.1	Hadron plus strips algorithm	55
3.7.2	Isolation	57
3.7.3	Electron and muon rejection	57
3.7.4	Energy scale	58
3.8	Di-tau mass reconstruction in $H \rightarrow \tau\tau$	58
4	Search for standard model $H \rightarrow \tau\tau$	63
4.1	Event selection	63
4.1.1	Candidate events in the $e\tau_h$ channel	64
4.1.2	Candidate events in the $\mu\tau_h$ channel	65
4.1.3	Extra lepton vetoes	67
4.1.4	Topological selection	68
4.2	Event categorisation	68
4.3	Datasets and Monte Carlo samples	71
4.4	Background estimation	72
4.4.1	$Z \rightarrow \tau\tau$	72
4.4.2	$Z \rightarrow \ell\ell$	73
4.4.3	W+jets	73
4.4.4	QCD	74
4.4.5	$t\bar{t}$	74
4.4.6	Diboson and single top	75
4.5	Data to Monte Carlo correction factors	76
4.5.1	Identification, isolation and trigger efficiencies	76
4.5.2	Other corrections	78
4.6	Systematic uncertainties	80
4.6.1	Normalisation uncertainties	81
4.6.2	Shape uncertainties	84

4.7	Results	85
4.7.1	Signal extraction	85
4.7.2	Post-fit $m_{\tau\tau}$ distributions	89
4.7.3	Limit and significance	93
4.7.4	Consistency with 125 GeV Higgs boson	96
5	Search for MSSM $\phi \rightarrow \tau\tau$	98
5.1	Event selection and categorisation	99
5.2	Datasets and Monte Carlo samples	99
5.3	Background estimation and systematic uncertainties	100
5.3.1	Background estimation	100
5.3.2	Tail fitting of backgrounds	101
5.3.3	Other systematic uncertainties	103
5.4	Results	103
5.4.1	Signal extraction	103
5.4.2	Model independent results	105
5.4.3	Model dependent results	110
6	Search for MSSM $H \rightarrow hh \rightarrow \tau\tau bb$	116
6.1	Event selection and categorisation	117
6.2	Kinematic fitting to extract m_H	120
6.3	Datasets and Monte Carlo samples	129
6.4	Background estimation	129
6.4.1	$Z \rightarrow \tau\tau$	129
6.4.2	$t\bar{t}$	130
6.4.3	W +jets	130
6.4.4	QCD	133
6.4.5	$Z \rightarrow \ell\ell$, single top and diboson	134
6.5	Systematic uncertainties	134
6.6	Results	136
6.6.1	Signal extraction	136
6.6.2	Contribution from a SM Higgs boson	140
6.6.3	Model independent results	140
6.6.4	Model dependent results	140
7	Conclusions	143

Bibliography	146
Acronyms	158

List of Figures

In the following figures, distributions with uniform binning are labelled with “Events”, while normalisations of distributions with variable bin widths are specified explicitly. For the figures in chapters 4 to 6, scalings to the normalisations of the simulated backgrounds resulting from a fit to data are applied unless otherwise stated. Where distributions are made in a signal sensitive event selection the expected contribution from signal is indicated.

1.1	Feynman diagrams for the dominant production processes of the SM Higgs boson.	7
1.2	Cross sections for Higgs production processes at $\sqrt{s} = 8$ TeV for a range of Higgs boson masses.	8
1.3	Higgs boson branching ratios in the SM for a range of Higgs boson masses.	9
1.4	Feynman diagrams illustrating the one-loop radiative corrections to the Higgs mass for a fermion, f (a) and scalar boson, S (b)	11
1.5	Masses of the h , H and $H^\pm$ bosons in the $m_h^{\max}$ scenario as a function of m_A .	15
1.6	Branching ratios of the pseudoscalar Higgs boson A in the $m_h^{\max}$ scenario.	15
1.7	Feynman diagrams illustrating example tree level production of neutral Higgs bosons in the MSSM.	16
1.8	Cross sections for the production of neutral MSSM Higgs bosons in the $m_h^{\max}$ scenario.	16
1.9	Region of m_A - $\tan\beta$ space which yields a scalar Higgs mass consistent with 125 GeV in the $m_h^{\max}$ scenario.	19
1.10	Region of m_A - $\tan\beta$ space which yields a scalar Higgs mass consistent with 125 GeV in the m_h^{mod} scenarios.	20
1.11	Contours in the M_{SUSY} - $\tan\beta$ plane for constant m_h values around 125 GeV.	23
1.12	Cross sections for the production of the three neutral Higgs bosons in the low $\tan\beta$ regime.	24
1.13	Branching ratios for the H and A bosons in the low $\tan\beta$ regime.	24

1.14	Region of m_A - $\tan \beta$ space which yields a scalar Higgs mass consistent with 125 GeV in the low- $\tan \beta$ -high scenario.	25
1.15	Branching ratios for the $H \rightarrow hh$ process in the low- $\tan \beta$ -high scenario for different values of m_A and $\tan \beta$	26
2.1	Schematic of the LHC accelerator, showing the positions of the four large detectors.	28
2.2	Cross sections for several processes in proton-proton or proton-anti proton collisions, dependent on centre of mass energy.	29
2.3	Illustration of the total integrated luminosity delivered to CMS during Run 1 of the LHC.	30
2.4	Distribution of number of pileup events per bunch crossing in 2012 data.	31
2.5	A schematic of the CMS detector, illustrating the positions of the various subdetectors.	32
2.6	Cross section of the CMS tracking system, indicating the pixel and strip detectors and their positions relative to the interaction point.	34
2.7	Transverse section through the ECAL, indicating its geometry.	36
2.8	Illustration of the HCAL in the r - z plane, indicating its geometry.	38
2.9	Layout of one quadrant of the muon systems.	39
3.1	Distributions of variables related to the electron supercluster in the ECAL.	45
3.2	Total jet energy scale correction factor and corresponding uncertainty as a function of jet η	51
3.3	The distribution of the CSV discriminator used to identify b-jets.	52
3.4	Distributions of PF E_T^{miss} in $Z \rightarrow \mu\mu$ and γ +jet events.	53
3.5	The dependence of the resolution of the hadronic recoil response on the number of primary vertices in the event for PF E_T^{miss} and MVA E_T^{miss}	54
3.6	Figure illustrating the fraction of events in each tau decay mode in the $\mu\tau_h$ channel of the $H \rightarrow \tau\tau$ analysis.	57
3.7	The invariant mass of the hadronic tau in $\mu\tau_h$ channel events of the $H \rightarrow \tau\tau$ analysis.	59
3.8	Di-tau mass for $Z \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ events, reconstructed using the visible products or the SVFit algorithm.	62
4.1	The p_T and η distributions for electron candidates in the $e\tau_h$ channel.	65
4.2	The p_T and η distributions for tau candidates in the $e\tau_h$ channel.	65
4.3	The p_T and η distributions for muon candidates in the $\mu\tau_h$ channel.	66

4.4	The p_T and η distributions for tau candidates in the $\mu\tau_h$ channel.	67
4.5	The transverse mass between the muon and the E_T^{miss} in the $\mu\tau_h$ channel.	69
4.6	Categories used in the $e\tau_h$ and $\mu\tau_h$ channels of the SM $H \rightarrow \tau\tau$ analysis.	69
4.7	Di-tau p_T in the $\mu\tau_h$ channel as used for the separation of events into categories.	70
4.8	Distribution of $m_{\tau\tau}$ for same sign candidate events in the 1-jet low- $p_T^{\tau_h}$ (a) and VBF-loose (b) categories of the $\mu\tau_h$ channel.	75
4.9	Combined electron ID and isolation efficiency in data and MC as a function of (a) η and (b) p_T	77
4.10	Combined muon ID and isolation efficiency in data and MC as a function of (a) η and (b) p_T	77
4.11	Fitted m_{ee} peaks for $Z \rightarrow ee$ tag and probe data events with a probe passing or failing matching to the electron leg of the $e\tau_h$ trigger.	78
4.12	Efficiency of the electron leg of the $e\tau_h$ trigger as a function of electron p_T measured in 2012 data and MC.	78
4.13	Efficiency of the muon leg of the $\mu\tau_h$ trigger as a function of muon p_T measured in 2012 data and MC.	79
4.14	Effect of the tau energy scale uncertainty on the $m_{\tau\tau}$ shape for the gluon-fusion signal with $m_H = 125$ GeV (a) and the $Z \rightarrow \tau\tau$ background (b).	84
4.15	Post-fit $m_{\tau\tau}$ distributions for the 0-jet and 1-jet low- p_T^{τ} categories of the $\mu\tau_h$ channel.	90
4.16	Post-fit $m_{\tau\tau}$ distributions for the 1-jet high- p_T^{τ} and VBF categories of the $\mu\tau_h$ channel.	91
4.17	Post-fit $m_{\tau\tau}$ distributions for the 0-jet and 1-jet low- p_T^{τ} categories of the $e\tau_h$ channel.	92
4.18	Post-fit $m_{\tau\tau}$ distributions for the 1-jet high- p_T^{τ} and VBF categories of the $e\tau_h$ channel.	93
4.19	Combined $m_{\tau\tau}$ distribution using the four most sensitive channels.	94
4.20	Expected and observed limits on μ obtained using the asymptotic CL_s method.	95
4.21	Significance/p-value of the observed data, compared with the expected significance for an SM Higgs boson at each m_H hypothesis.	95
4.22	Figures indicating the compatibility of the observed excess in data with a 125 GeV SM Higgs Boson.	97

5.1	Number of b-tagged jets in events in the $\mu\tau_h$ channel, as used to separate events into b-tag and no b-tag categories.	100
5.2	Analytic fits to the high mass tail of the $m_{\tau\tau}$ distribution, shown for the example of the W+jets background.	102
5.3	Post-fit $m_{\tau\tau}$ distributions for the no b-tag and b-tag categories.	106
5.4	2-D likelihood scans showing the best fit values for the cross section times branching ratio of the gluon fusion (x-axis) and b-associated production (y-axis) processes using 8 TeV data.	108
5.5	Limits on cross section times branching ratio for a) gluon fusion Higgs production and b) b-associated Higgs production for the combination of all channels and categories in the 8 TeV data.	109
5.6	Distributions of the test statistic for toys with SM or MSSM signal injected for $m_A = 300$ GeV, $\tan\beta = 13$ in the $m_h^{\max}$ scenario.	112
5.7	Expected and observed limit in the $m_A - \tan\beta$ plane of the $m_h^{\max}$ scenario.	113
5.8	Expected and observed limit in the $m_A - \tan\beta$ plane of the $m_h^{\text{mod}+}$ scenario (a) and $m_h^{\text{mod}-}$ scenario (b).	114
5.9	Expected and observed limit in the $m_A - \tan\beta$ plane of the light-stau scenario (a) and light-stop scenario (b).	115
5.10	Expected and observed limit in the $m_A - \tan\beta$ plane of the τ -phobic scenario (a) and the $\tan\beta$ - μ plane of the low- m_H scenario (b).	115
6.1	Number of jets in inclusive $\tau\tau$ events in backgrounds and $H \rightarrow hh$ signal.	118
6.2	Number of b-tagged jets in inclusive $\tau\tau$ events in backgrounds and $H \rightarrow hh$ signal.	118
6.3	Values of the combined secondary vertex (CSV) b-tagging discriminator for the highest CSV (leading) jet in the event (a) and second highest (subleading) CSV jet in the event (b), for events with at least two jets in the $\mu\tau_h$ channel.	119
6.4	Distributions of $m_{\tau\tau}$ (left) and m_{jj} (right) in the $\mu\tau_h$ (top) and $e\tau_h$ (bottom) channels for the 2jet-0tag category.	121
6.5	Distributions of $m_{\tau\tau}$ (left) and m_{jj} (right) in the $\mu\tau_h$ (top) and $e\tau_h$ (bottom) channels for the 2jet-1tag category.	122
6.6	Distributions of $m_{\tau\tau}$ (left) and m_{jj} (right) in the $\mu\tau_h$ (top) and $e\tau_h$ (bottom) channels for the 2jet-2tag category.	123
6.7	Four body mass of the candidate H in $H \rightarrow hh$ signal events with $m_H = 300$ GeV, reconstructed with or without a kinematic fit.	127

6.9	Four body mass of the candidate H in data and MC events reconstructed with and without a kinematic fit.	128
6.10	Leading and subleading b-jet p_T in the $t\bar{t}$ control regions.	131
6.11	Transverse mass distribution for events in the 2jet–1tag (a) and 2jet–2tag (b) categories.	132
6.12	Example of a template fit for data events in the high m_T region of the 2jet–1tag category, using the variable leading jet p_T	133
6.13	Number of b-tagged jets after the b-tag scale factor is applied for events which are originally in the 2jet–1tag (a) and 2jet–2tag (b) categories. . .	135
6.14	Effect of the jet energy scale uncertainty on the kinematic fit distribution for the signal with $m_H = 300$ GeV (a) and the $t\bar{t}$ background (b).	136
6.15	Distributions of kinematic fit mass following the maximum likelihood fit for events in the $\mu\tau_h$ channel.	138
6.16	Distributions of kinematic fit mass following the maximum likelihood fit for events in the $e\tau_h$ channel.	139
6.17	Expected and observed limits on cross section times branching ratio for the $gg \rightarrow H \rightarrow hh \rightarrow \tau\tau bb$ process for the $\mu\tau_h$ (a) and $e\tau_h$ (b) channels. .	141
6.18	Combined expected and observed limits on cross section times branching ratio for the $gg \rightarrow H \rightarrow hh \rightarrow \tau\tau bb$ process.	141
6.19	Combined expected and observed limits in the $m_A - \tan\beta$ plane of the low- $\tan\beta$ -high scenario.	142

List of Tables

1.1	Parameters defining the $m_h^{\max}$, $m_h^{\text{mod}+}$, $m_h^{\text{mod}-}$, light-stop, light-stau, τ -phobic and low- m_H MSSM benchmark scenarios.	22
3.1	List of the possible hadronic tau decay modes.	55
4.1	Summary of the background and signal processes used in the $H \rightarrow \tau\tau$ analysis along with the MC generator and cross section for the process for $\sqrt{s} = 7\text{ TeV}$ or 8 TeV	72
4.2	Systematic uncertainties that affect the estimated number of signal or background events in the $H \rightarrow \tau\tau$ analysis.	86
5.1	Systematic uncertainties that affect the estimated number of signal or background events in the MSSM $\phi \rightarrow \tau\tau$ analysis.	104
6.1	Systematic uncertainties that affect the estimated number of signal or background events in the $H \rightarrow hh \rightarrow \tau\tau b\bar{b}$ analysis.	137

Chapter 1

Theory and motivation

1.1 The standard model of particle physics

The standard model (SM) of particle physics is a theory which describes the electromagnetic, weak nuclear and strong nuclear interactions. The SM has successfully described data from a wide range of experiments, and in the years prior to the LHC, all of its predicted elementary particles were verified except for one: the Higgs boson. This chapter briefly describes the theory behind the SM and the Higgs mechanism, before discussing previous experimental results in SM Higgs boson searches and outlining the theory and motivation behind a possible extension to the SM - the minimal supersymmetric standard model (MSSM).

1.1.1 Particles and forces

The SM is a renormalisable quantum field theory, in which the constituents of matter are represented as spin- $\frac{1}{2}$ fermions which interact with forces mediated by spin-1 bosons. The addition of the Higgs mechanism (to be described in section 1.1.2) introduces a further spin-0 boson, with which both the fermions and bosons interact. The SM interactions are described by a Lagrangian which is invariant under $SU(3)_C \times SU(2)_L \times U(1)_Y$ local gauge symmetries. The $SU(3)_C$ part describes the strong interaction, mediated by particles which carry colour charge (C). In these interactions, described by the theory of Quantum Chromodynamics (QCD) [7, 8], the force mediators are massless gluons and the coloured fermions are the quarks. A notable property of QCD interactions is confinement, in which the coupling strength decreases and the interaction becomes asymptotically free at high energy, leading to quarks being bound at small distances in hadrons [9, 10].

The remaining fundamental fermions, the leptons, do not carry colour charge and hence do not interact via the strong force. Both the leptons and quarks do participate in electroweak interactions, which are governed by the $SU(2)_L \times U(1)_Y$ symmetry.

The electroweak symmetry describes the unified electromagnetic and weak interactions [11–13], and was one of the major achievements of the twentieth century in the SM. In electroweak theory the quantum numbers are weak isospin $t_{1,2,3}$ and hypercharge y . These are related to the electric charge Q as:

$$Q = t_3 + \frac{y}{2} \quad (1.1)$$

The gauge fields associated with these quantum numbers are the three weak isospin fields, W_μ^i , $i = 1, 2, 3$, and the hypercharge field B_μ . The weak isospin fields act on doublets:

$$\psi_L = \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L, \begin{pmatrix} \nu_i \\ l_i \end{pmatrix}_L \quad (1.2)$$

where u_i are the up-type quarks (u, c, t), d_i are the down-type quarks (d, s, b), l_i are the charged leptons (e, μ, τ) and ν_i are the corresponding neutrinos (ν_e, ν_μ, ν_τ). The index i indicates first, second or third generation fermions. The subscript L indicates that the doublets correspond to the left handed projection of the fermions. The weak force only interacts with left handed fermions, and as such is maximally parity violating. The right handed projections ψ_R transform as singlet states, which are invariant under $SU(2)_L$.

The physical γ , Z and $W^\pm$ bosons result from mixing between the gauge fields:

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp W_\mu^2), \quad (1.3)$$

$$\begin{pmatrix} A_\mu \\ Z_\mu^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \cdot \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}, \quad (1.4)$$

where A_μ is the photon field, Z_μ^0 is the Z field and θ_W is the weak mixing angle, which can be related to the couplings of the weak neutral (g) and electromagnetic interactions

(g') as $\theta_W = \tan^{-1} \frac{g'}{g}$. The fields $W_\mu^\pm$ correspond to the $W^\pm$ bosons. Weak neutral currents were discovered at the Gargamelle bubble chamber experiment in CERN in 1973 [14], and the Z and $W^\pm$ bosons themselves were discovered by the UA1 and UA2 collaborations at CERN in 1983 [15–18].

Crucially, this leads to a Lagrangian which doesn't contain any mass terms. Gauge mass terms of the form $-M^2 W_\mu W^\mu$ break the gauge invariance of the Lagrangian. Similarly fermion mass terms of the form $-m \bar{\psi} \psi = -m(\bar{\psi}_R \psi_L + \bar{\psi}_L \psi_R)$, where $\bar{\psi}$ indicates the adjoint of the field ψ , contain field pairs of left and right handed components which transform differently under the $SU(2)_L$ and $U(1)_Y$ groups, and so also break gauge invariance. Experimental results suggest that the photon is massless (or at least has a mass smaller than experimental resolution), but the W and Z bosons have finite masses of $\approx 80.4 \text{ GeV}$ and $\approx 91.2 \text{ GeV}$ respectively, and the fermions also have a range of finite masses [19]. As such the electroweak symmetry must be spontaneously broken. The mechanism of electroweak symmetry breaking in the SM is the Higgs mechanism.

1.1.2 The Higgs mechanism in the standard model

A symmetry in a quantum field theory is spontaneously broken when the Lagrangian itself remains invariant whilst the vacuum state does not [20]. For electroweak theory, this is achieved by introducing a complex scalar field which attains a non-zero vacuum expectation value (VEV) [21–25]. This field is an $SU(2)$ doublet, defined as:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad (1.5)$$

The electroweak Lagrangian can be written in the following simple form:

$$\mathcal{L}_{EW} = -\frac{1}{4}(\mathbf{F}_{\mu\nu} \cdot \mathbf{F}^{\mu\nu} + G_{\mu\nu} G^{\mu\nu}), \quad (1.6)$$

where $\mathbf{F}_{\mu\nu}$ and $G_{\mu\nu}$ are the weak isospin and field strength tensors respectively, related to the fields as:

$$\mathbf{F}_{\mu\nu} = \partial_\mu \mathbf{W}_\nu - \partial_\nu \mathbf{W}_\mu - g \mathbf{W}_\mu \times \mathbf{W}_\nu, \quad (1.7)$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu, \quad (1.8)$$

where $\mathbf{W}_\mu = (W_\mu^1, W_\mu^2, W_\mu^3)$. Introducing the complex scalar field ϕ yields an additional term of the form:

$$\mathcal{L}_\phi = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi), \quad (1.9)$$

$$\text{with } D_\mu = \partial_\mu - \frac{1}{2}(igT_i W_\mu^i - ig' B_\mu), \quad (1.10)$$

where T_i are the $SU(2)$ group generators. The term $V(\phi)$ is the potential term, given by:

$$V(\phi) = \lambda(\phi^\dagger \phi)^2 - \mu_{SM} \phi^\dagger \phi, \quad (1.11)$$

where λ and μ_{SM} are constants parametrising the self-interactions and masses of the scalar fields. The vacuum states correspond to the minima of $V(\phi)$ with expectation values of $\langle 0|\phi|0\rangle$, which are given by:

$$\langle 0|\phi|0\rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad (1.12)$$

$$\text{with } v = \sqrt{\frac{\mu_{SM}^2}{\lambda}}. \quad (1.13)$$

To obtain the physical particles, perturbations around the vacuum state are considered. If θ_i and H_{SM} represent small variations in the four degrees of freedom of the field ϕ then:

$$\phi = \exp(-i\theta_i T^i / 2v) \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H_{SM} \end{pmatrix} \quad (1.14)$$

An appropriate gauge transformation can set the phase fields θ_i to be zero, leaving only H_{SM} . Inserting this into the Lagrangian, H_{SM} is identified as a scalar field with mass $\sqrt{2}\mu_{SM}$ and the $W_\mu^\pm$ and Z_μ^0 fields acquire mass terms m_W and m_Z related by:

$$m_W = m_Z \cos \theta_W = \frac{gv}{2}. \quad (1.15)$$

Fermion mass terms are introduced via Yukawa interactions between the fermion and Higgs fields, with the form:

$$-\lambda_f (\overline{\psi}_L \phi \psi_R + \overline{\psi}_R \phi \psi_L), \quad (1.16)$$

where λ_f is the coupling for each fermion. The values λ_f are proportional to the mass of the fermion m_f , such that heavier fermions have stronger coupling to the Higgs boson. The SM does not predict values for these couplings, but they can be determined using the experimentally measured masses of the fermions. The experimentally measured W and Z masses can be used alongside the measured value of the fine structure constant to determine $\sin \theta_W$, v and g , but the value of μ_{SM} cannot be predicted. Hence the mass of the Higgs boson associated with the Higgs field, $m_H = \sqrt{2}\mu_{SM}$, is not directly predicted by the SM, although indirect constraints can be derived from theoretical considerations using precision electroweak data [26].

1.1.3 Searching for the SM Higgs boson

Since the mass of the Higgs boson is not directly predicted by the SM, searches covering a wide range of potential masses must be performed. The Higgs boson is produced in particle accelerators and searched for via a signature resulting from its decay to either fermions or bosons. The coupling of the Higgs boson to a particular final state is determined as in equation 1.16 for fermions and similarly for bosons - i.e. it depends on both the mass of the Higgs boson and the mass of the final state particles.

Production of the Higgs boson occurs via the processes shown in figure 1.1: gluon-gluon fusion, vector boson fusion (VBF) and associated production with either a vector boson or a pair of top quarks. The Higgs does not couple directly to gluons since they are massless, and hence the gluon fusion process proceeds via a quark loop dominated by the top quark, which is the heaviest quark. All four of these dominant production modes are accessible at the LHC.

Previous searches for the Higgs boson were carried out at LEP and the Tevatron. LEP collided electrons and positrons at centre of mass energies ($\sqrt{s}$) between 90 and 209 GeV. In such collisions the Higgs boson is predominantly produced in association with a Z boson, a process referred to as “Higgsstrahlung”. The decay channels used were predominantly decays to $b\bar{b}$ and $\tau^+\tau^-$ pairs. The fact that the Higgs boson was not observed at LEP yields the exclusion of masses with $m_H < 114.4$ GeV at the 95% confidence level (CL) [27]. Searches were also performed by the CDF and D0 Collaborations at the Tevatron accelerator, which collided protons and antiprotons with $\sqrt{s} = 1.96$ TeV. The searches were performed in a mass range of 90–200 GeV and focussed on decays into $b\bar{b}$, W^+W^- , $\gamma\gamma$ and $\tau^+\tau^-$ pairs, with $b\bar{b}$ and W^+W^- offering the highest sensitivity. The combined results from the Tevatron yielded exclusions of m_H in the ranges 90–109 GeV and

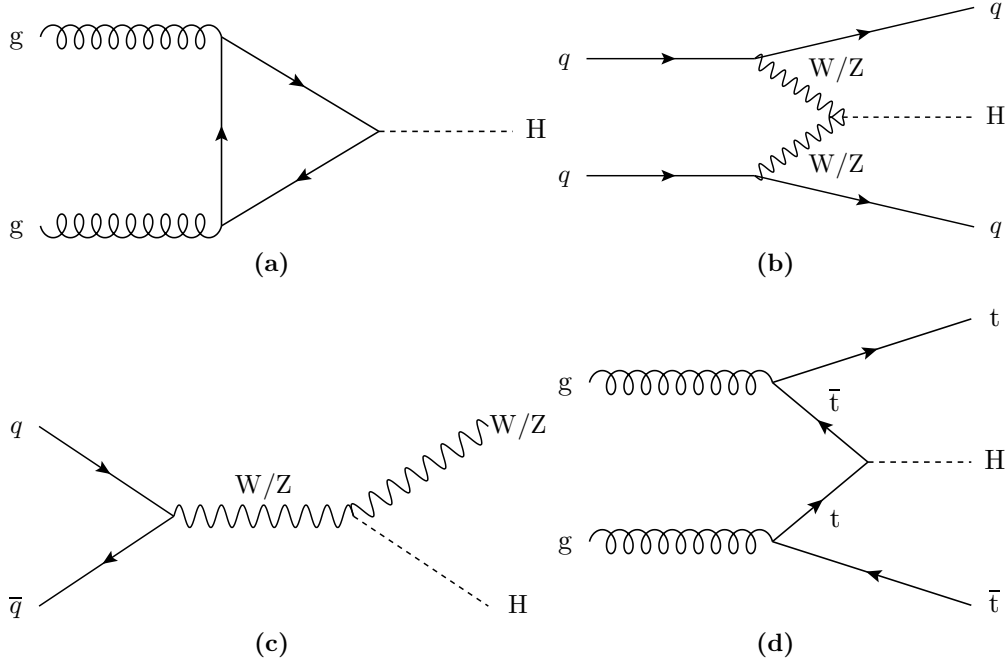


Figure 1.1: Feynman diagrams for the dominant production processes of the SM Higgs boson. Shown is a) gluon fusion, b) vector boson fusion and associated production with c) vector bosons and d) top quarks.

149–182 GeV [28]. The results of such direct searches can be combined with precision measurements of electroweak observables at LEP and by the SLAC Large Detector (SLD) to constrain the mass of the Higgs boson to 94^{+29}_{-24} GeV [26], where the uncertainty incorporates experimental effects only.

The LHC provides a higher centre of mass energy than the Tevatron, and so gives access to higher cross sections and a wider range of Higgs masses. Figure 1.2 indicates the cross sections of the different production processes, for proton-proton collisions at $\sqrt{s} = 8$ TeV as used during the 2012 operating period of the LHC. The gluon fusion production process dominates over the others by at least one order of magnitude in cross section. Despite this, the other production modes are useful as they have specific topologies which can be exploited in the selection of signal-like events. The VBF process is characterised by the two outgoing quarks which hadronise to form jets with high momentum, typically found in the forward detector region. Production via the associated production process consists of a vector boson or a pair of top quarks in the final state, yielding multi-lepton and multi-jet final states with reduced backgrounds from other SM processes.

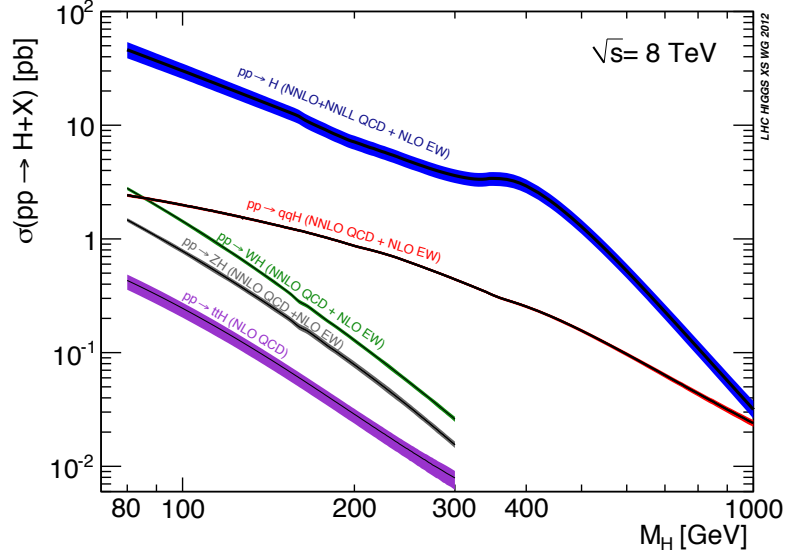


Figure 1.2: Cross sections for Higgs production processes at $\sqrt{s} = 8$ TeV for a range of Higgs boson masses m_H [29]. Across the mass range the gluon-fusion mode dominates, followed by the vector boson fusion and associated production modes. The widths of the lines represent the theoretical uncertainties on the cross section calculation.

The branching fractions to the different decay channels are shown in figure 1.3 for a range of possible Higgs masses. At low Higgs boson masses, a variety of different decay channels are accessible. The decay into two photons occurs via a fermion and W loop, and decays to W^+W^- , ZZ , $b\bar{b}$ and $\tau^+\tau^-$ pairs are also possible. At higher Higgs masses above 130 GeV, the decays into W^+W^- , ZZ are more kinematically favourable and hence dominate. In the discovery of a Higgs boson, identification of any of these decay channels is important, but the most sensitive channels for discovery in the low mass region are $\gamma\gamma$ and ZZ due to their clean signatures. However, upon discovery of a Higgs boson, decays into fermions are particularly important to establish the Yukawa couplings. In fermionic decays, the decay into $b\bar{b}$ dominates with a branching fraction of $\sim 57\%$ in this mass range. However, this final state is difficult to disentangle from the large QCD jet background at the LHC, meaning that the $\tau^+\tau^-$ final state has higher sensitivity.

On 4 July 2012 the ATLAS and CMS Collaborations announced the discovery of a new boson with a mass around 125 GeV [30, 31]. Both experiments analysed approximately 5 fb^{-1} of data collected at $\sqrt{s} = 7$ TeV and $5\text{--}6 \text{ fb}^{-1}$ at $\sqrt{s} = 8$ TeV. The discovery was made predominantly using the ZZ and $\gamma\gamma$ decay modes with a combined excess of events in data yielding a 5σ deviation from the background-only expectation.

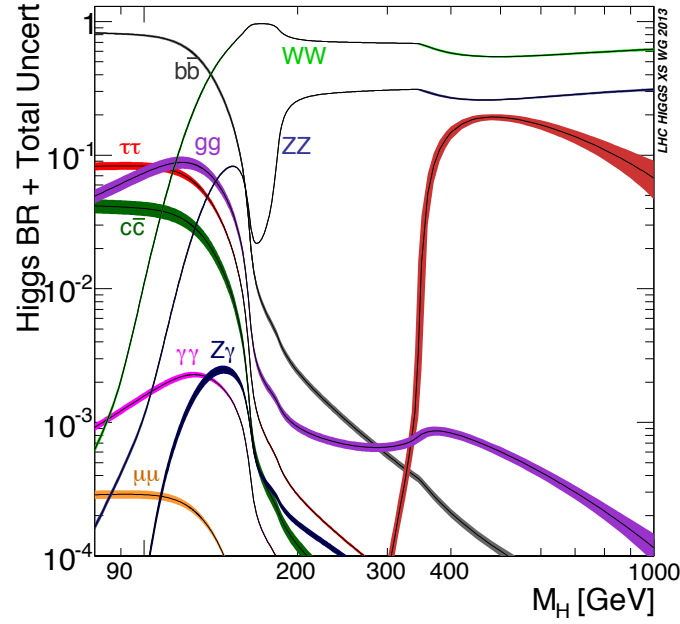


Figure 1.3: Higgs boson branching ratios in the SM for a range of Higgs boson masses m_H [29]. At high masses, above their kinematic thresholds, the WW , ZZ and $t\bar{t}$ (shown in red) decay modes dominate. At lower masses a wide range of different final states is possible. The widths of the lines represent the theoretical uncertainties on the branching ratio calculation.

Run 1 of the LHC was completed in early 2013, increasing the dataset to $\approx 20 \text{ fb}^{-1}$ at 8 TeV. The increased dataset allows access to the less sensitive decay modes. The most recent combination of CMS Higgs results yields a best fit mass of $125.02^{+0.26}_{-0.27}(\text{stat})^{+0.14}_{-0.15}(\text{syst}) \text{ GeV}$ and a signal strength relative to the SM expectation of $1.00 \pm 0.09(\text{stat})^{+0.08}_{-0.07}(\text{theo}) \pm 0.01(\text{syst})$, combining results from the $\gamma\gamma$, W^+W^- , ZZ , $b\bar{b}$, $\tau^+\tau^-$ and $\mu^+\mu^-$ final states, as well as searches for the $t\bar{t}H$ production mode and searches for an invisible Higgs [32]. Within the combination is a study of the compatibility of the couplings in each decay mode with the SM. These channels all show consistency with the SM predictions for a 125 GeV Higgs boson. Other analyses from ATLAS have studied the production rates and couplings in various channels [33–35], and results from both ATLAS and CMS study the spin-parity quantum numbers [36–38] and limits on the decay width [39] and invisible branching fraction [40, 41]. No significant deviations from SM predictions have been found to date in any of these results.

Future studies will further test the compatibility of the observed boson with the SM Higgs, including discovery and precision measurements in the channels which are less sensitive and require more data. The most recent CMS results for the search for the Higgs boson in the $H \rightarrow \tau\tau$ decay channel, corresponding to the complete Run 1 dataset and as included in the most recent combination, are reported in chapter 4.

1.2 Higgs boson physics beyond the standard model

1.2.1 Motivation for theories beyond the standard model

Despite its successes, the SM is known to have some shortcomings. As a theory, it does not predict a candidate to account for the large fraction of non-radiating, non-baryonic dark matter in the universe. It also does not predict the non-zero neutrino masses which are inferred from experimental results in neutrino oscillations [19]. As a theory it also suffers from a shortcoming in that the weak and strong coupling constants associated with the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group do not intersect at a high energy scale, as would be hoped for in a unified theory [42]. It also does not incorporate gravity. Finally, one shortcoming is of particular relevance in the Higgs sector, and is known as the Hierarchy Problem.

It is generally accepted that the SM is an effective theory up to some energy scale Λ where the effect of new physics becomes important. The Higgs mass at tree level is given

by $\sqrt{2}\mu_{SM}$. Radiative corrections adjust the mass as:

$$m_{H_{SM}}^2 = 2\mu_{SM}^2 - \Delta m_H^2. \quad (1.17)$$

Figure 1.4 indicates the radiative corrections to the Higgs mass resulting from a fermion and a boson loop. Considering the fermion loop (which would be dominated by the top quark, which has the strongest coupling to the Higgs boson as the result of its large mass), the coupling of the fermion to the Higgs boson in the form $\lambda_f \bar{\psi}\phi\psi$ yields a correction as [43]:

$$\Delta m_H^2 = -\frac{|\lambda_f^2|}{8\pi^2}(\Lambda^2) + \dots \quad (1.18)$$

In this equation, Λ is the momentum cut off used to regulate the loop integral. The scale Λ can be as high as the Planck scale, where gravitational interactions become significant [7]. For a Λ at the Planck scale then Δm_H^2 is some 30 orders of magnitude larger than $m_{H_{SM}}^2$ for $m_{H_{SM}} \ll 1$ TeV. This means that the bare Higgs boson mass requires extreme fine tuning of the bare mass term $2\mu_{SM}^2$ to allow cancellation.

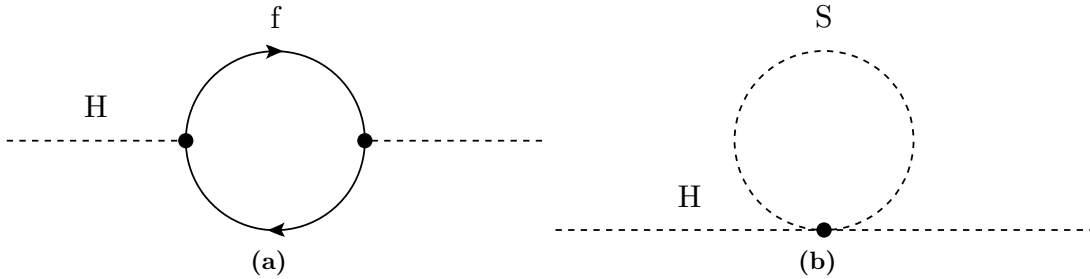


Figure 1.4: Feynman diagrams illustrating the one-loop radiative corrections to the Higgs mass for a fermion, f (a) and scalar boson, S (b)

Many beyond-the-standard-model (BSM) theories are proposed which provide solutions to this Hierarchy problem. One of the most popular is supersymmetry (SUSY). In SUSY, a new symmetry between fermions and bosons is introduced [44]. This can be used to solve the issue with the Higgs mass correction by exploiting the fact that the bosonic and fermionic loop contributions illustrated in figure 1.4 contribute with opposite signs. Thus the symmetry between bosons and fermions permits the cancellation of Δm_H^2 terms. In SUSY models, each SM fermion has a boson superpartner and each SM boson has a fermion superpartner. If SUSY is an unbroken symmetry then the superpartners have exactly the same mass as their SM partner. Since none of these superpartner particles have been observed in nature, SUSY must be a broken symmetry

in which the superpartner masses are larger than the SM masses. The necessity to avoid further fine tuning means the scale of SUSY cannot be much larger than $\mathcal{O}(1 \text{ TeV})$ [45]. An additional motivation for SUSY is the fact that the lightest SUSY particles, if stable, could provide candidates for dark matter. Also the behaviour of the running coupling constants is modified such that all three intersect at $\mathcal{O}(10^{16} \text{ GeV})$ [42].

1.2.2 The Higgs sector in the MSSM

The simplest addition of SUSY to the SM results in the MSSM. The MSSM is an extension to the SM which minimises the numbers of additional fields and interactions while preserving R-parity [46]. R-parity is an operator with eigenvalues of 1 for SM particles and -1 for superpartners. It is required to be conserved in order to explain the stability of the proton [19]. In order to generate the appropriate mass terms for the up-type and down-type fermions, two complex scalar weak isospin doublet fields ϕ_u and ϕ_d are added:

$$\phi_u = \begin{pmatrix} \phi_u^+ \\ \phi_u^0 \end{pmatrix}, \quad \phi_d = \begin{pmatrix} \phi_d^0 \\ \phi_d^- \end{pmatrix}. \quad (1.19)$$

This results in an MSSM Lagrangian with potential terms as:

$$V = \mu(\phi_u^+ \phi_d^- - \phi_u^0 \phi_d^0), \quad (1.20)$$

where μ is the MSSM equivalent of the SM Higgs mass parameter μ_{SM} . This potential provides spontaneous symmetry breaking as in the SM case yielding VEVs parameterised by:

$$\langle 0 | \phi_u | 0 \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \quad \langle 0 | \phi_d | 0 \rangle = \begin{pmatrix} v_d \\ 0 \end{pmatrix}, \quad (1.21)$$

which are related to the SM value and hence m_W by:

$$v^2 = v_u^2 + v_d^2 = \frac{2m_W^2}{g}, \quad (1.22)$$

Thus in the MSSM, the phenomenology is conveniently described in terms of the ratio of the VEVs, $\tan \beta = v_u/v_d$, which is not directly predicted by the model. Of the eight

initial degrees of freedom, three become longitudinal states of the $W^\pm$ and Z bosons which leaves five massive Higgs fields. These result in five physical Higgs bosons; a neutral pseudoscalar A , two neutral scalars h, H and two charged scalars $H^\pm$. These bosons are defined by the mixing of ϕ_u and ϕ_d , parameterised by a mixing angle α in addition to β :

$$A = \sqrt{2}(\text{Im}(\phi_u^0) \cos \beta + \text{Im}(\phi_d^0) \sin \beta), \quad (1.23)$$

$$\begin{pmatrix} h \\ H \end{pmatrix} = \sqrt{2} \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \text{Re}(\phi_u^0) - v_u \\ \text{Re}(\phi_d^0) - v_d \end{pmatrix}, \quad (1.24)$$

$$H^+ = \phi_u^+ \cos \beta + \phi_d^{+\dagger} \sin \beta, \quad (1.25)$$

$$H^- = \phi_u^{+\dagger} \cos \beta + \phi_d^- \sin \beta. \quad (1.26)$$

The self interactions of the scalar fields are not independent parameters in the MSSM and can be expressed in terms of g and g' . As a result, the masses and couplings of the MSSM Higgs bosons can be determined at tree level by two free parameters: $\tan \beta$ and the mass of one of the Higgs bosons, conventionally chosen to be the mass of the pseudoscalar, m_A . The masses of the other Higgs bosons can then be expressed as:

$$m_h^2 = \frac{1}{2} \left(m_A^2 + m_Z^2 - \sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta} \right), \quad (1.27)$$

$$m_H^2 = \frac{1}{2} \left(m_A^2 + m_Z^2 + \sqrt{(m_A^2 + m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta} \right), \quad (1.28)$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2, \quad (1.29)$$

where m_h , m_H and $m_{H^\pm}$ are the masses of the h , H and $H^\pm$ bosons respectively. This yields a constraint on α :

$$\cos^2(\beta - \alpha) = \frac{m_h^2(m_Z^2 - m_h^2)}{m_A^2(m_H^2 - m_h^2)}. \quad (1.30)$$

Equation 1.27 yields an upper bound on m_h :

$$m_h \leq m_Z |\cos 2\beta|. \quad (1.31)$$

This means that at tree level, the mass of the lightest scalar Higgs cannot exceed that of the Z boson (91.2 GeV). However, the tree level masses and couplings are modified by higher order corrections. The dominant effect is from incomplete cancellation of the

top and stop (the superpartner of the top) loops. These corrections, as illustrated in figure 1.4, do not completely cancel in the case that SUSY is broken. Hence the size of the corrections is strongly dependent on the top and stop masses, where the stop mass depends on μ and the parameters describing SUSY breaking. The upper bound on m_h is increased by these radiative corrections and is maximised for large m_A ($\gg m_Z$) and $\tan \beta$ ($\gg 1$). The maximum value of m_h for a particular choice of m_A and $\tan \beta$ is denoted $m_h^{\max}$. If the scale of SUSY breaking, M_{SUSY} , is chosen to be 1 TeV, $m_h^{\max} \approx 135$ GeV.

1.2.3 Searching for a neutral MSSM Higgs boson

It is important that the phenomenology of Higgs bosons, including the higher order corrections, is understood in order to define the masses of the neutral Higgs bosons and hence optimise an experimental search for them. This is complicated by the number of SUSY breaking parameters in the MSSM. Hence it is conventional to study particular benchmark scenarios where the SUSY breaking parameters and μ are fixed to a choice of values and only m_A and $\tan \beta$ are varied [43, 47]. One such scenario is the $m_h^{\max}$ scenario in which $m_h = m_h^{\max}$ for high m_A and $\tan \beta$ values, using the choice $M_{\text{SUSY}} = 1$ TeV and $\mu = \pm 200$ GeV. Other alternative benchmark scenarios are discussed in section 1.3.

Figure 1.5 indicates the masses of each of the Higgs bosons in the $m_h^{\max}$ scenario for $\tan \beta = 3$ and $\tan \beta = 30$ as a function of the mass of the pseudoscalar m_A . Two different regimes of the $m_h^{\max}$ scenario can be considered, in which one of the neutral scalars is approximately degenerate in mass with the pseudoscalar and has similar couplings. At large $\tan \beta$ and for $m_A \ll m_h^{\max}$, $m_A \approx m_h$ and the couplings of the A and h are very similar. The couplings of the A and h bosons to down-type fermions are enhanced by a factor $\sim \tan \beta$ relative to the SM value, with negligible couplings to vector bosons. The scalar H has couplings close to those in the SM. In the limit where $m_A \gg m_h^{\max}$, $m_A \approx m_H$ and the couplings of the A and H are very similar. The couplings of the A and H bosons to down-type fermions are enhanced by a factor $\sim \tan \beta$ relative to the SM value, with negligible couplings to vector bosons. The scalar h has couplings close to those in the SM.

The effect of enhanced couplings to down-type fermions is illustrated by the branching ratios of the A, shown in figure 1.6 for $\tan \beta$ values of 10 and 50. It can be seen that the $\tau\tau$ decay mode has a large branching ratio for a large range of m_A and $\tan \beta$ points. This motivates searches for the MSSM Higgs bosons in the final state of $\tau\tau$. Chapter 5

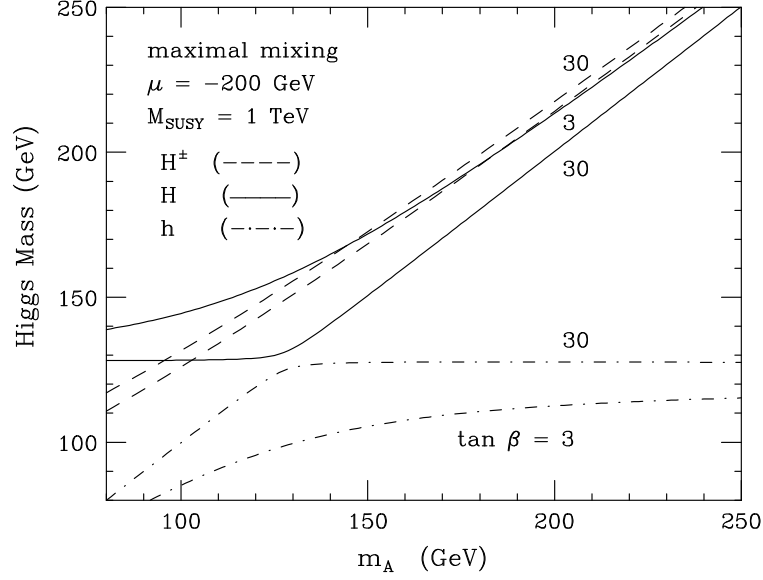


Figure 1.5: Masses of the h , H and $H^\pm$ bosons in the $m_h^{\max}$ scenario as a function of m_A . Values are shown for $\tan \beta = 3$ and $\tan \beta = 30$ [43].

discusses the most recent results from direct searches for neutral MSSM Higgs bosons using the $\tau\tau$ final state with the CMS detector.

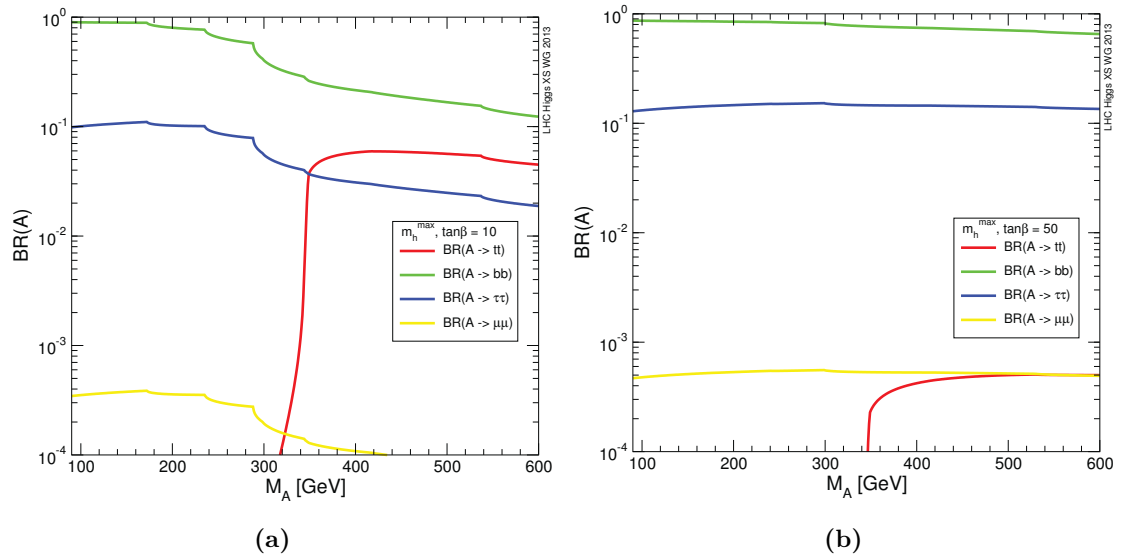


Figure 1.6: Branching ratios of the pseudoscalar Higgs boson A in the $m_h^{\max}$ scenario for $\tan \beta = 10$ (a) and $\tan \beta = 50$ (b). Branching ratios into SUSY particles are not included in the figure [29].

Analogously to the SM Higgs production, the dominant production mode at small $\tan\beta$ is the gluon fusion process, denoted $gg \rightarrow \phi$, where ϕ denotes any of the three neutral Higgs bosons, $\phi = H, A, h$. As in the SM case the gluon fusion process proceeds via a quark loop, which at low $\tan\beta$ is dominated by top quarks but at high $\tan\beta$ the b-quark loops dominate due to enhanced couplings to down-type fermions. At large $\tan\beta$, the dominant production mechanism is Higgs radiation by b-quarks, denoted $gg \rightarrow b\bar{b}\phi$. Example tree level Feynman diagrams illustrating these two production processes are shown in figure 1.7. The cross sections for each of these production processes are shown in figure 1.8 for $\sqrt{s} = 8 \text{ TeV}$, evaluated in the m_h^{max} scenario.

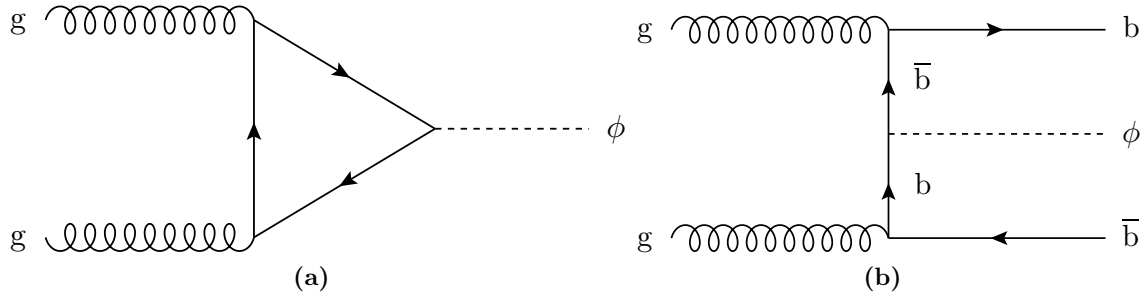


Figure 1.7: Feynman diagrams illustrating example tree level production for the gluon-fusion process (a) or b-associated production process (b). The particle ϕ indicates any one of the three neutral Higgs bosons, h , H or A .

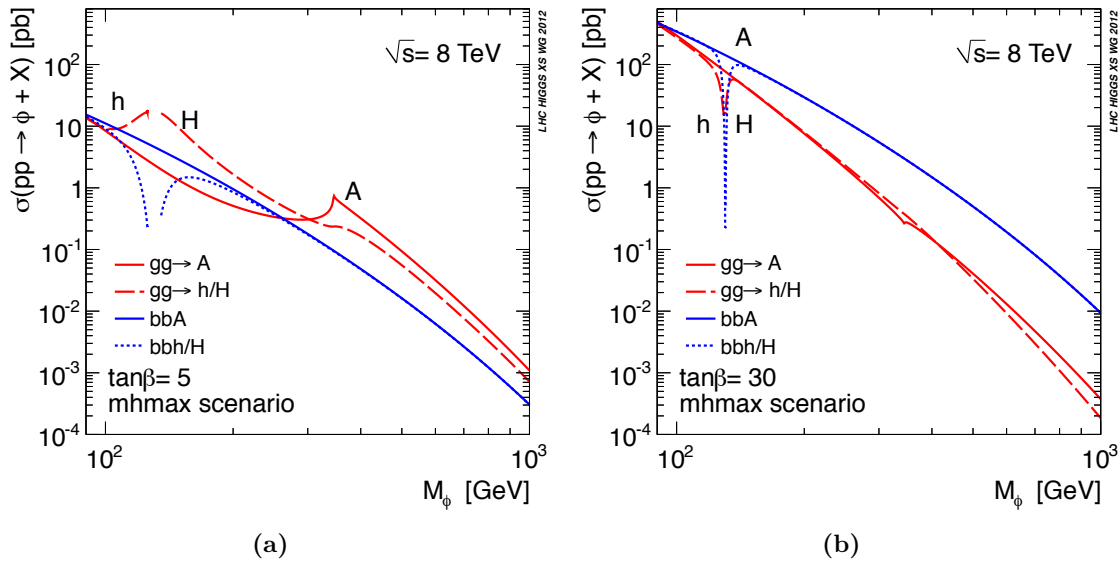


Figure 1.8: Cross sections for the production of neutral MSSM Higgs bosons in the m_h^{max} scenario for $\tan\beta = 5$ (a) and $\tan\beta = 30$ (b) [29].

Previous searches for neutral MSSM Higgs bosons were conducted at LEP, with interpretation in the $m_h^{\max}$ scenario [48]. The results were negative and yielded limits $m_A > 93.4 \text{ GeV}$ at 95% CL. Results from the Tevatron [49] provide complementary exclusion limits at high $\tan\beta$, considering masses up to $m_A = 200 \text{ GeV}$. The higher centre of mass energy of the LHC provides access to m_A values as high as 1 TeV. The most recent results from the LHC exclude large regions of previously unreachable phase space in the $m_h^{\max}$ scenario [2, 50]. The results discussed in chapter 5 follow those in [2].

1.3 MSSM models incorporating the LHC Higgs boson

With the discovery of a 125 GeV Higgs-like particle at the LHC, the number of possible MSSM scenarios is reduced to those which can incorporate this boson with its measured properties. This section details some possible MSSM scenarios which can incorporate this 125 GeV boson, whilst also exhibiting interesting phenomenology motivated by experimental measurements. In particular the scenarios must fulfil the condition $m_H = 125 \pm 3 \text{ GeV}$ over a wide range of parameter space, and satisfy the boundaries set by previous searches at LEP, the Tevatron and the LHC. The 3 GeV uncertainty on the Higgs mass is dominated by theoretical uncertainties in the MSSM models. All of the scenarios considered are defined without allowing CP violation. The scenarios follow those described in [51], with some small modifications. More detail can be found in [2], where these scenarios are discussed in the context of the MSSM $\phi \rightarrow \tau\tau$ analysis.

As described previously, at tree level the masses of the five Higgs bosons are defined by m_A and $\tan\beta$. These masses are adjusted via radiative corrections, necessary to produce a Higgs with mass consistent with 125 GeV. The parameters of interest in these radiative corrections are as follows:

- The mass of the top quark, m_t .
- The mass of the bottom quark, m_b .
- The mass of the 3rd generation squarks: stops and sbottoms, given by M_{SUSY} .
- The higgsino mass parameter, μ .
- The mass of the 3rd generation sleptons: the staus, given by $M_{\tilde{\ell}_3}$.
- The $U(1)$ gaugino mass parameter, M_1 .
- The $SU(2)$ gaugino mass parameter, M_2 .

- The trilinear couplings of the stops, sbottoms and staus, A_t , A_b and A_τ .
- The mixing parameters of the stops, sbottoms and staus, X_t , X_b and X_τ .

The dependence on these parameters can be reduced by exploiting relations between them. For most scenarios, M_1 and M_2 are assumed to be related at the GUT scale as:

$$M_1 = \frac{5}{3} \frac{\sin^2 \theta_W}{\cos^2 \theta_W} M_2, \quad (1.32)$$

Also the mixing parameters X_i ($i = t, b$ or τ), the trilinear couplings A_i and the higgsino mass parameter μ are related to the off-diagonal elements of the mixing matrices in the stop, sbottom or stau sector as:

$$X_t = A_t - \mu \cot \beta, \quad X_b = A_b - \mu \tan \beta, \quad X_\tau = A_\tau - \mu \tan \beta. \quad (1.33)$$

Thus the list of parameters upon which the following MSSM scenarios depend is reduced to: m_A , $\tan \beta$, m_t , m_b , M_{SUSY} , μ , $M_{\tilde{\ell}_3}$, M_2 , A_t , A_b , A_τ and X_t . Finally the following parameters have only a very small effect on the MSSM Higgs boson sector, and are fixed at chosen values which are compatible with the current exclusion limits in direct searches:

- Masses of the first and second generation squarks, $M_{\tilde{q}_{1,2}} = 1500 \text{ GeV}$.
- Masses of the first and second generation sleptons, $M_{\tilde{\ell}_{1,2}} = 500 \text{ GeV}$.
- Trilinear couplings of the first and second generation squarks and leptons, $A_f = 0$.

A summary of the scenarios considered is given in table 1.1, and a short description of each is given in the following sections.

The m_h^{max} scenario

The m_h^{max} scenario was already discussed in the previous section as the benchmark used at LEP, the Tevatron and early LHC searches. In this scenario the ratio of the stop mixing parameter and the masses of the third generation squarks is chosen equal to 2 ($|X_t/M_{\text{SUSY}}| = 2$). This yields a value of $m_h \sim 135 \text{ GeV}$ at high m_A and $\tan \beta$. In light of the 125 GeV boson discovery, this scenario becomes less relevant, since there is only a small amount of parameter space where either scalar Higgs mass is consistent with 125 GeV. Figure 1.9 indicates the region ruled out by this mass constraint. It should

be noted that the exact definition of the $m_h^{\max}$ scenario in terms of the choices made for radiative corrections has varied slightly over the last few years to take into account results from the most recent SUSY searches; the exact version used for the $H \rightarrow \tau\tau$ analysis is defined in table 1.1.

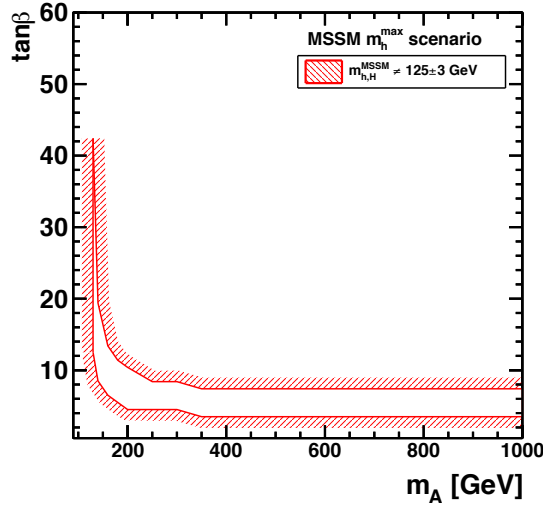


Figure 1.9: Region of m_A - $\tan\beta$ space which yields a scalar Higgs mass consistent with 125 GeV in the $m_h^{\max}$ scenario. The majority of this scenario is ruled out by the discovery of a 125 GeV Higgs boson at the LHC.

The m_h^{mod} scenario

As the name suggests, the m_h^{mod} is a slightly modified version of the $m_h^{\max}$, such that the mass of the light Higgs is consistent with 125 GeV over a much wider range of phase space. This is achieved by decreasing the ratio of the stop mixing parameter and the masses of the third generation squarks, $|X_t/M_{\text{SUSY}}|$. In the $m_h^{\text{mod}+}$ scenario, the stop mixing is positive, $X_t = 1.5 \cdot M_{\text{SUSY}}$, which gives better agreement with the experimental measurements of $(g - 2)_\mu$ [52]. In the $m_h^{\text{mod}-}$ scenario, the stop mixing parameter is negative, $X_t = -1.9 \cdot M_{\text{SUSY}}$, which results in a $B(b \rightarrow s\gamma)$ with better agreement with measurements [53].

Figure 1.10 indicates the region of parameter space which yields a Higgs consistent with 125 GeV. It can be seen that the area is a lot larger than in the $m_h^{\max}$ case. In all subsequent scenarios, the allowed region is very similar, excluding only very low $\tan\beta$ values. For the other scenarios these allowed regions are shown in chapter 5, in

the context of the results of the MSSM $\phi \rightarrow \tau\tau$ analysis which are interpreted in these scenarios.

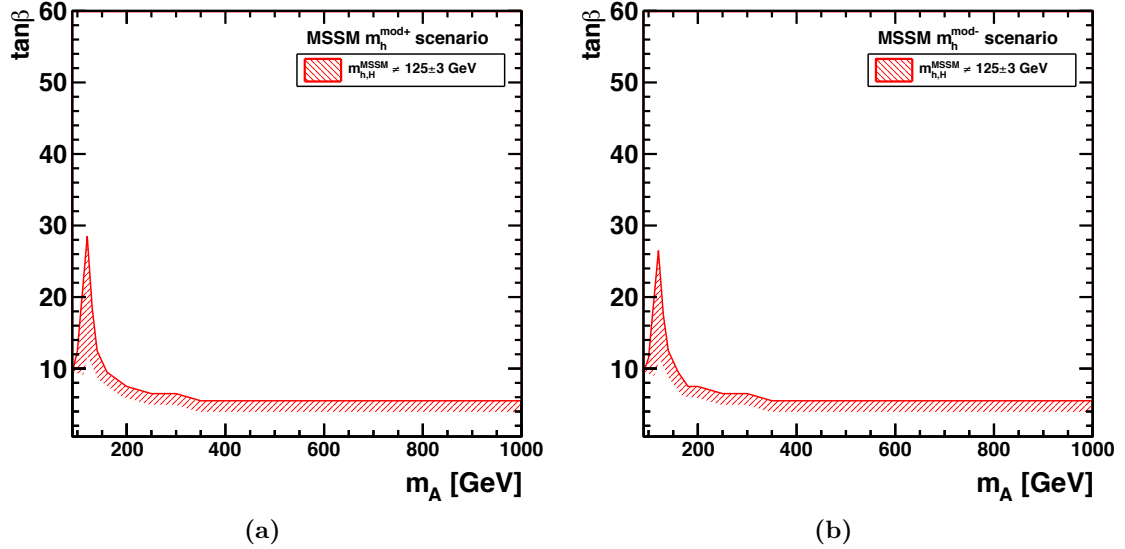


Figure 1.10: Region of m_A - $\tan\beta$ space which yields a scalar Higgs mass consistent with 125 GeV in the $m_h^{\text{mod}+}$ (a) and $m_h^{\text{mod}-}$ (b) scenarios. In such modified scenarios, the majority of phase space is consistent with the discovery of a 125 GeV Higgs.

The light stop scenario

The mass of the lightest CP-even Higgs depends logarithmically on the stop mass, and therefore a value of 125 GeV can be reached even with values of $M_{\text{GUT}} < 1$ TeV, provided the mixing in the stop sector is large. This leads to light stops, which could modify the gluon-fusion Higgs production rate. Such a scenario is referred to as the light-stop scenario. This scenario is defined to be in agreement with current results of direct searches for stops. Note that in this scenario M_1 and M_2 are not related by the GUT relation in equation 1.32.

The light stau scenario

The light stau scenario was motivated by the excess of events in the decay channel of the $H \rightarrow \gamma\gamma$ measured by ATLAS [54]. The most recent ATLAS $H \rightarrow \gamma\gamma$ result can be found in [55] and sees a slightly smaller excess. Light staus lead to a modification of the ratio of

the lightest Higgs boson decaying into two photons with respect to the SM expectation:

$$r_{\gamma\gamma} = \frac{\Gamma(h \rightarrow \gamma\gamma)_{\text{MSSM}}}{\Gamma(h \rightarrow \gamma\gamma)_{\text{SM}}}. \quad (1.34)$$

For high values of $\tan\beta$ and m_A this ratio can be as high as 1.3.

The τ -phobic scenario

Similarly to the case of the light stau scenario, the τ -phobic scenario is motivated by the possibility to allow reduced couplings to down-type fermions. In high $\tan\beta$ and m_A , the ratios:

$$r_{bb} = \frac{\Gamma(h \rightarrow bb)_{\text{MSSM}}}{\Gamma(h \rightarrow bb)_{\text{SM}}}, \quad r_{\tau\tau} = \frac{\Gamma(h \rightarrow \tau\tau)_{\text{MSSM}}}{\Gamma(h \rightarrow \tau\tau)_{\text{SM}}} \quad (1.35)$$

can be significantly lower than 1.

The low- m_H scenario

The low- m_H scenario is somewhat different from the other scenarios due to the fact that in this scenario, the Higgs boson with mass of 125 GeV is assumed to be the heavier scalar Higgs H . This means that the mass of the pseudoscalar Higgs must be chosen to be not too high, and is fixed at $m_A = 110$ GeV. Since m_A is fixed in this scenario, the 2-D parameter space for the scan is chosen as μ - $\tan\beta$, with μ varied between 300 and 3100 GeV and $\tan\beta$ between 1.5 and 9.5. All the other parameters are very similar to those in the τ -phobic scenario. In this scenario, the couplings of the lightest Higgs boson h to gauge bosons is significantly reduced compared with the SM expectations by a factor 2-10, to ensure that the h is not already excluded by LEP limits.

1.3.1 Modification of MSSM models at low $\tan\beta$

In all of the scenarios discussed in the previous sections, the mass of either the lighter or heavier scalar Higgs boson is consistent with 125 GeV over a wide range of phase space. However, one thing common to all of these scenarios is the fact that in general the mass is not consistent at very low $\tan\beta$ values, where the mass of the lightest Higgs becomes

Parameter	$m_h^{\max}$	$m_h^{\text{mod}+}$	$m_h^{\text{mod}-}$
m_A	90 – 1000 GeV	90 – 1000 GeV	90 – 1000 GeV
$\tan \beta$	0.5-60	0.5-60	0.5-60
M_{SUSY}	1000 GeV	1000 GeV	1000 GeV
μ	200 GeV	200 GeV	200 GeV
M_1	$(5/3)M_2 \tan \theta_W^2$	$(5/3)M_2 \tan \theta_W^2$	$(5/3)M_2 \tan \theta_W^2$
M_2	200 GeV	200 GeV	200 GeV
X_τ	$2M_{\text{SUSY}}$	$1.5M_{\text{SUSY}}$	$-1.9M_{\text{SUSY}}$
A_b, A_t, A_τ	$A_b = A_t = A_\tau$	$A_b = A_t = A_\tau$	$A_b = A_t = A_\tau$
$m_{\tilde{g}}$	1500 GeV	1500 GeV	1500 GeV
$m_{\tilde{\ell}_3}$	1000 GeV	1000 GeV	1000 GeV

Parameter	light-stop	light-stau	τ -phobic	low- m_H
m_A	90 – 1000 GeV	90 – 1000 GeV	90 – 1000 GeV	110 GeV
$\tan \beta$	0.7-60	0.5-60	0.9-50	1.5-9.5
M_{SUSY}	500 GeV	1000 GeV	1500 GeV	1500 GeV
μ	400 GeV	500 GeV	2000 GeV	300 – 3100 GeV
M_1	340 GeV	$(5/3)M_2 \tan \theta_W^2$	$(5/3)M_2 \tan \theta_W^2$	$(5/3)M_2 \tan \theta_W^2$
M_2	400 GeV	200 GeV	200 GeV	200 GeV
X_τ	$2M_{\text{SUSY}}$	$1.6M_{\text{SUSY}}$	$2.45M_{\text{SUSY}}$	$2.45M_{\text{SUSY}}$
A_b, A_t, A_τ	$A_b = A_t = A_\tau$	$A_b = A_t, A_\tau = 0$	$A_b = A_t = A_\tau$	$A_b = A_t = A_\tau$
$m_{\tilde{g}}$	1500 GeV	1500 GeV	1500 GeV	1500 GeV
$m_{\tilde{\ell}_3}$	1000 GeV	245 GeV	500 GeV	1000 GeV

Table 1.1: Parameters defining the $m_h^{\max}$, $m_h^{\text{mod}+}$, $m_h^{\text{mod}-}$, light-stop, light-stau, τ -phobic and low- m_H MSSM benchmark scenarios [2].

too light to be consistent with 125 GeV. As results such as those discussed in chapter 5 rule out larger regions of phase space at high $\tan \beta$, attention turns to this low $\tan \beta$ region and analyses which could access it.

The low $\tan \beta$ region can be re-opened if the value of M_{SUSY} is allowed to be higher than 1 TeV [56]. In the MSSM, values of M_{SUSY} must be lower than 3 TeV to avoid too much fine tuning in the model [45]. However, as searches at the LHC have yet to discover supersymmetric particles, it is natural that models with higher SUSY scales are being considered, and as the allowed amount of fine-tuning in a model is somewhat subjective, attention is turning more to these types of scenarios. Figure 1.11 illustrates the mass of the h boson at different choices of M_{SUSY} for a range of $\tan \beta$ values. It can be seen that

$m_h = 125 \pm 3 \text{ GeV}$ can be achieved for values of $\tan \beta$ as low as 1 if M_{SUSY} is allowed to be in the range $100 - 1000 \text{ TeV}$. Slightly higher $\tan \beta$ values in the range 2–5 can be achieved with M_{SUSY} values only as high as a few TeV.

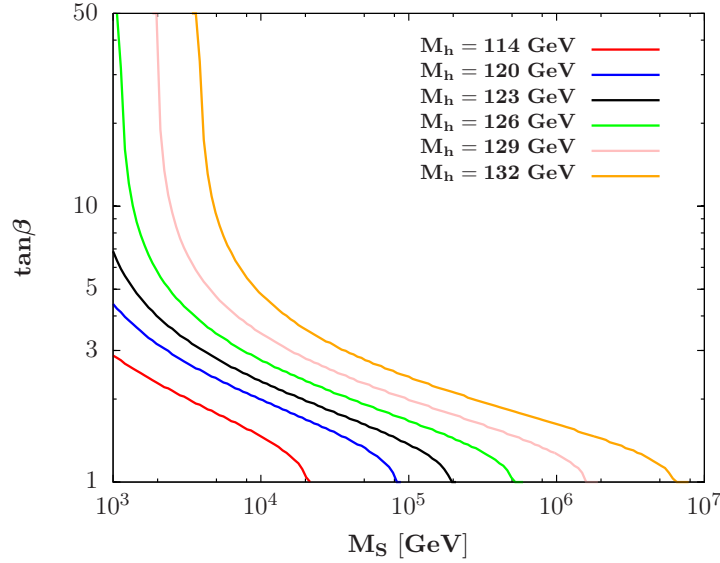


Figure 1.11: Contours in the $M_{\text{SUSY}}(M_S)$ - $\tan \beta$ plane for constant m_h values around 125 GeV, illustrating that higher M_{SUSY} values can allow a light Higgs consistent with 125 GeV for even very low $\tan \beta$ values [56].

In such a low $\tan \beta$ region, the gluon fusion production process dominates over any b-associated production. Figure 1.12 indicates the production cross sections for each of the neutral Higgs bosons in such a low $\tan \beta$ regime for $\sqrt{s} = 8 \text{ TeV}$. It can be seen that the production of the heavier A and H bosons via gluon fusion dominates over any of the other production mechanisms. To access information about such a scenario, the heavier Higgs bosons must be searched for. Figure 1.13 illustrates the branching ratios of the A and H bosons in such a mass range.

From figure 1.13, it can be seen that in the central region of $m_A - \tan \beta$ space, branching ratios for the decays of $H \rightarrow hh$ and $A \rightarrow Zh$ are enhanced. Several recent LHC analyses have made searches for these decays in the scenario where the h is the 125 GeV Higgs discovered at the LHC. Various final states have been studied including for the $H \rightarrow hh$ analysis $\gamma\gamma bb$ [57, 58] and $bbbb$ [59] and for the $A \rightarrow Zh$ analysis $\ell\ell bb$ and $\ell\ell\tau\tau$ [60, 61]. Chapter 6 documents a $H \rightarrow hh$ analysis in the final state of $\tau\tau bb$. Such results can be interpreted in an appropriate low $\tan \beta$ scenario.

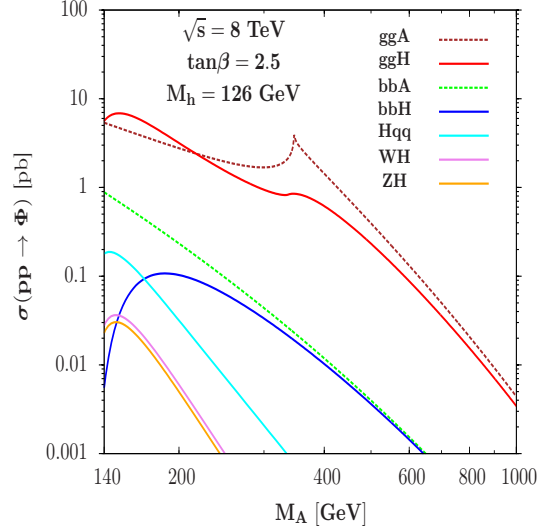


Figure 1.12: Cross sections for the production of the three neutral Higgs bosons in the low $\tan\beta$ regime. The production of the H and A bosons via gluon fusion dominates over any of the other production processes [56].

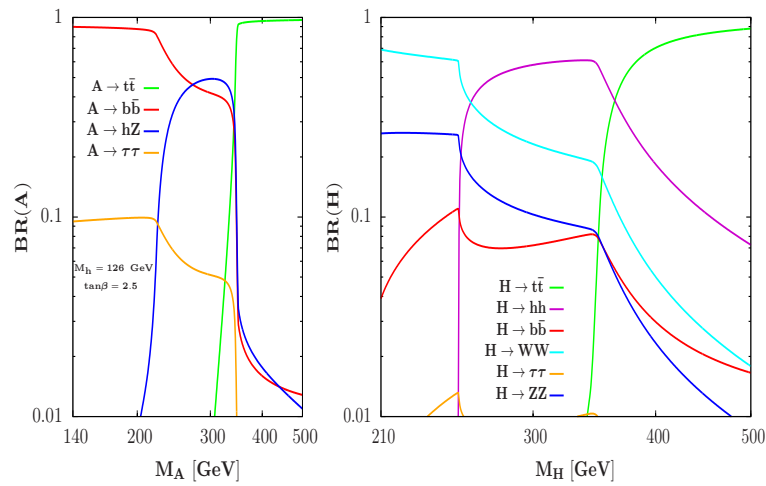


Figure 1.13: Branching ratios for the H and A bosons in the low $\tan\beta$ regime, for $\tan\beta = 2.5$ [56].

The low- $\tan\beta$ -high scenario

An appropriate MSSM scenario at low $\tan\beta$ is known as the low- $\tan\beta$ -high scenario (also called low-tb-high scenario) [62]. Such a scenario depends on radiative corrections like those described previously. To attain a light Higgs boson mass consistent with 125 ± 3 GeV for low- $\tan\beta$ values in the range 0.5-4, M_{SUSY} is varied between 1-100 TeV and the parameter X_t is varied such that:

$$\begin{aligned} \text{for } \tan\beta \leq 2 : \quad & |X_t/M_{\text{SUSY}}| = 2 \\ \text{for } 2 < \tan\beta \leq 8.6 : \quad & |X_t/M_{\text{SUSY}}| = 0.0375 \tan^2\beta - 0.7 \tan\beta + 3.25 \\ \text{for } 8.6 < \tan\beta : \quad & |X_t/M_{\text{SUSY}}| = 0 \end{aligned}$$

All other trilinear couplings are set to 2000 GeV, $\mu = 1500$ GeV and $M_2 = 2000$ GeV. With these choices, the region of $m_A - \tan\beta$ space consistent with the 125 GeV mass is as shown in figure 1.14.

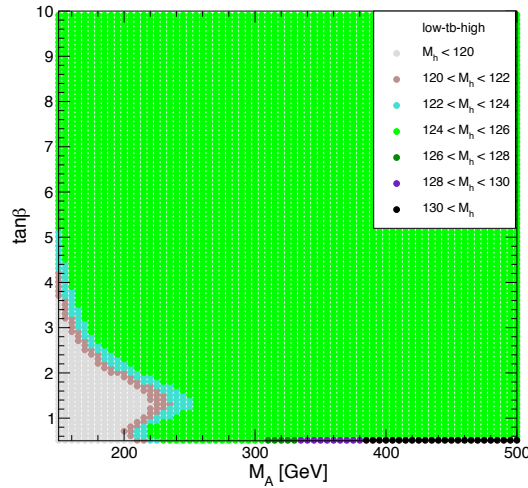


Figure 1.14: Region of m_A - $\tan\beta$ space which yields a scalar Higgs mass consistent with 125 GeV in the low- $\tan\beta$ -high scenario. The majority of phase space is consistent with the discovery of a 125 GeV Higgs boson [62].

Figure 1.15 shows the branching ratio for the $H \rightarrow hh$ process in the low- $\tan\beta$ -high scenario in the phase space of interest. It can be seen that there are regions of phase space where this branching ratio is significantly enhanced, illustrating how analyses targeting the $H \rightarrow hh$ process will be sensitive in such regions.

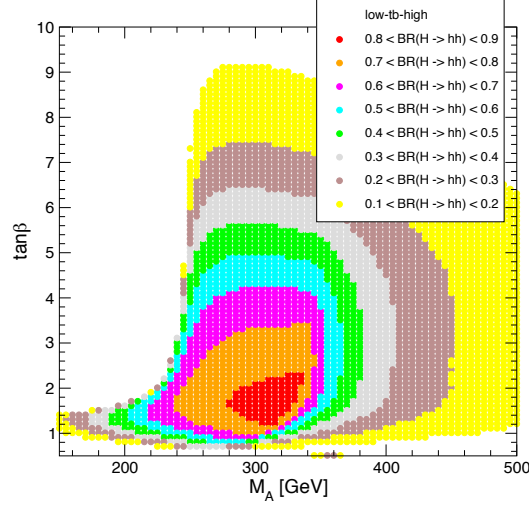


Figure 1.15: Branching ratios for the $H \rightarrow hh$ process in the low- $\tan \beta$ -high scenario for different values of m_A and $\tan \beta$. The branching ratio can be significantly enhanced in these regions [62].

An alternative method for defining such a scenario uses the $m_h = 125$ GeV mass constraint to define the radiative corrections at each point in the $m_A - \tan \beta$ space, such that no particular choices for the SUSY breaking parameters is necessary. This is found to produce similar cross sections times branching ratios as the low- $\tan \beta$ -high scenario. More detail on this method can be found in [63]. Both methods are currently being studied by the LHC Higgs Cross Section Working Group (LHCHXSWG).

Chapter 2

The CMS experiment

2.1 The LHC

The Large Hadron Collider (LHC) [64] is a synchrotron accelerator with a 27 km circumference designed to collide beams of protons at centre of mass energies as high as 14 TeV. It is hosted in the tunnel of the former Large Electron Positron (LEP) [65] accelerator on the French-Swiss border near Geneva and operated by the European Organisation for Nuclear Research (CERN). As well as proton-proton collisions, the LHC also accelerates beams of lead ions to produce both lead-lead (PbPb) and proton-lead (pPb) collisions.

Protons originate from hydrogen gas, the atoms of which are stripped of their electrons using an electric field. The protons are then accelerated to an energy of 50 MeV in the Linac 2 accelerator. Proton bunches are formed inside the Proton Synchrotron Booster (PSB), increasing the energy to 1.4 GeV. The Proton Synchrotron (PS) creates proton beams from the bunches, increasing the energy to 26 GeV. Further acceleration in the Super Proton Synchrotron (SPS) raises the beam energy to 450 GeV before being injected into the LHC. The LHC contains two beams circulating in opposite directions. The design operation conditions consist of each beam containing up to 2808 bunches spaced 25 ns apart and made up of $\mathcal{O}(10^{11})$ protons each. Approximately 1200 superconducting dipole magnets keep the beams circulating before collisions. The beams collide at four points around the LHC where they are recorded by four detectors: ALICE [66], ATLAS [67], CMS [68] and LHCb [69]. A schematic of the LHC ring and the detectors is shown in figure 2.1.

The LHC was designed to study physics at the TeV scale. One of the major goals of the ATLAS and CMS detectors is to understand the mechanism behind electroweak

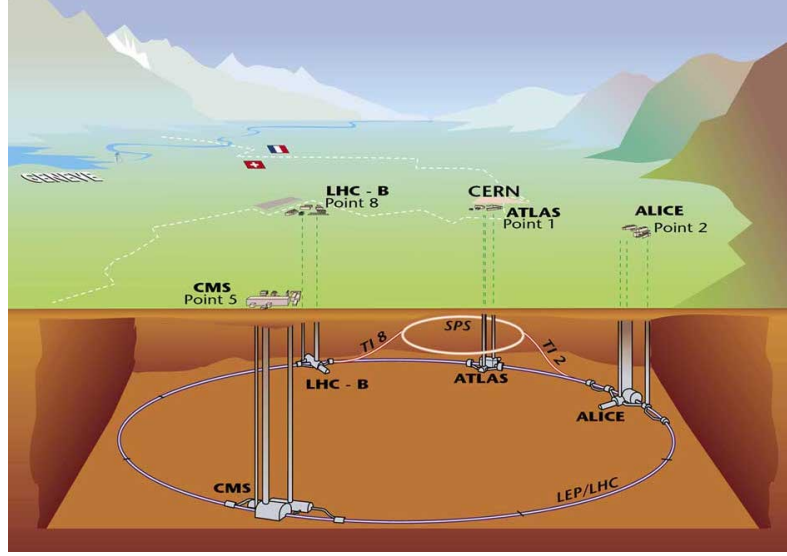


Figure 2.1: Schematic of the LHC accelerator, showing the positions of the four large detectors.

symmetry breaking and search for the Higgs boson predicted by this mechanism in the SM. The detectors are also used in searches for BSM physics, with the huge acceleration power of the LHC allowing studies of interactions at higher energies than have ever been possible before.

Higgs boson production occurs only rarely amongst other possible interactions from known SM processes. Figure 2.2 shows the cross sections of some of these processes compared with the total proton-proton cross section. It can be seen that SM Higgs boson production has a cross section some 10^9 times smaller than the total proton-proton cross section. As such, it is necessary to collect large numbers of collisions to ensure sufficient numbers of events containing these rare processes. Hence the LHC operates at a high instantaneous luminosity of up to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, where luminosity is given by:

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma}{4\pi \epsilon_n \beta^*} F, \quad (2.1)$$

where N_b is the number of protons in the bunch, n_b is the number of bunches, f_{rev} is the revolution frequency, γ is the Lorentz factor, ϵ_n is the normalised emittance, β^* is the beta function at the collision point and F is a reduction factor due to the crossing angle.

The LHC began its first major physics run in May 2010 with a centre of mass energy of $\sqrt{s} = 7 \text{ TeV}$ and produced an integrated luminosity of $\sim 48 \text{ pb}^{-1}$ before the winter

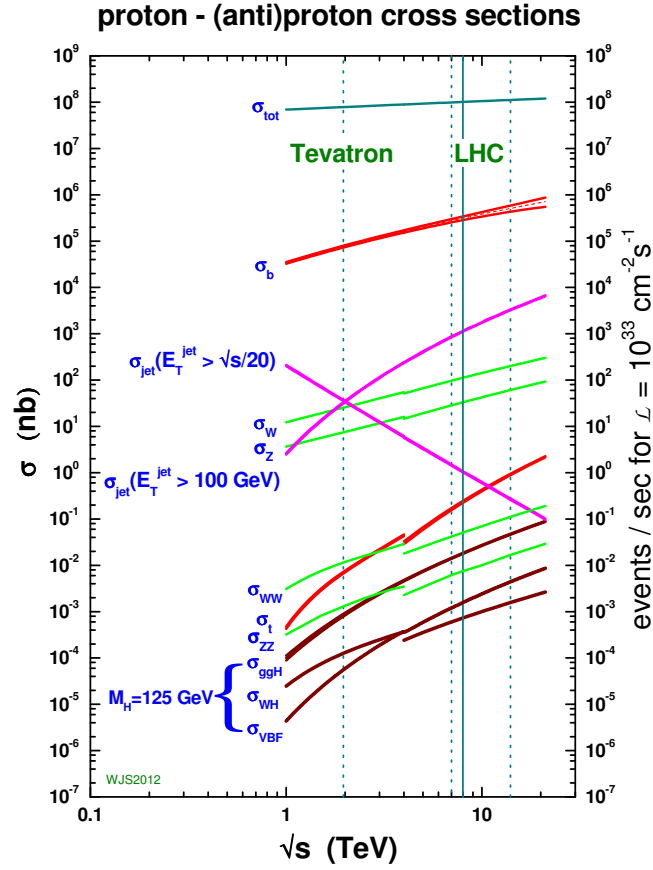


Figure 2.2: Cross sections for several processes in proton-proton or proton-anti proton collisions, dependent on centre of mass energy. Energies of the LHC at different points in running history are highlighted, as is the energy of the Tevatron. It can be seen that even with the high energies of the LHC, the cross section for Higgs boson production is several orders of magnitude smaller than the total cross section [70].

break. It then continued at $\sqrt{s} = 7$ TeV producing an integrated luminosity of $\sim 6.1 \text{ fb}^{-1}$ in 2011, before increasing to $\sqrt{s} = 8$ TeV for the 2012 run, where it provided 23.3 fb^{-1} , completing Run 1 of the LHC. During this time the LHC operated with a bunch spacing of 50 ns. Figure 2.3 shows the summary of the integrated luminosity delivered to the CMS detector during Run 1 of the LHC, which concluded in early 2013. The efficiency with which CMS took the available data was around 91% in 2011 and 93% in 2012. Not all luminosity delivered by the LHC is certified for use in physics analyses - only those events where it is known that the whole CMS detector was operating successfully, and so the usable luminosity was reduced to 5.1 fb^{-1} in 2011 and 19.7 fb^{-1} in 2012. It was after the 2011 run and $\approx 6 \text{ fb}^{-1}$ of the 2012 run that the observation of a boson consistent with the Higgs boson of the SM was announced in July 2012 [30, 31].

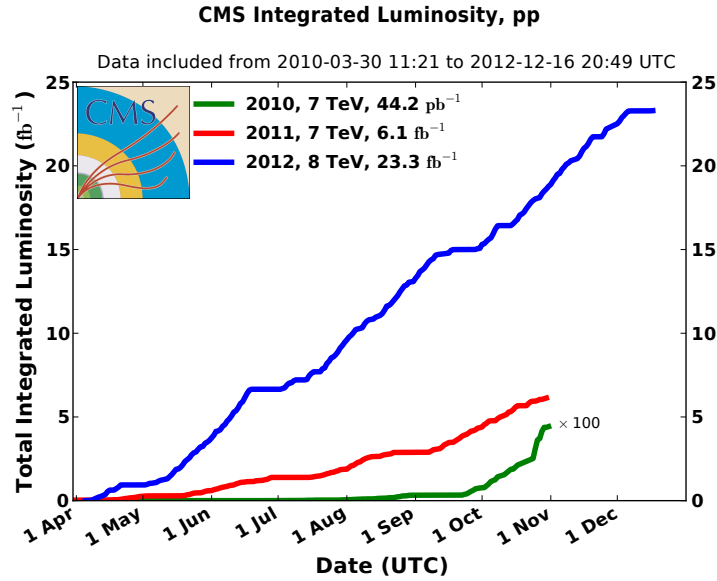


Figure 2.3: Illustration of the total integrated luminosity collected by CMS during Run 1 of the LHC, separated into the 3 years of running [71].

Since the LHC operates at such high luminosity, the probability of multiple proton-proton collisions occurring in each bunch crossing is very high. Figure 2.4 shows the number of interactions per bunch crossing in the 2012 dataset, where the average number was 21. The number for 2011 was slightly lower at 9 due to the lower instantaneous luminosity. These additional collisions on top of the interesting hard collision in an event are referred to as pile-up (PU).

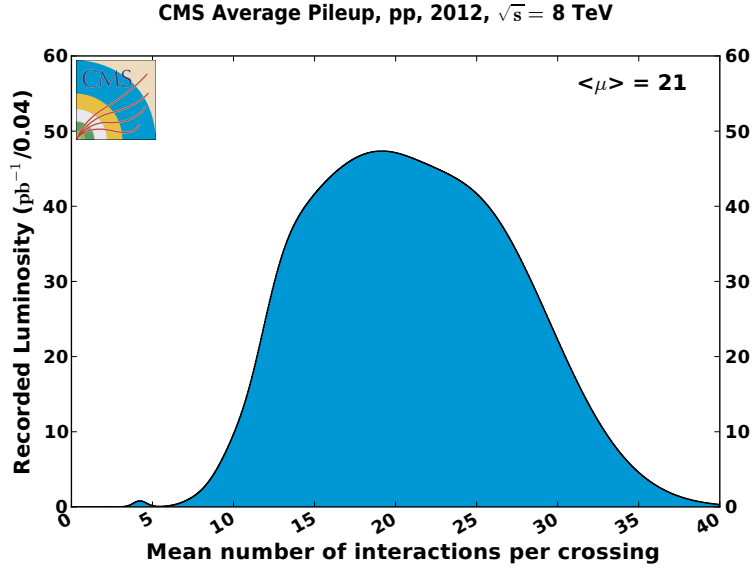


Figure 2.4: Distribution of number of pileup events per bunch crossing in 2012 data [71].

2.2 The CMS experiment

The CMS detector is a general purpose detector designed to search for the SM Higgs and new physics. As discussed in section 1.1.2, the mass of the Higgs boson is not directly predicted by the SM, and hence upon design it was important that CMS be able to achieve sensitivity to the SM Higgs for a wide range of possible masses. As shown in figure 1.3, at different Higgs masses the branching ratios of the Higgs boson to different final states vary considerably, and so CMS must be able to detect the particles from a wide range of possible decay channels. Thus CMS is a hermetic detector featuring a layered system of different subdetectors, each of importance to the detection of different particles.

A schematic of the CMS detector is shown in figure 2.5. The first layer is the tracker, which records the tracks of charged particles, from which can be extracted the particle's momentum and the location of the vertex from which it originated. This is followed by the electromagnetic calorimeter (ECAL) which measures energy deposited in electromagnetic showers from electrons or photons. The hadron calorimeter (HCAL) does a similar job for the hadronic activity, by providing energy measurements of collections of hadrons, known as jets, which deposit energy through nuclear interactions. The HCAL is a sampling calorimeter, meaning that the active material is sandwiched between dense absorbing material to increase the depth of the calorimeter to around 11 interaction lengths. The

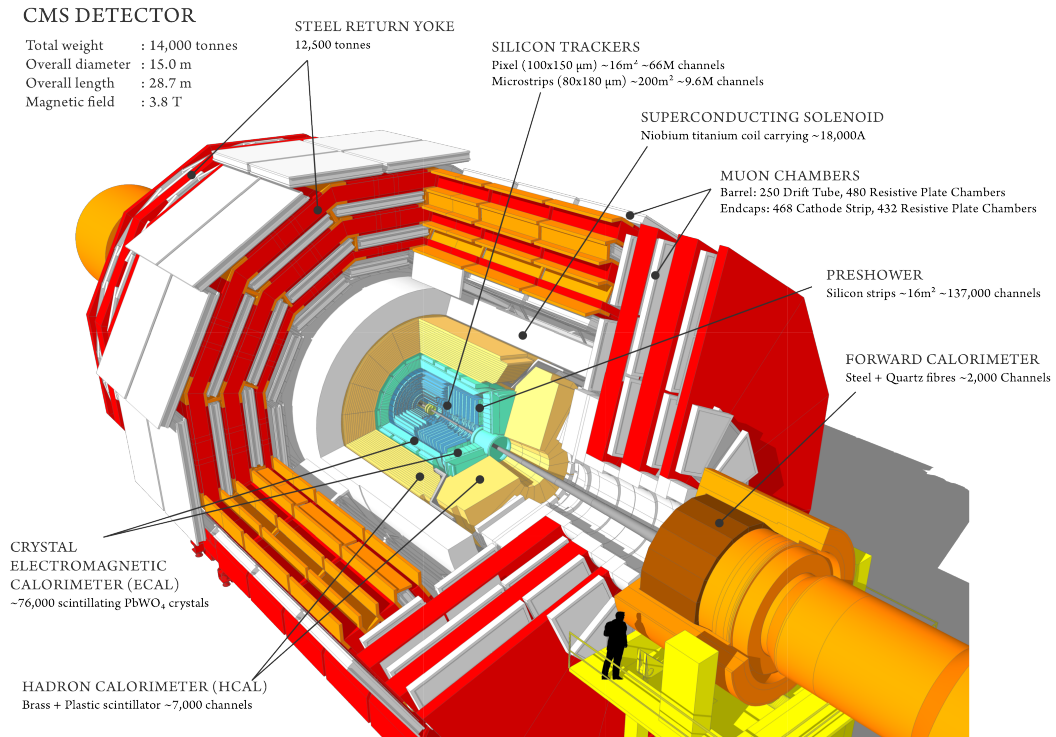


Figure 2.5: A schematic of the CMS detector, illustrating the positions of the various sub-detectors [72].

HCAL coverage is increased in the forward regions by the addition of the hadron forward (HF) calorimeter. The tracker and calorimeters are encased within a 3.8T axial magnetic field provided by a superconducting magnet which forms the next layer. This magnetic field provides the mechanism for deflecting the charged particle paths in a curve such that their momentum can be measured by the size of the curve in the track and their charge by the direction. The outermost layers form the muon detector systems, interspersed with iron plates of the return yoke of the magnet. Muons deposit little energy through the detector and often travel through to the surrounding cavern.

CMS uses a right handed cartesian coordinate system. The origin is placed at the nominal interaction point with the z axis collinear with the beam. Then the x axis is chosen to point towards the centre of the LHC ring and forms a plane with y , the remaining transverse coordinate perpendicular to x and z in the upwards direction. The angle ϕ is the azimuthal angle with respect to the x axis and θ is the polar angle in the x - y plane. The coordinate r is used for the radial coordinate when describing CMS in terms of a cylindrical coordinate system. Another coordinate often used is pseudorapidity, defined as:

$$\eta = -\ln[\tan(\theta/2)]. \quad (2.2)$$

Distance in the η - ϕ plane is given by $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2}$. Another important quantity relating to the measurement of collisions is the projection of the momentum of a particle onto the transverse plane: $p_T = \sqrt{p_x^2 + p_y^2}$. The corresponding transverse energy is referred to as E_T . Hard collisions generally produce particles with high p_T . Descriptions of the detector often separate the regions of “barrel” and “endcaps”, which correspond to the main cylindrical body of the detector or the circular ends enclosing the cylinder respectively.

2.2.1 Tracker

The CMS tracker is designed to reconstruct charged particles close to the interaction point [68]. The magnetic field in combination with the tracker allows measurement of the particle’s momentum and charge. This requires a high level of granularity to make precise measurements of positions of particles and hence to locate the vertex from which they originate. Due to the design bunch spacing of the LHC of 25 ns, the rate of collision

is extremely high, and so the tracker is required to be both fast response and radiation hard. This motivates the use of a silicon based tracking system.

The layout of the tracker is shown in figure 2.6. The tracker is composed of layers of silicon pixel and strip detectors covering the pseudorapidity range $|\eta| < 2.5$. The pixel detector consists of 66 million individual silicon pixels, each $100\text{ }\mu\text{m} \times 150\text{ }\mu\text{m}$ in size, forming three layers in the barrel region and two in each endcap. The spatial resolution of the pixel detector is 10 and $20\text{ }\mu\text{m}$ in the r - ϕ plane and the z direction respectively, allowing a three-dimensional vertex reconstruction. Surrounding the pixel detector are layers of strip detectors. These consist of four cylindrical layers which extend to $r = 55\text{ cm}$ referred to as the tracker inner barrel (TIB), and three disks in each endcap referred to as the tracker inner disks (TID). Each strip is 10–20 cm long and 80 – $180\text{ }\mu\text{m}$ wide. Surrounding the TIB and TID is the tracker outer barrel (TOB), which extends to $r = 116\text{ cm}$ and $z = \pm 118\text{ cm}$ and contains six barrel layers. The tracker endcaps (TEC) comprises nine disks covering the endcaps. The position resolution of the strip detectors is in the range 23 – $52\text{ }\mu\text{m}$ in the r - ϕ plane and 230 – $530\text{ }\mu\text{m}$ in the z direction depending on layer. Better resolution in the r - ϕ plane is required for the measurement of p_T .

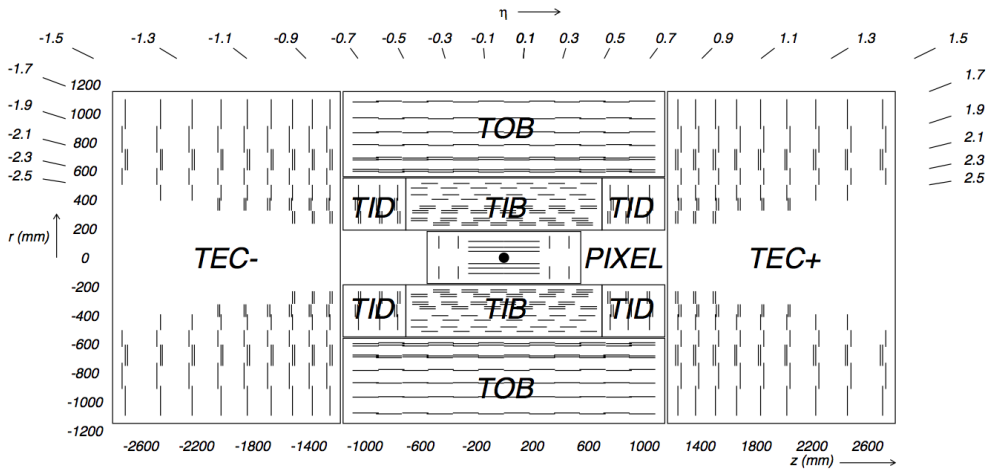


Figure 2.6: Cross section of the CMS tracking system, indicating the pixel and strip detectors and their positions relative to the interaction point [68].

Tracks are reconstructed using multiple precise measurements throughout the tracking system. The reconstruction is seeded by triplets of hits in the inner tracking layers. The trajectory of this seed is extrapolated to the outer tracking layers using the Kalman filter method [73]. The hits found in each layer which are compatible are added to the trajectory and its uncertainties are updated until no more compatible hits are found.

The use of the tracks to reconstruct the Primary Vertex (PV) is discussed further in section 3.1. Momentum resolution degrades with increasing momentum due to decreasing curvature in the tracks. The p_T resolution of muon tracks is approximately 1–2% for muons with p_T as high as 100 GeV in the region $|\eta| < 1.6$, rising as high as 8% in the larger η regions which have lower coverage [68].

2.2.2 Electromagnetic calorimeter

The ECAL is constructed from high density lead tungstate (PbWO_4) crystals which form a barrel section (EB) and two endcaps (EE) outside the tracker [68]. PbWO_4 was chosen for its radiation hardness, short radiation length (0.89 cm) and small Molière radius (2.2 cm), meaning that almost the entire photon or electron energy can be deposited in the ECAL. High energy electrons or photons entering a crystal initiate an electromagnetic shower, which produces a cascade of low energy electrons and photons which undergo bremsstrahlung and pair production respectively. The shower will continue until energy falls below pair production threshold and ionisation begins to dominate for electrons. The depth of each crystal is equivalent to 25.8 radiation lengths, and thus electrons and photons deposit most of their energy within the crystals. The atoms in the PbWO_4 de-excite by producing scintillation light that is read by photodetectors. The decay time of the scintillation light is short, such that about 80% is emitted before the next bunch crossing (within 25 ns). This results in a calorimeter with excellent energy resolution, granularity and timing precision.

Figure 2.7 shows the layout of the ECAL. The EB covers the pseudorapidity range $|\eta| < 1.479$. The crystals are arranged in 36 modules such that the gap between modules are offset by 3° with respect to the axis from the detector origin to avoid particles travelling along the gaps between crystals. In the endcaps the crystals are arranged in an x – y grid each with an area of $28.6 \times 28.6 \text{ mm}^2$. Two lead plates and two silicon strip layers mounted before the EE form the pre-shower detectors (PS). These correspond to about three radiation lengths of absorber material and are designed to initiate showering and provide sufficient resolution to distinguish single photons from the pairs produced in neutral pion decays. Uninstrumented regions exist between the EB and EE, $1.442 < |\eta| < 1.566$, through which cables pass. It is not possible to provide good measurement of electrons and photons traversing this region. Overall the ECAL covers a pseudorapidity range of $|\eta| < 3$.

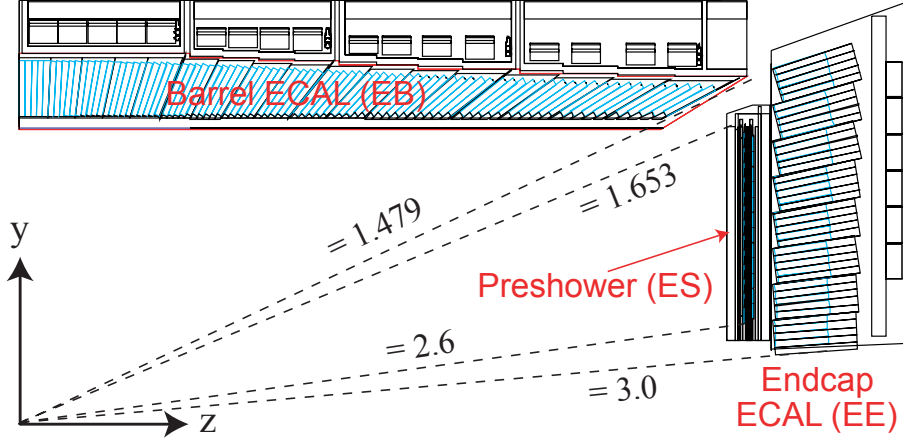


Figure 2.7: Transverse section through the ECAL, indicating its geometry. The parts of the detector in the barrel (EB) and endcaps (EE) are indicated [74].

The energy resolution of the ECAL can be parametrised as a combination of three unrelated uncertainties as follows:

$$\frac{\sigma}{E} = \frac{A}{\sqrt{E}} \oplus \frac{B}{E} \oplus C, \quad (2.3)$$

where E is the energy of the incident particle in GeV and A , B and C are the stochastic, noise and constant contributions respectively. The constants are derived from test beam data [68]. The stochastic term, ($A = 2.83 \pm 0.3\%$), parametrises stochastic fluctuations in scintillation and shower shape, and is very low for lead tungstate since the shower can mostly be contained within the crystals. The noise term $B = 0.12 \text{ GeV}$ is determined by the electronics. The constant term $C = 0.26 \pm 0.4\%$ accounts for non uniformity of read-out, and limits the ECAL accuracy at high energies. High resolution is essential to allow accurate reconstruction of high energy photons, such as those produced in $H \rightarrow \gamma\gamma$ decays, an important discovery channel for the SM Higgs.

2.2.3 Hadronic calorimeter

The sampling HCAL surrounds the ECAL and also covers the pseudorapidity range $|\eta| < 3$ [68]. The HCAL is designed to detect and measure the energy of strongly interacting particles. It consists of alternating layers of brass absorber and plastic

scintillator. Brass is used as the absorber material due to its fairly short nuclear interaction length (16.42 cm) and the fact that it is not magnetic [19]. A hadron shower initiated in an absorber layer causes pulses of light in the plastic scintillator tiles which are fed to hybrid photodiodes by wavelength shifting fibres. Surrounding the HCAL is the solenoid magnet, the additional material of which maximises shower containment and reduces non-Gaussian tails in energy resolution due to energy loss.

The layout of the HCAL is shown in figure 2.8. The hadron barrel (HB) covers $|\eta| < 1.4$ and is read out in towers of size $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$. The hadron outer (HO) is a layer of scintillating tiles lining the outside of the solenoid, and samples the tails of the highly penetrating or late starting showers using the magnet coil as an absorber. The hadron endcaps (HE) at each end of the barrel consist of towers with dimensions varying between $\Delta\eta \times \Delta\phi = 0.087 \times 0.8$ and 0.35×0.8 . The HB provides between 5.8 and 10.6 interaction lengths of absorber, and in combination with the HO this increases to a minimum of 11.8 interaction lengths. The HE provides approximately 10 interaction lengths.

The HF detectors extend the HCAL to cover up to $|\eta| = 5.2$ and experience the highest fluxes of particles in the whole detector, and so are made using radiation hard quartz fibres as the active medium embedded in a steel absorber. In the HF a signal is generated when charged showering hadrons emit Cherenkov radiation in the fibre, which is detected by photomultiplier tubes. The HCAL contains no uninstrumented regions. The large coverage of the HCAL is necessary to be able to accurately calculate the missing transverse energy (E_T^{miss}) in an event as a result of neutrinos which are invisible to the detector, using energy balance with the visible objects. This is discussed further in section 3.6.

Both the granularity and the energy resolution of the HCAL are worse than the ECAL. The resolution is measured using a test beam of charged pions and found to be [75]:

$$\frac{\sigma}{E} = \frac{94.3\%}{\sqrt{E}} \oplus 8.4\%, \quad (2.4)$$

where E is the energy of the showering particle.

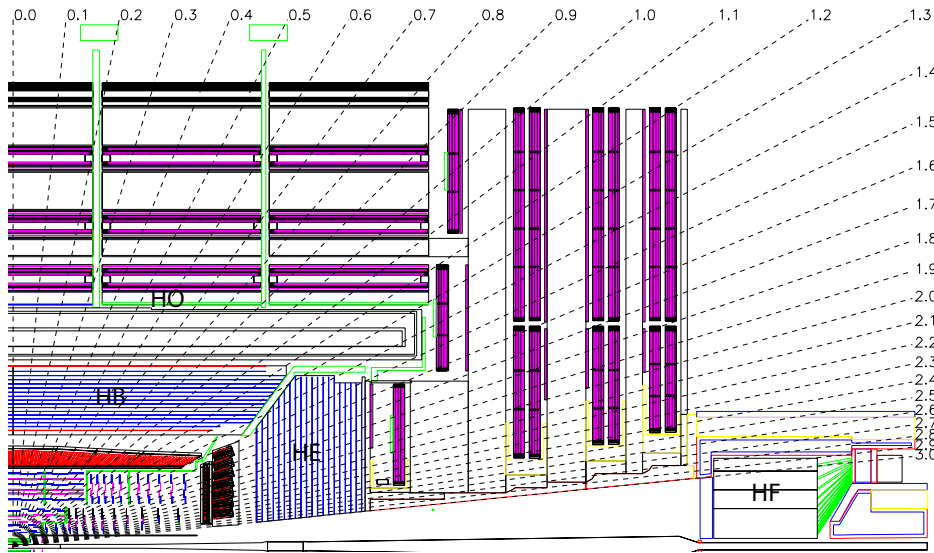


Figure 2.8: Illustration of the HCAL in the r - z plane, indicating its geometry [68].

2.2.4 Muon detector

The iron return flux of the magnet is instrumented with the muon detectors [68], covering a pseudorapidity range of $|\eta| < 2.4$. Due to the fact that muons have considerably higher masses than electrons, they lose little energy via bremsstrahlung or ionisation, and so typically pass through the calorimeters and the solenoid without depositing much energy. The muon systems are therefore used for efficient identification of muons, as well as being able to provide a complementary measurement of their momentum additional to the one made in the tracker. The best momentum resolution is achieved by combining hits in the tracker and the muon chambers, as described in section 3.3.

The muon detector is shown in figure 2.9. The barrel region (covering $|\eta| < 1.2$) consists of the drift tube (DT) chambers arranged in four cylindrical layers positioned between the plates of the magnet return yoke. The DTs are augmented by resistive plate chamber (RPC) in the range covering $|\eta| < 1.6$. The DT chambers consist of a tube of cross section $13 \times 42 \text{ mm}^2$, each filled with wires about 2.4 m long. The tubes are filled with a mixture of argon and carbon dioxide gas. When a muon travels through the tube, it ionises the gas, and free electrons drift towards the anode wire resulting in an electrical signal. Each chamber consists of several layers of tubes, oriented in different directions to measure the muon ϕ direction and the z coordinate. The position resolution of the DTs is approximately $200 \text{ }\mu\text{m}$.

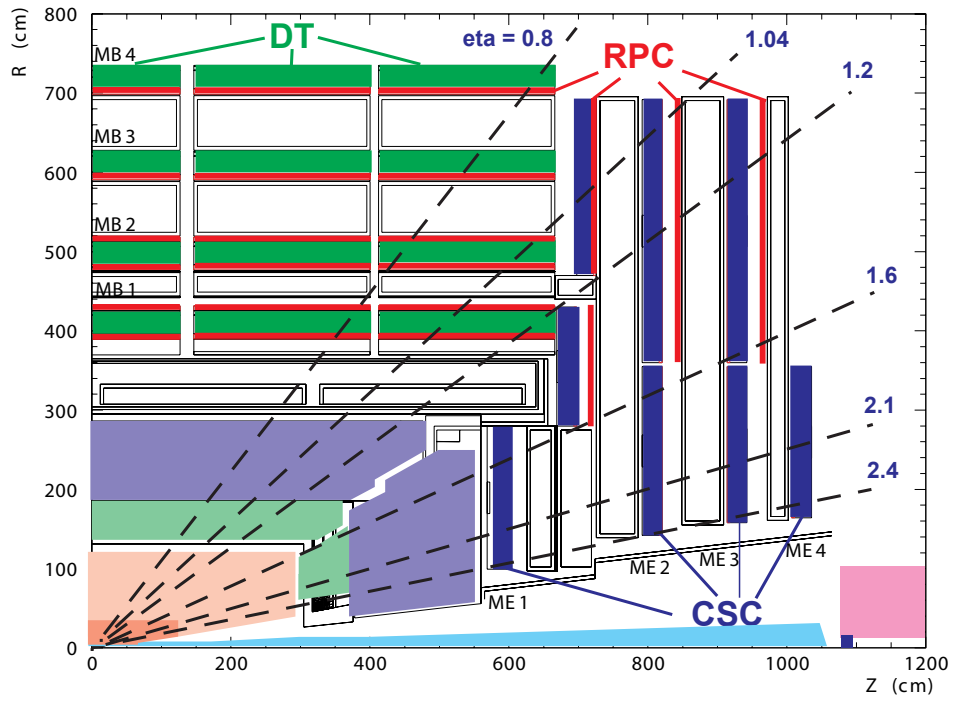


Figure 2.9: Layout of one quadrant of the muon systems, indicating the positions of the DT, CSC and RPC [74].

The endcaps use cathode strip chamber (CSC)s, which have a fast response, fine segmentation and are radiation hard. This is necessary in the endcaps due to the higher rate of muons and backgrounds from soft neutrons. Each CSC has six gas layers with cathode strips running radially outward to measure hits in the r - ϕ plane, with anode wires running perpendicular to the cathodes to measure η . The position resolution of the CSCs varies between 100 and 200 μm depending on η . In the region $|\eta| < 1.6$, the CSCs are augmented by RPCs, as in the barrel. The RPCs consist of a gas gap enclosed by parallel anode and cathode plates, in which the muon ionisation is detected by arrays of metallic strips running parallel to the beam axis. The RPCs have worse resolution than the DTs and CSCs but an extremely fast time response of 1 ns, meaning they can be used to correctly identify the bunch crossing in which a muon originates, and can be used as a dedicated muon trigger.

2.2.5 Triggering and data processing

At the design specification of the LHC, the proton bunch crossing rate is 40 MHz, and to date collisions have been recorded at 20 MHz, which will increase to the design 40 MHz in Run 2 starting this year. Each event consists of approximately 1 MB of data and it is not feasible to write data at this rate to tape, nor is it feasible for the data acquisition (DAQ) system to perform read-out of the events at this rate. Thus the rate at which events are saved is reduced to $\mathcal{O}(1 \text{ kHz})$ using a trigger system to select the interesting events.

The first stage of the trigger system is the Level-1 (L1) trigger, which is constructed using custom electronics to incorporate information from the calorimeters and muon systems only [68]. The L1 starts with local information such as calorimeter energy deposits and hit patterns in the muon chambers. A regional trigger combines this local trigger information from different sections of the detector to give a p_T sorted list of candidate objects. Finally the global trigger issues a decision to accept or reject the event based on the L1 information from all parts of the detector. This decision is made within $3.2 \mu\text{s}$ and uses only the front-end electronics. The L1 trigger reduces the rate to around 100 kHz.

Events accepted by the L1 trigger are then read out to the high-level trigger (HLT). This operates on a processor farm of several thousand CPU cores and processes the complete detector information, including input from the tracker. The HLT is capable of determining the object momenta with much greater accuracy, and apply tighter identification criteria, using algorithms much closer to those used in offline reconstruction. Due to the fact that the instantaneous luminosity increased across the Run 1 period, the

trigger p_T and energy thresholds were changed several times in order to retain a stable rate of read-out. Over the Run 1 period, CMS operated at a rate of about 1 kHz, with 300 Hz being promptly reconstructed and the rest being “parked” to be reconstructed after the LHC running finished when more computing power was freed [76].

Even incorporating the trigger, the rate of production of data by CMS is at several petabytes per year. The CMS and the other LHC experiments make use of the Worldwide LHC Computing Grid (WLCG) [77], a global data storage and analysis network which integrates the computing facilities of universities and research institutes around the world. The system consists of different tiers: the Tier 0 centre at CERN performs full event reconstruction, before all data are distributed to at least one Tier 1 centre, to keep a copy at several sites across the globe. A larger number of Tier 2 centres process these data for specific analyses to give access to researchers across the globe.

Chapter 3

Event reconstruction

This chapter describes the reconstruction of events collected by the CMS detector. The $H \rightarrow \tau\tau$ analysis requires almost every object measured in CMS and makes use of information from every subdetector. The reconstruction of each of these objects is summarised, followed by a description of a likelihood based reconstruction of the di-tau mass.

3.1 Primary Vertex reconstruction

As discussed in section 2.1, in the high instantaneous luminosity conditions at the LHC there is a large probability for multiple proton-proton collisions occurring in each bunch crossing. The reconstruction of the PV of the event allows the identification of the hard pp interaction amongst other vertices due to such additional collisions. It also provides distinction between “prompt” particles, i.e. production at the PV from the hard interaction, and in-flight decays of hadrons or photon conversions which occur after the hard interaction.

The vertices are reconstructed using the tracks collected in the inner tracker. A clustering algorithm, deterministic annealing (DA) [78], is used to assign tracks to their most likely vertex. Each vertex is seeded by at least two tracks separated in z by less than 1 cm at the point of closest approach to the z axis. The most likely position of each vertex is then determined using the adaptive vertex fitter [79]. In this algorithm each track is assigned a weight, w_i , which is close to one for tracks which are highly compatible with the fitted vertex position and close to zero for tracks with low compatibility. These weights are used to define the number of degrees of freedom for the fit: $n_{\text{dof}}^{\text{vertex}} = 2 \sum_i^{\text{tracks}} w_i - 3$.

This variable is an assessment of the mutual compatibility of the component tracks of the vertex, and is used to distinguish real pp interactions from misreconstructed vertices. For most analyses, the following quality cuts are applied on each vertex [80]:

- The distance in the z direction from the vertex to the nominal interaction point must be smaller than 24 cm.
- The corresponding distance in the transverse plane must be smaller than 2 cm.
- $n_{\text{dof}}^{\text{vertex}} > 4$.

The PV is taken to be the vertex with the highest sum squared transverse momentum (p_T) of its associated tracks.

3.2 Electrons

Electrons are reconstructed by matching ECAL deposits with tracks from the inner tracker. This is made more difficult by the electrons undergoing bremsstrahlung when interacting with the material of the tracker. The photons produced can also convert to e^+e^- pairs before reaching the ECAL. This means that the energy deposited in the ECAL can be spread out in the ϕ direction. Hence dedicated algorithms are used to combine the energy deposits from both the initial electron and the bremsstrahlung products, known as “supercluster” algorithms [81].

Separate algorithms are used for electrons in the barrel and endcaps, in order to be optimal for the different geometries. In both cases, a clustering is performed in the η – ϕ plane starting from the ECAL crystal with the most energetic deposit, and continuing outwards to the surrounding crystals until there are no more unclustered crystals above a certain energy threshold. In the barrel, the “hybrid” clustering algorithm is used. In this algorithm the seed crystal has $E_T > 1$ GeV and the clustering is performed in a “domino” of 3×1 or 5×1 crystals, with additional dominoes (which attempt to collect radiation deposits) stepping in both ϕ directions around the seed up to $\Delta\phi \approx 0.3$. The energy threshold below which crystals are not clustered is 100 MeV. In the endcaps the approach is similar with a clustering algorithm called the “Multi 5×5 ” algorithm using 5×5 arrays of crystals within $\Delta\eta < 0.07$ and $\Delta\phi < 0.3$ [82].

The energy-weighted average position of the supercluster is computed, which is the equivalent of the impact point in the ECAL of a non-radiating electron with energy equal to the supercluster energy. This is matched to a compatible hit in a loose ϕ – z

search region in the first pixel layer, under the hypothesis that the electron could be either charge. If a compatible hit is found, the hit in the first layer is used to update the estimated electron trajectory which would result in hits in the outer layers. This seeds the reconstruction of the electron trajectory through the tracker using the Gaussian sum filter (GSF) algorithm [83]. This provides an additional momentum measurement which is used to improve the electron energy resolution.

Electron identification (ID) criteria are used in many analyses to improve the efficiency of selecting real electrons over backgrounds which tend to originate from hadronic jets. The most commonly used variables are [84]:

- $\Delta\eta_{in}$ and $\Delta\phi_{in}$, the separation in the η and ϕ between the supercluster and track direction evaluated at the PV position and extrapolated to the ECAL (generally smaller for prompt electrons).
- $\sigma_{\eta\eta}$, the energy-weighted η width of the cluster. This is typically small for prompt electrons, which have a more localised cluster.
- H/E , the ratio of hadronic to electromagnetic (EM) energy in the region of the seed cluster. This is also generally lower for prompt electrons.

Figure 3.1 shows the distributions of these variables in both simulated electrons and backgrounds from jets in the barrel.

The electron ID used in the $H \rightarrow \tau\tau$ analysis makes use of these four variables and additional conditions on the track quality and kinematics [84] to provide improved ID efficiency. These variables are combined in a multivariate boosted decision tree (BDT) [85], which is trained in two bins of p_T and three bins of η using $Z/\gamma^* \rightarrow ee$ events in data. The additional variables used as inputs to the BDT are:

- Quantities relating to the quality of the tracks, including the normalised χ^2 and the number of valid hits in the track fit.
- Additional quantities relating to the cluster shape, including the variable $f_e = 1 - e_{1 \times 5}/e_{5 \times 5}$, in which $e_{1 \times 5}$ ($e_{5 \times 5}$) denotes the energy deposited in an array of 1×5 (5×5) cells in the vicinity of the supercluster seed, and the variable R_9 , which gives the fraction of the supercluster energy in an array of 3×3 cells in the vicinity of the supercluster seed.
- Additional variables relating to the compatibility of the hadronic and EM energy with the track momentum, including the ratio of supercluster energy over the momentum

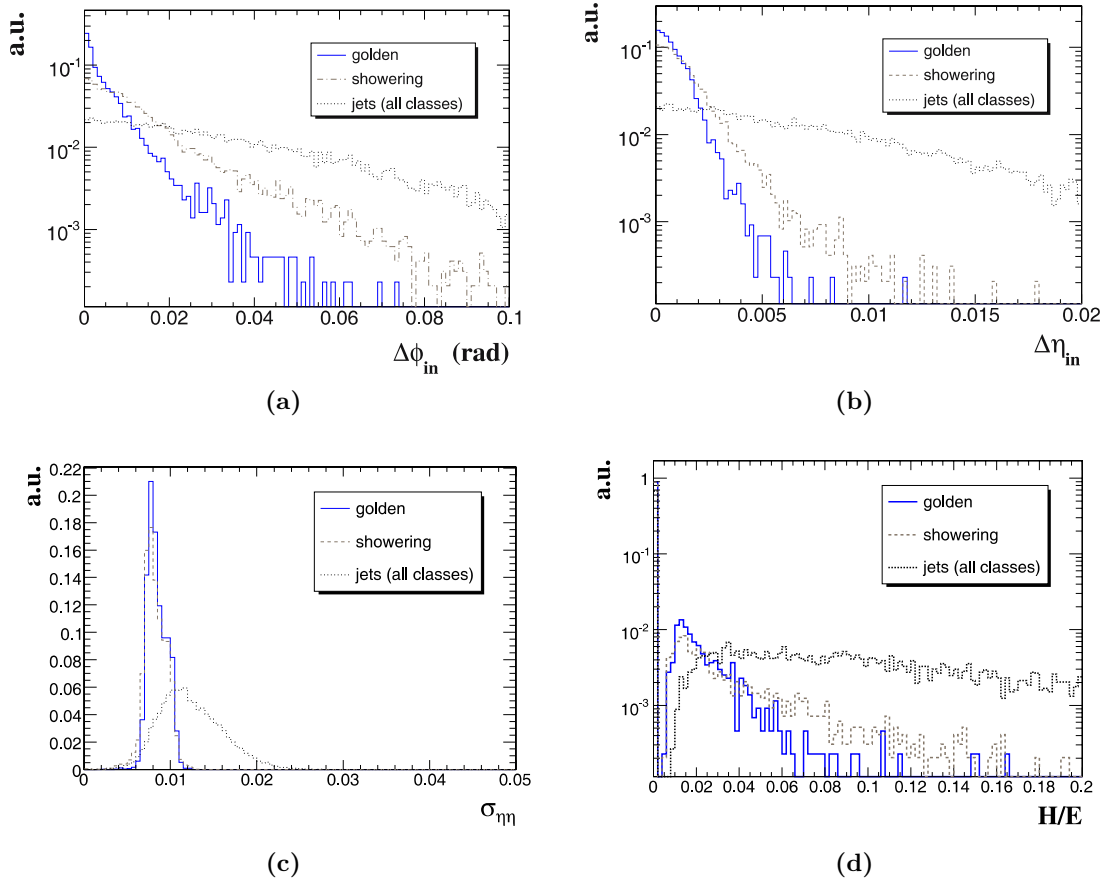


Figure 3.1: Distributions showing: the separation in a) ϕ and b) η between the supercluster and the track direction, c) the energy-weighted η width of the cluster and d) the ratio of hadronic and electromagnetic energy in the region of the seed cluster. Shown for electrons and backgrounds from jets [84].

of the associated track evaluated at the PV (E/P), the quantity $1/E - 1/p$ which quantifies the energy-momentum compatibility, the ratio of the electron cluster energy to the momentum of the associated track evaluated at the surface of the calorimeter and the ratio of the energy reconstructed in the pre-shower detector over the raw energy of the supercluster.

The BDT output is a p_T and η dependent cut threshold. Finally non-prompt electrons from photons interacting with the tracker are suppressed by requiring there are no missing hits in the inner tracker and that the electron is not matched to a reconstructed conversion. The electron must also be consistent with the PV, by having small impact parameters. Studies of the efficiency of the electron ID in the $H \rightarrow \tau\tau$ analysis can be found in section 4.5.

3.3 Muons

Muons typically travel through the CMS calorimeters with minimal energy deposit and are reconstructed in the muon chambers. Thus muons can be reconstructed in two independent places - the tracker and the muon chambers. This greatly improves the ability to isolate muons from hadronic activity. The “global” muon reconstruction algorithm [86] uses both sets of information by starting from each track in the muon chambers and searching for a compatible track in the inner tracker. If a compatible track is found, the energy and momentum of the muon is determined by a fit to the hits in both the inner tracker and the muon chambers, taking into account the expected energy loss within the magnet. This improves the momentum resolution compared to the track only measurement for muons with p_T larger than 200 GeV. For lower p_T muons, the momentum resolution is driven by the fit to the tracker hits. For muons with $p_T < 5$ GeV, the reconstruction starting from the inner tracker is more efficient due to the lower probability of these muons reaching the muon chambers. This is known as “tracker” muon reconstruction.

Backgrounds to prompt muons consist of non-prompt muons from in-flight decays of hadrons and “punch-through” of charged hadrons which pass through the calorimeters into the muon chambers. These backgrounds are reduced through the use of ID requirements based on the properties of the muon track. In flight decays are reduced by the requirement of hits in at least one pixel detector and 5 tracking layers. The χ^2 of the global track fit must be better than 10, and the global track fit must include hits from at least one

segment in the muon detector, both of which provide rejection of punch-through hadrons. In addition, track segments must be found in at least two stations of the muon detector. These conditions taken together provide the “tight” muon ID used in many analyses, including the $H \rightarrow \tau\tau$ analysis. The efficiency of CMS muon reconstruction is found to be better than 96% for muons with $p_T > 10$ GeV [86]. Studies of the ID efficiency of muons in data and Monte Carlo (MC) in the context of the $H \rightarrow \tau\tau$ analysis can be found in section 4.5.

3.4 Lepton isolation

In order to further reduce background contributions from misidentified QCD jets, electrons and muons are required to be isolated [82, 86]. Isolation is computed as the scalar sum of transverse momenta of the particles within a cone in η - ϕ space of size $\Delta R = 0.4$ centred on the lepton direction. This sum includes all charged particles, neutral hadrons and photon candidates. To reduce the contamination of particles which originate from PU events in this cone, charged candidates with an impact parameter greater than 0.1 cm from the primary vertex are excluded from the sum. An estimate of the neutral pileup contribution is made based on the charged pileup contamination, multiplied by a factor 0.5, which is approximately the ratio of neutral to charged components of the hadronisation, as determined from simulation. The isolation is then defined as follows:

$$I = \sum^{\text{charged non-pileup}} p_T + \max \left(0, \sum^{\text{neutral}} p_T + \sum^{\text{photon}} p_T - \frac{1}{2} \sum^{\text{charged pileup}} p_T \right). \quad (3.1)$$

Requirements are usually placed on relative isolation, defined as $I_{\text{rel}} = I/p_T^{\text{lepton}}$.

3.5 Jets

Jets result from the large numbers of quarks and gluons present in a hadron collider. The term ‘jet’ is used to refer to the collimated shower of particles which is produced from the hadronisation of a quark or gluon. In order to reconstruct the original parton, these showers of particles are collected and combined.

3.5.1 Particle flow

CMS uses a particle flow (PF) [87–89] algorithm to combine the individual track and energy deposits in each sub-detector. This allows the reconstruction of individual particles emerging from all vertices: charged hadrons, neutral hadrons, photons and the muons and electrons already discussed. These particles can then be used to calculate the missing transverse energy E_T^{miss} , reconstruct jets and quantify the isolation of leptons and photons. A separate algorithm is used to reconstruct hadronic decays of taus, discussed in section 3.7. The PF algorithm combines the high resolution of the tracker with the energy resolution and high granularity of the calorimeters.

The output of the PF algorithm is a set of the stable particles in the event resulting from the hard interaction, from the inputs of charged particle tracks, calorimeter energy deposits and muon chamber hits. The clustering of energy deposits is performed separately in the ECAL and HCAL. For electrons as discussed in section 3.2 this allows the combination of bremsstrahlung photons with the parent electrons and in the HCAL this allows the separation of the neutral and charged hadrons. The clustering proceeds by first defining a cluster seed, which corresponds to the calorimeter cell with the highest local energy. The threshold for clustering neighbouring cells is that they must have energy greater than 2 standard deviations above noise level. After the clustering, the different PF elements are linked into blocks to be interpreted as a particular particle. This can be done using extrapolation of tracks into the calorimeters, where the two elements are linked if the track falls inside the cluster volume.

3.5.2 Jet identification by clustering

Jets can be composed of many sub-particles, which may interact in the detector in different ways. These particles must be combined using a clustering algorithm [90], where the choice of algorithm defines how the particles should be combined taking into account the distance between the objects. In particular the algorithm should be infrared- and collinear- safe, meaning that the jet reconstruction is not affected by soft QCD radiation or gluon splitting. The algorithm used for the $H \rightarrow \tau\tau$ analysis is the ‘anti- k_T ’ algorithm [91] as implemented in the FASTJET package [92], which considers all objects within a certain jet ‘size’ defined by a parameter $R = 0.5$, and sequentially combines them starting from the one with the smallest distance from the beamline. If this distance is smaller than the distance between this object and the closest second object then the

first is taken to be a final state jet and removed from the object list, otherwise the two objects are combined into one and the process repeats. This process is repeated for all objects until none remain in the list. The effect of this is to form a cluster around the hardest particles in a cone in η - ϕ .

Jet identification criteria are applied to reduce the contribution of jets from noise in the calorimeters. These include the following:

- Jets must consist of at least one PF component.
- The jet energy must have contributions from both the ECAL and HCAL (above a given noise threshold).
- The fraction of the total jet energy as a result of photons or neutral hadrons should be less than 0.99 of the total jet energy.
- Jets within the acceptance of the inner tracker must have at least one charged object and a charged energy fraction greater than zero and an electron energy fraction less than 0.99.

3.5.3 Jet energy corrections

An important aspect of jet identification is the correct measurement of the jet energy, which is typically different between reconstructed and true hadron-level jet energy due to experimental effects. This can be due to uninstrumented regions of the detector, non-linear calorimeter response and contamination by jets from PU interactions. Particles from different PU vertices can be clustered and identified as a jet, or overlap with a jet from the primary vertex affecting the measurement of the jet energy. Pileup jet identification [93] is used to classify these events, which uses a BDT [85] with input variables such as momentum and spatial distribution of the jet particles. In addition a calibration factor is applied to account for imperfections in the neutral-hadron calibration, the jet energy containment and small differences between the simulated and observed response.

To account for the detector effects and remaining PU, a correction to the jet energy scale is derived [94]:

$$P_{\text{corr}}^{\mu} = C_{\text{PU}}(p_{\text{T}}^{\text{raw}}, \eta) \cdot C_{\text{rel}}(p_{\text{T}}^{\text{PU}}, \eta) \cdot C_{\text{abs}}(p_{\text{T}}^{\text{rel}}, \eta) \cdot P_{\text{raw}}^{\mu} . \quad (3.2)$$

In this equation, C_{PU} is the correction for PU, C_{rel} is a relative correction and C_{abs} is an absolute correction. The corrections are applied sequentially such that the PU correction is a function of raw jet p_{T} ($p_{\text{T}}^{\text{raw}}$), the relative correction is a function of the p_{T} corrected for the pileup effects (p_{T}^{PU}) and finally the absolute correction is a function of the relative-corrected p_{T} ($p_{\text{T}}^{\text{rel}}$). All of the corrections are applied as a function of jet η . These subsequent corrections are applied to the raw 4-vector of the jet P_{raw}^{μ} to yield the corrected 4-vector P_{corr}^{μ} .

The PU correction C_{PU} is determined using the p_{T} density in the event to estimate the contribution from PU on a per-jet basis. The relative correction is determined using a dijet p_{T} balance method which uses dijet events containing a reference jet with $|\eta| < 1.3$ and exploits momentum conservation. The probe jet (which can have any value of η), is used to calculate the average of a balance quantity, defined as: $(p_{\text{T}}^{\text{probe jet}} - p_{\text{T}}^{\text{ref jet}})/p_{\text{T}}^{\text{average}}$, in bins of average dijet p_{T} and probe η .

The absolute correction is measured using the missing transverse energy projection fraction (MPF) method [95], using γ +jets and Z+jets events and enforcing momentum conservation exploiting the fact that these events shouldn't contain any real $E_{\text{T}}^{\text{miss}}$. Thus any measured $E_{\text{T}}^{\text{miss}}$ can be used to calibrate the p_{T} of the jets. The total uncertainty on the jet energy scale is given by the sum in quadrature of the estimated uncertainties in each of the correction factors. Figure 3.2 shows the total value of the jet energy scale correction factor for two different p_{T} values for jets reconstructed using the PF algorithm and two other types also used at CMS. Only PF jets are used in the $\text{H} \rightarrow \tau\tau$ analysis and so the other two types are not described in this thesis. The bands show the corresponding total jet energy scale uncertainty. The total uncertainty varies between approximately 3 and 5% depending on p_{T} and η [94].

3.5.4 B-tagged jets

The identification of jets which originate from b-quarks is important in studying many SM and BSM processes. The decays of b-quarks are suppressed by small CKM matrix elements [19], giving b-flavoured hadrons relatively long lifetimes. Such hadrons are also relatively heavy due to the large mass of the b-quark, and as such the decay products typically have large momenta perpendicular to the b-hadron momentum direction. Both of these features are exploited in identification of b-tagged jets.

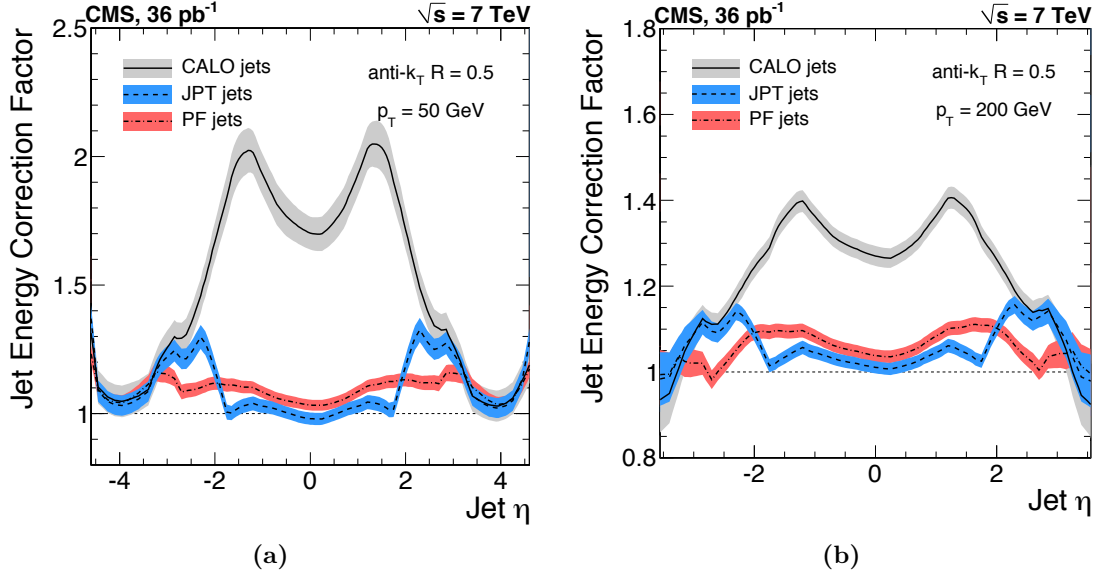


Figure 3.2: Total jet energy scale correction factor and corresponding uncertainty as a function of jet η . Shown for jets with $p_T = 50$ GeV (a) and $p_T = 200$ GeV (b) [94]. The correction factor is shown for three different types of jets; only PF jets are used in the $H \rightarrow \tau\tau$ analysis. For PF jets the total uncertainty varies between 3 and 5% depending on p_T and η .

In the $H \rightarrow \tau\tau$ analysis, jets originating from b-quark hadronisation are identified using the CSV b-tagging algorithm [96]. The long lifetime of the b-hadrons results in a secondary decay vertex which can be reconstructed. In the CSV algorithm, a jet is considered b-tagged if it has $p_T > 20$ GeV, $|\eta| < 2.4$ and a CSV discriminator output greater than a loose, medium or tight working point, chosen to give different levels of ID efficiency and mis-tag rates. The inputs to the calculation of the CSV discriminator include secondary vertex information and the track-based lifetime information. Two likelihoods are built from these variables, one to discriminate between b and c jets and one to discriminate between b and light jets.

In the $H \rightarrow \tau\tau$ analysis, the medium working point of the CSV discriminator is used to identify b-jets, corresponding to a discriminator output greater than 0.679. The distribution of the CSV discriminator can be seen in figure 3.3. The medium working point corresponds to a b-tag efficiency of $\approx 85\%$ and a light jet mis-tag rate of $\approx 1\%$.

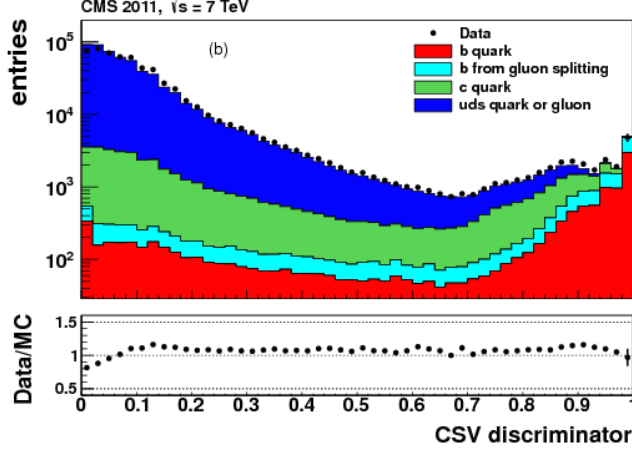


Figure 3.3: The distribution of the CSV discriminator used to identify b-jets. The CSV distribution in different types of jets is highlighted [96].

3.6 Missing energy

Neutrinos and any hypothetical weakly interacting stable particles do not interact with the CMS detector. Their production is inferred from the resulting imbalance in E_T in a given event, of which the hermeticity of the CMS detector allows measurement to a high degree of accuracy. This is crucial not only in many searches for new physics involving such hypothetical particles, but also for SM processes involving neutrinos. In particular for the $H \rightarrow \tau\tau$ analysis accurate measurement of the E_T^{miss} is essential in order to reconstruct the candidate taus after they decay via the weak interaction.

The PF algorithm allows the calculation of E_T^{miss} as the opposite of the vectorial sum of the transverse momenta of all PF particles. The performance of the PF E_T^{miss} response differs in data and MC, and a correction is derived from an independent $Z \rightarrow \mu\mu$ sample which should not contain any real E_T^{miss} from neutrinos. The longitudinal and transverse component of the p_T response and the resolution of the Z boson recoil is parametrised as a function of p_T and jet multiplicity. This parameterisation is then applied to all simulated events as a function of the p_T of the boson. Then finally the E_T^{miss} is taken as the transverse energy of the opposite of the vectorial sum of the visible decay products and the recoil [97]. Figure 3.4 shows the distribution of the PF E_T^{miss} in $Z \rightarrow \mu\mu$ and γ +jet events in $\sqrt{s} = 8$ TeV data and MC. Since neither process produces any real E_T^{miss} , and the energy resolution of muons and photons is good, the resolution of the E_T^{miss} is limited by the resolution of hadronic activity in the event.

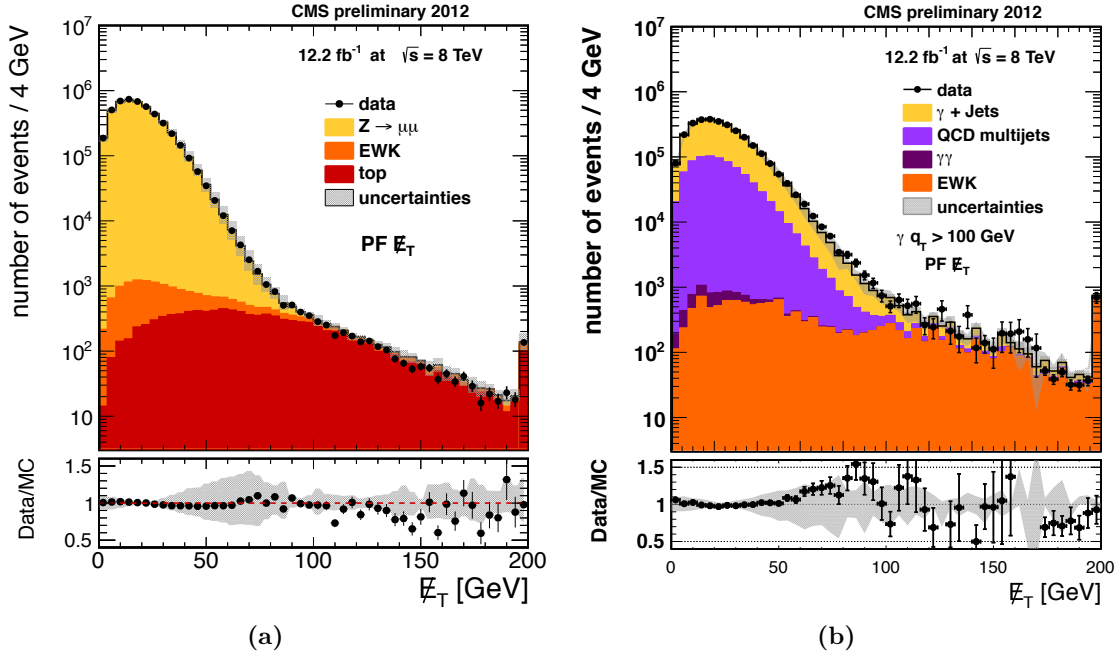


Figure 3.4: Distributions of PF E_T^{miss} in $Z \rightarrow \mu\mu$ and γ +jet events for 8 TeV data and MC[97].

The resolution of the E_T^{miss} can be degraded by a number of factors. These include minimum energy thresholds in the calorimeters, non-instrumented detector regions and multiple PU interactions. To reduce the dependence of resolution on PU, the $H \rightarrow \tau\tau$ analysis uses MVA E_T^{miss} [97], which uses a BDT regression multivariate analysis including the PF E_T^{miss} as one input. Other inputs are versions of the E_T^{miss} calculated using the following combinations of PF particles:

- charged hadrons from the primary vertex;
- charged hadrons from the primary vertex and neutral particles in jets passing the pileup jet ID;
- charged hadrons from pileup vertices and neutral particles in jets failing the pileup jet ID;
- charged hadrons from the primary vertex and all neutral particles in the event, to which is added the vectorial sum of the transverse momenta of neutral particles within jets failing the pileup jet identification.

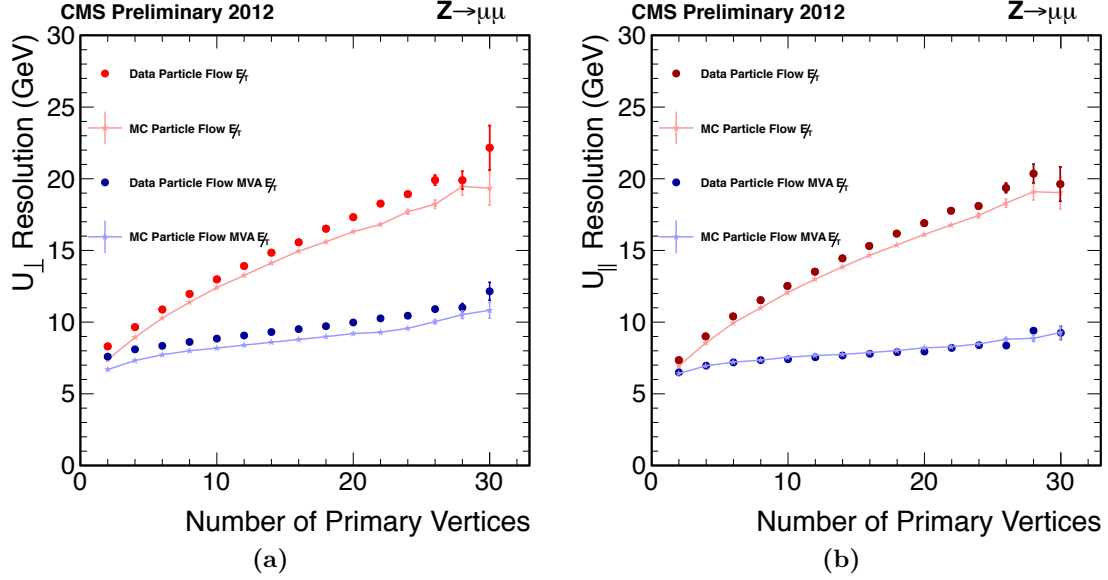


Figure 3.5: The dependence of the resolution of the hadronic recoil response on the number of primary vertices in the event for PF E_T^{miss} and MVA E_T^{miss} [97].

For each type of E_T^{miss} the recoil is calculated as:

$$\vec{u} = \vec{E}_T^{\text{miss}} \cdot \hat{\phi} - \sum_i \vec{p}_T^{\text{lep}}, \quad (3.3)$$

where $\hat{\phi}$ is the direction of the $\vec{E}_T^{\text{miss}}$ in the transverse plane and $\vec{p}_T^{\text{lep}}$ is the p_T vector of the leptons originating from the hard interaction. The BDT produces a correction to both the angle and the magnitude of the PF recoil. The final computed recoil is added to the vector sum of leptons as in equation 3.3 and the resulting corrected E_T^{miss} is then taken. As in the case of the PF E_T^{miss} , a correction is applied for measured differences in E_T^{miss} response in data and MC using recoil corrections.

The MVA E_T^{miss} has a resolution which is much less dependent on pileup, as can be seen in figure 3.5.

3.7 Hadronic taus

Taus decay via the weak force. Approximately 35% of the time, they decay into a final state consisting of a tau neutrino, an electron/muon and the associated electron/muon

neutrino. This section describes the identification of taus for the other $\sim 65\%$ of the time, when they decay into a tau neutrino plus quarks yielding a hadronic tau, τ_h . The different possibilities for hadronic tau decays are listed in table 3.1.

Decay Mode	Intermediate Resonance	Branching Fraction [%]
$\tau^\pm \rightarrow \pi^\pm \pi^0 \nu_\tau$	$\rho(770)$	25.5
$\tau^\pm \rightarrow \pi^\pm \nu_\tau$	-	10.8
$\tau^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.3
$\tau^\pm \rightarrow \pi^\pm \pi^\mp \pi^\pm \nu_\tau$	$a_1(1260)$	9.3
$\tau^\pm \rightarrow \pi^\pm \pi^\mp \pi^\pm \pi^0 \nu_\tau$	-	4.6
Other hadronic modes	-	5.3
Total		64.8

Table 3.1: List of the possible hadronic tau decay modes. The branching ratios for each is given, and where the decay proceeds via an intermediate resonance this is given along with its mass in MeV [19].

The largest fraction of hadronic decays proceed via the $\rho(770)$ resonance resulting in one charged and one neutral pion. Other common modes produce different numbers of neutral or charged pions. Decays with more than 3 charged pions are included in the other hadronic modes listed in the table and are relatively rare. The knowledge of the number of pions in the final state is used in the identification of hadronic taus.

Hadronic taus are a collection of hadronic particles and as such the first level of identification is similar to jet ID. Since the decay products come directly from the tau they are constrained by the tau mass. This results in a highly collimated hadronic system compared with the typical jet. This provides differentiation between hadronic taus and quark and gluon jets. This property is utilised in the tau isolation.

3.7.1 Hadron plus strips algorithm

For the $H \rightarrow \tau\tau$ analysis, the hadron plus strips (HPS) algorithm is used to identify hadronic taus [98]. The HPS algorithm makes use of PF candidates to reconstruct the charged pions and the photons resulting from the decays of the neutral pions. In addition, the masses of the intermediate resonances listed in table 3.1 can be applied. In this algorithm only the visible products of the taus are considered - the tau neutrino forms part of the missing energy.

The algorithm is seeded by a PF jet, which is reconstructed as described in section 3.5.2 with distance parameter $R = 0.5$. The photons from the neutral pion decay have a high probability to convert to electron-positron pairs within the tracker, resulting in an EM shower spread in the ϕ direction. These candidates are clustered using strips with size $\Delta\eta = 0.05$ and $\Delta\phi = 0.2$ initially centred on the most energetic EM candidate in the PF jet. Strips with $p_T > 1$ GeV are considered. The extracted mass of the strip is required to be consistent with the mass of the neutral pion, and hence between 50 and 200 MeV. The strips are then combined with the charged hadrons from PF to give four different cases:

- Single charged hadron or “prong”, no strips: corresponds to $\tau^\pm \rightarrow \pi^\pm \nu_\tau$, with some contribution from $\tau^\pm \rightarrow \pi^\pm \nu_\tau \pi^0$ in the case that the neutral pion is not energetic enough to be detected.
- Single charged hadron or prong, one strip: this selects decays to the intermediate resonance of $\rho(770)$, $\tau^\pm \rightarrow \rho^\pm \nu_\tau \rightarrow \pi^\pm \pi^0 \nu_\tau$. In this case the combined system must have invariant mass m in the range $0.4 < m < 1.3$ GeV if $p_T < 200$ GeV. The upper limit of the range increases with p_T for candidates with $p_T > 200$ GeV (up to a maximum of 2.1 GeV) to account for changes in resolution.
- Single charged hadron or prong, two strips: corresponds to $\tau^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \nu_\tau$. Here, consistency of the mass with the $a_1(1260)$ resonance is required using the range $0.4 < m < 1.2$ GeV if $p_T < 200$ GeV, with the upper limit of the range increasing with p_T up to a maximum of 2.0 GeV.
- Three charged hadrons or prongs: these correspond to $\tau^\pm \rightarrow \pi^\pm \pi^\mp \pi^\pm \pi^0 \nu_\tau$ or $\tau^\pm \rightarrow \pi^\pm \pi^\mp \pi^\pm \nu_\tau$. In this case, the tracks are required to come from the same vertex, with a minimum impact parameter in the transverse plane of 2 mm. The three candidates must also have total charge of 1, and a mass consistent with $a_1(1260)$ using the range $0.8 < m < 1.5$ GeV.

In all of the above cases, the charged hadrons and strips must be contained within a cone defined by $\Delta R = 2.8 \text{ GeV} / p_T^{\tau_h}$, where $p_T^{\tau_h}$ is the p_T of the hadronic tau candidate, for taus with $28 < p_T^{\tau_h} < 56$ GeV. For taus with $p_T^{\tau_h} < 28$ GeV the cone is fixed at 0.1 and for taus with $p_T^{\tau_h} > 56$ GeV at 0.05. Figure 3.6 illustrates the number of events reconstructed in each of the tau decay modes in the backgrounds to the $H \rightarrow \tau\tau$ analysis.

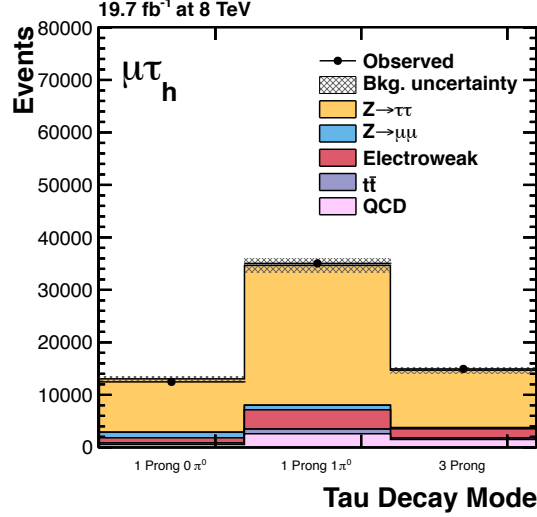


Figure 3.6: Figure illustrating the fraction of events in each tau decay mode in the $\mu\tau_h$ channel of the $H \rightarrow \tau\tau$ analysis. The term “prong” refers to a charged hadron. The “1 prong 1 π^0 ” bin contains both single charged hadron with one strip and single charged hadron with two strips, defined in the text.

3.7.2 Isolation

A measure of the isolation of the hadronic tau candidate is used to exploit the collimated nature of the τ -jets to reduce the background from quark and gluon jets. The isolation is computed in the same way as in equation 3.1 for electrons and muons. The isolation variable is constructed from the sum of the p_T of the hadronic and photon PF candidates with $p_T > 0.5$ GeV within a cone centred on the τ_h with size $\Delta R = 0.5$. The charged hadrons in the sum are required to have $\Delta z < 2$ mm with respect to the production vertex of the τ_h . The charged hadrons associated with other vertices (i.e. with $\Delta z > 2$ mm) are used to estimate and subtract the contribution to the isolation from photons produced in PU interactions, using a cone of size $\Delta R = 0.8$. All constituent particles of the τ_h candidate are excluded from the calculation. Different working points of the isolation are chosen to correspond to loose, medium and tight working points of tau isolation.

3.7.3 Electron and muon rejection

An electron can be misidentified as an hadronic tau with one charged hadron when it has an isolated energy deposit in the calorimeters. Electrons can also be reconstructed as hadronic taus in the one charged hadron plus strips modes when they emit photons via

bremsstrahlung. A BDT is trained to reduce misidentified electrons, using many of the same variables exploited in electron ID described in section 3.2. The $H \rightarrow \tau\tau$ analysis makes use of this discriminator in a tight working point in all final states except for $e\tau_h$, which reduces the rate of misidentified electrons to around 3% with an efficiency for real taus of around 90%.

The probability of a muon to produce a fake hadronic tau is much lower. Such events are suppressed by requiring that the track of the leading charged hadron constituent in the hadronic tau is not also reconstructed as a tracker muon. Loose, medium and tight working points are available for this discriminator also, depending on how strict the criteria are in determining whether or not this track matches a signal in the muon systems.

3.7.4 Energy scale

As with jets, corrections are needed to ensure that the energy scale of hadronic taus in MC matches that in data. The inclusive selection in the $H \rightarrow \tau\tau$ analysis yields a large number of $Z \rightarrow \tau\tau$ events. The distribution of the tau mass can be fit separately for each decay mode, allowing the $Z \rightarrow \tau\tau$ events to constrain the tau energy scale. This is done separately for different ranges of tau p_T , allowing the tau energy scale to float freely in each fit. The result is a set of p_T and decay mode dependent corrections which are applied to MC. Figure 3.7 shows the resulting tau mass distribution for the $\mu\tau_h$ channel of the $H \rightarrow \tau\tau$ analysis. The resulting uncertainty on the tau energy scale is found to be 3%.

In subsequent chapters, the term “tau” is often used to mean “hadronic tau”, where the meaning is clear from the context.

3.8 Di-tau mass reconstruction in $H \rightarrow \tau\tau$

In $H \rightarrow \tau\tau$ events, the mass of the Higgs boson is reconstructed by the di-tau mass, $m_{\tau\tau}$. This is important in distinguishing possible $H \rightarrow \tau\tau$ events from the irreducible $Z \rightarrow \tau\tau$ process, since both processes include real taus in the final state and only differ in the invariant mass of the tau pair. The reconstruction of the mass of the tau pair is made less straightforward by the fact that the taus themselves decay to both visible and invisible products. The visible products of leptons and hadronic taus can be combined to

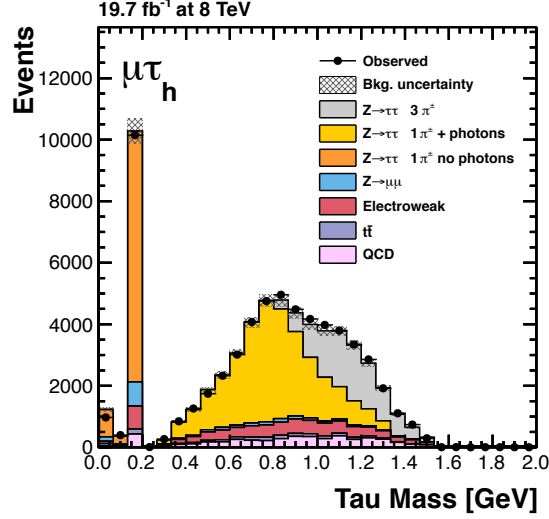


Figure 3.7: The invariant mass of the hadronic tau in $\mu\tau_h$ channel events of the $H \rightarrow \tau\tau$ analysis. The $Z \rightarrow \tau\tau$ component is separated into the different decay modes of the tau. Decays with only one charged hadron are typically assigned the pion mass by the PF algorithm, except for a small fraction which are assigned the muon or electron mass and are found in the first two bins. The contribution from candidates with one charged hadron and photons peaks near the mass of the intermediate $\rho(770)$ meson, and from those with three charged hadrons peaks near the mass of the $a_1(1260)$ meson.

reconstruct a quantity referred to as visible mass, m_{vis} , but greater accuracy is achieved if the full mass is reconstructed including the invisible neutrinos. This can be achieved using a likelihood based algorithm called SVFit [1], which combines the visible decay products and the reconstructed E_T^{miss} . A short description of this method is given in this section. A more detailed description can be found in [1, 99].

The inputs to the SVFit algorithm are the kinematics of the visible decay products and the missing transverse energy. If all visible components of a hadronic tau decay are treated as a single composite object, the visible part of the decay is specified by five parameters, which are chosen to be the momentum, polar and azimuthal angles in the lab frame, and two decay angles in the rest frame of the tau lepton. Leptonic tau decays produce an additional neutrino, and so an additional variable is required to describe the invisible part of the decay, which is chosen to be the invariant mass of the two-neutrino system (this is zero in the case of hadronic tau decays). The unknown parameters are constrained by three observables: the momentum, polar and azimuthal angles of the visible products measured in the lab frame. Further constraints are provided by E_x^{miss} and E_y^{miss} , the x and y components of the E_T^{miss} , within the experimental resolution. This

leaves either two or three unconstrained parameters for the hadronic or leptonic tau decay respectively. These are chosen to be:

- x : the fraction of the energy of the tau carried by the visible decay products in the lab frame.
- ϕ : the azimuthal angle of the tau in the lab frame.
- $m_{\nu\nu}$: the mass of the neutrino system. This is set to zero for hadronic tau decays which have only one neutrino.

The SVFit algorithm employs a likelihood approach, in which possible $m_{\tau\tau}$ values are reconstructed by combining E_x^{miss} and E_y^{miss} with a probability model with terms to account for the tau decay kinematics and E_T^{miss} resolution. The vector $\vec{a}$ is defined to specify the kinematics of each tau decay as $\vec{a} = (x_1, \phi_1, m_{\nu\nu}^1, x_2, \phi_2, m_{\nu\nu}^2)$, where the labels 1 and 2 refer to each of the two taus. Then the probability that the values of $\vec{x} = (E_x^{\text{miss}}, E_y^{\text{miss}})$ are observed, given that the momenta of the visible decay products are equal to the observed $\vec{y} = (p_1^{\text{vis}}, p_2^{\text{vis}})$, yielding a value of $m_{\tau\tau}^i$, is given by:

$$P(m_{\tau\tau}^i) = \int \delta(m_{\tau\tau}^i - m_{\tau\tau}(\vec{y}, \vec{a})) p(\vec{x}, \vec{y}, \vec{a}) d\vec{a}. \quad (3.4)$$

The best estimate $m_{\tau\tau}^i$ for the value of $m_{\tau\tau}$ is then the value which maximises this probability.

Likelihood functions are used to model the tau decay kinematics. These are different for hadronic and leptonic tau decays. For hadronic tau decays, a model based on two-body phase space is used [19], in which all the decay products of the tau are grouped to be one particle:

$$\mathcal{L}_\tau^{\text{had}} = \frac{d\Gamma}{dx d\phi} \propto \frac{1}{1 - m_{\text{vis}}^2/m_\tau^2}, \quad (3.5)$$

which is valid in the physically allowed region of $m_{\text{vis}}^2/m_\tau^2 \leq x \leq 1$. The leptonic function is derived using a matrix element approach [100]:

$$\mathcal{L}_\tau^{\text{lep}} = \frac{d\Gamma}{dx dm_{\nu\nu} d\phi} \propto \frac{m_{\nu\nu}}{4m_\tau^2} [(m_\tau^2 + 2m_{\nu\nu}^2)(m_\tau^2 - m_{\nu\nu}^2)], \quad (3.6)$$

for which the physically allowed region constitutes $0 \leq x \leq 1$ and $0 \leq m_{\nu\nu} \leq m_\tau \sqrt{1-x}$. The final part of the likelihood quantifies the compatibility of a particular tau decay hypothesis with the reconstructed E_T^{miss} . The resolution of the neutrino energy measurement is modelled using a Gaussian form:

$$\mathcal{L}_\nu(E_x^{\text{miss}}, E_y^{\text{miss}}) = \frac{1}{2\pi\sqrt{|V|}} \exp \left[-\frac{1}{2} \begin{pmatrix} E_x^{\text{miss}} - \sum p_x^\nu \\ E_y^{\text{miss}} - \sum p_y^\nu \end{pmatrix}^T V^{-1} \begin{pmatrix} E_x^{\text{miss}} - \sum p_x^\nu \\ E_y^{\text{miss}} - \sum p_y^\nu \end{pmatrix} \right]. \quad (3.7)$$

In this equation V is the covariance matrix which accounts for the expected resolution of the E_T^{miss} reconstruction, and is determined for each event from the MVA MET algorithm described in section 3.6. This resolution is typically 10-15 GeV.

Figure 3.8 shows the shape comparison between $H \rightarrow \tau\tau$ signal and $Z \rightarrow \tau\tau$ background in the case of using the visible mass or the mass from SVFit. It can be seen that the shape separation is greatly improved in the SVFit case. The improvement in expected limit from using SVFit over visible mass in the $H \rightarrow \tau\tau$ analysis is around 40%. The use of SVFit mass in the $H \rightarrow \tau\tau$ analysis is discussed further in the next chapter.

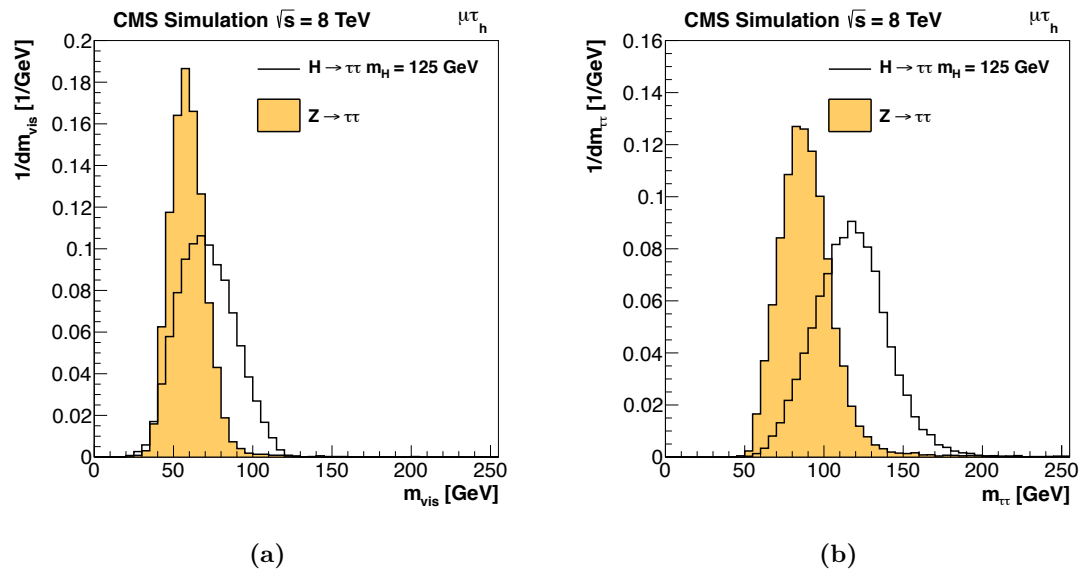


Figure 3.8: Visible di-tau (a) and SVFit di-tau (b) mass for $Z \rightarrow \tau\tau$ and $H \rightarrow \tau\tau$ events [1].

Chapter 4

Search for standard model $H \rightarrow \tau\tau$

As discussed in chapter 1, the Higgs boson was the final missing piece of the Standard Model of particle physics. In order to complete the SM, the discovered Higgs boson should have all the predicted properties of the SM Higgs, including decaying to predicted final states at the correct rates. This chapter describes the search for the Higgs boson of the Standard Model decaying into two tau leptons.

This chapter outlines the SM $H \rightarrow \tau\tau$ results from Run 1 of the LHC, using the full dataset collected in 2011 and 2012 by CMS. This corresponds to an integrated luminosity of 4.9 fb^{-1} at a centre of mass energy of 7 TeV and 19.7 fb^{-1} at 8 TeV. The results in this chapter are parts of a CMS publication [1]. The material included here is particularly focussed towards the parts of the analysis which included the work of the author.

The $H \rightarrow \tau\tau$ analysis is performed in different final states dependent on the decay products of the taus. As discussed in section 3.7, taus can decay into electrons e , muons μ and hadrons (denoted τ_h), all with associated neutrinos. This gives a total of six possible final states: ee , $\mu\mu$, $e\mu$, $e\tau_h$, $\mu\tau_h$ and $\tau_h\tau_h$. The analysis details in this chapter focus on the $\mu\tau_h$ and $e\tau_h$ final states, whilst results including the combination of all six $H \rightarrow \tau\tau$ channels, and additional channels from a dedicated WH, $H \rightarrow \tau\tau$ and ZH, $H \rightarrow \tau\tau$ analysis, are shown in 4.7. More detail on the other channels not described here can be found in [1].

4.1 Event selection

This section describes how the objects discussed in chapter 3 are used to select the most signal-like events.

4.1.1 Candidate events in the $e\tau_h$ channel

Selected events in the $e\tau_h$ channel require an electron and hadronic tau candidate. The events are first selected by a trigger algorithm which requires an electron and tau object. At the L1 trigger the requirement is simply a single electron. At the HLT, loose ID and isolation requirements are placed on the electron, and additionally a τ_h object is required. A simplified version of the PF algorithm is used to select the τ_h candidate, and a loose isolation is applied. Such ID and isolation requirements are looser and more approximate than the more sophisticated algorithms which can then be applied offline.

In the offline selection the electron is required to have p_T larger than 20 GeV or 24 GeV in 2011 or 2012 data respectively. The higher p_T cut in 2012 data is necessary due to increased trigger thresholds necessary to maintain stable rates in the higher instantaneous luminosity conditions. In all data taking periods the η requirement on the electron is $|\eta| < 2.1$. The electron is required to pass the electron ID BDT as described in section 3.2, using a p_T and η dependent cut which corresponds to the tight working point. The isolation definition described in section 3.4 is applied with a threshold of $I_{\text{rel}} < 0.1$. Finally, the electron must be compatible with originating at the chosen PV, and so the impact parameters in the transverse and beam directions, d_{xy} and d_z respectively, must be less than 0.045 cm and 0.2 cm.

The selected hadronic tau has $p_T > 30$ GeV and $|\eta| < 2.3$. The tau is identified using the HPS algorithm as described in section 3.7.1. The tau must be compatible with originating at the chosen PV, and so the impact parameter in the beam direction, d_z , must be smaller than 0.2 cm. As described in section 3.7.3, tau candidates are required to pass criteria to reduce the misidentification of electrons and muons. In the $e\tau_h$ channel, a tight working point for electron rejection is used, and a loose working point for muon rejection. Isolation as described in section 3.7.2 is applied using an optimised working point of 1.5 GeV.

The electron and hadronic tau are required to be of opposite charge. If more than one such pair exists in the event, then the pair with the highest sum p_T is selected. The p_T and η distributions of the selected particles in the $e\tau_h$ channel are shown in figure 4.1 for the electron and figure 4.2 for the tau.

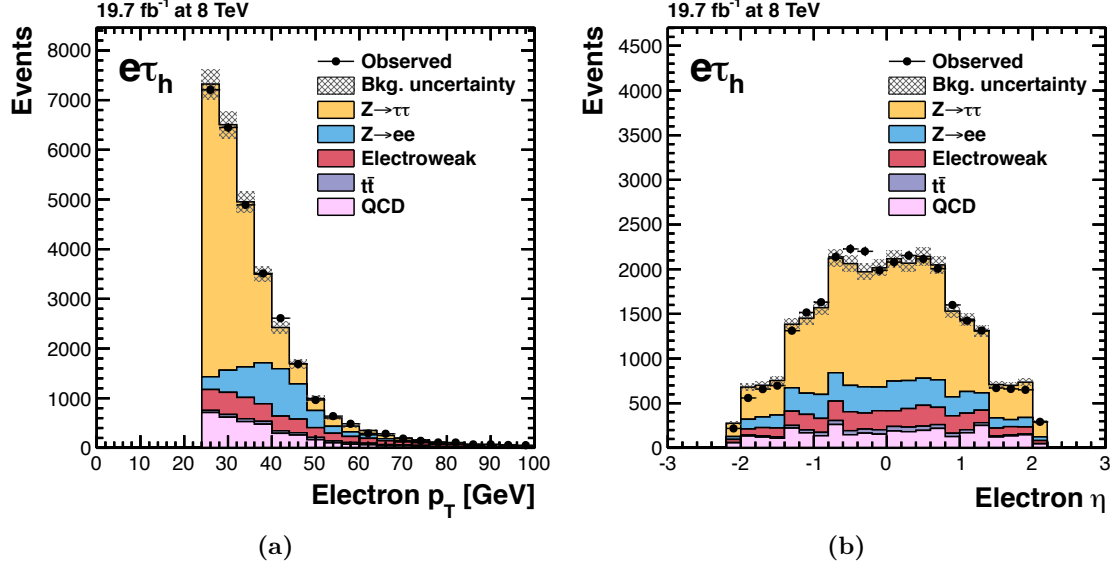


Figure 4.1: The p_T and η distributions for electron candidates in the $e\tau_h$ channel.

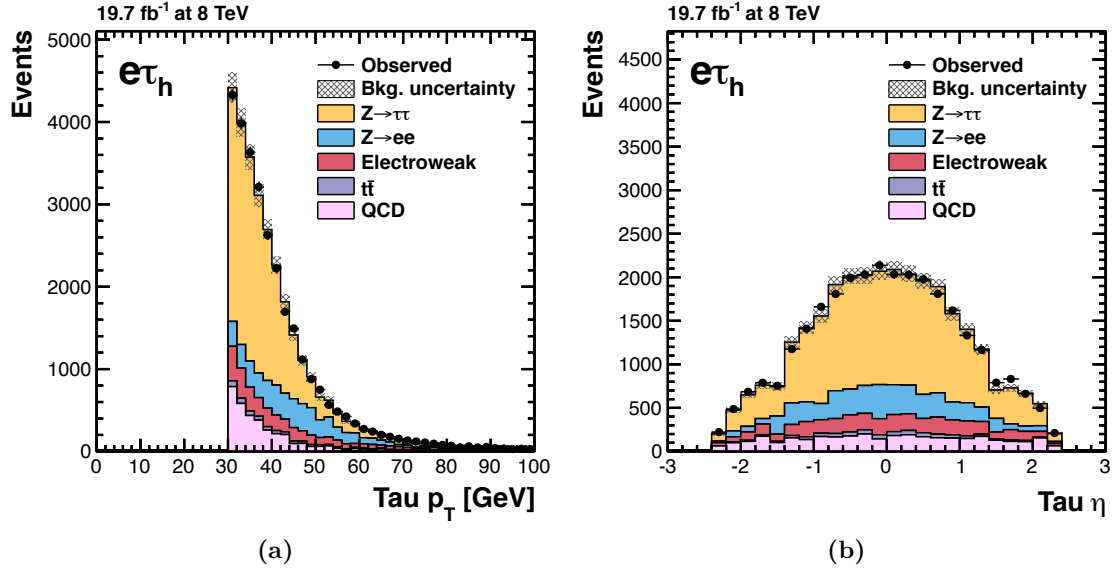


Figure 4.2: The p_T and η distributions for tau candidates in the $e\tau_h$ channel.

4.1.2 Candidate events in the $\mu\tau_h$ channel

Selected events in the $\mu\tau_h$ channel require a muon and hadronic tau candidate. The events are first selected by a trigger algorithm which requires a muon and tau object.

This is done analogously to the $e\tau_h$ channel, where the trigger object at L1 is a muon and the hadronic tau is reconstructed at HLT level.

In the offline selection the muon is required to have p_T larger than 17 GeV or 20 GeV in 2011 or 2012 data respectively. As in the $e\tau_h$ channel, the higher p_T cut is necessary for the higher trigger threshold in 2012. In all data taking periods the η requirement on the muon is $|\eta| < 2.1$. The muon is required to pass tight muon ID as defined in section 3.3. The isolation definition described in section 3.4 is applied with a threshold of $I_{\text{rel}} < 0.1$. Finally, impact parameter cuts on the muon are applied in exactly the same way as for the electron of the $e\tau_h$ channel.

The hadronic tau has the same ID and isolation definition as described for the $e\tau_h$ channel, with the exception of the anti-electron and anti-muon discriminators. In the $\mu\tau_h$ channel a tight anti-muon discriminator and a loose anti-electron discriminator are used.

Similarly to the $e\tau_h$ channel, the muon and hadronic tau are required to be of opposite charge, and if more than one such pair exists then the pair with the highest sum p_T is selected. The p_T and η distributions of the candidate particles in the $\mu\tau_h$ channel are shown in figure 4.3 for the muon and figure 4.4 for the tau.

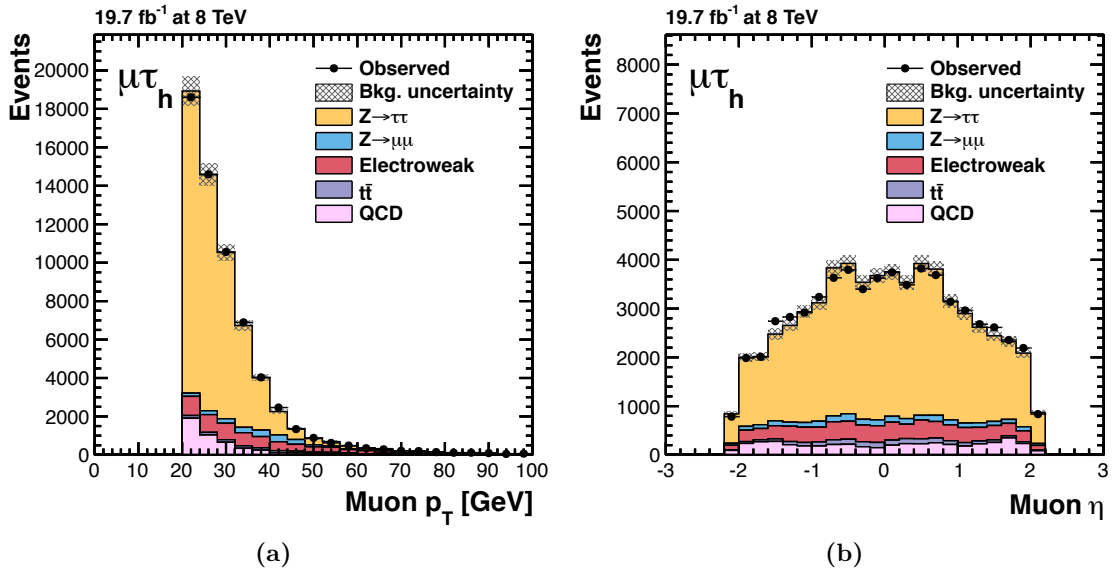


Figure 4.3: The p_T and η distributions for muon candidates in the $\mu\tau_h$ channel.

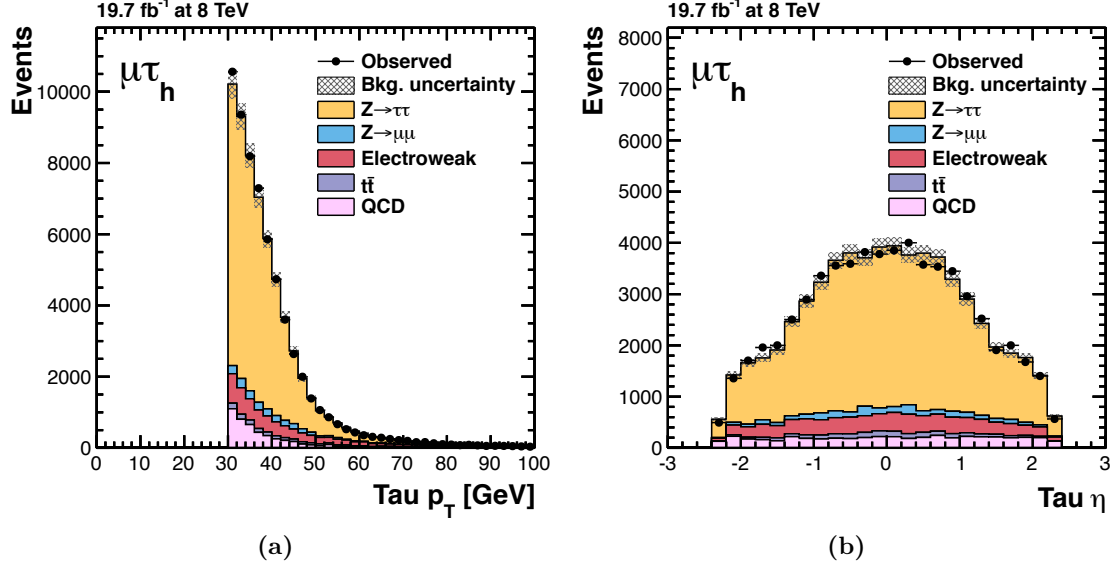


Figure 4.4: The p_T and η distributions for tau candidates in the $\mu\tau_h$ channel.

4.1.3 Extra lepton vetoes

The contribution of certain backgrounds is reduced by vetoing events with extra leptons in them. In the $\mu\tau_h$ and $e\tau_h$ channels, events are vetoed if they contain an extra opposite sign muon or electron respectively, to reduce contribution from $Z \rightarrow \ell\ell$ events in which the τ_h is a fake from a misidentified jet in the event. In this veto, the definition of the extra lepton is slightly looser than the lepton ID used for the candidate pair, with a p_T requirement of > 15 GeV and passing loose ID and isolation. An additional veto is applied which ensures that the number of electrons/muons with $p_T > 10$ GeV passing a slightly tighter ID and isolation is exactly one/zero in the $e\tau_h$ channel and exactly zero/one in the $\mu\tau_h$ channel, with no charge requirement. This reduces the contribution of backgrounds such as WZ events which can decay to combinations of two or three electrons and muons. It was found that the combination of both vetoes was optimal for signal efficiency compared with background rejection. Note that such vetoes are also crucial to ensure there is no event overlap between categories entering a final combined result, for example between the $\mu\tau_h$ channel and the WH, $H \rightarrow \tau\tau$ analysis in the $\mu\mu\tau_h$ final state.

4.1.4 Topological selection

After selection of the candidate pair, a large background from W+jets remains in the $e\tau_h$ and $\mu\tau_h$ channels, usually with the lepton from the W and a jet faking the hadronic tau. The contribution of this background is indicated in the figures with the label “Electroweak”, which also includes the smaller contributions from diboson (WW, ZZ and WZ) and single top events. A useful quantity to reduce this background is the transverse mass between the lepton and the E_T^{miss} :

$$m_T \equiv \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(\Delta\phi))}, \quad (4.1)$$

where p_T^ℓ is the p_T of the electron or muon and $\Delta\phi$ is the difference in azimuthal angle between the lepton and the E_T^{miss} . In real tau events from $Z \rightarrow \tau\tau$ or $H \rightarrow \tau\tau$ the neutrinos in the τ decay tend to be produced collinearly with the visible products, whereas in W+jets events the neutrinos originate from the W which has a much higher mass than the τ , and hence the neutrino is more likely to travel in the opposite direction to the lepton in the transverse plane. Hence W+jets events have a higher transverse mass than signal events, and so a cut of $m_T < 30$ GeV is found to reduce a large amount of W+jets events whilst still retaining a good signal efficiency.

Figure 4.5 shows the distribution of m_T for all events in the $\mu\tau_h$ channel before the $m_T < 30$ GeV cut is applied.

4.2 Event categorisation

The selection as described up until this point is referred to as the “inclusive” $H \rightarrow \tau\tau$ selection. Events with a good candidate lepton and tau pair are further categorised in order to group events which are more background-like or signal-like. The categorisation uses properties consistent with the different production modes of the Higgs boson as described in section 1.1.2. Figure 4.6 illustrates these categories for the $\mu\tau_h$ and $e\tau_h$ channels.

The categorisation separates events which have zero, one or $\geq$ two jets with $p_T > 30$ GeV and $|\eta| < 4.7$. The jets are required to be separate from the lepton candidates by $\Delta R > 0.5$. Events which contain a b-tagged jet as described in section 3.5.4 are vetoed

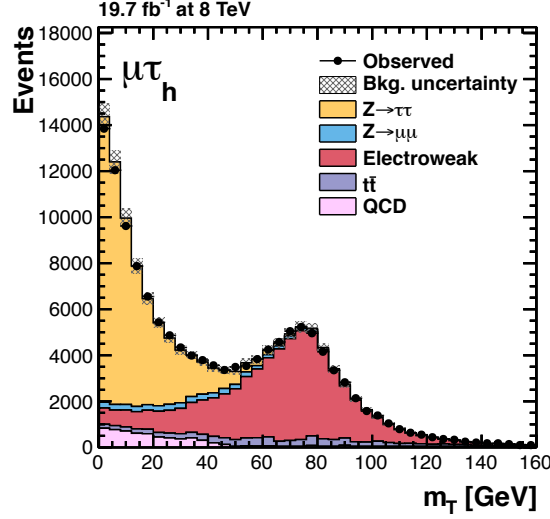


Figure 4.5: The transverse mass between the muon and the E_T^{miss} in the $\mu\tau_h$ channel. Events with high transverse mass largely result from the W +jets background, whereas events with real taus generally have lower transverse mass.

		0-jet	1-jet	2-jet
			$p_T^{\tau\tau} > 100 \text{ GeV}$	$p_T^{\tau\tau} > 100 \text{ GeV}$ $m_{jj} > 500 \text{ GeV}$ $ \Delta\eta_{jj} > 3.5$ $p_T^{\tau\tau} > 700 \text{ GeV}$ $ \Delta\eta_{jj} > 4.0$
$\mu\tau_h$	$p_T^{\text{th}} > 45 \text{ GeV}$	high- p_T^{th}	high- p_T^{th}	loose VBF tag
	baseline	low- p_T^{th}	low- p_T^{th}	tight VBF tag (2012 only)
$e\tau_h$	$p_T^{\text{th}} > 45 \text{ GeV}$	high- p_T^{th}	high- p_T^{th}	loose VBF tag
	baseline	low- p_T^{th}	low- p_T^{th}	tight VBF tag (2012 only)
			$E_T^{\text{miss}} > 30 \text{ GeV}$	

Figure 4.6: Categories used in the $e\tau_h$ and $\mu\tau_h$ channels of the SM $H \rightarrow \tau\tau$ analysis [1]. Events are separated according to the numbers of jets in the event, to target the properties of gluon fusion and VBF Higgs production. Events with large tau or Higgs candidate p_T are more signal sensitive, and so further separations are made using these variables. The signal sensitivity in the 2-jet events is enhanced using cuts on m_{jj} and $\Delta\eta_{jj}$, which are both expected to be large in VBF signal events. The 1-jet low $p_T^{\tau\tau}$ category is removed in the $e\tau_h$ channel since such events are suppressed by the E_T^{miss} cut.

to reduce the contribution of the $t\bar{t}$ background. The 0-jet categories are background dominant, and are included in the final signal extraction to provide constraints on the

backgrounds for the more signal sensitive categories. The 1-jet categories are sensitive to gluon fusion Higgs production in association with a jet and VBF Higgs production where one jet is not picked up by the detector. The 2-jet (VBF) categories are sensitive to VBF Higgs production, and the additional cuts on the invariant mass, m_{jj} , and η separation, $\Delta\eta_{jj}$, of the two leading jets exploit the topology of this process. Events with additional jets in the $\Delta\eta_{jj}$ gap are vetoed to reduce the QCD multijet background.

To improve sensitivity, categories are further separated into more signal-like and background-like events. The 0-jet and 1-jet categories are separated by $\tau_h p_T$. The high $p_T^{\tau_h}$ events are more likely to be consistent with a $H \rightarrow \tau\tau$ event than a $Z \rightarrow \tau\tau$ event due to the higher mass of the Higgs than the Z. This also reduces contributions from QCD and W+jets processes, where the jet faking the hadronic tau is likely to be softer. An additional boosted category is used in 1-jet high $p_T^{\tau_h}$ events with a cut on the di-tau p_T , defined as:

$$p_T^{\tau\tau} = |\vec{p}_T^{e/\mu} + \vec{p}_T^{\tau_h} + \vec{E}_T^{\text{miss}}|, \quad (4.2)$$

where $\vec{p}_T$ is the vector p_T of the candidate, with the requirement $p_T^{\tau\tau} > 100 \text{ GeV}$. The VBF categories are split into VBF “tight” and “loose” based on tighter or looser m_{jj} and $\Delta\eta_{jj}$ cuts and the inclusion of the same ditau p_T cut as in the boosted 1-jet category. The distribution of the $p_T^{\tau\tau}$ in the $\mu\tau_h$ channel is shown in figure 4.7.

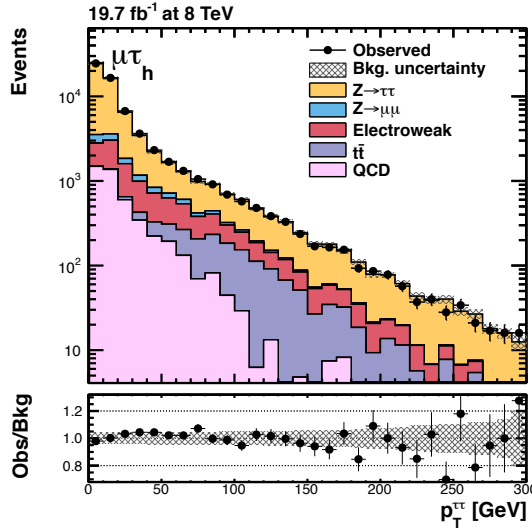


Figure 4.7: Di-tau p_T in the $\mu\tau_h$ channel as used for the separation of events into categories.

The boosted 1-jet and the VBF tight categories are very signal sensitive, and also select events with the best $m_{\tau\tau}$ resolution. The VBF tight category is not possible in 2011 data due to the lower statistics, so the VBF tight and VBF loose categories are merged.

In the $e\tau_h$ channel, 1-jet categories have an additional cut of $E_T^{\text{miss}} > 30 \text{ GeV}$ to reduce the background from $Z \rightarrow ee$. This cut also suppresses the signal and $Z \rightarrow \tau\tau$ events with low $p_T^{\tau\tau}$, and so the 1-jet low $p_T^{\tau\tau}$ category is not possible in the $e\tau_h$ channel.

In all categories in the $e\tau_h$ and $\mu\tau_h$ channels, the final discriminating distribution for signal extraction is the SVFit di-tau mass, as described in section 3.8. The method used for signal extraction is described further in section 4.7.1.

4.3 Datasets and Monte Carlo samples

The datasets used in this analysis correspond to all data collected during the 2011 and 2012 running periods of the LHC. Samples of background and signal events are produced using several different MC generators. The MADGRAPH [101] matrix element generator is used for the Z+jets, W+jets, diboson (WW, ZZ and WZ) and $t\bar{t}$ backgrounds. In order to have high enough statistics to evaluate the backgrounds in categories with varying jet multiplicities, extra samples are generated with fixed jet multiplicities up to four. These are combined with inclusive samples using the expected ratio to retain the correct cross section ratios between different jet multiplicities.

The single top samples are generated using POWHEG [102–104], as are the SM signal samples for gluon-fusion and VBF at next-to-leading order (NLO) precision. Signal samples for production in association with a vector boson or a pair of top quarks are generated using PYTHIA [105] at leading order (LO) precision. In all samples, PYTHIA is used for parton showering and hadronisation and TAUOLA [106] is used for tau decays. Minimum bias events generated by PYTHIA are added to all generated MC samples to simulate additional proton-proton interactions, and then the events are weighted to match the pile-up distribution observed in data.

For the signal, MC samples are produced in 5 GeV steps between $m_H = 90 \text{ GeV}$ and $m_H = 145 \text{ GeV}$. The cross sections and branching ratios are taken from the LHCHXSWG [29, 107, 108]. The full set of simulated processes, the MC generators used and the corresponding cross sections can be found in table 4.1.

Process	MC Generator	Cross Section [pb]	
		7 TeV	8 TeV
$W \rightarrow L\nu$	MADGRAPH	31314	36257
$t\bar{t}$	MADGRAPH	164.4	249.5
$Z \rightarrow LL$	MADGRAPH	3048	3504
$WZ \rightarrow qq'LL$	MADGRAPH	1.8	2.2
$WZ \rightarrow L\nu LL$	MADGRAPH	0.9	1.1
$ZZ \rightarrow LLLL$	MADGRAPH	0.06	0.18
$ZZ \rightarrow LLqq$	MADGRAPH	0.8	2.5
$ZZ \rightarrow LL\nu\nu$	MADGRAPH	0.3	0.7
Single-top (tW channel)	POWHEG	15.7	22.2
SM $ggH(\tau\tau)$	POWHEG	0.96	1.22
SM $qqH(\tau\tau)$	POWHEG	0.077	0.010
SM $ZH(\tau\tau)+WH(\tau\tau)+t\bar{t}H(\tau\tau)$	PYTHIA	0.063	0.079

Table 4.1: Summary of the background and signal processes used in the $H \rightarrow \tau\tau$ analysis along with the MC generator and cross section for the process for $\sqrt{s} = 7$ TeV or 8 TeV. The notation L indicates a leptonic decay into e , μ or τ , and q indicates a quark. For the W, Z and diboson backgrounds samples are produced for jet multiplicities of 0, 1, 2, 3 and 4. The cross sections listed for the signal process are for $m_H = 125$ GeV.

4.4 Background estimation

There are many backgrounds to $H \rightarrow \tau\tau$. Where possible, data driven methods are used to minimise systematic uncertainty related to the modelling in the MC. It is essential to accurately estimate both the shape and the overall yield of each background, and the following sections describe how this is done individually for each source of background.

4.4.1 $Z \rightarrow \tau\tau$

The $Z \rightarrow \tau\tau$ background is the largest and is usually referred to as “irreducible”, due to its final state involving two real taus which only differ from the $H \rightarrow \tau\tau$ signal by having an invariant mass closer to m_Z than m_H . The contribution from $Z \rightarrow \tau\tau$ in each category is estimated using an “embedded” sample. In this process a sample of $Z \rightarrow \mu\mu$ events in data are collected and the muons replaced with simulated taus. The muons are required to pass PF identification and loose isolation and be of opposite charge. The

simulated taus are assigned the 4-momenta of the muons, and all other quantities such as jets, E_T^{miss} and tau isolation are re-computed. The taus are simulated using TAUOLA. The advantage of this method is that the majority of event objects are taken from data, and hence the systematic uncertainties related to E_T^{miss} and jet reconstruction are much smaller.

To estimate the normalisation of the background in each category, the $Z \rightarrow \tau\tau$ MC sample is used to estimate the inclusive yield of this background without the topological m_T cut. Then the yield in each category is estimated by scaling this inclusive yield by the efficiency for inclusive events to pass the category selection plus m_T cut, which is estimated using the embedded sample. The shape is then taken from the embedded sample within the category selection.

4.4.2 $Z \rightarrow \ell\ell$

The $Z \rightarrow \ell\ell$ ($\ell = e, \mu$) background results when one lepton provides the electron or muon and either the other lepton or an associated jet fakes the hadronic tau. This background is much smaller than $Z \rightarrow \tau\tau$ but is especially important in the $e\tau_h$ channel where electrons have a 3-4% probability to pass the anti-electron discrimination in the tau ID. Both yield and shape of this background are taken from simulation.

4.4.3 $W + \text{jets}$

$W + \text{jets}$ events have already been discussed in section 4.1.4, and form a background in this analysis where there is a real electron or muon from the W and one of the associated jets fakes a hadronic tau. This background is largely reduced by the $m_T < 30$ GeV cut. The remaining contribution is estimated using events with $m_T > 70$ GeV, which are dominated by $W + \text{jets}$ events as can be seen in figure 4.5. This is used to estimate the sideband normalisation of the $W + \text{jets}$, by subtracting all other backgrounds from data and taking the rest to be W . An extrapolation factor from $m_T > 70$ GeV to $m_T < 30$ GeV, is then calculated from MC and used to scale the sideband normalisation.

The shape of the $W + \text{jets}$ is taken from MC in each category. Due to the low number of events passing the VBF categories, the m_{jj} and $|\Delta\eta_{jj}|$ conditions are relaxed in both calculating the extrapolation factor and obtaining the shape.

4.4.4 QCD

The QCD multijet background occurs when both the lepton and the tau are misidentified jets, and is estimated entirely from data. It is expected that the contribution of events with a candidate pair in which the pair have opposite or the same charges (signs) is roughly the same in QCD. Thus the same sign data is used with all other backgrounds subtracted, to predict the rate of QCD in the opposite sign events in the signal region. For the background subtraction, the W+jets is estimated as described in the previous section simply using same sign events instead of opposite sign, and all other background contributions are estimated from MC. The rates of opposite sign to same sign QCD events are not quite exactly the same, and an extrapolation factor of 1.06 is applied to correct for this. This factor is measured using data with the electron/muon isolation inverted to give a pure QCD sample.

The same sign data is used in this way for extracting the normalisation in all of the 0-jet and 1-jet categories, with the exception of 1-jet high- $p_T^{\tau_h}$ boosted. Due to the low statistics in the 1-jet high- $p_T^{\tau_h}$ boosted and in the VBF categories, it is necessary to define another sideband from which to extract the QCD estimate. This is done by inverting the electron/muon isolation to $0.2 < I_{\text{rel}} < 0.5$ in same-sign events. The high purity for QCD multijet events in anti-isolated same sign data makes it unnecessary to subtract other backgrounds, which are negligible. The inclusive same-sign data yield is taken from the normal isolation region, and scaled by the efficiency to go from the inclusive to the category selection as estimated in the anti-isolated data.

In the 0-jet low- $p_T^{\tau_h}$ category the shape is taken from the normal isolation same-sign data with other backgrounds subtracted. In all other categories the anti-isolated data is used for the shape. Figure 4.8 shows the distribution of $m_{\tau\tau}$ in same sign events in the 1-jet low- $p_T^{\tau_h}$ and VBF-loose categories in the $\mu\tau_h$ channel, in which the shape has been taken from the anti-isolated data. It can be seen that the predictions from the anti-isolated data agree well with the same sign normal isolation data. In the 1-jet high- $p_T^{\tau_h}$ boosted and tight VBF categories the isolation on the τ_h is also loosened to obtain a sufficiently smooth shape.

4.4.5 $t\bar{t}$

For the $t\bar{t}$ both shape and normalisation are taken from MC. Both are checked against data by defining a control region which is at least 90% pure in $t\bar{t}$. This is done using

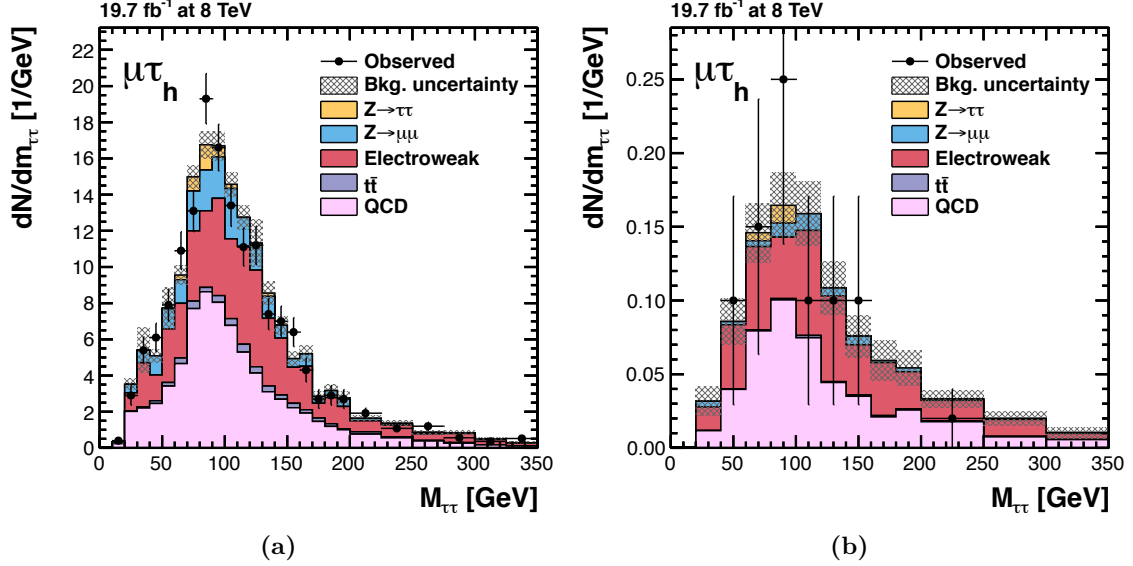


Figure 4.8: Distribution of $m_{\tau\tau}$ for same sign candidate events in the 1-jet low- $p_T^{\tau_h}$ (a) and VBF-loose (b) categories of the $\mu\tau_h$ channel. The shape of the QCD estimate is taken from anti-isolated data. For the VBF-loose events, the normalisation of the QCD is also estimated using an efficiency calculated with anti-isolated data, as described in the text. The figures indicate that the agreement with the data in the normal isolation same sign region is good. Here the uncertainty band includes only statistical uncertainty on the background estimate.

the $e\mu$ channel, which has a much higher quantity of $t\bar{t}$ than $e\tau_h$ and $\mu\tau_h$. The control region is used to derive a scale factor on the MC normalisation. This control region will be discussed further in chapter 6 in the context of an analysis which has much larger contributions from $t\bar{t}$ background. In this analysis the contribution from $t\bar{t}$ is reasonably low due to the b-jet veto.

4.4.6 Diboson and single top

Both the normalisation and shapes of these backgrounds are estimated using MC. The contributions from these backgrounds are much smaller than the others.

4.5 Data to Monte Carlo correction factors

Whilst data-driven methods are used wherever possible, MC is still relied on in predicting expected shapes and yields of signal and some of the backgrounds. As such it is important that the MC is corrected for any effects which are known to be imperfectly modelled. Many of these corrections are derived by studying the agreement between MC and data in dedicated samples or control regions.

4.5.1 Identification, isolation and trigger efficiencies

For ID, isolation and trigger efficiencies of the candidate electron/muon and tau in the analysis, the MC is corrected for measured differences in the efficiency of the selection in MC compared with data. This section documents measurements of these efficiencies for the electron/muon of the $e\tau_h$ and $\mu\tau_h$ channels. This is done using a “tag and probe” method [109]. The method makes use of a well known resonance decaying into a light lepton pair, in this case $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$, in which one the light leptons is assigned as the ‘tag’ and one is the ‘probe’. The tag is constrained by a very tight selection such that it is known with near certainty to be a real electron/muon. The probe is subject to a looser selection, but only tag/probe pairs with an invariant mass close to the Z mass are used. This ensures that the probe is also a true electron/muon with high probability. Then the probe can be subjected to further cuts or constraints to measure the efficiency of such a selection to select real leptons.

The invariant mass distributions of the tag and probe events are used to extract the different selection efficiencies. A simultaneous fit of the lepton pair mass shapes is performed for events with a passing and failing probe, and the ratio of the integral of the fitted Z signal in the pass and fail distributions is used to extract the efficiency. To account for any background to the real Z events, signal and background are both accounted for separately in the fit. An example of such a fit can be seen in figure 4.11.

The electron/muon ID efficiency is measured with a reconstructed electron/muon as the probe, subject only to p_T and η cuts. Then the electron/muon isolation efficiency is measured with a probe which already fulfils the full ID selection criteria. The efficiencies for combined ID and isolation are shown in Figures 4.9 and 4.10, measured in the complete 2012 dataset and MC, as a function of the lepton η and p_T . The scale factor which is used in the analysis to correct the MC is given by the ratio of the measured efficiency in data (black) and MC (red/blue), and is evaluated separately in selected p_T and η bins.

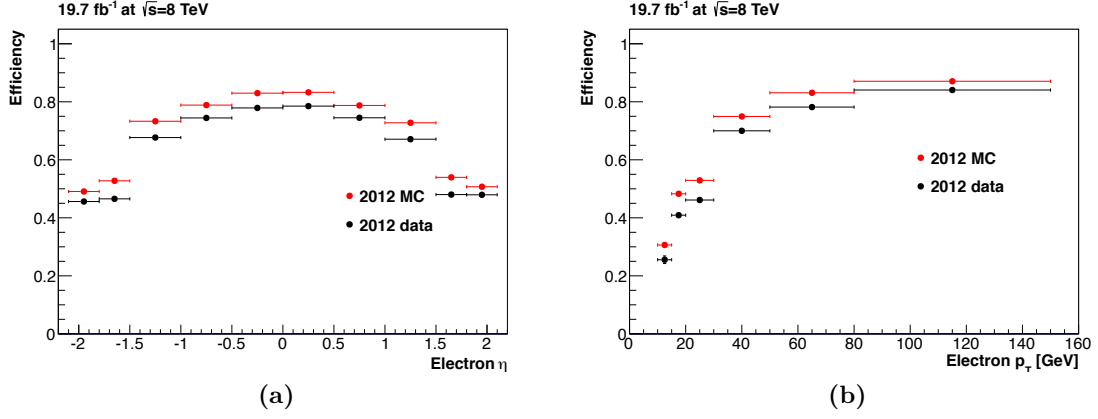


Figure 4.9: Combined electron ID and isolation efficiency in data and MC as a function of (a) η and (b) p_T .

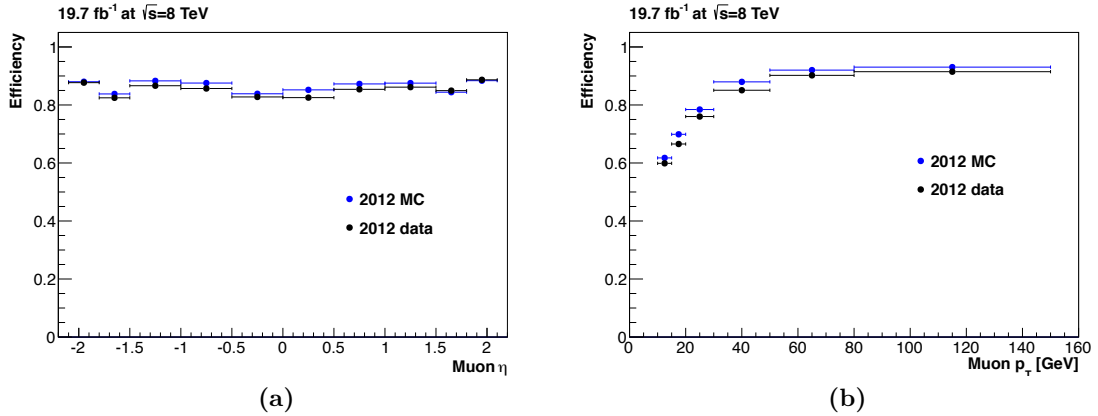


Figure 4.10: Combined muon ID and isolation efficiency in data and MC as a function of (a) η and (b) p_T .

The same method is used to measure the efficiencies of the trigger in data and MC. In this case a probe is used which has already passed both ID and isolation, and the passing probe condition is that the lepton is responsible for firing the lepton plus tau trigger. Figures 4.12 and 4.13 show the trigger efficiency as a function of p_T measured in both 2012 data and MC. For the electrons, the trigger is measured separately in the barrel and endcap regions, which correspond to $|\eta| < 1.479$ and $|\eta| > 1.479$ respectively. For the muons, the trigger is measured in three regions, corresponding to the different regions of the muon chambers as discussed in chapter 2.

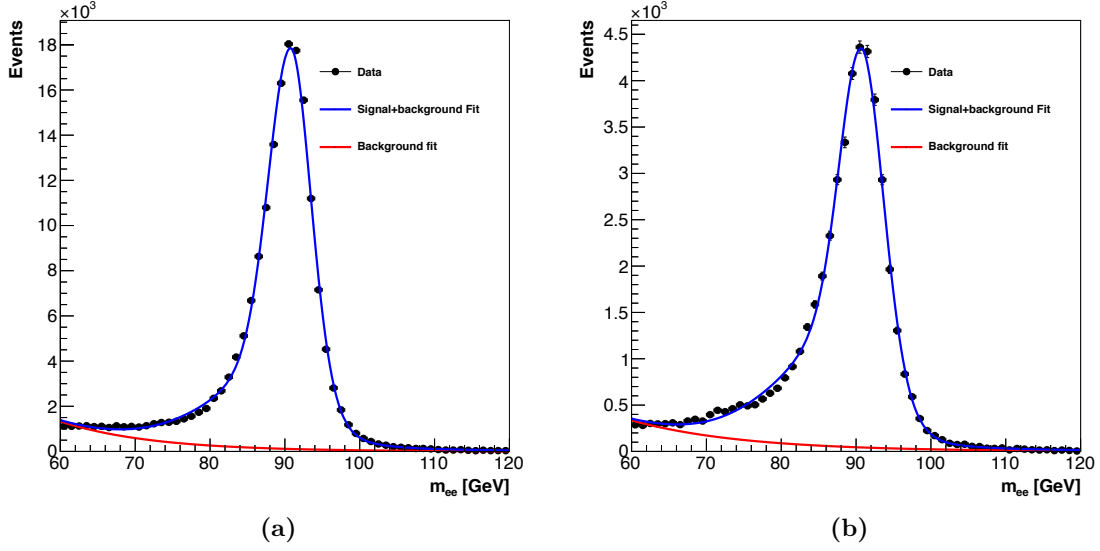


Figure 4.11: Fitted m_{ee} peaks for $Z \rightarrow ee$ tag and probe data events with a probe passing (a) and failing (b) matching to the electron leg of the $e\tau_h$ trigger. This example fit is for electrons with $26 < p_T < 30$ GeV in the barrel. A separate function is fitted for the background and signal ($Z \rightarrow ee$) contributions. The ratio of the integrals of these two fits gives the trigger efficiency of the electrons, which is approximately 80% for this p_T and η range.

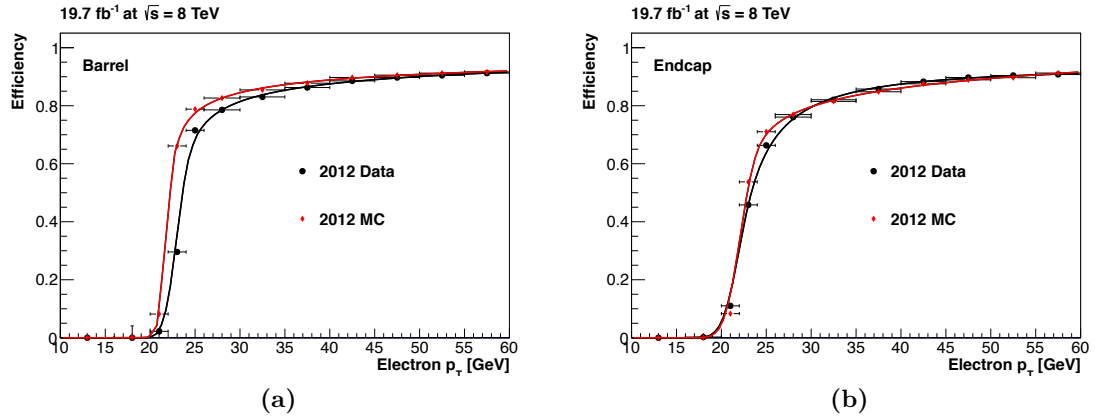


Figure 4.12: Efficiency of the electron leg of the $e\tau_h$ trigger as a function of electron p_T measured in 2012 data and MC in the (a) barrel and (b) endcaps.

4.5.2 Other corrections

Several other data to MC corrections are applied in this analysis. More detailed information on each correction can be found in [1].

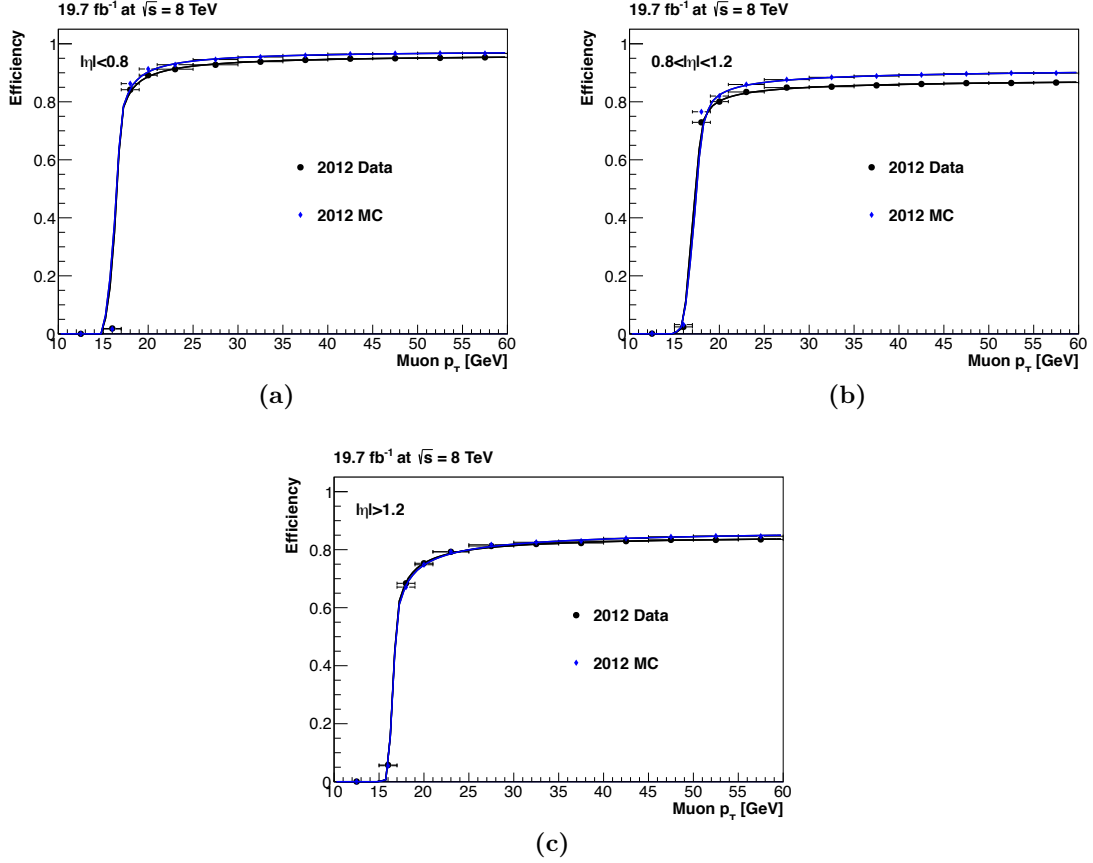


Figure 4.13: Efficiency of the muon leg of the $\mu\tau_h$ trigger as a function of muon p_T measured in 2012 data and MC in the region (a) $|\eta| < 0.8$, (b) $0.8 < |\eta| < 1.2$ and (c) $|\eta| > 1.2$.

Corrections for the tau trigger efficiency are obtained in a similar way as for the light leptons, using $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$ events. As described in section 3.7.4, a correction to MC for the tau energy scale is derived by fitting the di-tau mass and applied to the MC samples which contain real taus.

As described in section 4.3, a weight is applied to all MC such that the pileup distribution matches that observed in data.

B-tagging is used in this analysis as a veto, to reduce the contribution of $t\bar{t}$ background, and so the MC must be corrected for differing b-tag and light jet mis-tag efficiencies in data and MC. The description of how these efficiencies are obtained can be found in [110] for 2011 data and [111] for 2012 data. Since the categorisation depends only on the number of b-tagged jets (which should be 0 for selected events), this efficiency is applied

using a promote/demote method to reclassify jets in MC to make the overall b-tagging rate in the MC match the data. This is done by assigning each jet a probability defined as:

$$P(\text{demote}) = 1 - \text{b-tag}_{SF} \quad \text{for } \text{b-tag}_{SF} < 1 \quad (4.3)$$

$$P(\text{promote}) = \frac{(\text{b-tag}_{SF} - 1)}{\frac{\text{b-tag}_{SF}}{\epsilon_{MC}} - 1} \quad \text{for } \text{b-tag}_{SF} > 1, \quad (4.4)$$

where b-tag_{SF} is the p_T and η dependent scale factor and ϵ_{MC} is the tagging efficiency in MC. This is performed separately for light jets and b-jets, with an explicit check for flavour.

A correction is applied in the SM gluon-gluon fusion signal samples to account for the difference in Higgs p_T distribution at next-to-next-to-leading order (NNLO) compared with NLO. Events are reweighted to make the Higgs p_T distribution match that obtained in the NNLO HRES [112] program. A correction for the difference between the finite and infinite top mass approximations is also applied [113].

The contribution of $Z \rightarrow ee$ background to the $e\tau_h$ channel is additionally corrected by $e \rightarrow \tau_h$ fake-rate MC to data scale factors. These are obtained by fitting the distribution of the $e + \tau_h$ visible mass for taus reconstructed in different decay modes.

4.6 Systematic uncertainties

The systematic uncertainties consist of two different types:

- Normalisation uncertainties: these affect the yield of a particular background or signal.
- Shape uncertainties: these affect the shape of the signal or background, i.e. the number of signal or background events in a particular bin rather than the overall number.

The way in which these different types of uncertainties are incorporated in the final results is described in section 4.7.1. The different sources of uncertainties and their chosen values are described separately for the normalisation and shape uncertainties. A summary of all systematics applied in this analysis is given in table 4.2.

4.6.1 Normalisation uncertainties

ID, isolation and trigger efficiencies for the electrons, muons and hadronic taus

As discussed in the previous section, MC is corrected using scale factors to account for differences in ID, isolation and trigger efficiencies. The estimated uncertainties in these measurements are combined in quadrature. For the electrons and muons this amounts to a 2% normalisation uncertainty. For the hadronic taus a 8% uncertainty on the tau identification efficiency is measured using $Z \rightarrow \tau\tau \rightarrow \mu\tau_h$ events [114]. An additional 3% is applied in the high $p_T^{\tau_h}$ categories due to limited sample sizes in the measurement. The uncertainty on the tau leg of the $e\tau_h$ and $\mu\tau_h$ triggers is 3%. These uncertainties are applied to signal and all backgrounds in which the yield is taken from MC.

b-tag scale factors

Uncertainties on b-tagging efficiencies and mis-tag rates as function of jet p_T and η are incorporated through variations of the scale factors described in the previous section within their estimated uncertainties to modify the promote/demote probabilities. This results in an overall change in yield for backgrounds and signal. For those backgrounds with a non-negligible variation as a result of this uncertainty the yield change is applied as a normalisation uncertainty. The largest effect of this uncertainty is on the $t\bar{t}$ background which contains real b-jets and can vary by up to 10%. The values of the uncertainties are determined as part of the measurement of the efficiencies as described in [110] for 2011 data and [111] for 2012 data.

E_T^{miss} scale uncertainty

Uncertainties on E_T^{miss} resolution and response are accounted for by varying the Z-recoil correction parameters within the uncertainties determined in the recoil correction method. This can result in a change in yield as a result of the m_T cut. In the $e\tau_h$ channel it also directly effects the 1-jet categories via the $E_T^{\text{miss}} > 30 \text{ GeV}$ cut. The E_T^{miss} scale uncertainty is controlled to within 5% [97] by the recoil fits and the resulting uncertainty on each category is similar.

Jet energy scale

Uncertainty on jet energy scale was discussed in section 3.5.3, and is in the region 3-5% dependent on p_T and η . This uncertainty can change the number of events in each category via the change in jet p_T and m_{jj} . The normalisation uncertainties as result of these changes are in the region of 5-15% depending on category, with the largest in the VBF categories.

Background normalisation

The systematic uncertainty on the $Z \rightarrow \tau\tau$ estimate is significantly reduced through the use of embedded samples. However, systematics must be evaluated for the embedding process to account for imperfections in the removal of the $Z \rightarrow \mu\mu$ event. This process is studied by applying the embedding procedure to $Z \rightarrow \mu\mu$ MC and comparing with pure $Z \rightarrow \tau\tau$ MC, and an uncertainty of approximately 5% in the category efficiencies is observed. An overall uncertainty of 3% on the normalisation from $Z \rightarrow LL$ MC is also applied to both the $Z \rightarrow \tau\tau$ and $Z \rightarrow \ell\ell$ predictions to account for uncertainty in the inclusive cross section.

The normalization of the W +jets background is obtained from data, using the high m_T sideband extrapolation method described in section 4.4.3. Uncertainties on the extrapolation factor obtained using MC are found to be in the region of 10-25% depending on category. These are estimated by comparing the shape of the m_T distribution in data and MC in a sample of $Z \rightarrow \mu\mu$ events in which one muon is treated as invisible in the event reconstruction to mimic a W decay.

The uncertainty on the normalization of QCD background is obtained by adding the statistical uncertainty on the yield of events selected in the QCD dominated control regions described in section 4.4.4 in quadrature with the uncertainty on the opposite sign - same sign factor of 1.06, which is found to be 10% as measured in an anti-isolated sample.

The uncertainty on the $t\bar{t}$ cross section amounts to 10%, and on the single top and diboson production cross sections amounts to 15% [115, 116]. For some categories, in particular the VBF-tag, an additional uncertainty on these backgrounds is added to account for low MC statistics.

τ_h fake-rates

The uncertainty on the $e \rightarrow \tau_h$ fakerate is determined as part of its measurement. This amounts to an uncertainty of 20%, correlated between τ_h candidates reconstructed in any tau decay mode [1]. The uncertainty on the rate of $\mu \rightarrow \tau_h$ fakes amounts to 30%. The uncertainty on the rate of jets faking taus is 20% and primarily affects the $Z \rightarrow \ell\ell$ background, and not the QCD or W+jets which are normalised using data driven methods. The $Z \rightarrow \ell\ell$ prediction in the boosted and VBF categories also suffers from low event statistics, yielding larger statistical uncertainties as high as 70%.

Luminosity

The uncertainty on the luminosity amounts to 2.2% for the 2011 data and 2.6% for the 2012 data as described in [117, 118]. This uncertainty is applied to the signal and to $Z \rightarrow \ell\ell$, $Z \rightarrow \tau\tau$, $t\bar{t}$, single top and diboson backgrounds. The normalisation of the W+jets and QCD backgrounds is obtained from data and hence not subject to the luminosity uncertainty.

Theoretical uncertainties

Theoretical uncertainties on the MC predictions of the different signal contributions are estimated in the form of an uncertainty on the acceptance in each category. The parton distribution function (PDF) uncertainty is estimated by calculating the acceptance with several different PDF sets and taking the largest possible variation. The uncertainties as a result of the choice of PDF amount to approximately 2% for gluon fusion and 1% for VBF. The uncertainties on the inclusive cross sections for gluon-fusion and VBF are 7.5% and 2.8% respectively from [29, 107, 108].

Uncertainties due to the renormalisation and factorisation scale uncertainties are around 5-20% for gluon fusion and 1-5% for VBF dependent on category [1]. An additional uncertainty on the gluon-fusion contribution in the VBF categories is estimated to account for the fact that the gluon-fusion is simulated using POWHEG which only includes up to one jet in the matrix element calculation. This is done by comparing the acceptances from other generators, MADGRAPH, POWHEG+MINLO [119] and MC@NLO [120], resulting in an uncertainty of 30%. Uncertainty in the underlying event simulation and parton showering is between 2 and 10% depending on the category.

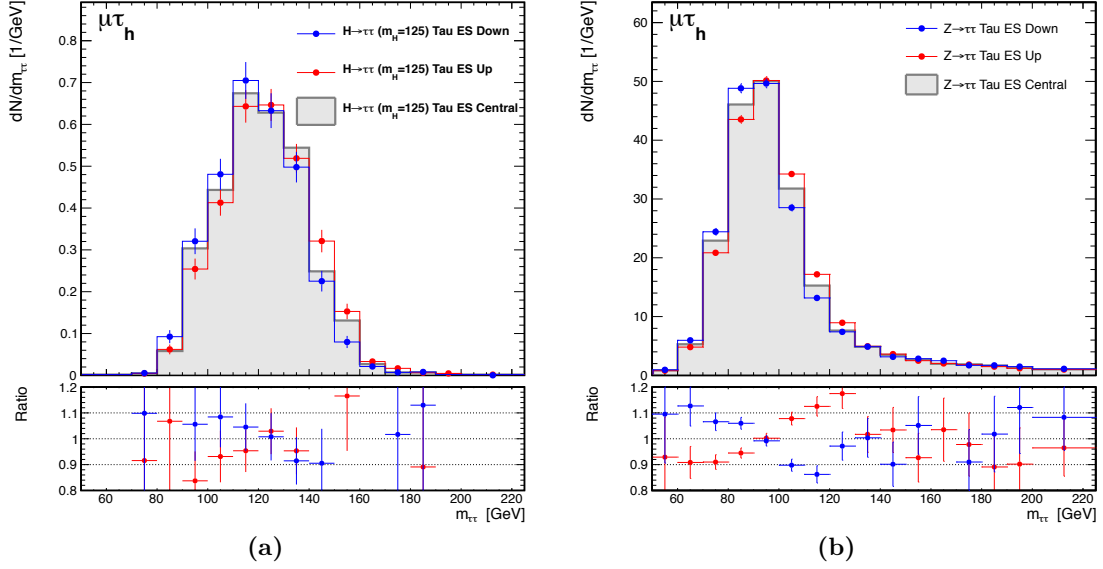


Figure 4.14: Effect of the tau energy scale (ES) uncertainty on the $m_{\tau\tau}$ shape for the gluon-fusion signal with $m_H = 125$ GeV (a) and the $Z \rightarrow \tau\tau$ background (b), for events in the 1-jet high- p_T^τ category of the $\mu\tau_h$ channel. The signal in the left hand plot is normalised to the SM cross section times branching ratio. Only the variation in shape as a result of the tau energy scale is shown here, but small variations in normalisation are also possible.

4.6.2 Shape uncertainties

τ_h energy scale

When studying mass distributions, the shape of the distribution is directly dependent on the energy scale of the objects used in calculating the mass. Thus the $m_{\tau\tau}$ shape is sensitive to the tau energy scale. To incorporate this uncertainty, the energy scale of hadronically decaying taus is varied by 3%, which is constrained by fits to the tau mass discussed in section 3.7.4. Note that compared with the tau energy scale, the effect of the electron or muon energy scale is negligible. Figure 4.14 shows the effect of the tau energy scale uncertainty on the shape of the gluon fusion signal and the $Z \rightarrow \tau\tau$ background for events in the 1-jet low- p_T^τ category of the $\mu\tau_h$ channel. Note that the tau energy scale uncertainty can also change the normalisations slightly, due to events migrating either side of the kinematic cuts.

$Z \rightarrow \ell\ell$ lepton energy scale

A shape uncertainty is also added for the $Z \rightarrow \ell\ell$ contribution for events where a lepton fakes a hadronic tau, to account for the effect of the energy scale of the lepton fake. From studies in control regions, this energy scale mismeasurement is estimated to give a shift of up to 2% in the $m_{\tau\tau}$ shape, and hence a shape systematic amounting to the 2% shift up and down is included to cover this effect.

Bin-by-bin statistical uncertainties

As described when discussing the background methods, selections are often relaxed to obtain smooth templates for certain backgrounds in the most signal sensitive categories. Despite this, low statistics in background templates must still be accounted for in the fit. This often affects some bins in the template more than others, in particular at low or high $m_{\tau\tau}$ values where event statistics are naturally lower. For these bins the statistical uncertainty in the bin is considered a single uncorrelated source of uncertainty, using a method described in [121].

4.7 Results

4.7.1 Signal extraction

The discriminating distribution used for signal extraction is the di-tau mass, reconstructed using the SVFit algorithm described in section 3.8. The methods employed in the statistical interpretation of the data were developed by the LHC Higgs Combination Group and are common methods used across the ATLAS and CMS experiments [122].

The final $m_{\tau\tau}$ distribution for each category of each channel gives a prediction for the expected number and shape of background events and possible signal events in the presence of a SM Higgs of a given mass. Using this distribution, the consistency of the data with either the background only or signal-plus-background hypotheses can be assessed. All bins of all of the $m_{\tau\tau}$ distributions are used for this, i.e. a shape analysis is performed rather than just a counting experiment. Thus a likelihood is built for an observed dataset, dependent on the predictions for signal and background in each bin and taking into account the systematic uncertainties described in the previous section.

Source of uncertainty and affected processes		Yield changes by event category		
Experimental uncertainty	Affected process	0-jet	1-jet	2-jet (VBF)
Integrated lumi. 7/8 TeV	All MC	2.2/2.6%	2.2/2.6%	2.2/2.6%
e ID & trigger	All MC	2%	2%	2%
μ ID & trigger	All MC	2%	2%	2%
τ ID & trigger	All MC	8–11%	8–11%	8–11%
b-tag efficiency	All MC	2–10%	2–10%	3–15%
Z production	$Z \rightarrow \tau\tau, Z \rightarrow \ell\ell$	3.3%	3.3%	3.3%
$Z \rightarrow \tau\tau$: category	$Z \rightarrow \tau\tau$	3–5%	3–5%	10–15%
Norm. $t\bar{t}$	$t\bar{t}$	10%	10%	10–34%
Norm. di-boson	diboson	15%	15%	15–52%
Norm. QCD	QCD	6–20%	10%	22–100%
Norm. W+jets	W+jets	20%	10–17%	20–55%
e misid. as τ_h	$Z \rightarrow ee$	30%	30%	30%
μ misid. as τ_h	$Z \rightarrow \mu\mu$	30%	30%	30%
Jet misid. as τ_h	$Z \rightarrow \ell\ell$	20%	20%	20–80%
Shape misid. e/μ	$Z \rightarrow \ell\ell$	shape	shape	shape
Shape QCD	QCD	shape	shape	shape
Tau energy scale	$Z \rightarrow \tau\tau$, signal	1–27%, shape	1–13%, shape	1–7%, shape
Jet energy scale	All MC	1–16%	1–6%	3–25%
E_T^{miss} scale	All MC	1–7%	1–12%	1–10%
PDF (qq)	signal	1–10%	10%	10%
PDF (gg)	signal	1–4%	2–4%	2–4%
Scale variation	signal	1–8%	1–20%	2–31%
UE & PS	signal	1–9%	1–5%	1–12%
Limited bin statistics	all backgrounds	shape	shape	shape

Table 4.2: Systematic uncertainties that affect the estimated number of signal or background events. Several uncertainties are treated as correlated for the different decay channels and event categories. Some uncertainties vary across final states and for different affected processes, so ranges are given. Adapted from [1].

The likelihood function $\mathcal{L}$ is given by the product of Poisson probabilities $\text{Poisson}(n_i | \nu_i(\mu, \theta))$ to observe n_i events in each bin i of the $m_{\tau\tau}$ distribution:

$$\mathcal{L} = \prod_i \text{Poisson}(n_i | \nu_i(\mu, \theta)) \cdot \prod_j \text{Constraint}(\theta_j, \tilde{\theta}_j), \quad (4.5)$$

with

$$\text{Poisson}(n_i | \nu_i(\mu, \theta)) = \frac{\nu_i^{n_i}}{n_i!} \exp(-\nu_i), \quad (4.6)$$

where ν_i is the number of events expected in that bin, given by the sum of expected signal plus expected background events, which are given by $\mu \cdot s_i$ and b_i respectively. The parameter μ is known as the *signal strength modifier*. It represents the unknown rate of the signal and can be given in reference to a benchmark cross section times branching ratio, in this case that of the SM Higgs. The background-only hypothesis implies $\mu = 0$ and any signal hypothesis $\mu > 0$, with SM Higgs predictions corresponding to $\mu = 1$. Both the number of signal and the number of background events expected in bin i are functions of a set of nuisance parameters θ : $s_i = s_i(\theta)$ and $b_i = b_i(\theta)$. Individual components θ_j each represent one of the systematic uncertainties discussed in section 4.6.

The first product in equation 4.5 extends over all bins i of the $m_{\tau\tau}$ distributions in all of the 0-jet, 1-jet and VBF categories for the $e\tau_h$ and $\mu\tau_h$ channels, as well as the other channels included in the final combination: $e\mu$, $\tau_h\tau_h$, ee , $\mu\mu$ and all the associated production channels WH and ZH. The second product reflects the knowledge that one has about the values of nuisance parameters: each $\text{Constraint}(\theta_j, \tilde{\theta}_j)$ term represents the probability for the true value of a nuisance parameter to be equal to θ_j , given that the best estimate that one has for that parameter is $\tilde{\theta}_j$. The choice of $\tilde{\theta}_j$ is determined by external measurements as discussed in section 4.6.

The functional form of the $\text{Constraint}(\theta_j, \tilde{\theta}_j)$ term depends on the type of systematic uncertainty that it represents. Systematics can take the form of both yield and shape uncertainties as discussed in section 4.6. Yield uncertainties which correspond to multiplicative factors on the signal or background yield are represented by log-normal constraints, which prevent the fit from choosing negative yields. Shape uncertainties are accounted for using a template morphing technique. For each quantity that affects the shape of a background or signal, multiple versions of the template are produced by varying the quantity on which it depends by ± 1 standard deviation. A nuisance parameter λ representing a Gaussian constraint is added to the likelihood model to

smoothly interpolate between the nominal template and the templates representing the variations by $+1\sigma$ and -1σ .

A ratio of likelihoods can be used to define a test statistic, which is a single value which can be used to distinguish between two hypotheses and set upper limits on the rate of signal production. The definition of this test statistic for LHC Higgs analyses is:

$$q_\mu = -2 \ln \frac{\mathcal{L}(\text{data} \mid \mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data} \mid \hat{\mu}, \hat{\theta})}, \quad \text{with the constraint } 0 \leq \hat{\mu} \leq \mu, \quad (4.7)$$

where μ is the signal strength modifier for the signal hypothesis being tested, $\hat{\theta}_\mu$ are the values of the nuisance parameters which maximise the likelihood for that μ and $\hat{\mu}$ and $\hat{\theta}$ are the values which give the global maximum of the likelihood. This is known as the profile likelihood test statistic. The constraint $0 \leq \hat{\mu}$ avoids unphysical negative signal strengths. The constraint $\hat{\mu} \leq \mu$ prevents the exclusion of any μ smaller than the best fit $\hat{\mu}$, ensuring the construction of a one-sided confidence interval. Small values of q_μ indicate good compatibility between the data and the μ hypothesis. The confidence can then be defined as the probability of finding a value of q_μ at least as large as the observed value q_μ^{obs} :

$$\text{CL}_{\text{s+b}} = \int_{q_\mu^{\text{obs}}}^{\infty} f(q_\mu \mid \mu, \hat{\theta}_\mu) dq_\mu, \quad (4.8)$$

and

$$\text{CL}_{\text{s}} = \frac{\text{CL}_{\text{s+b}}}{\text{CL}_{\text{b}}}. \quad (4.9)$$

In the above equations, $f(q_\mu \mid \mu, \hat{\theta}_\mu)$ is the probability density function (pdf) for q_μ .

Finally the 95% confidence level (CL) upper limit on SM Higgs boson production cross-section times branching fraction is determined by the value of μ for which the value of CL_{s} equals 0.05. This is referred to as the modified frequentist approach [123].

Toy MC datasets are used to determine the distributions of $f(q_\mu \mid \mu, \hat{\theta}_\mu)$ and $f(q_\mu \mid 0, \hat{\theta}_0)$, in which pseudo-data is generated from the sum of the background plus signal or background only expectations respectively. In these toys the nuisance parameters are fixed to the values found in the fit to the observed data. The value of q_μ is then calculated

for each toy. The effect of systematic uncertainties is incorporated by sampling a set of pseudo-measurements $\tilde{\theta}$ in each toy using the chosen nuisance pdf (constraint term). Typically it is useful to compare the observed exclusion limit to the expectation from the background-only hypothesis. Thus background-only toys are generated and a distribution for the 95% CL limit is built in a cumulative pdf, from which the median, ± 1 sigma and ± 2 sigma exclusions can be calculated.

Generating large numbers of toys can be computationally expensive. In the limit of a large data sample, the distribution $f(q_\mu)$ follows a calculable formula [124] known as the asymptotic limit approximation. Using this form removes the need to generate toys. It is also possible to derive a formula for the median expected limit and uncertainty bands using this method, completely removing the need to generate toys and greatly improving the speed of the statistical interpretation.

In the case that an excess of events is observed, one useful quantity is the p-value - the probability that such an excess could be the result of the background-only hypothesis. This is computed by modifying the test statistic as:

$$q_0 = -2 \ln \frac{\mathcal{L}(\text{data} \mid 0, \hat{\theta}_0)}{\mathcal{L}(\text{data} \mid \hat{\mu}, \hat{\theta})}, \text{ with the constraint } \hat{\mu} \geq 0, \quad (4.10)$$

From this, the p-value to observe an excess as large or larger than the observed data can be defined as:

$$p_0 = \int_{q_0^{\text{obs}}}^{\infty} f(q_0 \mid 0, \hat{\theta}_0) dq_0. \quad (4.11)$$

4.7.2 Post-fit $m_{\tau\tau}$ distributions

A simultaneous maximum likelihood fit is performed for all channels and categories. The result of the fit is to select the values of the nuisance parameters which maximise the likelihood for the signal plus background fit. This results in small changes in the shape and yield of the backgrounds. The $m_{\tau\tau}$ distributions obtained as a result of this fit are shown in figures 4.15 to 4.18 for the 8 TeV data of the $\mu\tau_h$ and $e\tau_h$ channels. The signal component shown is that expected for a 125 GeV Higgs boson of the SM. The

complete set of distributions including the 7 TeV data and the channels and categories not discussed in this thesis can be found in [1].

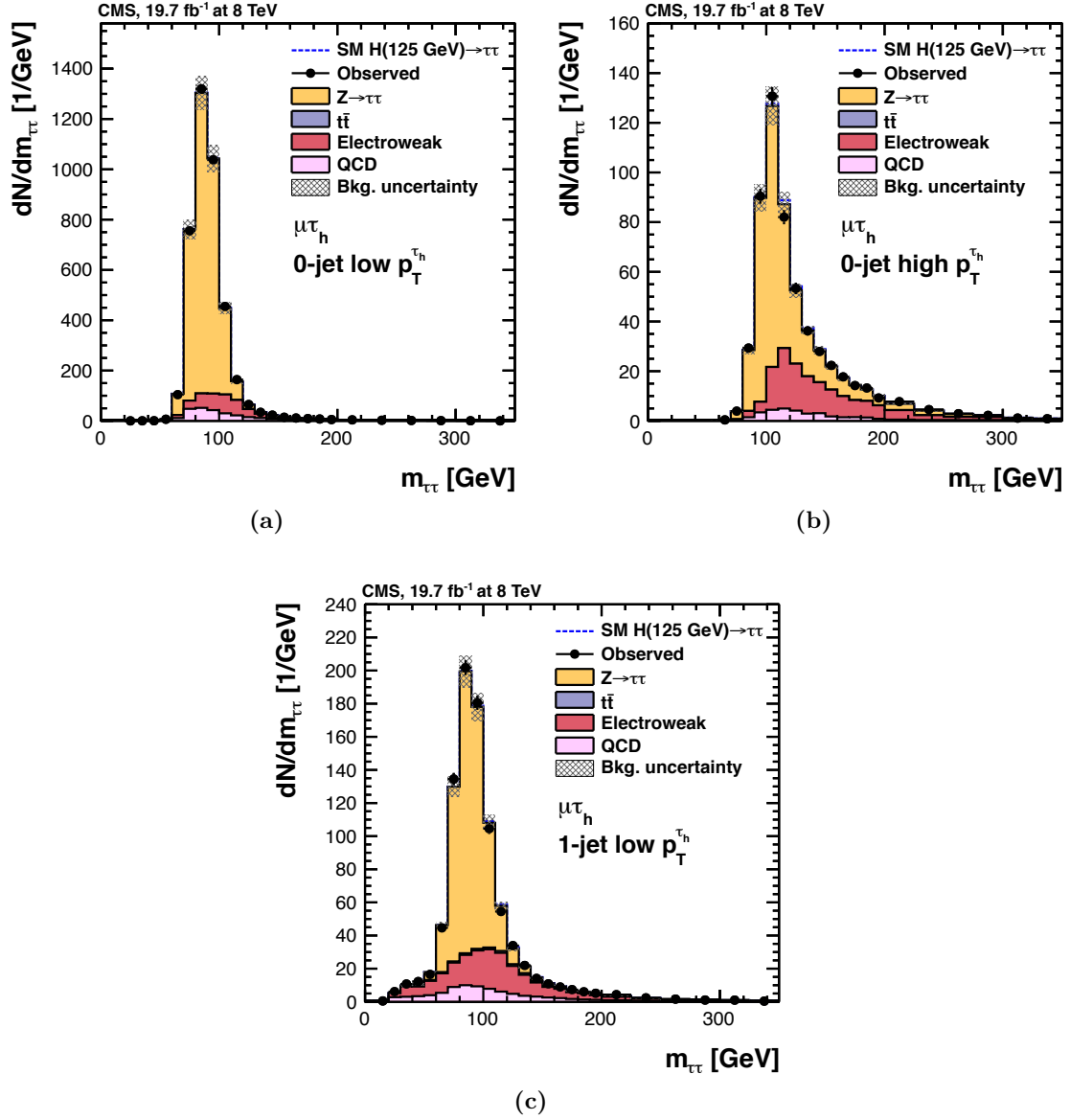


Figure 4.15: Post-fit $m_{\tau\tau}$ distributions for the 0-jet and 1-jet low- p_T^{τ} categories of the $\mu\tau_h$ channel. Shown are the 0-jet low- p_T^{τ} (a), 0-jet high- p_T^{τ} (b) and 1-jet low- p_T^{τ} (c) categories. These are the three least sensitive categories [1].

From the individual $m_{\tau\tau}$ distributions it is difficult to assess the importance of any excess in data over the background prediction. Figure 4.19 shows the $m_{\tau\tau}$ distribution built using the four most sensitive channels: $e\tau_h$, $\mu\tau_h$, $e\mu$ and $\tau_h\tau_h$. To produce this

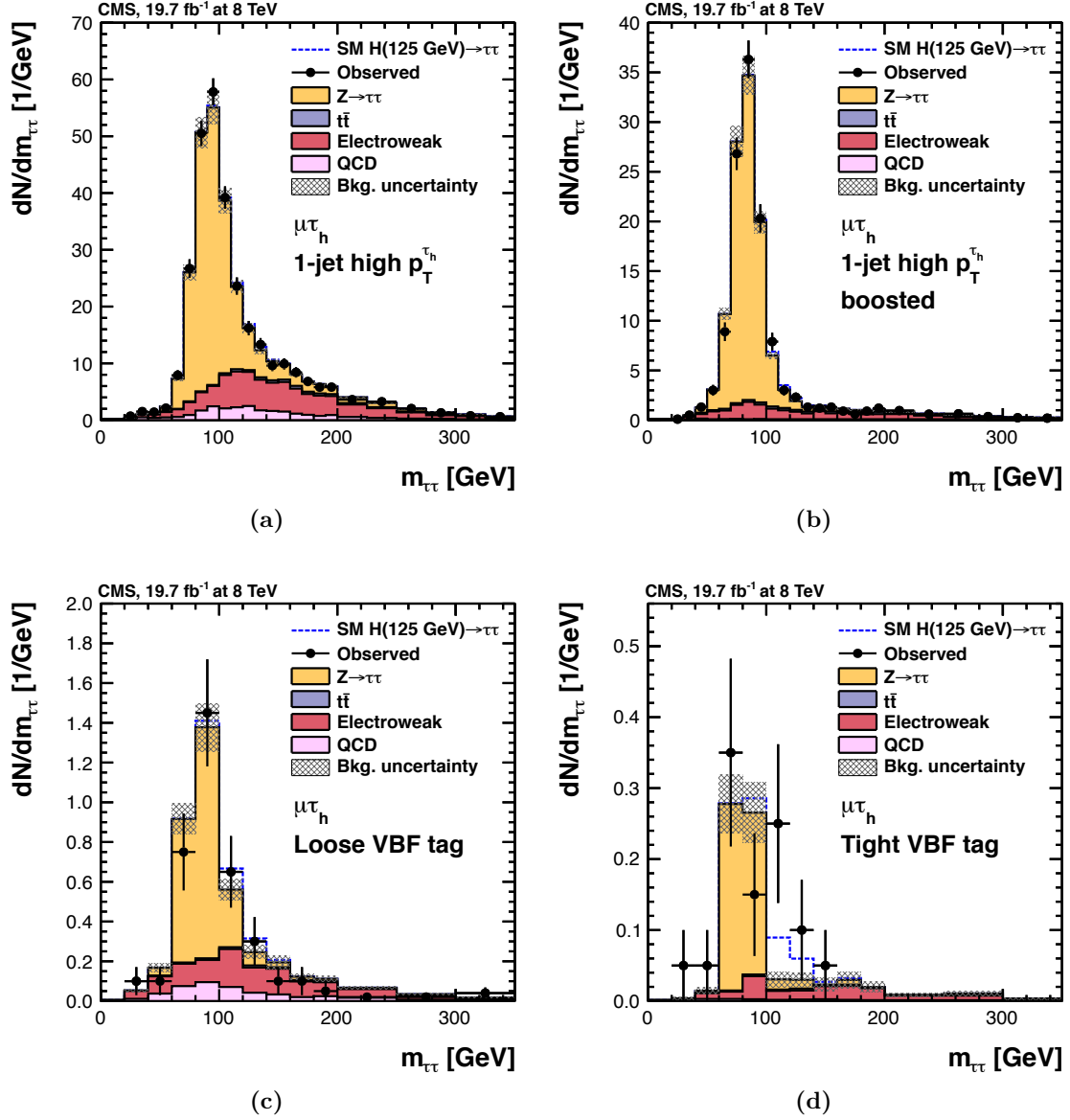


Figure 4.16: Post-fit $m_{\tau\tau}$ distributions for the 1-jet high- p_T^τ and VBF categories of the $\mu\tau_h$ channel. Shown are the 1-jet high- p_T^τ (a), 1-jet high- p_T^τ boosted (b), VBF loose (c) and VBF tight (d) categories. These are the four most sensitive categories [1].

combined distribution, each individual $m_{\tau\tau}$ distribution for each category is weighted by its expected signal to background ratio. This gives a visual representation of the combined sensitivity of all channels and categories. The inset in the figure shows the data with the expected backgrounds subtracted. A clear excess in data over the background

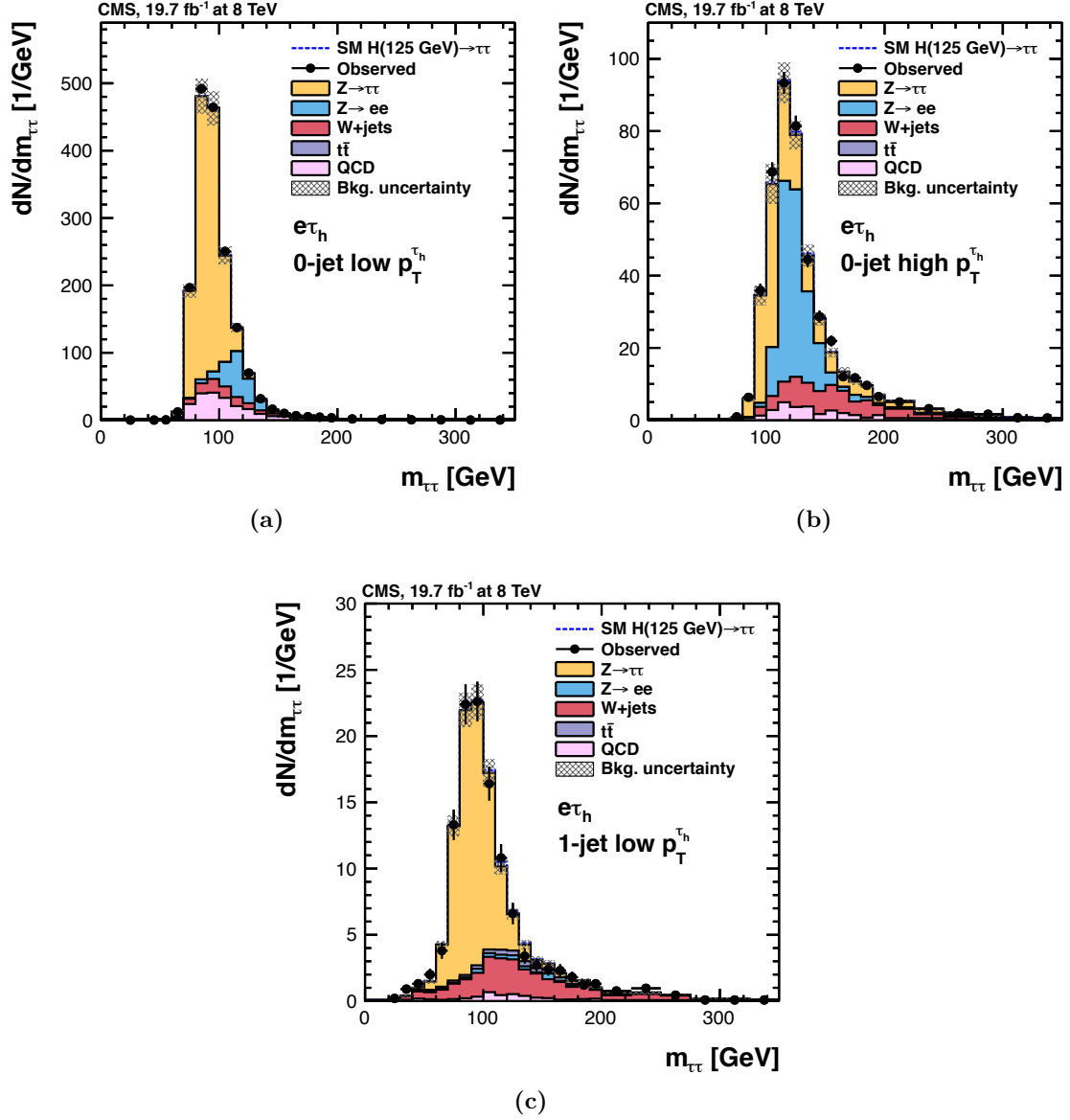


Figure 4.17: Post-fit $m_{\tau\tau}$ distributions for the 0-jet and 1-jet low- p_T^{τ} categories of the $e\tau_h$ channel. Shown are the 0-jet low- p_T^{τ} (a), 0-jet high- p_T^{τ} (b) and 1-jet low- p_T^{τ} (c) categories. These are the three least sensitive categories [1].

prediction is seen. The red band indicates the excess that would be expected for a 125 GeV Higgs boson of the SM. It can be seen that the excess in data is compatible with this.

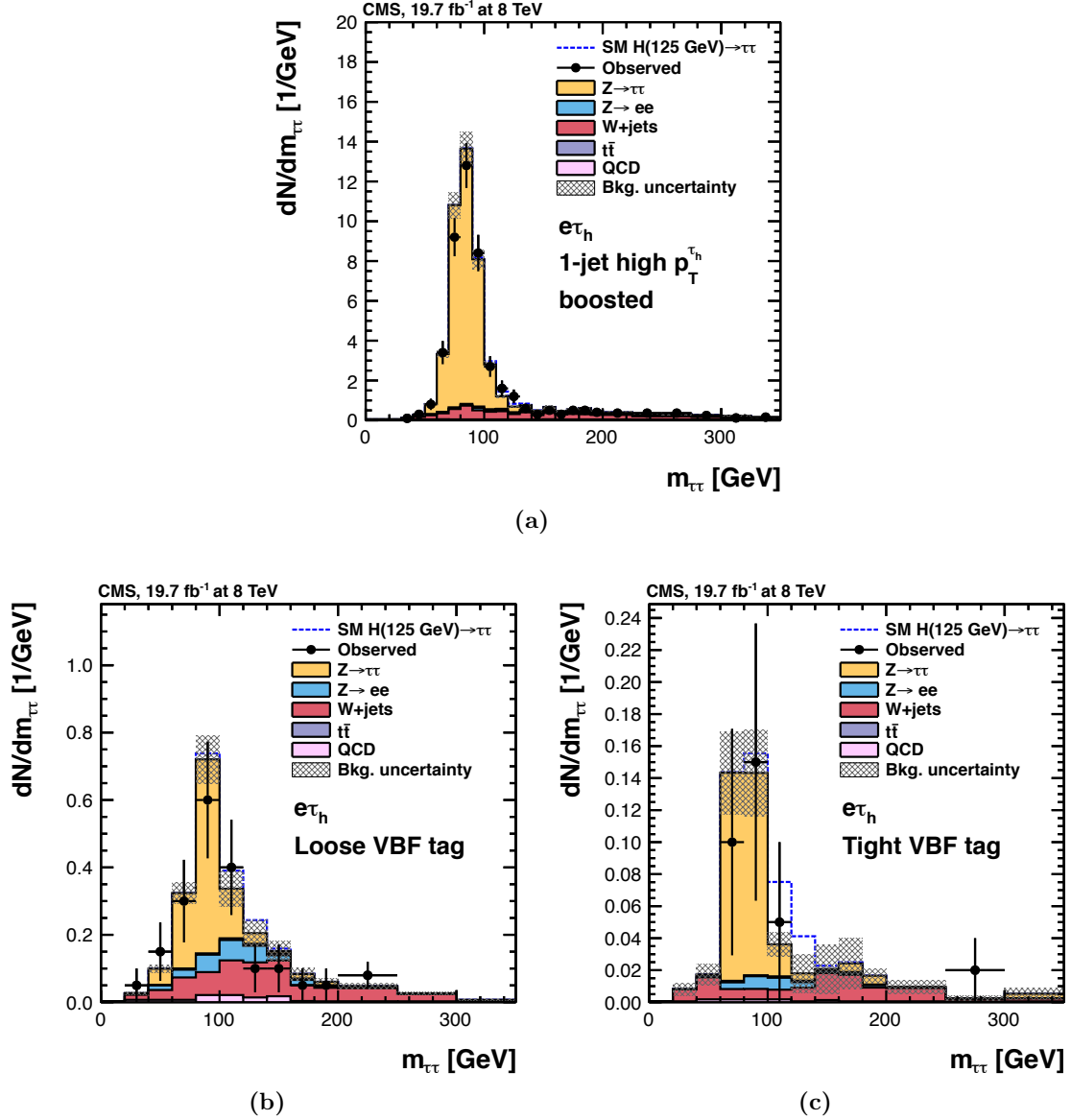


Figure 4.18: Post-fit $m_{\tau\tau}$ distributions for the 1-jet high- p_T^τ and VBF categories of the $e\tau_h$ channel. Shown are the 1-jet high- p_T^τ boosted (a), VBF loose (b) and VBF tight (c) categories. There is no 1-jet high- p_T^τ not boosted category in the $e\tau_h$ channel since such events are suppressed by the E_T^{miss} cut. These are the three most sensitive categories [1].

4.7.3 Limit and significance

The compatibility of the data with either the signal plus background or background only hypothesis is better assessed in terms of the expected and observed limit and significance

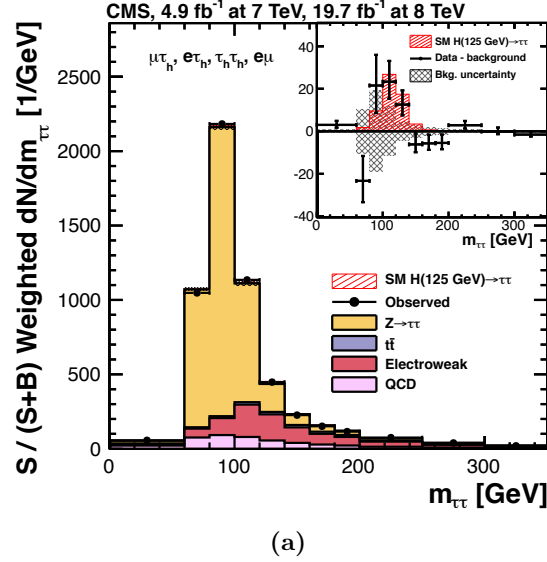


Figure 4.19: Combined $m_{\tau\tau}$ distribution using the four most sensitive channels. The $m_{\tau\tau}$ distribution from each individual category is weighted by its expected signal over background ratio. The inset shows the data with the background expectation subtracted. A clear excess in data over the background prediction is seen. The red band indicates the expected excess from a 125 GeV Higgs in the SM. It can be seen that the excess is compatible with this band [1].

from the combination of all channels and categories. The expected limit can be seen in figure 4.20. The left hand plot shows the expected and observed limit on μ in the context of the background-only hypothesis for a range of Higgs mass hypotheses m_H . It can clearly be seen that the observed limit does not agree with the background-only hypothesis, indicating an excess in data over the background-only prediction. The right hand plot compares the same observed limit this time with an expected prediction that includes a SM 125 GeV Higgs. The observed agrees much more closely with the expected including an SM Higgs, indicating the possible presence of an SM Higgs in the data.

Figure 4.21 shows the expected and observed significance for each m_H hypothesis. The significance is obtained from the p-value by determining the number of standard deviations of a one-sided normal distribution which would yield a tail probability of that p-value. The observed (expected) significance at 125 GeV corresponds to 3.2σ (3.7σ). The significance is larger than 3σ for values of m_H between 115 GeV and 130 GeV.

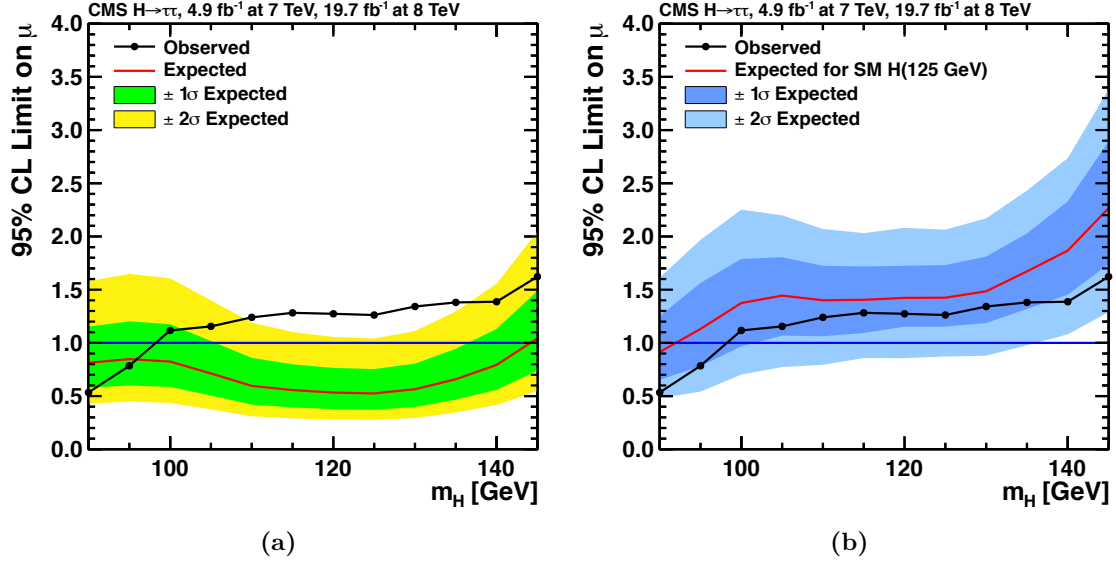


Figure 4.20: Expected and observed limits obtained using the asymptotic CL_s method. The left hand plot compares the observed limit with the expected limit for the background-only hypothesis, and the right hand plot compares the observed limit with the expected limit for background only plus SM Higgs boson of 125 GeV [1].

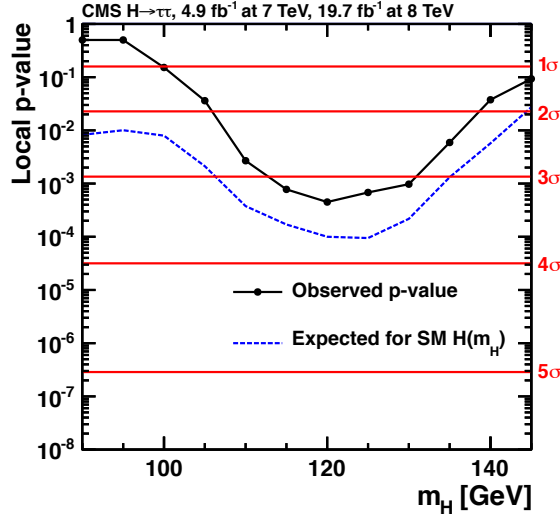


Figure 4.21: Significance/p-value of the observed data, compared with the expected significance for an SM Higgs boson at each m_H hypothesis [1].

4.7.4 Consistency with 125 GeV Higgs boson

Having seen that there is an excess in data, the compatibility with a 125 GeV Higgs boson predicted by the SM can be established. From figures 4.20 and 4.21, it can be seen the excess in data is not only consistent with signal plus background hypothesis for a 125 GeV Higgs but also for several other masses. Figure 4.20 b) already indicates that this is to be expected - it can clearly be seen that the expected limit for a 125 GeV Higgs is broad across several m_H points, and the observed limit seen is consistent with this shape. This can also be looked at in the form of a mass scan. Figure 4.22 a) shows the value of the observed likelihood at each mass point compared with the expected likelihood for a 125 GeV SM Higgs boson. The expected distribution of likelihoods is obtained by generating toys with an SM Higgs injected, and the 1 and 2σ bands come from the spread in distribution of these toys. A parabolic fit is performed to the observed values, yielding a best likelihood value at 122 GeV. The uncertainty on this number is obtained from the 1σ width of the likelihood curve in combination with an estimated systematic uncertainty from the energy scales of the objects, yielding a total uncertainty of 7 GeV. Hence the result is consistent with 125 GeV within the large uncertainty on this measurement.

The consistency of the excess with a 125 GeV SM Higgs also relies on the Higgs being produced at the predicted rates according to the SM cross sections times branching ratios. Figure 4.22 b) shows for a mass of 125 GeV the best fit values for κ_f and κ_V , the couplings to fermions and vector bosons respectively, normalised to the SM predictions such that the value (1,1) would be perfectly consistent with the SM. The best fit value is shown in the black cross, and the contours indicate the uncertainty on this value. It can be seen that the couplings are consistent with the SM within the uncertainties.

Hence the data indicates an excess over the background-only prediction which is consistent with a 125 GeV Higgs boson predicted by the SM. The significance of this excess is 3.2σ , constituting evidence for $H \rightarrow \tau\tau$. This result, along with the corresponding result from the ATLAS experiment, provides the first evidence of the 125 GeV Higgs boson decaying into fermions, and marks an extremely important milestone in Higgs boson physics at the LHC.

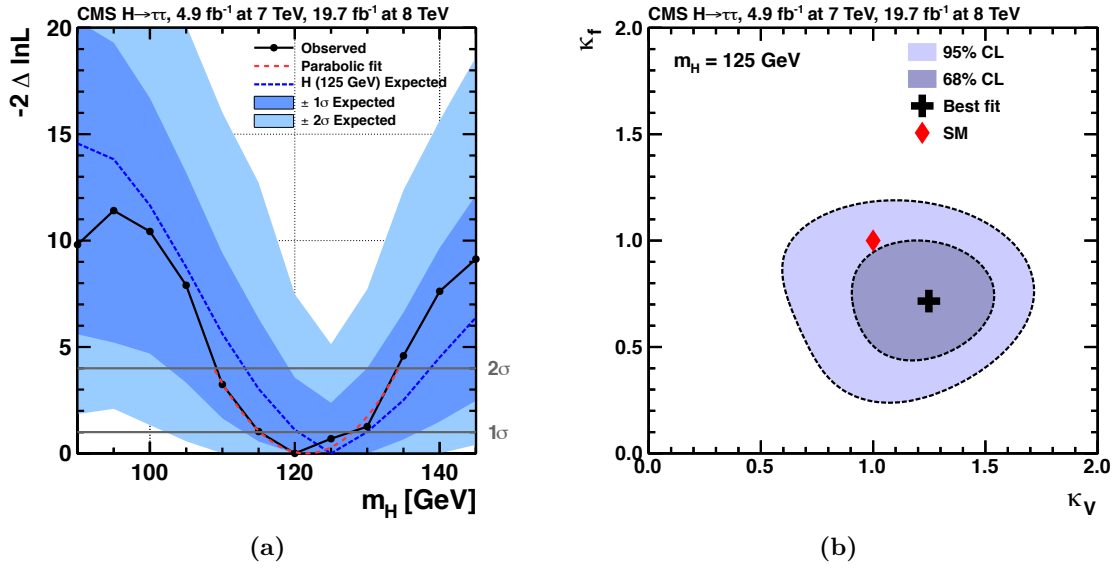


Figure 4.22: Figures indicating the compatibility of the observed excess in data with a 125 GeV SM Higgs boson. The left hand plot indicates the best fit value of the mass of the Higgs boson, and the right hand plot indicates the best fit value of the couplings to vector bosons and fermions compared with the SM predictions [1].

Chapter 5

Search for MSSM $\phi \rightarrow \tau\tau$

As discussed in chapter 1, the most recent results from the LHC indicate the discovery of a 125 GeV Higgs boson which is, so far, consistent with the SM. Furthermore, the analysis discussed in chapter 4 yields evidence at the 3σ level of a Higgs boson decaying into tau leptons, which has properties consistent with the boson discovered in the other decay channels and the SM. However, as discussed in section 1.2.2, the MSSM is an alternative theory to the SM which could provide a 125 GeV Higgs boson consistent with the properties observed so far. This theory also predicts two additional neutral Higgs bosons.

This chapter describes the search for the three neutral Higgs bosons of the MSSM decaying into the $\tau\tau$ final state. Throughout the chapter, the symbol ϕ is used to refer to any one of the three neutral Higgs bosons: H, h or A. This analysis largely uses the same techniques as the SM $H \rightarrow \tau\tau$ analysis described in chapter 4 and as such this chapter focusses on the places where the analysis is different and on the interpretation of results in the context of the MSSM. The material in this chapter is from the MSSM $\phi \rightarrow \tau\tau$ result from Run 1 of the LHC, using the full dataset collected in 2011 and 2012 by CMS, and forms part of a CMS publication [2]. As in chapter 4, the information is focussed initially on the analysis in the $e\tau_h$ and $\mu\tau_h$ final states, while the results shown in section 5.4 include the combination of all channels, which for the MSSM analysis includes the $e\tau_h$, $\mu\tau_h$, $e\mu$, $\tau_h\tau_h$ and $\mu\mu$ final states. The author made significant contributions to the statistical interpretations of the combined results, documented in sections 5.4.2 and 5.4.3.

5.1 Event selection and categorisation

The inclusive selection of the candidate di-tau pair in the $e\tau_h$ and $\mu\tau_h$ final states is almost exactly the same as that used for the SM $H \rightarrow \tau\tau$ analysis described in section 4.1, with one small difference. In the MSSM analysis the τ_h p_T threshold is lowered from 30 GeV to 20 GeV. This is not possible in the SM analysis due to an observed data - MC discrepancy in the tau p_T distribution between 20 and 30 GeV, as a result of imperfect modelling of the trigger. The SM analysis is sensitive to this because of the p_T^τ cut used in the categorisation of events, whereas the MSSM analysis does not use this variable and hence is not affected by the disagreement. A lower p_T cut on the τ_h gives a larger overall number of events and improves the statistics in the background templates across the $m_{\tau\tau}$ range. This is important in the MSSM analysis, because the heavier Higgs bosons can have masses as high as 1 TeV, meaning that a much larger range of $m_{\tau\tau}$ values is used, making it difficult to achieve well populated background templates across the entire range. This is discussed further in section 5.3.2.

Much like in the SM analysis, events are categorised to target the production modes and enhance sensitivity. Events are separated into those with at least one b-tagged jet, or exactly zero b-tagged jets, referred to as the “b-tag” and “no b-tag” categories respectively. The definition of a b-tagged jet is any jet with $p_T > 20$ GeV and $|\eta| < 2.4$ which passes the medium CSV working point as described in section 3.5.4. Events in the b-tag category are also required to have no more than one jet of any flavour with $p_T > 30$ GeV and $|\eta| < 4.7$, which reduces the contribution from $t\bar{t}$ background. As in the SM analysis, all considered jets must be separated from the lepton candidates by $\Delta R > 0.5$. The b-tag category is more sensitive to b-associated Higgs production, and the no b-tag category to gluon fusion, referred to as $bb\phi$ and $gg\phi$ throughout this chapter. Figure 5.1 shows the number of b-tagged jets in the $\mu\tau_h$ channel, with the two signal contributions shown. It can be seen that a large amount of the b-associated production signal has zero b-tagged jets and hence will fall into the no b-tag category. In these events the b-jets associated with the production fall outside the acceptance of the analysis.

5.2 Datasets and Monte Carlo samples

The datasets in this analysis correspond to all data collected during the 2011 and 2012 running periods of the LHC. The MC samples for each of the background processes

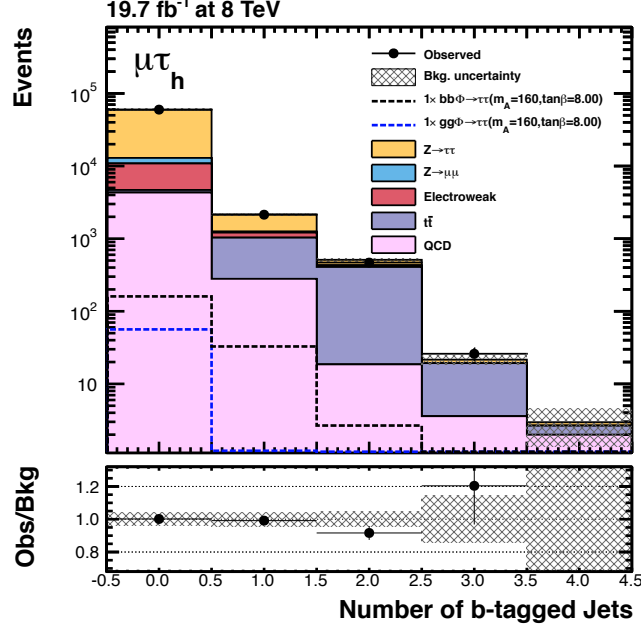


Figure 5.1: Number of b-tagged jets in events in the $\mu\tau_h$ channel, as used to separate events into b-tag and no b-tag categories. Signal contributions are shown separately for b-associated production $bb\phi$ and gluon fusion $gg\phi$, normalised to a benchmark cross section times branching ratio.

are identical to those described in section 4.3 for the SM analysis. The signal samples for the two production processes are generated using PYTHIA [105] at LO. They both use PYTHIA for parton showering and hadronisation and TAUOLA [106] for tau decays. Additional proton-proton collisions to simulate pileup events are added as they are for the other samples. The signal samples are generated in a mass range from 90 GeV up to 1 TeV in steps of varying size. Cross sections times branching ratios for the signal are taken from the LHCHSWG [29, 107, 108].

5.3 Background estimation and systematic uncertainties

5.3.1 Background estimation

The background composition is very similar to that of the SM $H \rightarrow \tau\tau$ analysis and the methods used to estimate the contributions follow those described in section 4.4. The requirement of at least one b-tagged jet in the b-tag category reduces background from $Z \rightarrow \tau\tau$ and increases the contribution of $t\bar{t}$. As described in section 4.4.1, an embedding

procedure is used for the $Z \rightarrow \tau\tau$ estimate, in which $Z \rightarrow \mu\mu$ events in data are replaced with simulated taus. It is known that a small fraction of selected data events are $t\bar{t}$ events instead of $Z \rightarrow \mu\mu$ events, and hence it is necessary to calculate this contamination in the b-tag category so as to avoid double counting of $t\bar{t}$. The contamination is estimated by running the embedding procedure on a $t\bar{t}$ MC sample. For the $e\tau_h$ and $\mu\tau_h$ channels, this contamination is around 1.5% of the $Z \rightarrow \tau\tau$ yield, and so the $t\bar{t}$ yield is reduced accordingly by 14%. The contribution is negligible in the no b-tag category (as well as in all the categories of the SM analysis).

Similarly to the way cuts on m_{jj} and $|\Delta\eta_{jj}|$ are relaxed to obtain smooth shapes for the W+jets background in the VBF categories, the b-tagging working point for the jets is relaxed to the loose CSV working point to obtain the shape for the b-tag category. This is also done for the shape of the $Z \rightarrow \ell\ell$ background. For the QCD estimate, the same-sign data is used for both shape and normalisation in the no b-tag category, whereas for the b-tag category the shape is taken from anti-isolated same-sign data using again the relaxed b-tagging working point.

Data to MC corrections are the same as those used in the SM $H \rightarrow \tau\tau$ analysis as described in section 4.5. An additional correction is derived for the W+jets background to account for observed differences in the jet-tau fake-rate at high p_T , which in particular affects the high mass tail of the W+jets. This correction is measured in the W+jets control region using high m_T events.

5.3.2 Tail fitting of backgrounds

The largest difference between the MSSM $\phi \rightarrow \tau\tau$ analysis and the SM $H \rightarrow \tau\tau$ analysis is the fact that Higgs bosons of masses up to 1 TeV are considered. This means that events with high $m_{\tau\tau}$ are used up to 1.5 TeV. In these high mass regions, the number of events in the backgrounds is greatly reduced, and it becomes more difficult to obtain smooth background templates. This results in a need for a large number of bin-by-bin uncertainties like those described in section 4.6.2 to cover bins with low statistics. A better method for dealing with this is to ensure that the bins are all populated by fitting the template in the high mass region using an analytic function, and replacing the tail of the distribution with the binned form of the function.

The function used for the fits takes the following form:

$$f = \exp\left(\frac{-m_{\tau\tau}}{c_0 + c_1 \cdot m_{\tau\tau}}\right), \quad (5.1)$$

where c_0 and c_1 are free parameters in the fit. The fit is made to the MC in the region $m_{\tau\tau} > 150$ GeV and then the template is replaced by the values of the analytical function for this region. To represent the uncertainty on this high mass fit in the final maximum-likelihood fit for signal extraction, shape uncertainties are generated corresponding to the values of the function for the $\pm 1\sigma$ shift in the fit parameters c_0 and c_1 . The values of these uncertainties are the eigenvalues of the covariance matrix of the fit. Figure 5.2 shows an example of the fit obtained for the W+jets background in the $\mu\tau_h$ channel, showing the central fit to the template and the shape nuisances which are added to the maximum likelihood fit.

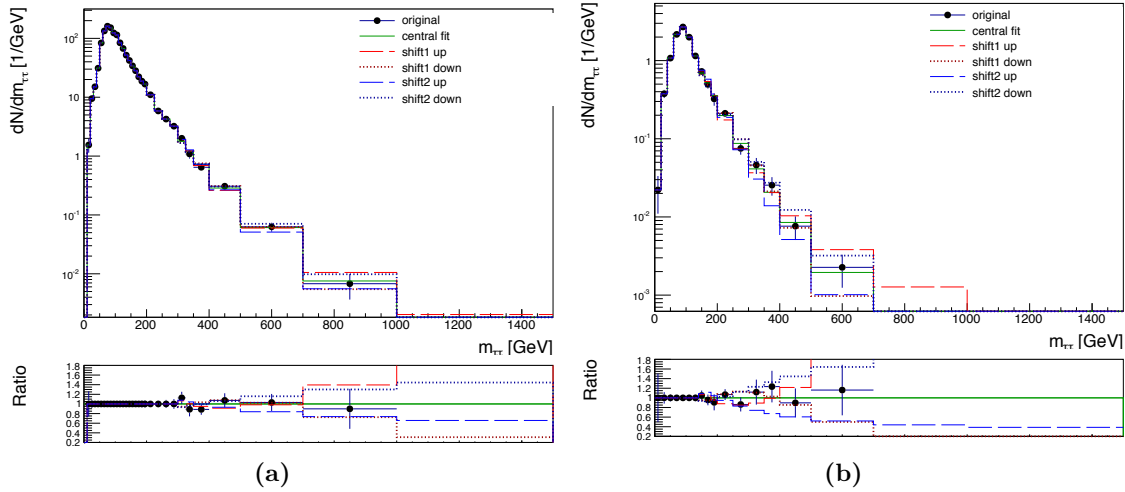


Figure 5.2: Analytic fits to the high mass tail of the $m_{\tau\tau}$ distribution, shown here for the example of the W+jets background. Fits are shown for the no b-tag (a) and b-tag (b) categories of the $\mu\tau_h$ channel for $\sqrt{s} = 8$ TeV. The green line corresponds to the central fit, and the red and blue lines indicate the systematic uncertainties added to the final maximum-likelihood fit to propagate through the uncertainties in the two fitted parameters.

Fits are performed for the W+jets, QCD, $t\bar{t}$ and diboson backgrounds in the $e\tau_h$ and $\mu\tau_h$ channels, where the statistics in the templates are good enough to produce a reliable fit. In the backgrounds in which a tail fit is not used, and in the low mass regions of the fitted backgrounds, bin-by-bin uncertainties as described in section 4.6.2 are applied.

5.3.3 Other systematic uncertainties

The majority of the systematic uncertainties in the MSSM analysis are the same as those in the SM analysis as described in section 4.6. Exactly the same values are taken for ID, isolation and trigger efficiencies and luminosity uncertainty. Jet and E_T^{miss} scale uncertainties are evaluated in the same way as in the SM analysis for the categories of the MSSM. Uncertainties due to b-tagging are also evaluated in the same way, and are generally larger in the MSSM analysis due to the direct dependence on number of b-tagged jets. The effect of the b-tag scale factor is to migrate MC events between the two categories.

Normalisation uncertainties on the $Z \rightarrow \tau\tau$ background are similar, with the same 3% cross section uncertainty and 5% extrapolation uncertainty from the embedded sample. Uncertainties on W+jets and QCD are calculated analogously to the SM analysis. The same cross section uncertainties are taken on the $t\bar{t}$ and diboson backgrounds. The magnitude of the correction to the $t\bar{t}$ as a result of the embedding contamination is taken as an uncertainty in the rate of $t\bar{t}$ events. A shape uncertainty for the correction for jet-tau fake-rate at high p_T on the W+jets background is also applied, where the shapes are generated by shifting the fake-rate correction up and down by the uncertainty in its measurement.

A shape uncertainty to account for the tau energy scale is applied in the same way as the SM analysis. Another shape uncertainty is included on the signal to account for differences in tau ID efficiency at high p_T , affecting the high $m_{\tau\tau}$ events. Theoretical uncertainties on the signal are similar to those on the SM signal, and vary with m_A and $\tan\beta$. The PDF uncertainties range from 2–10% and scale uncertainties range from 5–25% for gluon-gluon fusion and 8–15% for b-associated production [2]. A summary of all systematics applied in this analysis can be found in table 5.1.

5.4 Results

5.4.1 Signal extraction

The discriminating variable used for signal extraction is the same as in the SM analysis - the di-tau mass $m_{\tau\tau}$, using values up 1.5 TeV. The maximum likelihood fit is performed

Source of uncertainty and affected processes		Event yield uncertainty by event category	
Experimental uncertainty	Affected processes	no b-tag	b-tag
Integrated lumi. 7/8 TeV	All MC	2.2/2.6%	2.2/2.6%
e ID & trigger	All MC	2%	2%
μ ID & trigger	All MC	2–3%	2–3%
τ ID & trigger	All MC	8%, shape	8%, shape
b-tag efficiency	All MC	1–5%	1–6%
b-mistag rate	All MC	1–3%	2–9%
Z production	$Z \rightarrow \tau\tau, Z \rightarrow \ell\ell$	3.3%	3.3%
$Z \rightarrow \tau\tau$: category selection	$Z \rightarrow \tau\tau$	-	3%
$Z \rightarrow \tau\tau$: $t\bar{t}$ contamination	$t\bar{t}$	-	14%
Norm. $t\bar{t}$	$t\bar{t}$	10%	10%
Norm. di-boson	diboson	15%	15%
Norm. QCD	QCD	10%	20%
Norm. W+jets	W+jets	10%	30%
e misid. as τ_h	$Z \rightarrow ee$	30%	30%
μ misid. as τ_h	$Z \rightarrow \mu\mu$	30%	30%
Jet misid. as τ_h	$Z \rightarrow \ell\ell, W$ +jets	20%, shape	20%, shape
Tau energy scale	$Z \rightarrow \tau\tau$, signal	2–4%, shape	2–4%, shape
Jet energy scale	All MC	1%	1–11%
E_T^{miss} scale	All MC	1%	1%
PDF	signal	2–10%	2–10%
Scale variation (gluon fusion)	signal	5–25%	5–25%
Scale variation (b-associated)	signal	8–15%	8–15%
Limited bin statistics	all backgrounds	shape	shape
High- $m_{\tau\tau}$ tail fit	QCD, $t\bar{t}$, W+jets, diboson	shape	shape

Table 5.1: Systematic uncertainties that affect the estimated number of signal or background events. Several uncertainties are treated as correlated for the different decay channels and event categories. Some uncertainties vary across final states and for different affected processes, so ranges are given. Adapted from [2].

using similar methods to those described in section 4.7.1, using a simultaneous fit to all channels and categories as described by equations 4.5 and 4.6.

Figure 5.3 shows the post-fit di-tau mass distribution in the $e\tau_h$ and $\mu\tau_h$ channels for the b-tag and no b-tag categories. The plots are shown on a logarithmic scale to highlight the tail of the distribution, of interest in the MSSM analysis. The signal shown is for a benchmark cross section times branching ratio and combines the two signal production processes and all three neutral Higgs bosons. No significant excess of events in data is seen compared with the prediction from backgrounds.

The MSSM analysis differs from the SM analysis in the interpretation of the results of the maximum likelihood fit in the form of a limit. This is done differently for the two types of result produced - referred to as ‘model independent’ and ‘model dependent’.

5.4.2 Model independent results

2D likelihood scan

As discussed in section 4.7.1, the maximum-likelihood fit is generally performed in the signal plus background hypothesis, allowing the signal to float as controlled by the signal strength modifier μ . In the SM analysis the contributions from all different types of SM Higgs signal: gluon fusion, VBF and associated production, are controlled by the same μ which is normalised to the SM prediction for cross section times branching ratio of each process. For the MSSM analysis there are many alternative predictions for the cross section times branching ratio for each of the two production processes: gluon fusion and b-associated production, dependent on the choice of the parameters of the MSSM model. Hence the maximum likelihood fit can be used to obtain the best choice of cross section times branching ratio for each of the two production processes from the fit to data, by letting them both float independently, without any necessary choice of MSSM model.

The signal prediction is defined as follows:

$$\mu \cdot s(\theta) = \mu_{gg\phi} \cdot s_{gg\phi}(\theta) + \mu_{bb\phi} \cdot s_{bb\phi}(\theta), \quad (5.2)$$

where $s_{gg\phi}(\theta)$ and $s_{bb\phi}(\theta)$ are the signal expectations for the gluon fusion and b-associated production process and $\mu_{gg\phi}$ and $\mu_{bb\phi}$ the signal strength modifiers corresponding to the cross section times branching ratio of each process. This can be directly inserted into the likelihood term defined in equation 4.5 to obtain a modified likelihood which depends on

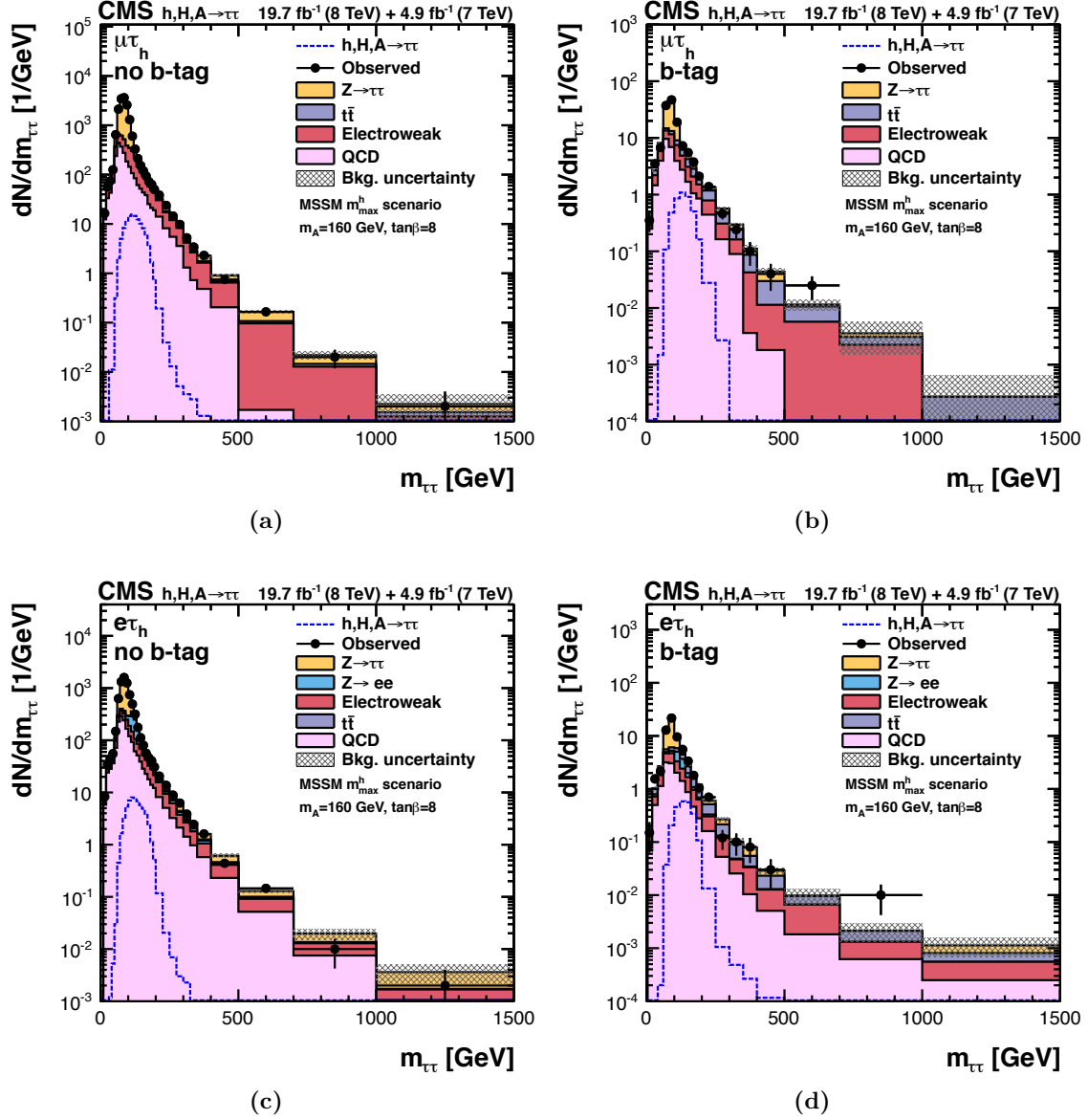


Figure 5.3: Post-fit $m_{\tau\tau}$ distributions for the no b-tag (left) and b-tag (right) categories. Plots are shown for the $\mu\tau_h$ channel (top) and $e\tau_h$ channel (bottom), for the combination of 7 and 8 TeV data [2].

two signal strength modifiers instead of one. A likelihood scan is performed, restricting the signal strength modifiers to be positive, in steps of cross section times branching ratio in picobarns. For each point in the 2-D plane of the two signal strength modifiers,

the negative log likelihood, defined as:

$$\text{NLL} = -\ln \mathcal{L}, \quad (5.3)$$

is evaluated. The lowest value of NLL in the 2D plane is the best fit value for the two signal strength modifiers. The one and two sigma contours are calculated as the points x in the plane where:

$$\Delta(\text{NLL})_{1\sigma} = \text{NLL}(\text{best fit}) - \text{NLL}(x) = 0.5, \quad (5.4)$$

$$\Delta(\text{NLL})_{2\sigma} = \text{NLL}(\text{best fit}) - \text{NLL}(x) = 1.92, \quad (5.5)$$

where $\text{NLL}(\text{best fit})$ is the lowest NLL value in the plane and the values of 0.5 and 1.92 correspond to the 68% and 95% confidence intervals respectively.

A likelihood scan is performed for each mass hypothesis m_ϕ . This type of result is referred to as a ‘single-resonance’ search, due to the fact that there is no requirement that the three Higgs bosons of the MSSM are included, the search is simply for the production of ϕ , which represents any of the three bosons. Figure 5.4 shows the result for four example m_ϕ values across the range. The best fit point is indicated by a black cross and the 1 and 2 σ contours are shown. The fit result is compared with the result obtained in the case where an SM Higgs is in our dataset and no MSSM Higgs is present - this indicates that a small positive value of cross section times branching ratio for the gluon fusion production mode can be obtained as a result of the SM gluon fusion production. Consideration of the effect of a possible SM Higgs on the results of the MSSM analysis is discussed further in the next sections.

Limits on $\sigma \times \mathcal{B}$

The simplest type of limit produced in the MSSM analysis is analogous to the expected limit on μ produced in the SM analysis (figure 4.20). In the MSSM analysis, instead of setting a limit on the signal strength modifier with reference to a benchmark cross section, a more model-independent limit is given on cross section times branching ratio for the Higgs production process. This can then be interpreted in many different benchmark models. A limit is set separately for each of the two dominant production modes, $bb\phi$ and $gg\phi$, again in a ‘single resonance’ search for ϕ . It is not possible to completely

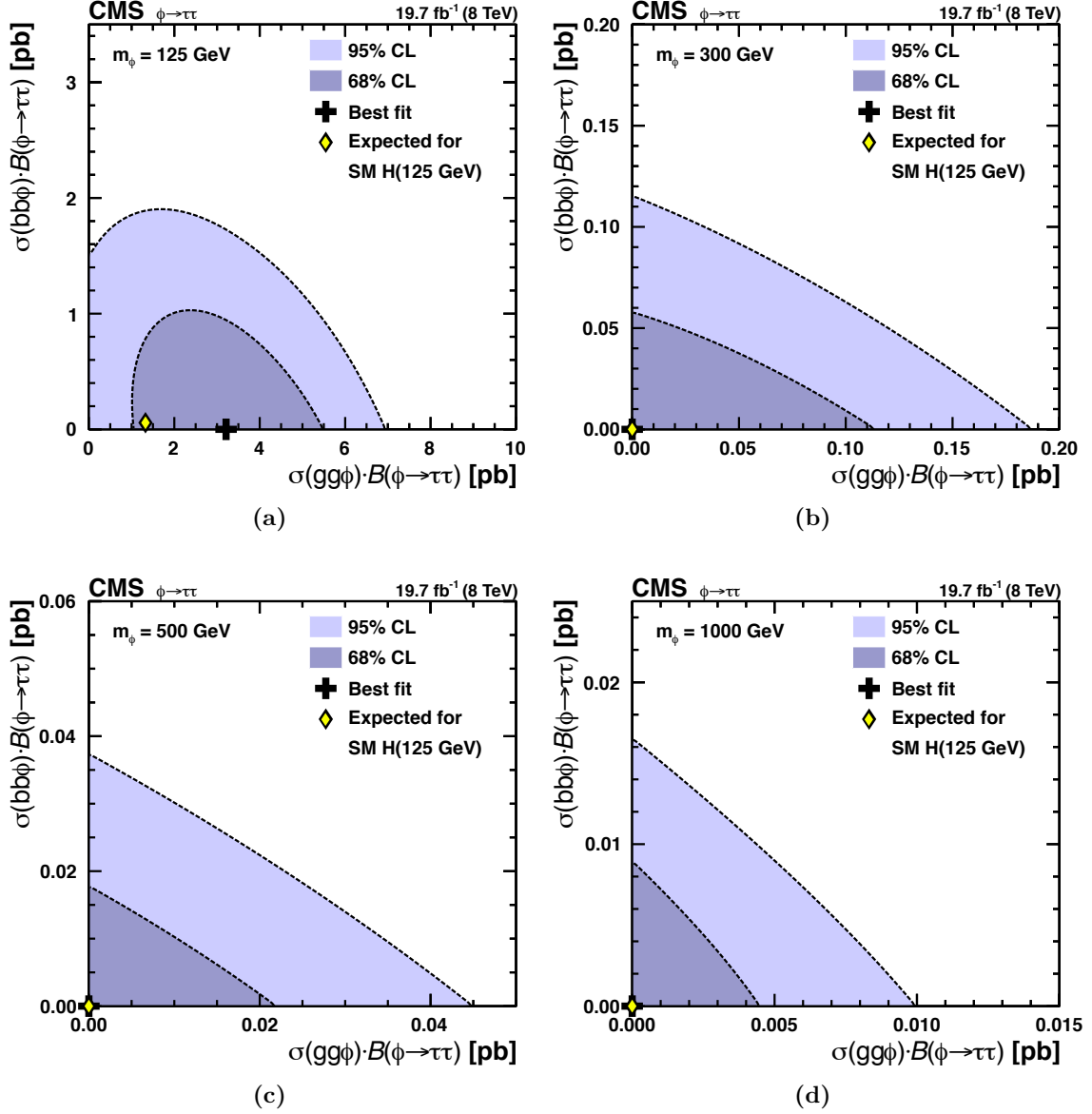


Figure 5.4: 2-D likelihood scans showing the best fit values for the cross section times branching ratio of the gluon fusion (x-axis) and b-associated production (y-axis) processes using 8 TeV data. Shown for m_ϕ values of 125 GeV (a), 300 GeV (b), 500 GeV (c) and 1 TeV (d). The best fit point is indicated along with the best fit point which would be obtained if there was a 125 GeV SM Higgs boson in the data [2].

disentangle the two production modes - as shown in section 5.1 the categorisation does not completely separate the signal contributions, and some $bb\phi$ signal is found in no b-tag category and some $gg\phi$ in the b-tag category. Hence to produce a limit on each

process separately, the other signal process is ‘profiled’. This means that it is allowed to float in the fit in a similar way to one of the nuisance parameters.

Figure 5.5 shows the expected and observed limit on cross section times branching ratio for the $gg\phi$ and $bb\phi$ production processes. The expected limit and the corresponding 1 and 2 σ bands are generated in the same way as in figure 4.20 b), by running toys with an SM Higgs injected. In this way the observed limit is compared to an expected limit including both the backgrounds and an SM Higgs.

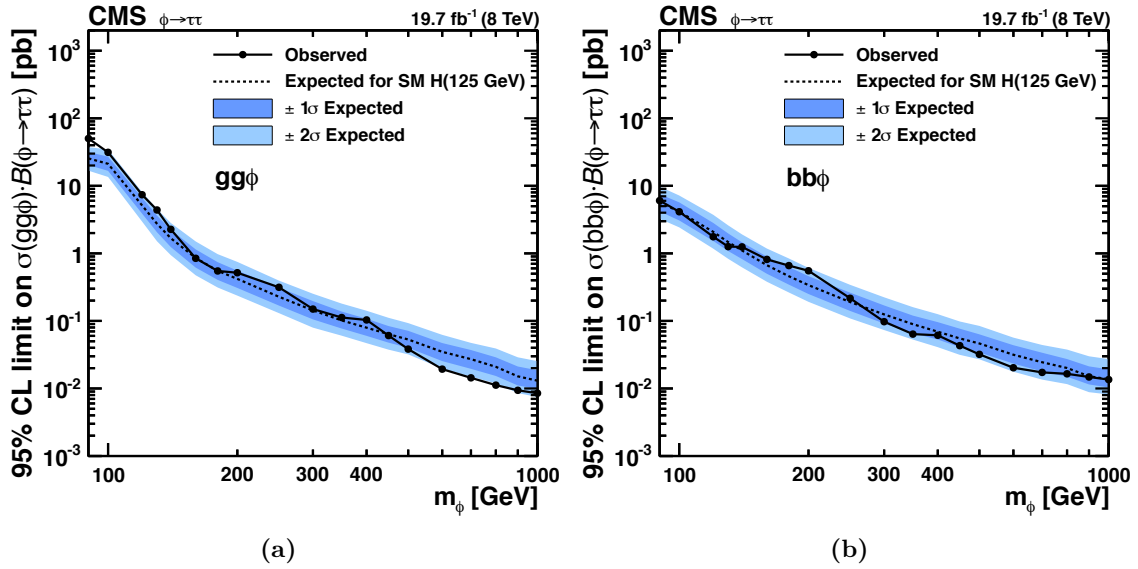


Figure 5.5: Limits on cross section times branching ratio for a) gluon fusion Higgs production and b) b-associated Higgs production for the combination of all channels and categories in the 8 TeV data. For each limit the other production process is profiled. The observed limit is compared with an expected limit which includes the SM Higgs [2].

The reason for comparing the observed with an expected limit including the SM Higgs, both here and in the 2D likelihood results, is that the results cannot be interpreted in the context of the MSSM without taking into account the fact that there is 3 σ evidence of an SM-like Higgs boson decaying into taus. Despite the fact that the categorisation of events is chosen to enhance selection of a MSSM signal rather than a SM signal, the selection is still very close to that of the SM analysis and hence there is still some sensitivity to the SM Higgs in the MSSM analysis. Thus any excess in data over background must be interpreted very carefully, since it does not automatically mean evidence of an MSSM signal when it could be from the SM Higgs.

5.4.3 Model dependent results

The model independent results described in the previous section are open to interpretation in a variety of models. It is also interesting to look more closely at the interpretation of the results in particular benchmark scenarios. Such results are referred to as ‘model-dependent’. Model-dependent searches are conducted in a plane of the two free parameters in the model, usually m_A and $\tan\beta$. At each point in the phase space, the cross section times branching ratio for each of the three neutral Higgs bosons is calculated, taking into account both production processes. The contributions of the three Higgs bosons are then combined into one template for the final fit. Hence, unlike in the model-independent ‘single resonance’ searches, the consistency of the data with all three Higgs bosons is considered.

The sensitivity to the SM Higgs becomes even more important in a model-dependent result. As discussed in section 1.3, the MSSM benchmark scenarios being tested in this analysis are required to be consistent with experimental measurements of the 125 GeV Higgs bosons. Hence in such scenarios, one of the three neutral Higgs bosons must be very similar to the SM 125 GeV Higgs boson. This means that by construction an MSSM signal from one of these benchmarks looks a lot like the SM signal, with the exception of the requirement of the additional two Higgs bosons.

Hence when interpreting the results of the MSSM search in the context of an MSSM benchmark scenario, it is not enough to simply construct a limit from considering the background-only hypothesis compared with the signal-plus-background hypothesis. Instead, a limit is built based on whether the data agrees better than the background plus SM signal or background plus MSSM signal hypothesis.

MSSM and SM hypothesis testing

To compare two different signal hypotheses, the likelihood function as described in equation 4.5 must be modified. This likelihood compares the observed data with an expected constructed as $\mu \cdot s(\theta) + b(\theta)$. This must be modified to compare the data with the following:

$$\mathcal{L}(\text{data}|\mu \cdot s(\theta) + b(\theta)) \rightarrow \mathcal{L}(\text{data}|M(\mu, \theta)), \quad (5.6)$$

with

$$M(\mu, \theta) = \mu \cdot s_{\text{MSSM}}(\theta) + (1 - \mu) \cdot s_{\text{SM}}(\theta) + b(\theta), \quad (5.7)$$

where $s_{\text{MSSM}}(\theta)$ and $s_{\text{SM}}(\theta)$ are the signal expectations in the MSSM and SM hypotheses respectively. In this likelihood the signal strength modifier μ connects both expectations, with the null hypothesis being the SM for $\mu = 0$ and the alternative hypothesis the MSSM for $\mu = 1$. This choice ensures that the model does not allow for the coexistence of the SM and MSSM hypotheses.

With this likelihood, a slightly different form of the test statistic must be built compared with that of equation 4.7. In the test statistic used at the LHC, the numerator is defined for some signal strength μ compared with the signal strength which maximises the likelihood, $\hat{\mu}$. Here is required instead a version of the test statistic which tests two fixed values of μ against on another. For this a test statistic which was used at the Tevatron, and hence is referred to as the “TEV” test statistic, is used, which takes the general form:

$$q_0 = -2 \ln \frac{\mathcal{L}(\text{data}|\mu, \hat{\theta}_\mu)}{\mathcal{L}(\text{data}|\mu = 0, \hat{\theta}_0)} \text{ with the constraint } 0 \leq \mu. \quad (5.8)$$

In this test statistic a numerator corresponding to the signal strength μ is compared with a denominator corresponding to $\mu = 0$. Hence the required form of this test statistic corresponds to the comparison between $\mu = 1$ and $\mu = 0$, hence:

$$q_{\text{MSSMvsSM}} = -2 \ln \frac{\mathcal{L}(\text{data}|M(1, \hat{\theta}_1))}{\mathcal{L}(\text{data}|M(0, \hat{\theta}_0))}. \quad (5.9)$$

The disadvantage of a test statistic of this type is that there is no asymptotic approximation, and so the distributions of the probability distribution functions for the test statistic must be generated using toys. Figure 5.6 shows the distributions obtained using toys with either the SM or MSSM signal hypothesis, and the observed value of the test statistic is shown. For this example $m_A - \tan \beta$ point, it can be seen that the separation between the two distributions is good, and hence this point is able to be excluded in the absence of an excess. It can be seen that the observed agrees better with the SM

hypothesis than the MSSM hypothesis, indicating the lack of such an excess over the expectation from backgrounds plus SM Higgs.

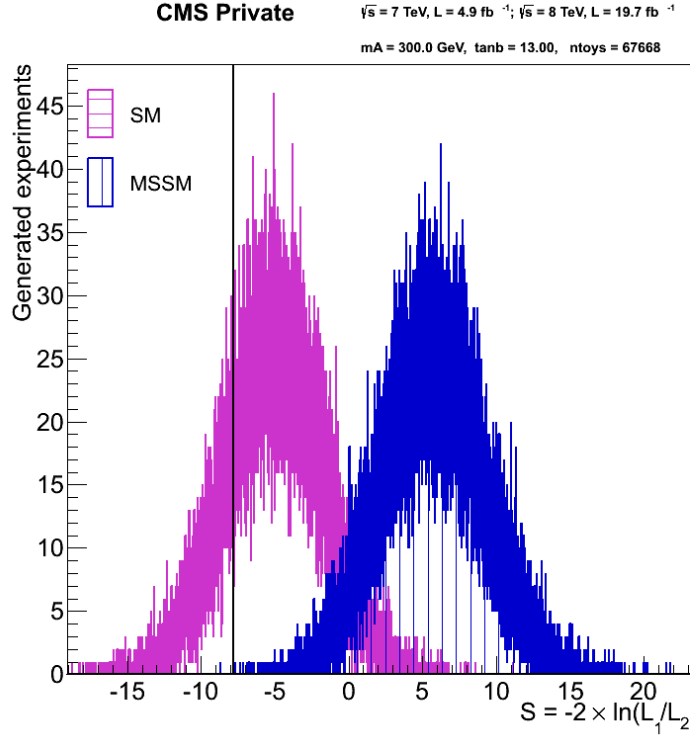


Figure 5.6: Distributions of the test statistic for toys with SM or MSSM signal injected for $m_A = 300 \text{ GeV}$, $\tan\beta = 13$ in the m_h^{max} scenario. The black vertical line indicates the observed value of the test statistic. The separation of the distributions is such that this point can be excluded at 95% CL

The CL_s values are obtained using these probability distributions as follows:

$$A = \int_{q_0^x}^{\infty} f(q_0, \hat{\theta}_0) dq_0 \quad (5.10)$$

$$B = \int_{q_1^x}^{\infty} f(q_1, \hat{\theta}_1) dq_1 \quad (5.11)$$

$$\text{CL}_s = \frac{B}{A}, \quad (5.12)$$

where x is either the 0.025, 0.16, 0.5, 0.84 or 0.975 quantile of the SM probability density function (corresponding to -2σ , -1σ , expected, $+1\sigma$, $+2\sigma$ exclusion) or the observed value. To obtain the final limit, a scan is performed in the two parameter plane and

the CL_s is calculated at each point in a 2D grid. Each point is excluded at 95% CL if $CL_s < 0.05$. A contour is drawn to connect the excluded points using interpolation between neighbouring points in the grid.

Figure 5.7 shows the comparison between the exclusion limits obtained using the conventional method of comparing MSSM signal hypothesis against background-only with the asymptotic approximation and using this new method to compare the MSSM and SM hypotheses for the example of the $m_h^{\max}$ scenario. The left hand plot includes a line which shows the effect of injecting an SM signal into this limit. It can clearly be seen that the effect of a possible SM Higgs is not negligible and that a possible difference between observed and expected limit in these plots could be the result of the SM Higgs in the dataset. In these results the data are consistent with both the background only and the background plus SM signal hypotheses.

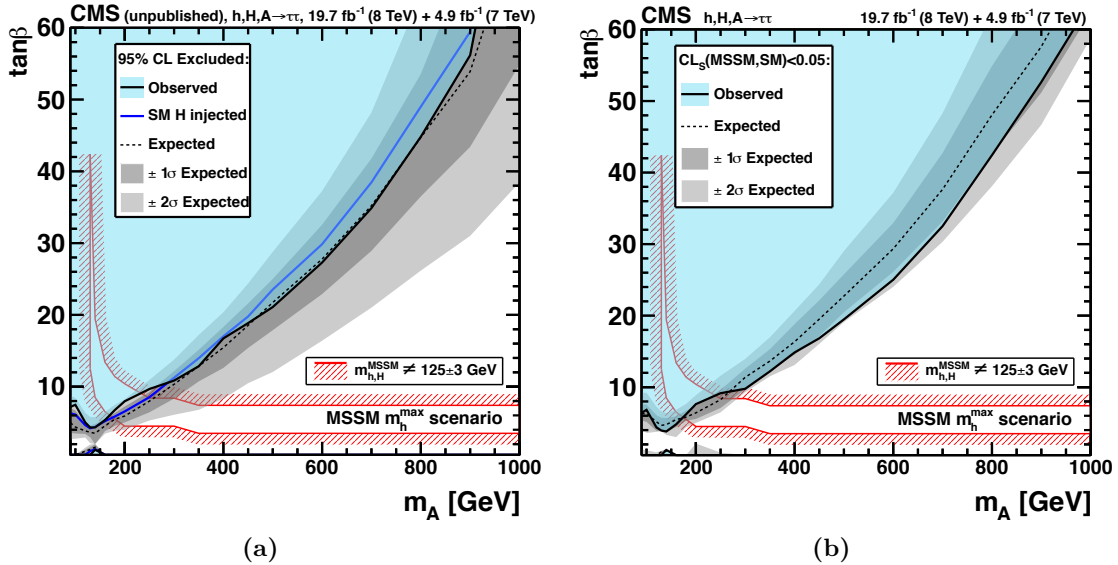


Figure 5.7: Expected and observed limit in the $m_A - \tan\beta$ plane of the $m_h^{\max}$ scenario. In the left hand plot, the MSSM signal is compared with the background only hypothesis. In the right hand plot, hypothesis separation testing compares the MSSM hypothesis with the SM hypothesis. The red area indicates the region of phase space which is already excluded by the Higgs mass constraint of 125 ± 3 GeV [2, 125].

Note that the red areas indicated in figure 5.7 show the region of phase space which is already ruled out by the constraint on the Higgs mass being close to 125 GeV, with a ± 3 GeV uncertainty due to theoretical calculations in the MSSM. The $m_h^{\max}$ scenario is almost entirely ruled out by this constraint, as discussed in section 1.3. Figures 5.8 to

5.10 show the result interpreted in newer scenarios which better incorporate a 125 GeV Higgs. Large areas of the phase space in these scenarios is ruled out by the lack of an excess in this analysis.

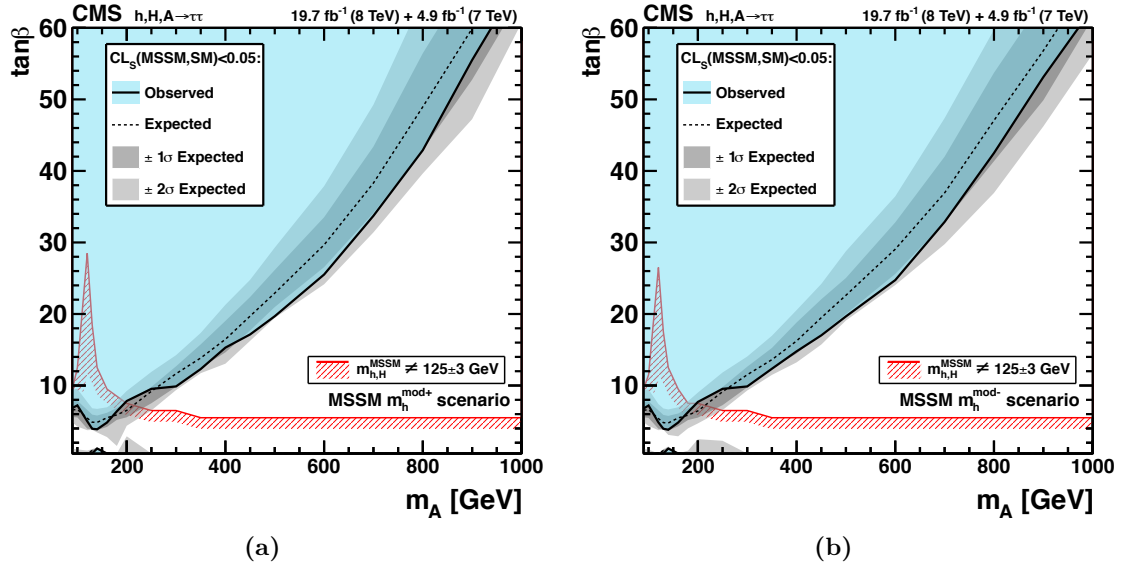


Figure 5.8: Expected and observed limit in the $m_A - \tan\beta$ plane of the $m_h^{\text{mod}+}$ scenario (a) and $m_h^{\text{mod}-}$ scenario (b). Hypothesis separation testing is used to compare the MSSM hypothesis with the SM hypothesis. The red area indicates the region of phase space which is already excluded by the Higgs mass constraint of 125 ± 3 GeV [2].

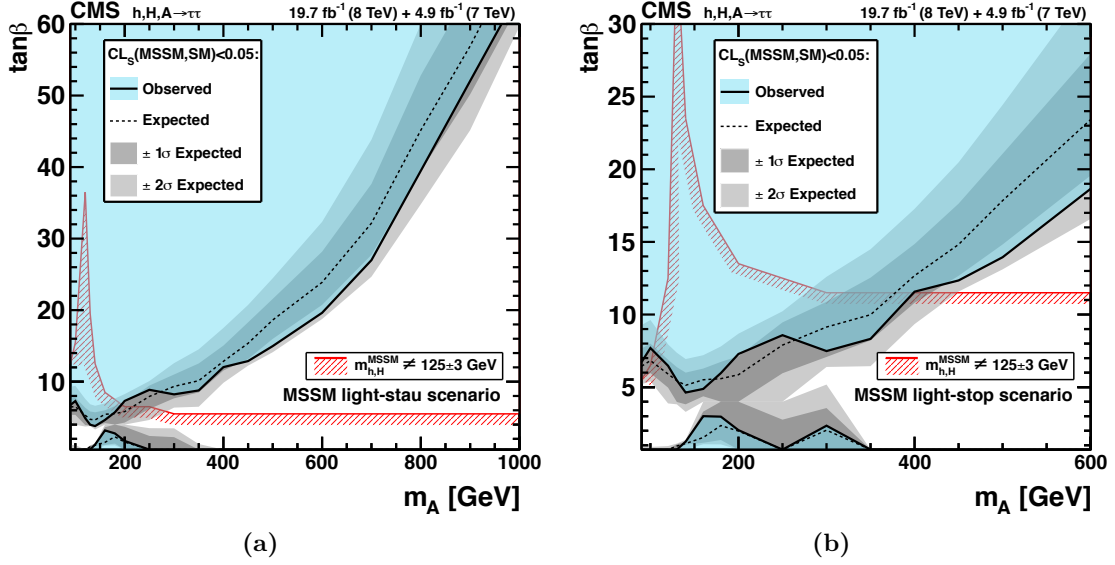


Figure 5.9: Expected and observed limit in the $m_A - \tan\beta$ plane of the light-stau scenario (a) and light-stop scenario (b). Hypothesis separation testing is used to compare the MSSM hypothesis with the SM hypothesis. The red area indicates the region of phase space which is already excluded by the Higgs mass constraint of $125 \pm 3 \text{ GeV}$ [2].

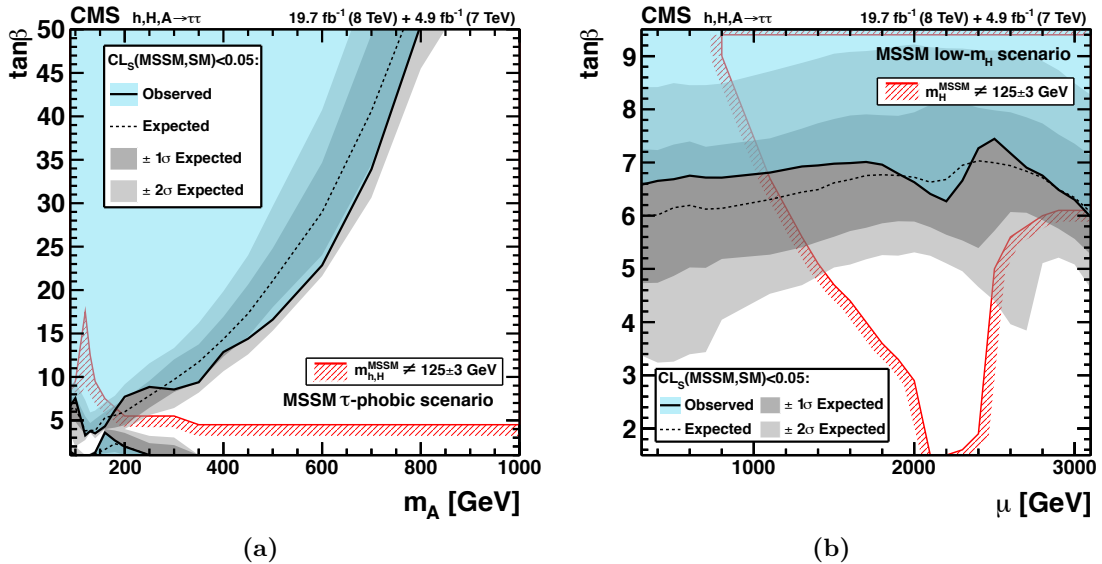


Figure 5.10: Expected and observed limit in the $m_A - \tan\beta$ plane of the τ -phobic scenario (a) and the $\tan\beta - \mu$ plane of the low- m_H scenario (b). Hypothesis separation testing is used to compare the MSSM hypothesis with the SM hypothesis. The red area indicates the region of phase space which is already excluded by the Higgs mass constraint of $125 \pm 3 \text{ GeV}$ [2].

Chapter 6

Search for MSSM $H \rightarrow hh \rightarrow \tau\tau bb$

As illustrated in section 1.3, there are many popular MSSM models which can incorporate a 125 GeV Higgs boson consistent with the boson discovered at the LHC. As seen in chapter 5, the $\phi \rightarrow \tau\tau$ analysis is very successful in setting limits on various MSSM models. The $\phi \rightarrow \tau\tau$ result primarily sets limits on the high $\tan\beta$ regions, and so with large amounts of the m_A - $\tan\beta$ space ruled out for such MSSM scenarios, focus shifts more to the regions which are still allowed, in particular at low $\tan\beta$ values.

As discussed in section 1.3.1, in certain low $\tan\beta$ regions of the MSSM, the branching ratio for the decay of the heavy neutral scalar Higgs boson H into two of the light Higgs boson bosons h , $\mathcal{B}(H \rightarrow hh)$, is large. Thus models in which the light Higgs boson h has a mass of 125 GeV and is the Higgs boson particle discovered at the LHC can be studied via production of a pair of such bosons from a heavier Higgs boson H . As illustrated by figure 1.13, the range of heavy Higgs boson masses of relevance to such a search in the MSSM is from $m_H \approx 260$ GeV (driven by the kinematic threshold for the production of two 125 GeV Higgs boson bosons) up to $m_H \approx 350$ GeV, above which the branching ratio for H decaying into a pair of top quarks becomes overwhelmingly high.

In searching for two 125 GeV Higgs bosons, the final state consisting of two τ leptons and two b quarks combines the higher branching ratio of the h into b quarks with the relative cleanness of a final state containing taus. A natural way to search for such a final state is to use the inclusive selection already defined by the $H \rightarrow \tau\tau$ analysis to select $h \rightarrow \tau\tau$, and require additional b -jets to form the $h \rightarrow bb$ part. Therefore, a large amount of the methods discussed in chapters 4 and 5 can be applied to this analysis.

6.1 Event selection and categorisation

The inclusive selection of the di-tau candidate pair is identical to that of the MSSM $\phi \rightarrow \tau\tau$ analysis discussed in section 5.1. On top of the selection of a candidate $\tau\tau$, a $H \rightarrow hh \rightarrow \tau\tau bb$ signal would consist of two b quarks which hadronise to form b-jets. A selection similar to that used in the b-tag category of the MSSM analysis, in which events are selected which contain at least one jet passing the medium CSV b-tagging working point, can be used with some small improvements. Firstly, there is no veto on any additional jet with $p_T > 30$ GeV, and instead at least two jets with $p_T > 20$ GeV and $|\eta| < 2.4$ are required. This is necessary to provide a minimum of two jet candidates to reconstruct the $h \rightarrow bb$. For a signal of the type $H \rightarrow hh \rightarrow \tau\tau bb$, where m_H is only slightly larger than $2 \times m_h$, the final state products will be fairly soft. Thus a lower p_T cut of 20 GeV on the jets is necessary not to cut out too much signal in this analysis. The chosen η range is necessary to ensure the jets are within the valid kinematic range for the CSV b-tagging algorithm.

Figure 6.1 shows the number of jets in inclusive events in the $e\tau_h$ and $\mu\tau_h$ final states, and figure 6.2 shows the number of jets which are b-tagged, where the b-tagging condition is such that the jet passes the medium CSV working point. Two conclusions can be drawn from these plots. Firstly, signal events can contain large numbers of jets, beyond the expected two from $h \rightarrow bb$. Secondly, the signal does not always contain two jets passing the medium CSV working point; in fact the majority of the events have zero or one b-tagged jet. The latter indicates that in many events the b-jets in signal resulting from the true $h \rightarrow bb$ process either do not pass the medium CSV working point or are not inside the jet acceptance cuts. The combination of these two facts means that if the two jets selected to reconstruct the $h \rightarrow bb$ are simply those with the highest p_T , there is a high probability that these will not be the correct jets originating from the b quarks. From studies using the generator level information of the signal MC, it was found that a higher success rate for selecting the correct two jets is achieved if the jets are ordered by their CSV discriminator value, and the two jets with the highest CSV discriminator value are taken to be the $h \rightarrow bb$ candidate. Figure 6.3 shows the CSV values for the leading and subleading jets in the $\mu\tau_h$ channel, when the jets are ordered in this way.

As in the $H \rightarrow \tau\tau$ analyses, a cut on transverse mass of $m_T < 30$ GeV is applied, which was found to be optimal in rejection of W +jets and the increased $t\bar{t}$ in this analysis. Finally, events are categorised depending on whether zero, one or two of the selected jets pass the medium CSV b-tagging working point. This allows all of the potential

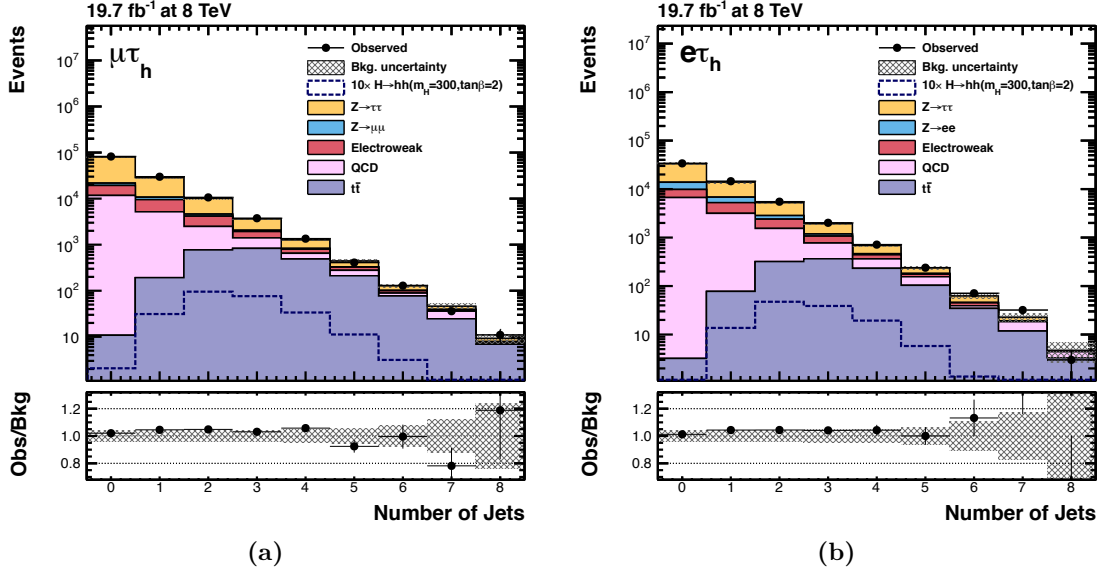


Figure 6.1: Number of jets in inclusive $\tau\tau$ events in backgrounds and $H \rightarrow hh$ signal. Distribution shown for events in the $\mu\tau_h$ (a) and $e\tau_h$ (b) channels. Note that the effect of the b-tag scale factor correction between data and MC is not included in this figure.

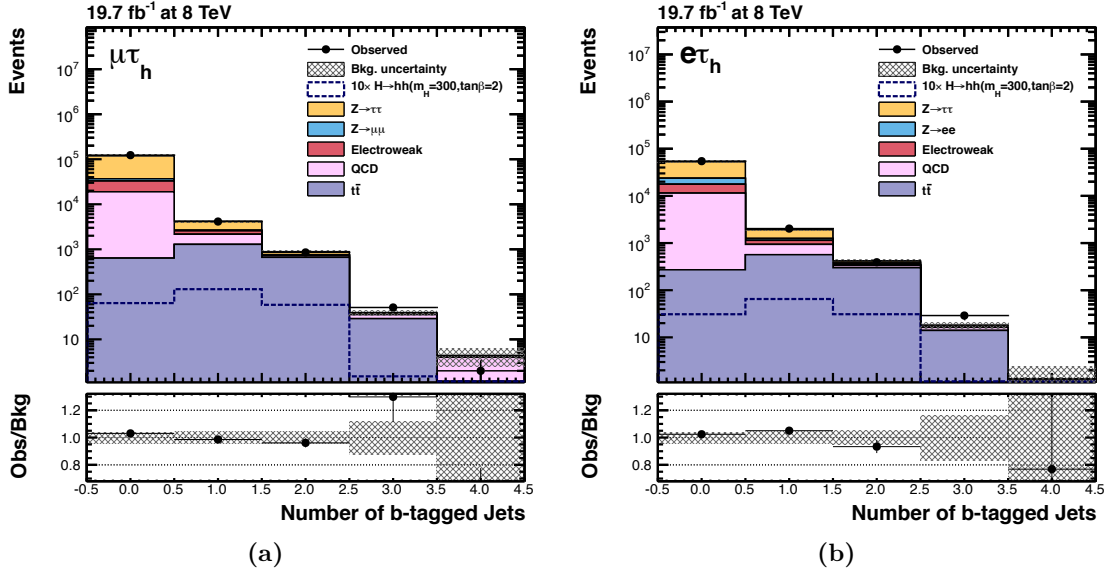


Figure 6.2: Number of b-tagged jets in inclusive $\tau\tau$ events in backgrounds and $H \rightarrow hh$ signal. Distribution shown for events in the $\mu\tau_h$ (a) and $e\tau_h$ (b) channels.

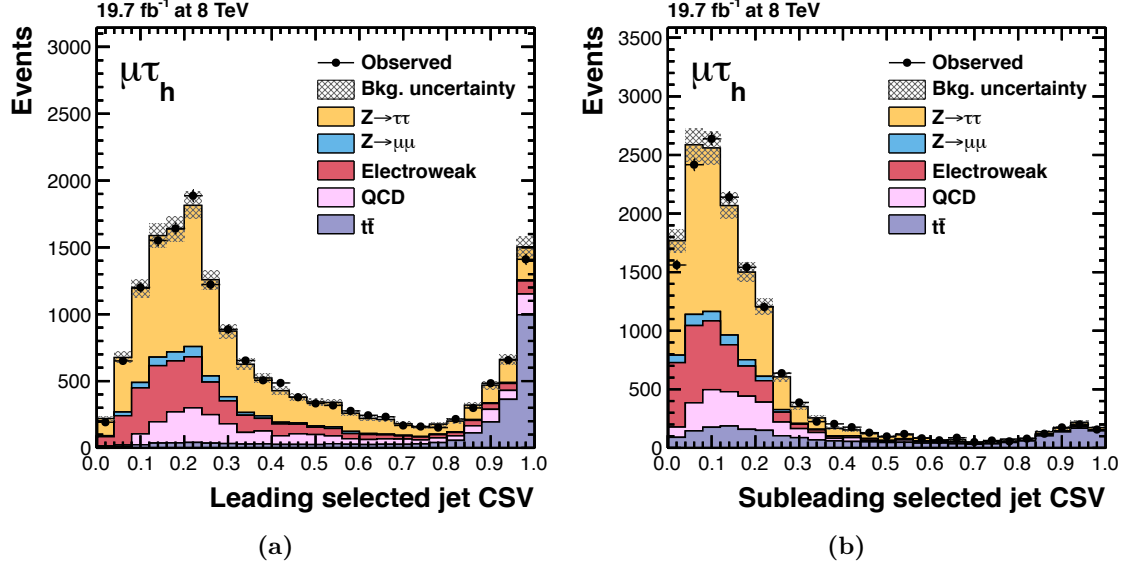


Figure 6.3: Values of the CSV b-tagging discriminator for the highest CSV (leading) jet in the event (a) and second highest (subleading) CSV jet in the event (b), for events with at least two jets in the $\mu\tau_h$ channel.

signal events in the inclusive selection which have at least two jets to be retained, whilst separating them into regions with very different background compositions and varying signal sensitivity. The categories are defined as follows:

- **2jet–0tag** Events in this category are such that neither of the leading and subleading jets passes the medium CSV working point. This category only collects a small amount of signal and is dominated by backgrounds, in particular $Z \rightarrow \tau\tau$, QCD and W +jets.
- **2jet–1tag** Events in this category are such that only the leading but not the subleading jet passes the medium CSV working point. This category collects more than half of the signal events, but is still quite high in backgrounds, including increased $t\bar{t}$.
- **2jet–2tag** Events in this category are such that both the leading and subleading jets pass the medium CSV working point. This is the most signal-sensitive category, since the requirement of 2 b-tagged jets greatly reduces the backgrounds with the exception of $t\bar{t}$.

In signal events of all heavy Higgs boson mass hypotheses, both the reconstructed $m_{b\bar{b}}$ and $m_{\tau\tau}$ will be consistent with a 125 GeV h decay. Figures 6.4, 6.5 and 6.6

illustrate the distributions of $m_{\tau\tau}$ and $m_{b\bar{b}}$ for events in the 2jet–0tag, 2jet–1tag and 2jet–2tag categories respectively. These distributions illustrate the different background compositions and varying sensitivities of the categories. It can also be seen from the 2jet–1tag and 2jet–2tag categories that the signal peaks around 125 GeV in both variables, whereas the backgrounds are more spread across the mass range. This fact is exploited to greatly enhance the selection of signal over background events, by applying cuts in windows of $70 < m_{b\bar{b}} < 150$ GeV and $90 < m_{\tau\tau} < 150$ GeV to select signal-like events. For all subsequent results in this chapter these cuts on $m_{b\bar{b}}$ and $m_{\tau\tau}$ are applied as part of the baseline event selection unless otherwise stated.

6.2 Kinematic fitting to extract m_H

In addition to applying cuts on $m_{b\bar{b}}$ and $m_{\tau\tau}$, the condition that both values should be consistent with 125 GeV can be used further in calculating the reconstructed heavy Higgs boson mass, m_H . This quantity can be reconstructed simply by combining the visible taus, E_T^{miss} and the b-jets, denoted by $m_{\tau\tau+jj}$. A better reconstruction is obtained by using the conditions on $m_{b\bar{b}}$ and $m_{\tau\tau}$ in a kinematic fit.

In such a method, observables related to the event kinematics are varied within their measurement uncertainties in order to find the values which best fulfil a kinematic constraint. In this case, the variables being varied correspond to the energies of the taus and b-jets and the kinematic constraints are that $m_{b\bar{b}} = m_{\tau\tau} = m_h = 125$ GeV. Differences between the measured value and the constraint are accounted for in a cost function χ^2 which is minimised in the fitting procedure.

For the b-jets, it is assumed that the reconstructed position in terms of the angles η and ϕ is known to great accuracy, and the largest uncertainty is in the measurement of the energy. Thus in the fit only the energy of the jets is varied and the position is kept constant. To first approximation any uncertainty in energy directly translates to an uncertainty in momentum related by the quantity $\vec{\beta} = \vec{p}/E$, which is assumed to be constant and not varied in the fit. The energy of the first b-jet is varied, and the energy of the second b-jet can be related to the first using the following kinematic conditions:

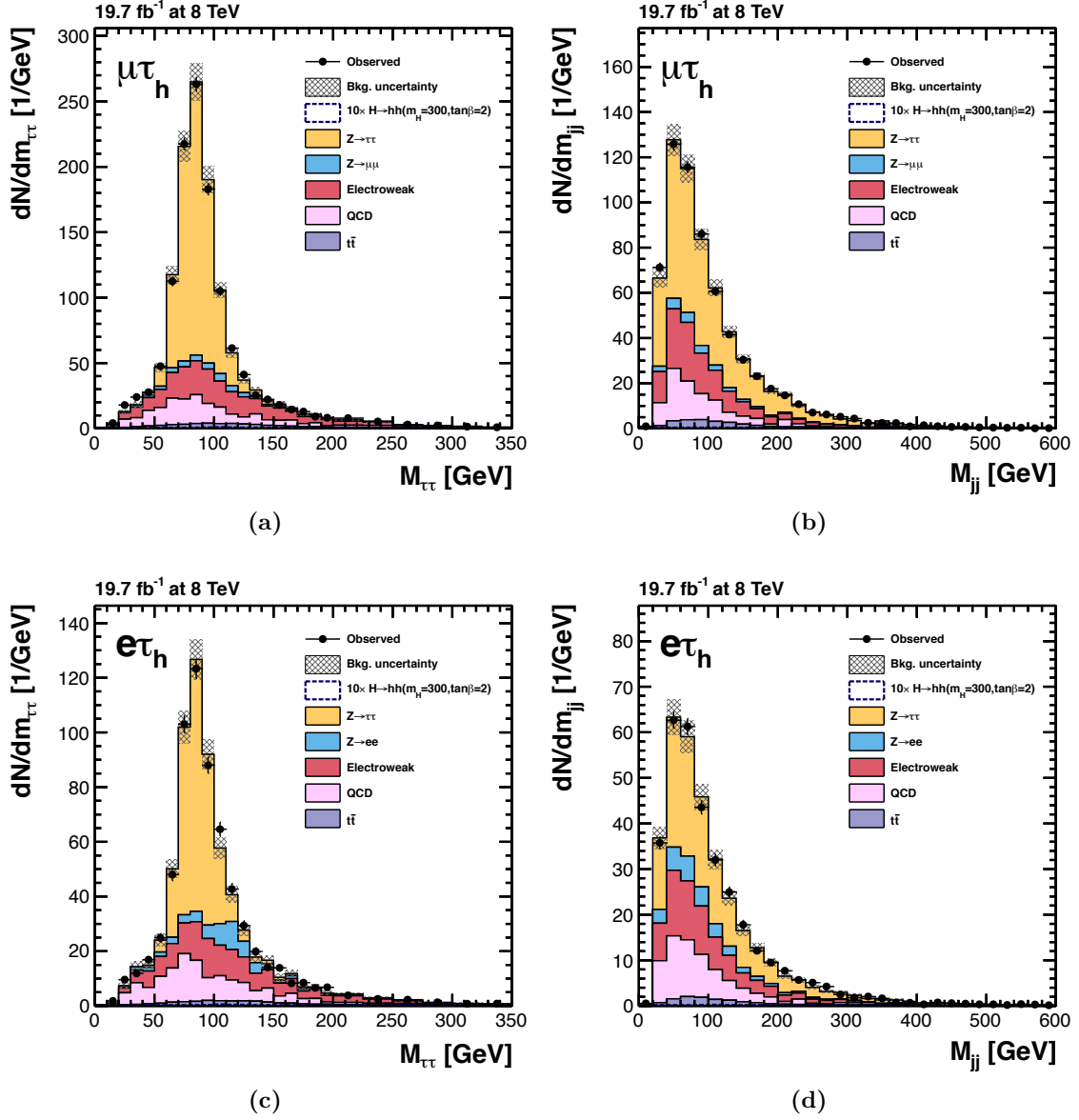


Figure 6.4: Distributions of $m_{\tau\tau}$ (left) and m_{bb} (m_{jj}) (right) in the $\mu\tau_h$ (top) and $e\tau_h$ (bottom) channels for the 2jet-0tag category. The signal cannot be seen in these figures since this category is background dominated.

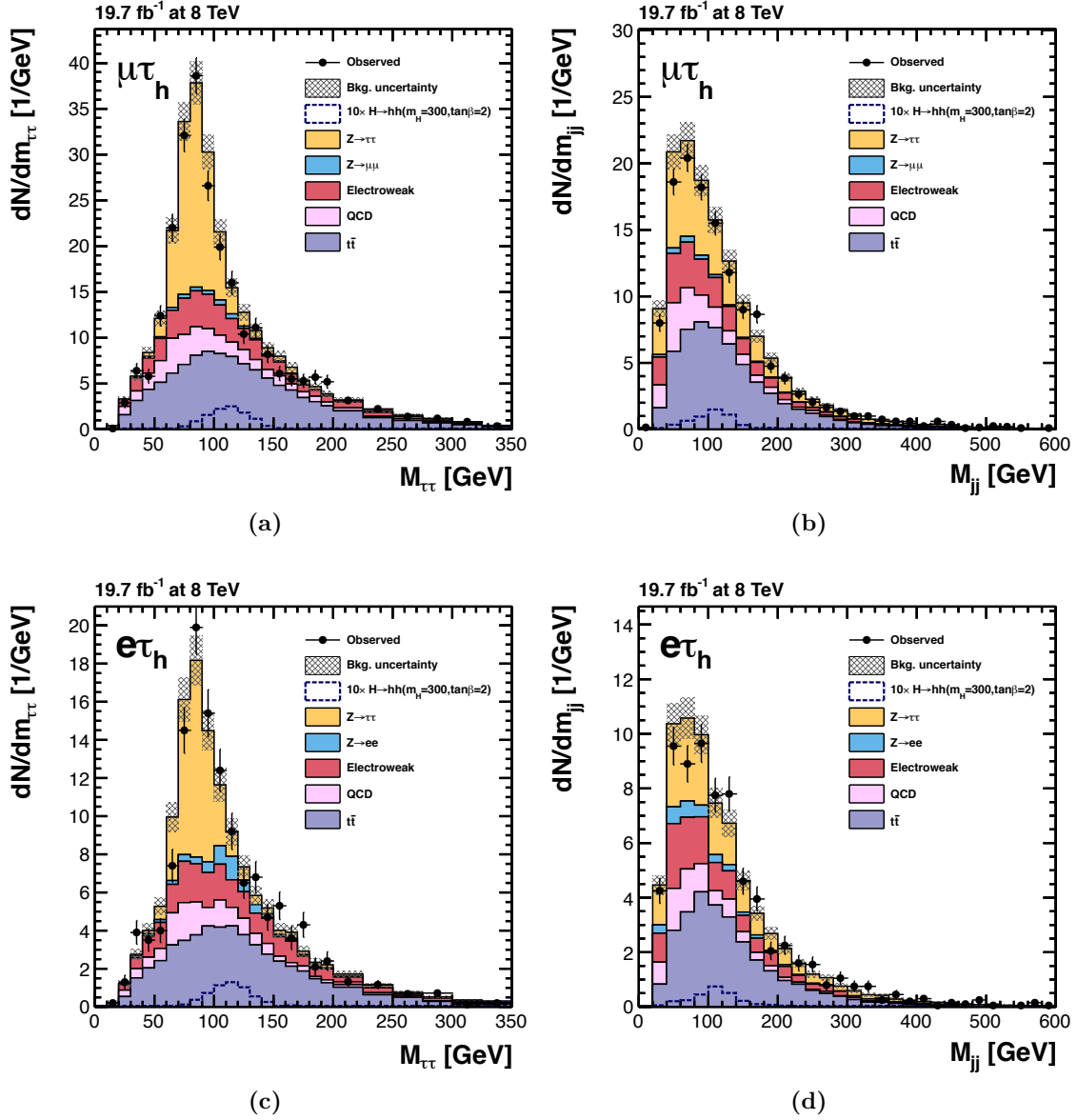


Figure 6.5: Distributions of $m_{\tau\tau}$ (left) and m_{bb} (m_{jj}) (right) in the $\mu\tau_h$ (top) and $e\tau_h$ (bottom) channels for the 2jet–1tag category. The signal peaks close to 125 GeV in both variables, motivating the application of cuts in a window around 125 GeV to select the most signal-like events.

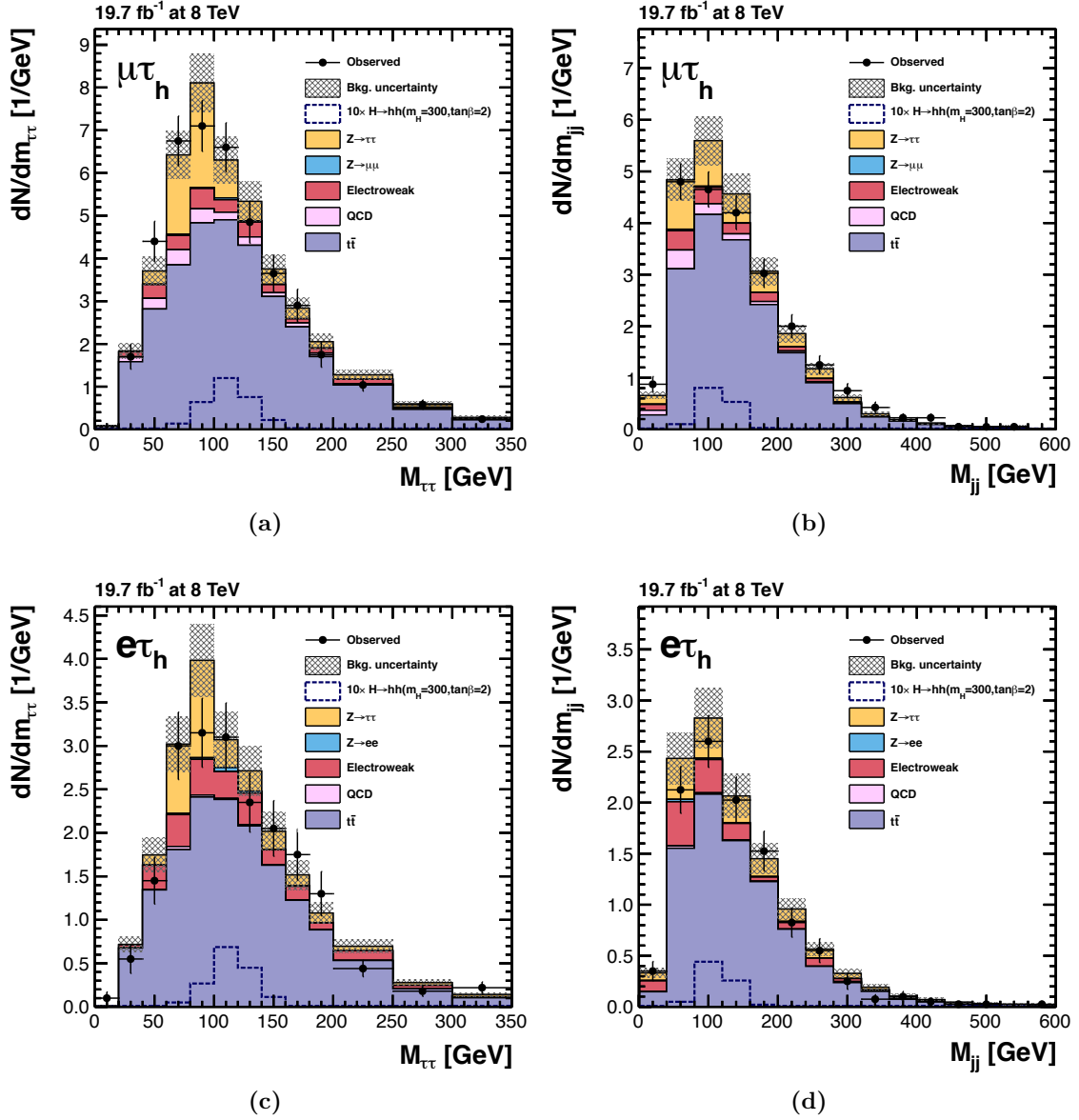


Figure 6.6: Distributions of $m_{\tau\tau}$ (left) and m_{bb} (m_{jj}) (right) in the $\mu\tau_h$ (top) and $e\tau_h$ (bottom) channels for the 2jet-2tag category. The signal peaks close to 125 GeV in both variables, motivating the application of cuts in a window around 125 GeV to select the most signal-like events.

$$m_h^2 = \left(E_{b_1} + E_{b_2}^{\text{fit}}\right)^2 - \left(\vec{p}_{b_1} + \vec{p}_{b_2}^{\text{fit}}\right)^2 = m_{b_1}^2 + \frac{E_{b_2}^{2,\text{fit}}}{\gamma_{b_2}^2} + 2E_{b_1}E_{b_2}^{\text{fit}} \underbrace{\left(1 - \vec{\beta}_{b_1}\vec{\beta}_{b_2}\right)}_A, \quad (6.1)$$

where $\gamma_{b_{1,2}} = 1/\sqrt{1 - \vec{\beta}_{b_{1,2}}^2}$. The term A is assumed to be constant and hence can be derived from the pre-fit event kinematics as:

$$A = \frac{m_{b_1 b_2}^2 - m_{b_1}^2 - m_{b_2}^2}{2E_{b_1}E_{b_2}}, \quad (6.2)$$

which allows equation 6.1 to be reduced to:

$$E_{b_2}^{\text{fit}} = E_{b_1} A \gamma_{b_2}^2 \left(-1 + \sqrt{1 + \frac{m_h^2 - m_{b_1}^2}{(E_{b_1} A \gamma_{b_2})^2}} \right). \quad (6.3)$$

During the fitting procedure, the masses of the b-jets are allowed to scale according to the ratio of the fitted energy:

$$m_{b_{1,2}}^{\text{fit}} = m_{b_{1,2}} \frac{E_{b_{1,2}}^{\text{fit}}}{E_{b_{1,2}}} \quad (6.4)$$

A χ^2 quantity for each b-jet is constructed to quantify how much the fit has modified the b-jet energy as:

$$\chi_{b_{1,2}}^2 = \frac{E_{b_{1,2}}^{\text{fit}} - E_{b_{1,2}}^{\text{meas}}}{\sigma_{b_{1,2}}} \quad (6.5)$$

where $E_{b_{1,2}}^{\text{meas}}$ is the measured b-jet energy and $\sigma_{b_{1,2}}$ is the b-jet energy resolution. The value of $\sigma_{b_{1,2}}$ is estimated using a MC sample in different bins of η and p_T [126].

The taus are treated in a slightly different way in the fit due to the E_T^{miss} associated with their decays. It is assumed that the collinear approximation holds such that the visible products are produced in the same direction as the original tau. This direction is assumed to be known to a high degree of accuracy, as in the case of the b-jets, and so is not varied in the fit. Thus only the energy of one tau is free in the fit, and the energy of the other tau can be related to the first analogously to equation 6.3. The mass of both tau leptons is kept constant at m_τ .

In order to find the correct tau energies, additional constraints are put on the event using the E_T^{miss} to enforce that the heavy Higgs boson recoil from the fit is close to the reconstructed recoil. The recoil from the fit can be defined as:

$$\vec{p}_{T,\text{recoil}}^{\text{fit}} = -\vec{p}_{T,b_1}^{\text{fit}} - \vec{p}_{T,b_2}^{\text{fit}} - \vec{p}_{T,\tau_1}^{\text{fit}} - \vec{p}_{T,\tau_2}^{\text{fit}} = -\vec{p}_{T,H}^{\text{fit}}, \quad (6.6)$$

and the measured recoil as:

$$\vec{p}_{T,\text{recoil}}^{\text{meas}} = -\vec{p}_{T,\text{miss}}^{\text{meas}} - \vec{p}_{T,b_1}^{\text{meas}} - \vec{p}_{T,b_2}^{\text{meas}} - \vec{p}_{T,\tau_1^{\text{vis}}}^{\text{meas}} - \vec{p}_{T,\tau_2^{\text{vis}}}^{\text{meas}} = -\vec{p}_{T,H}^{\text{meas}}, \quad (6.7)$$

where $\vec{p}_{T,\text{miss}}^{\text{meas}}$ is the vector of the reconstructed E_T^{miss} . The χ^2 term corresponding to the agreement between these two quantities can be constructed as:

$$\chi_{\text{recoil}}^2 = \vec{p}_{T,\text{recoil}}^{\text{res},T} \cdot V_{\text{recoil}}^{-1} \cdot \vec{p}_{T,\text{recoil}}^{\text{res}}, \quad (6.8)$$

where $\vec{p}_{T,\text{recoil}}^{\text{res}}$ is the residuum vector between $\vec{p}_{T,\text{recoil}}^{\text{fit}}$ and $\vec{p}_{T,\text{recoil}}^{\text{meas}}$, and $\vec{p}_{T,\text{recoil}}^{\text{res},T}$ indicates the transpose. The covariance matrix of the recoil vector is estimated from the covariance matrix of the $\vec{p}_{T,\text{miss}}$ and the uncertainties of the b-jets as follows:

$$V_{\text{recoil}} = V_{\vec{p}_{T,\text{miss}}} - V_{b_1} - V_{b_2}. \quad (6.9)$$

The covariance matrices of the b-jets can be expressed entirely in terms of the b-jet energy/momentum and position. Hence with inputs of the values and covariance matrix of

the missing transverse momentum (which comes directly from MVA E_T^{miss}) this component of the χ^2 is entirely specified.

The total χ^2 to be minimised by the fit is then given by:

$$\chi_{\text{total}}^2 = \chi_{b_1}^2 + \chi_{b_2}^2 + \chi_{\text{recoil}}^2, \quad (6.10)$$

which is a two dimensional function in variables E_{b_1} and E_{τ_1} .

The output of the kinematic fit is the 4-vector of each of the taus and b-jets, with the energy and momentum corrected by the result of the fit. These 4-vectors can be combined to yield the 4-body mass of the candidate m_H . Figure 6.7 shows the difference between the heavy Higgs boson mass as reconstructed with and without the kinematic fit for signal events with $m_H = 300 \text{ GeV}$. It can be seen that both the mean and resolution of the reconstructed m_H is greatly improved by the kinematic fit. Figure 6.8 shows the m_H distribution with the kinematic fit (denoted m_H^{kinfit}) for different signal mass hypotheses in the range considered for this analysis, using the example points of $m_H = 260, 300$ and 350 GeV . From this figure it can be seen that the 4-body mass from the kinematic fit provides good discrimination between the different mass hypotheses, such that in the event of an excess of events in data, it would provide a good variable to make a prediction for the most likely m_H consistent with the data. This is not true, for example, in variables such as $m_{\tau\tau}$ and $m_{b\bar{b}}$ where the signals look very similar with a peak at 125 GeV for all m_H hypotheses.

Figure 6.9 shows the effect of the kinematic fit on the full distribution including all of the backgrounds and data, for the example of events in the 2jet–1tag category. The shape of the backgrounds is not altered greatly by the fit, with the exception of forcing a minimum at 250 GeV due to the threshold for $2 \times m_h$, whereas the shape of signal is greatly improved leading to much better shape discrimination between signal and background. For this reason, the 4-body mass from the kinematic fit is chosen as the discriminating variable for signal extraction. Note that the narrow width approximation is valid for all mass points considered in this analysis, since the resolution in m_H is always at least 10 GeV worse than the theoretical width of the H in the signal samples.

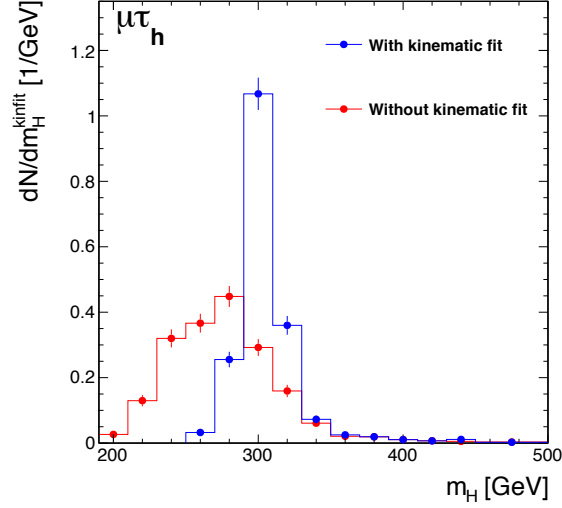


Figure 6.7: Four body mass of the candidate H in $H \rightarrow hh$ signal events with $m_H = 300$ GeV, as reconstructed using a simple sum of the individual components (without kinematic fit) or using a kinematic fit as described in the text. Shown for events in the 2jet–2tag category of the $\mu\tau_h$ channel.

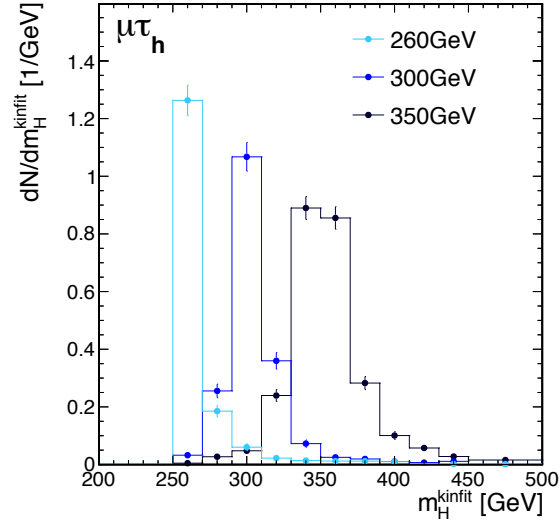


Figure 6.8: Four body mass of the candidate H in $H \rightarrow hh$ signal events with $m_H = 260, 300$ or 350 GeV, as reconstructed using the kinematic fit. Shown for events in the 2jet–2tag category of the $\mu\tau_h$ channel.

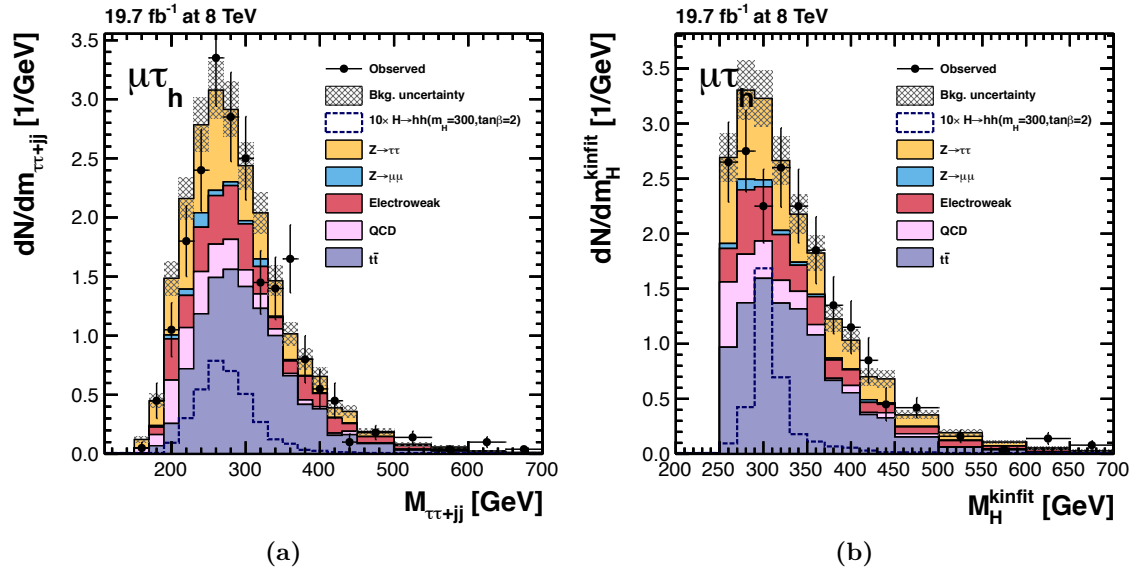


Figure 6.9: Four body mass of the candidate H as reconstructed using a simple vector sum of the individual components (a) and using a kinematic fit (b) as described in the text. Shown for events in the 2jet-1tag category of the $\mu\tau_h$ channel. The effect of the kinematic fit on the backgrounds is to force a minimum at $2 \times 125 = 250$ GeV, but otherwise the shapes are largely unchanged, while the shape of the signal is greatly improved.

6.3 Datasets and Monte Carlo samples

The dataset used for this analysis corresponds to the complete 2012 dataset at $\sqrt{s} = 8$ TeV. Samples of background events correspond exactly to those described in section 4.3. For the signal, MC samples are produced for m_H masses between 260 GeV and 350 GeV in 10 GeV steps using PYTHIA for parton showering and hadronisation and TAUOLA [106] for tau decays. Values for cross section times branching ratio are calculated for the low- $\tan\beta$ -high scenario as described in section 1.3.1. For displaying the signal on figures, a benchmark point in this scenario is chosen for illustration purposes.

6.4 Background estimation

Inclusively, the background composition is the same as discussed in the previous chapters. The additional requirement that the events contain at least two jets changes the composition slightly, with the largest effect being an increase in $t\bar{t}$ background and a decrease in $Z \rightarrow \tau\tau$, W +jets and QCD. The variation with category is large, with 2jet–0tag events containing mostly $Z \rightarrow \tau\tau$, W +jets and QCD, and 2jet–2tag events containing almost entirely $t\bar{t}$. In general the background methods follow those described in the previous chapters, with the exception of adaptations necessary to deal with the increased amount of $t\bar{t}$ and the generally lower statistics in the categories after applying the mass cuts on $m_{b\bar{b}}$ and $m_{\tau\tau}$.

6.4.1 $Z \rightarrow \tau\tau$

The $Z \rightarrow \tau\tau$ background exists in the categories from Z plus ≥ 2 jet events. This is greatly reduced by the b-tagging requirements, and so most events fall in the 2jet–0tag category. This component is also reduced somewhat by the mass cut on $m_{\tau\tau}$, but the lower edge of the window at 90 GeV is such that the higher half of the $Z \rightarrow \tau\tau$ peak is still retained in the signal region.

As in the previous analyses, the $Z \rightarrow \tau\tau$ component is estimated using an embedded sample. As in the MSSM analysis, there is a known contamination in this sample from $t\bar{t}$ events. This contribution is more important in this analysis because there is no veto on events with more than one jet which is applied in the b-tag category of the MSSM analysis, and hence the analysis selects very $t\bar{t}$ -like events, especially in the 2jet–1tag

and 2jet–2tag categories. The contribution is estimated using a $t\bar{t}$ embedded sample as described in section 5.3.1. The contribution to the total normalisation is approximately 10% in 2jet–1tag and 27% in 2jet–2tag. This is much larger than in the MSSM analysis, and so a more careful method is used to subtract this contribution to avoid double counting. Instead of simply reducing the yield of the $t\bar{t}$ prediction to account for this, the normalised shape of the embedded $t\bar{t}$ is subtracted from the $Z \rightarrow \tau\tau$ estimate.

6.4.2 $t\bar{t}$

For the estimate of the large $t\bar{t}$ background, both shape and normalisation are taken from MC. As this background is so large in this analysis, it is extremely important that this estimate is accurate. To improve the confidence in this estimate, both shape and normalisation are checked against a data control region. In the SM and MSSM $H \rightarrow \tau\tau$ analyses, this is done using events in the $e\mu$ final state, and the crucial distributions to check the shapes of are mostly related to the taus, in particular $m_{\tau\tau}$. In this analysis it is also important that the b-jets are well modelled in the $t\bar{t}$ MC. Since the $e\mu$ final state is not actually used for this analysis, it is also important to check $\mu\tau_h$ and $e\tau_h$ events. Hence two $t\bar{t}$ control regions are defined: the first is the same as is used in the SM and MSSM $H \rightarrow \tau\tau$ analyses using the $e\mu$ channel, and takes events with at least two jets, at least one b-tagged jet and $E_T^{\text{miss}} > 80$ GeV. The second is defined using the $\mu\tau_h$ final state and uses events with at least two b-tagged jets and in the high $m_T > 100$ GeV region. Both control regions have purity in $t\bar{t}$ events of larger than 90%. Figure 6.10 shows distributions made in these control regions for the example distribution of the leading and subleading b-jet p_T . There are no obvious differences in shape or normalisation between the data and the MC in these, or any of the other distributions the analysis is sensitive to.

6.4.3 W+jets

The W+jets background estimation follows that of the previous analyses, with the normalisation in a high m_T control region taken from data with other backgrounds subtracted, and extrapolated to the low m_T signal region using a scale factor from MC. Here, care must be taken due to the high quantity of $t\bar{t}$ in the W+jets control region at high m_T in the 2jet–1tag and 2jet–2tag categories. Figure 6.11 shows the m_T distribution in the 2jet–1tag and 2jet–2tag categories for events in the $\mu\tau_h$ channel. It can be seen

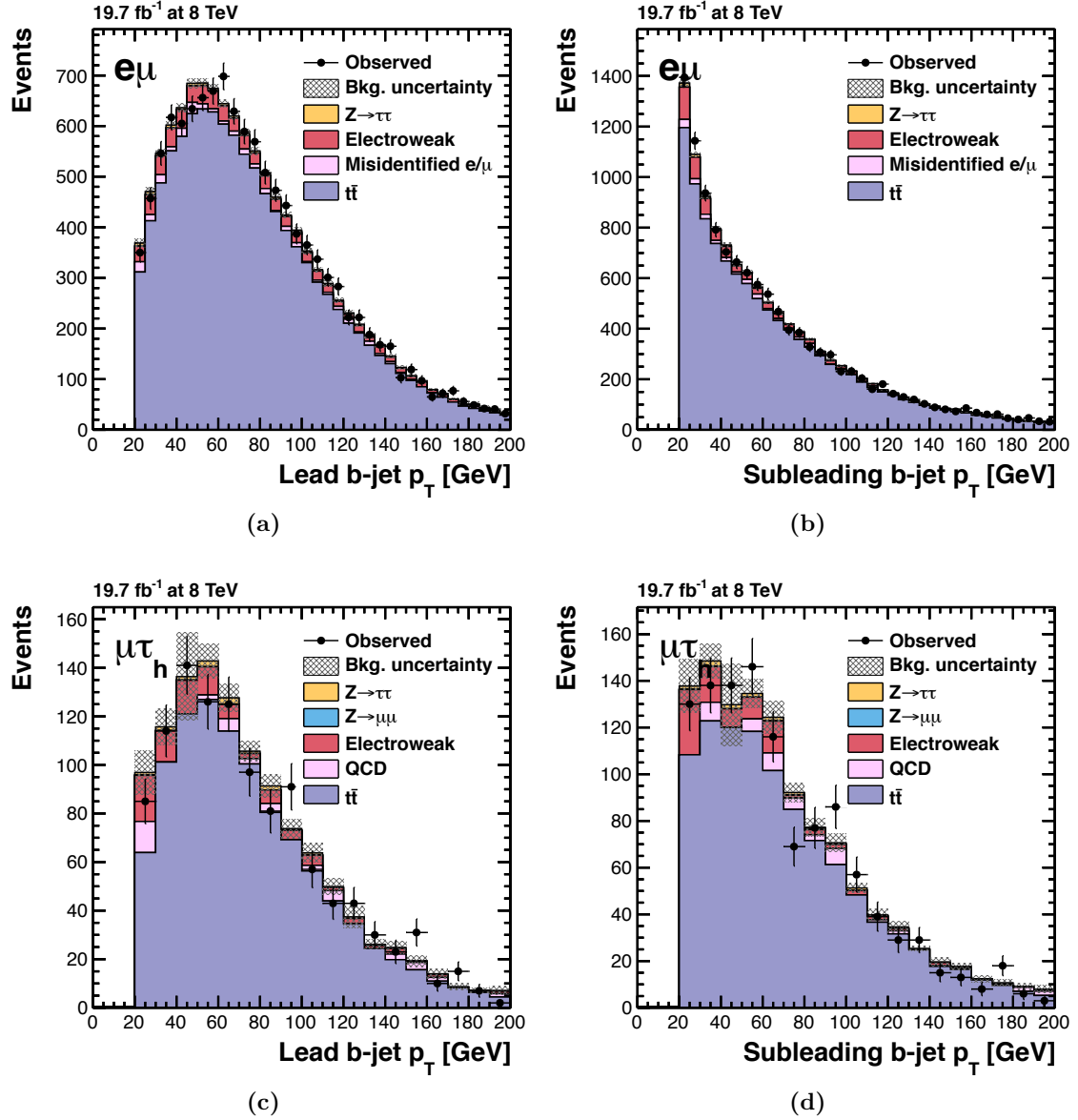


Figure 6.10: Leading (left) and subleading (right) b-jet p_T in the $t\bar{t}$ control regions for the $e\mu$ (top) and $\mu\tau_h$ (bottom) channels as defined in the text.

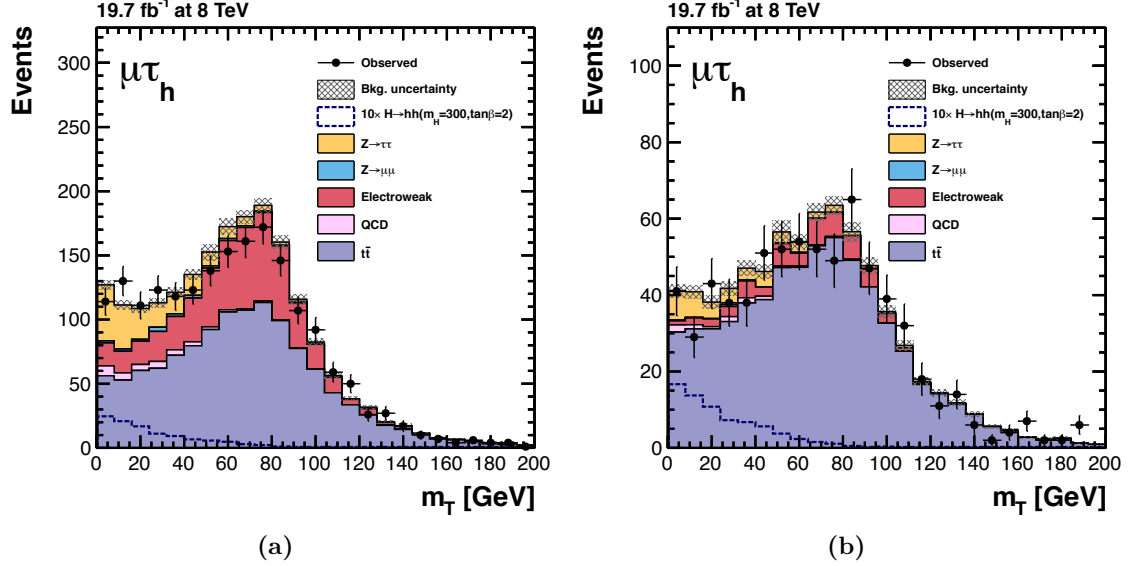


Figure 6.11: Transverse mass distribution for events in the 2jet-1tag (a) and 2jet-2tag (b) categories. The W normalisation is taken from data in the high m_T region, and extrapolated to low m_T using MC. The shape is also taken from MC. In these categories, a large amount of $t\bar{t}$ is present in the high m_T region. These figures are made without any fit to data and the uncertainty band contains only statistical uncertainty.

that the contribution of $t\bar{t}$ in the high m_T control regions is extremely high. If the $t\bar{t}$ prediction is trusted, then the data driven subtraction method is still safe. Additional cross-checks were performed by using events in the high m_T region and fitting a variable in data with good shape discrimination between W +jets and $t\bar{t}$. Figure 6.12 shows an example of such a fit in the 2jet-1tag category using the discriminator of leading jet p_T . In the fit the contributions of both backgrounds are allowed to float unconstrained, such that only the shapes of the templates affect the fit. The results of such fits were generally found to be consistent with the subtraction method within the statistical uncertainties. The subtraction method is kept as the default method for its simplicity.

A small modification in the normalisation estimate is made to deal with the extremely low statistics in the 2jet-2tag category. A higher purity of W +jets compared with $t\bar{t}$ is found if the high m_T control region is modified slightly from $m_T > 70$ GeV to $60 < m_T < 120$ GeV. Additionally, to avoid a huge statistical uncertainty on the extrapolation factor estimated in MC, the calculation is done for a relaxed category selection using the loose CSV working point instead of medium. The W +jets shape is taken from the MC estimate within the category. As in the previous analyses, in

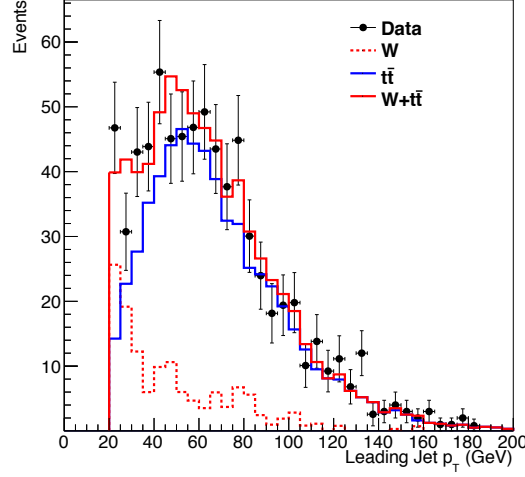


Figure 6.12: Example of a template fit for data events in the high m_T region of the 2jet–1tag category, using the variable leading jet p_T . The fit floats the normalisations of the W+jets and $t\bar{t}$ backgrounds unconstrained to best fit the data.

places it is necessary to relax the category definition to obtain a smooth shape. For both the 2jet–1tag and the 2jet–2tag categories, this is achieved by relaxing the b-tagging condition to the loose CSV working point. This is found to introduce minimal bias in the shape of the kinematic fit distribution.

6.4.4 QCD

The QCD estimation is performed in the same data-driven way as in the previous analyses. In the 2jet–0tag and 2jet–1tag categories, the normalisation is taken from the same-sign data with other backgrounds subtracted. In 2jet–1tag and 2jet–2tag, there is again a reasonable contribution from $t\bar{t}$ in the data control region. The normalisation estimate is cross-checked using the anti-isolated same-sign data, which is found to be almost entirely QCD with negligible contributions from other backgrounds and hence does not have the same issues with background subtraction. The same-sign estimate for inclusive events including at least two jets (which has a lower overall fraction of $t\bar{t}$ events compared with pure QCD) is extrapolated to the 2jet–1tag or 2jet–2tag categories using an extrapolation factor calculated using the anti-isolated data. This prediction is found to be consistent with the prediction from the default method within the statistical uncertainties. Thus the default method is retained for 2jet–1tag, while for 2jet–2tag the anti-isolated method is used due to its greatly reduced statistical uncertainty.

Shapes are taken from anti-isolated data. As used previously, in the 2jet–1tag and 2jet–2tag categories the shape is taken from a relaxed category definition in which the CSV b-tag working point is relaxed to loose.

6.4.5 $Z \rightarrow \ell\ell$, single top and diboson

Estimates for the remaining smaller backgrounds are taken from MC. For the $Z \rightarrow \ell\ell$ component, the CSV b-tagging condition is relaxed to the loose working point to obtain smooth shapes in 2jet–1tag and 2jet–2tag.

6.5 Systematic uncertainties

The systematic uncertainties follow those discussed in the previous analyses, with some small differences.

As the CSV values are not directly used in this analysis except to make the choice of leading and subleading jets, it is safe to use the promote/demote method to evaluate the b-tag scale factor uncertainties. The effect of these uncertainties in this analysis is illustrated in figure 6.13. The figure on the left hand side shows MC events which have exactly one jet with CSV value passing the medium working point, and so in the absence of a correction would fall into the 2jet–1tag category. It can be seen that jets are promoted or demoted such that after the correction is applied some of the events have zero or two b-tagged jets. Hence after the correction, only events in the central bin would fall into the 2jet–1tag category, and the other events are reassigned to either the 2jet–0tag category (first bin) or the 2jet–2tag category (third bin). The right hand plot shows the same effect for the events which originally have 2 b-tagged jets and would fall in the 2jet–2tag category. After the re-tagging, some events have zero or one b-tagged jet and are reassigned to the 2jet–0tag or 2jet–1tag categories respectively. All remaining events in the third bin and above fall into the 2jet–2tag category. It can be seen from this plot that the number of events being reassigned is relatively small, and the largest effect is up to 10% on $t\bar{t}$ events.

The uncertainties relating to the background normalisations are re-considered for this analysis. Some aspects, such as the $Z \rightarrow \tau\tau$ extrapolation factor uncertainty, fake-rates for $Z \rightarrow \ell\ell$ and cross section uncertainties on $t\bar{t}$ and diboson, are the same as the previous analyses. For the $Z \rightarrow \ell\ell$ background, the statistical uncertainty on the estimate is not

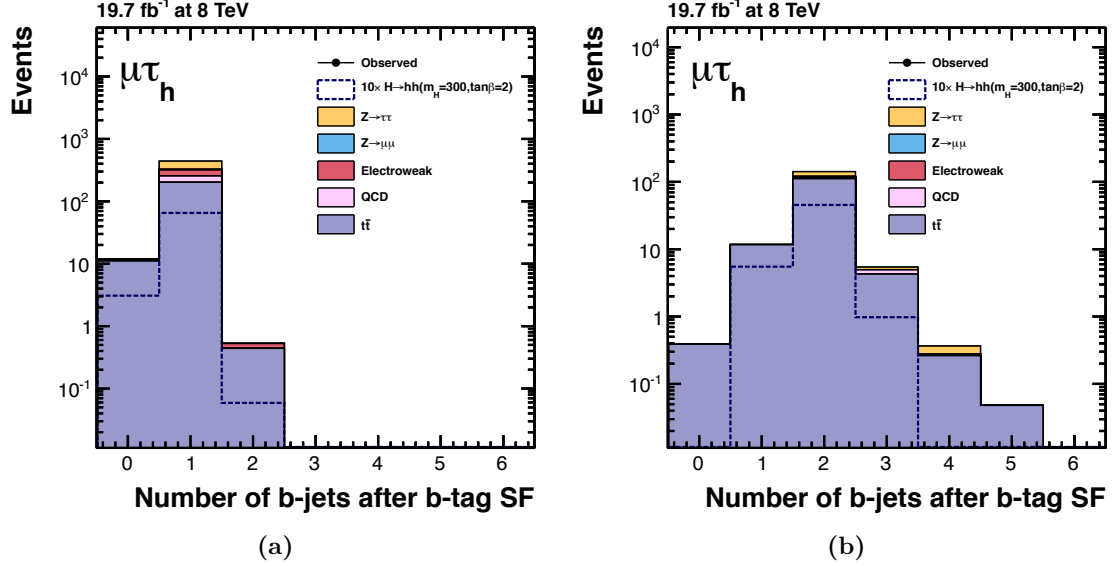


Figure 6.13: Number of b-tagged jets after the b-tag scale factor (SF) is applied for events which are originally in the 2jet-1tag (a) and 2jet-2tag (b) categories. Jets are promoted and demoted such that the events from one category migrate to the other categories.

negligible in the 2jet-1tag and 2jet-2tag categories, and so is added in quadrature with the uncertainty due to fake-rate. The uncertainty on the W and QCD estimates are dominated by limited statistics in the data control region, and are as high as 100% in 2jet-2tag. The uncertainty on the QCD estimate includes the 10% uncertainty on the opposite sign to same sign ratio added in quadrature. For the W estimate in 2jet-1tag, the uncertainty is separated into two parts: one part is the propagated effect of the 10% uncertainty on the $t\bar{t}$ control region, affecting the subtraction of $t\bar{t}$ in the data control region - this is 25% and is anti-correlated with the corresponding uncertainty on the $t\bar{t}$ normalisation. The second part covers the limited statistics in the data control region and is uncorrelated with any other uncertainty, with a size of 30%.

An additional uncertainty on the $Z \rightarrow \tau\tau$ estimate, corresponding to the size of the subtraction of the $t\bar{t}$ contamination in the embedded sample, is included.

Since the discriminating variable in this analysis is computed using the taus and the jets, both the tau and jet energy scales must be applied as a shape uncertainty. The size of the jet energy scale uncertainty is computed exactly as in section 4.6.1, but the change in the shape as a result of the shift up and down in energy scale is retained as well as

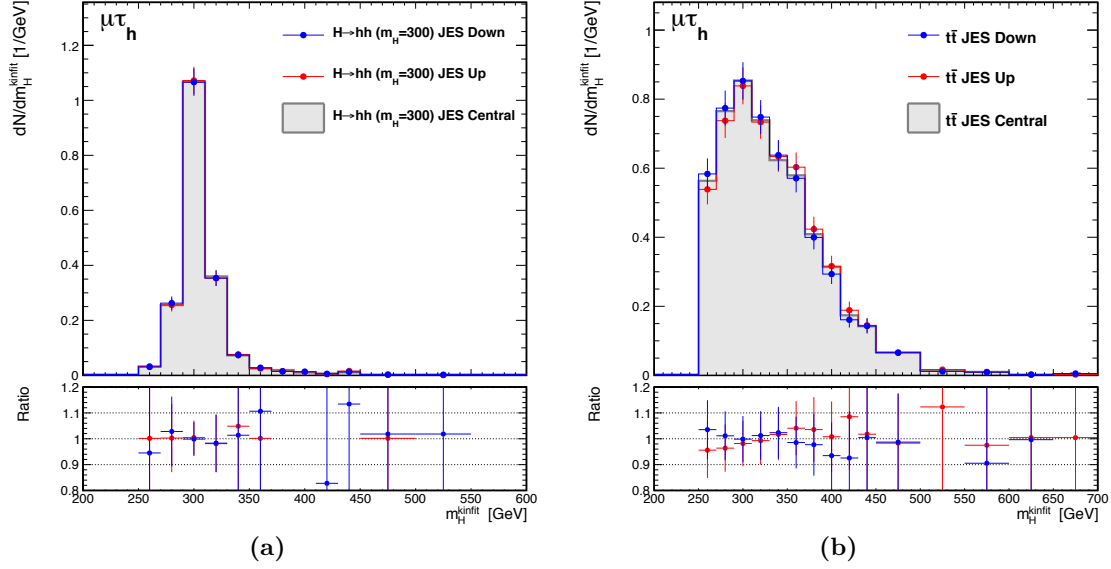


Figure 6.14: Effect of the jet energy scale (JES) uncertainty on the kinematic fit distribution for the signal with $m_H = 300$ GeV (a) and the $t\bar{t}$ background (b). The shift up or down in the JES can cause both the shape and normalisation to vary, but only the effect on the shape is shown here. The signal is normalised to a cross section of 1 pb in this figure.

computing the change in normalisation. The effect of the jet energy scale on the shape of the distributions for the $t\bar{t}$ background and the signal is shown in figure 6.14.

The treatment for templates with bins with large statistical uncertainties follows the bin-by-bin approach used in the SM analysis and described in section 4.6.2.

The full set of systematic uncertainties and their chosen sizes for each channel and category is given in table 6.1.

6.6 Results

6.6.1 Signal extraction

The 4-body mass after kinematic fit is used as the discriminating variable for signal extraction. A maximum likelihood fit is performed in all channels and categories simultaneously following exactly the methods described in section 4.7.1. The final kinematic fit distributions are shown in figures 6.15 and 6.16.

Source of uncertainty and affected processes		Yield changes by event category		
Experimental uncertainty	Affected processes	2jet-0tag	2jet-1tag	2jet-2tag
Integrated lumi. 8 TeV	All MC	2.6%	2.6%	2.6%
e ID & trigger	All MC	2%	2%	2%
μ ID & trigger	All MC	2–3%	2–3%	2–3%
τ ID & trigger	All MC	8%	8%	8%
b-tagging efficiency	All MC	1–7%	1–5%	1–70 ¹ %
b-mistag rate	All MC	1%	1–4%	1–5%
Z production	$Z \rightarrow \tau\tau, Z \rightarrow \ell\ell$	3.3%	3.3%	3.3%
$Z \rightarrow \tau\tau$: category	$Z \rightarrow \tau\tau$	5%	5%	6%
$Z \rightarrow \tau\tau$: $t\bar{t}$ contam.	$Z \rightarrow \tau\tau$	-	8%	27–32%
Norm. $t\bar{t}$	$t\bar{t}$, W+jets	10%	10–25%	10%
Norm. di-boson	diboson	15%	15%	15%
Norm. QCD	QCD	10%	40%	60–100%
Norm. W+jets	W+jets	10%	30%	100%
e misid. as τ_h	$Z \rightarrow ee$	20%	20%	40%
μ misid. as τ_h	$Z \rightarrow \mu\mu$	30%	60%	60%
Jet misid. as τ_h	Z+jets	20%	20–25%	70–90%
Tau energy scale	$Z \rightarrow \tau\tau$, signal	3%, shape	3%, shape	3–4%, shape
Jet energy scale	All MC	1–8%, shape	1–8%, shape	1–30%, shape
E_T^{miss} scale	All MC	1–7%	1–5%	1–10%
PDF	signal	2–3%	2–3%	2–3%
Scale variation	signal	5–7%	5–7%	5–7%
Limited bin statistics	all backgrounds	shape	shape	shape

Table 6.1: Systematic uncertainties that affect the estimated number of signal or background events. Several uncertainties are treated as correlated for the different decay channels and event categories. Some uncertainties vary across final states and for different affected processes, so ranges are given.

¹ This large uncertainty only applies to the W+jets background, which is affected by the b-tag efficiency due to the large contamination of $t\bar{t}$ in the W+jets control region. The statistical uncertainty on W+jets in 2jet-2tag is overwhelmingly larger than any systematic component.

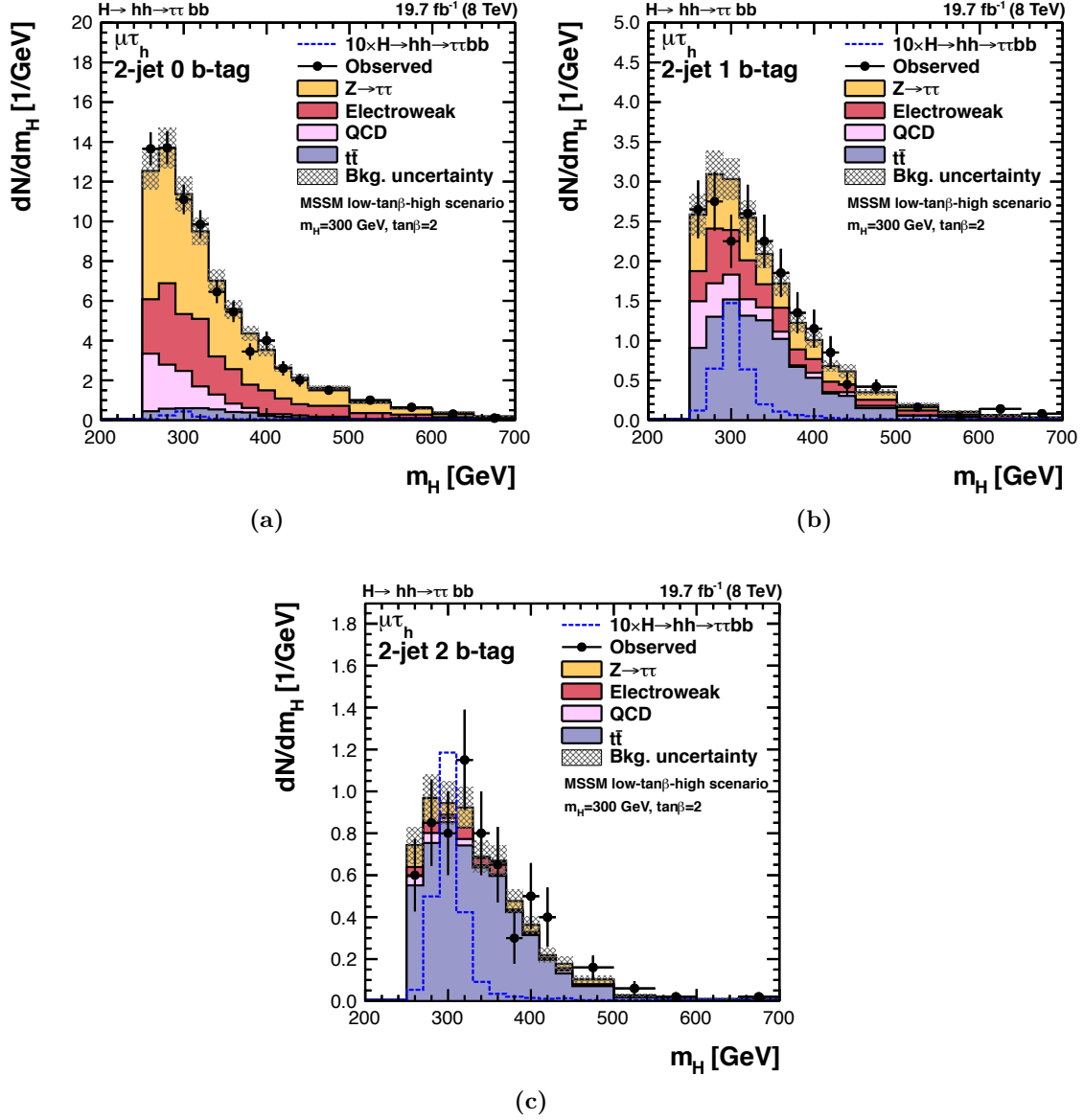


Figure 6.15: Distributions of kinematic fit mass following the maximum likelihood fit for events in the $\mu\tau_h$ channel and the 2jet-0tag (a) 2jet-1tag (b) and 2jet-2tag (c) categories. Signal is shown for a benchmark cross section times branching ratio for $m_H = 300 \text{ GeV}$ and $\tan\beta = 2$ and scaled by a factor of 10 to make it visible.

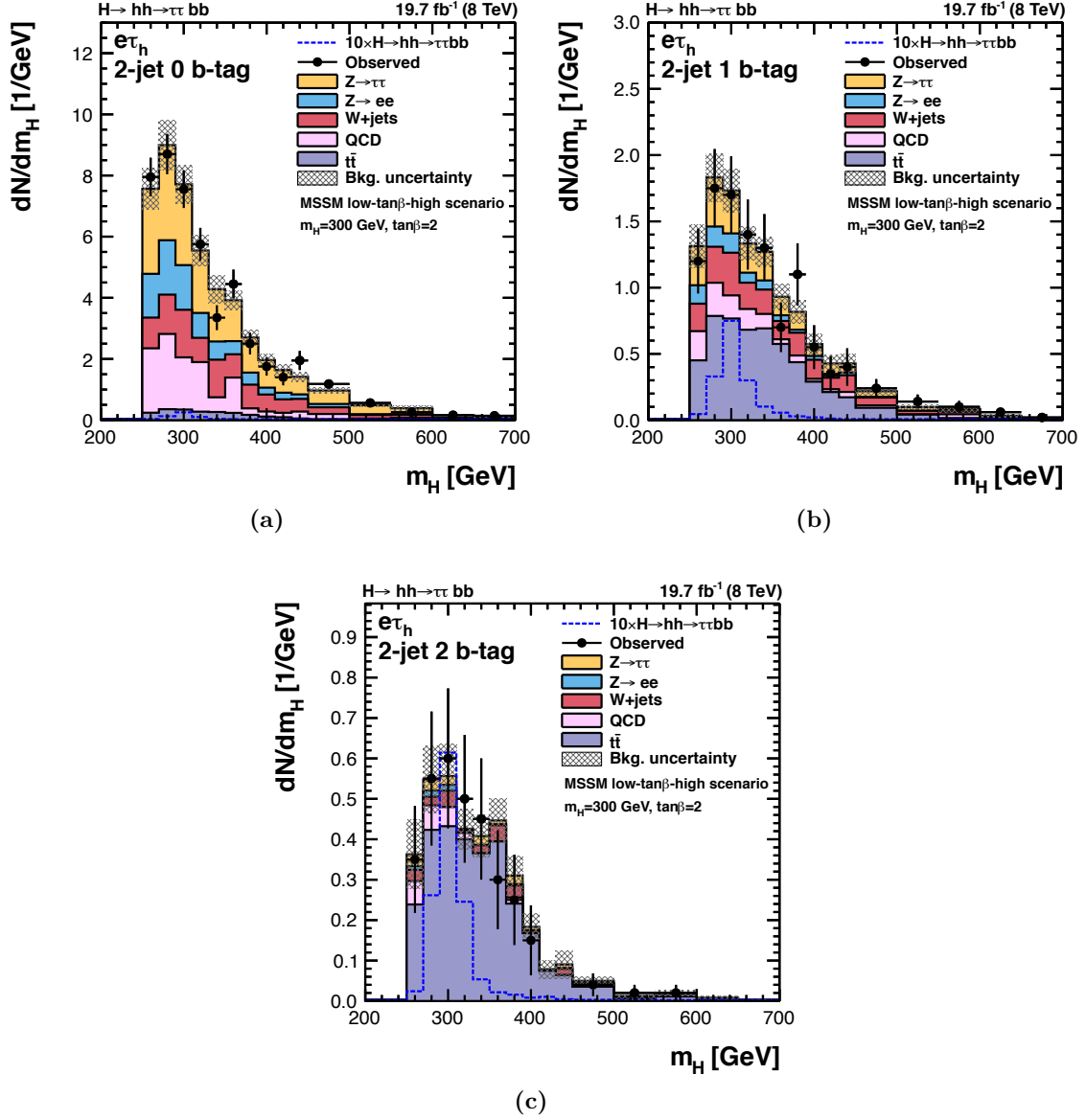


Figure 6.16: Distributions of kinematic fit mass following the maximum likelihood fit for events in the $e\tau_h$ channel and the 2jet-0tag (a) 2jet-1tag (b) and 2jet-2tag (c) categories. Signal is shown for a benchmark cross section times branching ratio for $m_H = 300$ GeV and $\tan\beta = 2$ and scaled by a factor of 10 to make it visible.

6.6.2 Contribution from a SM Higgs boson

SM Higgs boson events can pass the selections for this analysis via both the $H \rightarrow \tau\tau$ and $H \rightarrow bb$ processes, and their contributions in the event categories have been evaluated. The largest contribution occurs in the 2jet-0tag category, where gluon fusion production dominates. In the more signal sensitive categories associated production, especially $ZH \rightarrow \tau\tau bb$ or $bb\tau\tau$, is possible. However, these contributions are reduced somewhat by the mass cuts on m_{bb} and $m_{\tau\tau}$, and are less than 10% when compared with the cross section times branching ratio the analysis is sensitive to in $H \rightarrow hh$. The effect on the expected limit has been estimated by injecting the SM signal and found to be smaller than 3%. Thus it is sufficient to neglect the SM contribution for now. In future this relative contribution will become more important, as more data are obtained and the analysis becomes more sensitive, and measures following those described for the MSSM $\phi \rightarrow \tau\tau$ analysis will need to be employed.

6.6.3 Model independent results

An expected limit on cross section times branching ratio for the $H \rightarrow hh \rightarrow \tau\tau bb$ process is obtained using the methods described in 4.7.1 with a signal strength modifier μ corresponding to the cross section times branching ratio in pb. This result is analogous to the model independent limits in the MSSM analysis, except without the need to profile other signal contributions. Figure 6.17 shows these expected and observed limits for the $e\tau_h$ and $\mu\tau_h$ channels separately.

Figure 6.18 shows the result for the combination of the $e\tau_h$ and $\mu\tau_h$ channels (a) and a further combination with the fully hadronic channel not described in this thesis (b).

6.6.4 Model dependent results

As described in section 1.3.1, this analysis is sensitive in a particular region of MSSM phase space at low $\tan\beta$, provided appropriate choices are made for the radiative corrections which define the benchmark scenario. Thus a model dependent result can be produced in such a scenario, analogous to those described in 5.4.3. As discussed above, this analysis is not so sensitive to the SM Higgs boson, and hence the special statistical treatment to separate the MSSM and SM hypotheses is not required. Thus the limit in $m_A - \tan\beta$ is derived by calculating the CL_s values using the asymptotic approximation, comparing

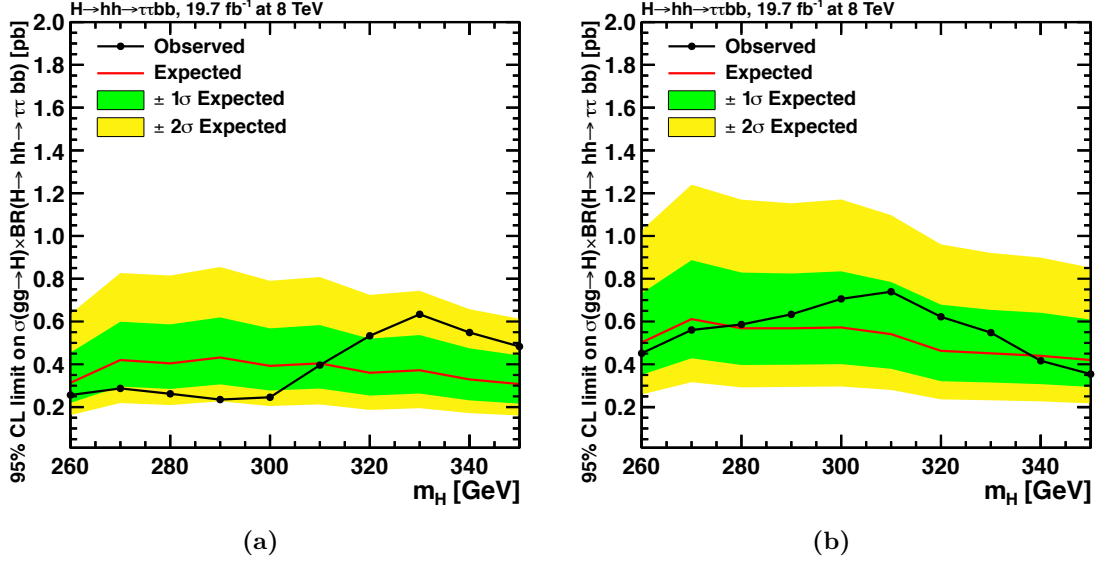


Figure 6.17: Expected and observed limits on cross section times branching ratio for the $gg \rightarrow H \rightarrow hh \rightarrow \tau\tau bb$ process for the $\mu\tau_h$ (a) and $e\tau_h$ (b) channels.

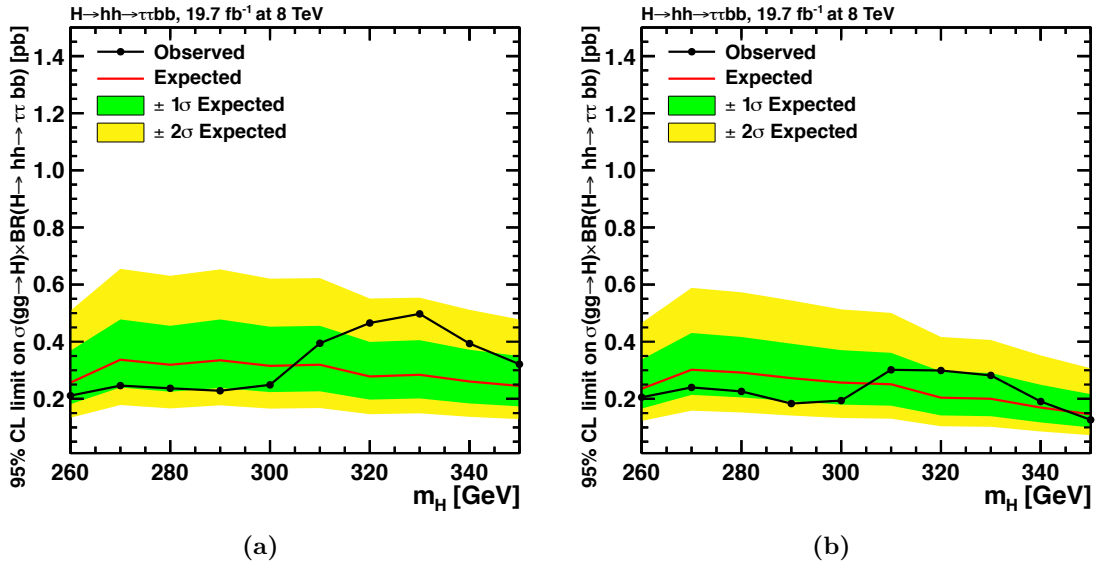


Figure 6.18: Combined expected and observed limits on cross section times branching ratio for the $gg \rightarrow H \rightarrow hh \rightarrow \tau\tau bb$ process. The left hand plot is for the combination of the $e\tau_h$ and $\mu\tau_h$ channels discussed in this chapter, and the right hand plot includes a combination with the $\tau_h\tau_h$ channel not described in this thesis.

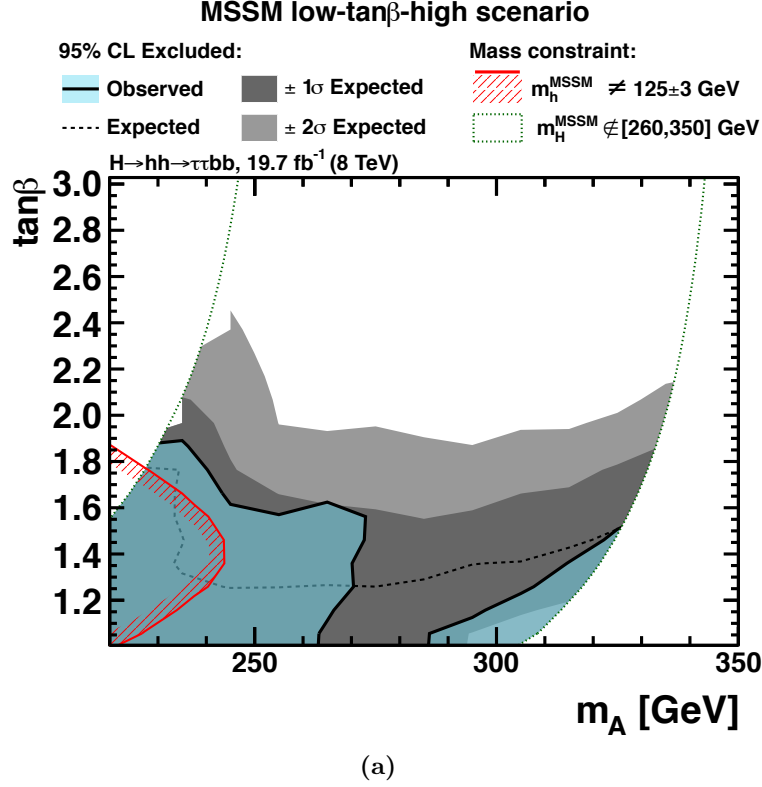


Figure 6.19: Combined expected and observed limits in the $m_A - \tan\beta$ plane of the low- $\tan\beta$ -high scenario. This includes a combination of the $e\tau_h$ and $\mu\tau_h$ channels with the $\tau_h\tau_h$ channel not described in this thesis. The red area indicates the region of phase space which is already excluded by the Higgs boson mass constraint of $125 \pm 3 \text{ GeV}$. The green dashed lines indicate the region which is outside of the range of the m_H values considered in this analysis. The lack of an excess of events in this analysis allows a small amount of the low $\tan\beta$ phase space to be excluded.

the MSSM signal hypothesis with the background-only hypothesis. The resulting limit in the low- $\tan\beta$ -high scenario for the combination of the $e\tau_h$ and $\mu\tau_h$ channels with the $\tau_h\tau_h$ channel is shown in figure 6.19. The lack of an excess of events in this analysis allows a small amount of the low $\tan\beta$ phase space to be excluded. Note that limits going as low as $\tan\beta = 1$ are shown and not any lower since this is the region of the cross-section calculations which was fully validated by the LHCHSWG at the time of writing this thesis.

Chapter 7

Conclusions

Three analyses have been presented in this thesis using proton-proton collision data recorded by the CMS detector during Run 1 of the LHC. The analyses include searches for a neutral Higgs boson in the context of the SM and MSSM in the $\tau\tau$ final state. This channel provides direct access to the Yukawa couplings between fermions and the Higgs field. The SM and MSSM $H \rightarrow \tau\tau$ analyses share a common baseline and many analysis techniques, both making use of $m_{\tau\tau}$ as discriminating variable for signal extraction. The MSSM $H \rightarrow hh$ analysis uses the same baseline with the exception of requiring at least two jets to form the $h \rightarrow b\bar{b}$ part. For maximal sensitivity, cuts on $m_{\tau\tau}$ and $m_{b\bar{b}}$ are used in a window around 125 GeV before using the 4 body mass of the two taus and the two b-quarks evaluated using a kinematic fit as the variable for signal extraction. All three analyses make use of event categorisation to target the signatures of the Higgs production process and decay and separate more signal-like and background-like events.

An excess of data over the background prediction is seen in the SM analysis, with local observed (expected) significance of (3.2σ) 3.7σ . This excess is found to be consistent with predictions for an SM Higgs boson with a mass of 125 GeV, both in measurements of the couplings and the mass. No significant excess of events is seen in either of the MSSM analyses. This results in upper limits at 95% CL on the cross-section times branching ratio for MSSM Higgs production processes. In the MSSM $H \rightarrow \tau\tau$ analyses limits are also set in interesting benchmark scenarios which incorporate a 125 GeV Higgs boson. For the interpretation of the MSSM results, the possible contribution from an SM Higgs in the dataset is taken into account.

The discovery of a Higgs boson with a mass around 125 GeV was a huge success for the LHC and the theory of electroweak symmetry breaking. Establishing whether or not this particle is the Higgs boson of the SM or from some other theory remains an extremely

interesting field. Later this year, the LHC will re-commence collisions at a centre of mass energy of 13 TeV. Data from Run 2 will be used to continue to test the compatibility of the Higgs boson with the SM.

Bibliography

- [1] CMS Collaboration, “Evidence for the 125 GeV Higgs boson decaying to a pair of τ leptons”, *JHEP* **1405** (2014) 104, doi:10.1007/JHEP05(2014)104, arXiv:1401.5041.
- [2] CMS Collaboration, “Search for neutral MSSM Higgs bosons decaying to a pair of tau leptons in pp collisions”, *JHEP* **1410** (2014) 160, doi:10.1007/JHEP10(2014)160, arXiv:1408.3316.
- [3] CMS Collaboration, “Search for MSSM Neutral Higgs Bosons Decaying to Tau Pairs in pp Collisions”, *CMS Physics Analysis Summary CMS-PAS-HIG-12-050* (2012).
- [4] CMS Collaboration, “Search for the standard model Higgs boson decaying to tau pairs”, *CMS Physics Analysis Summary CMS-PAS-HIG-12-043* (2012).
- [5] CMS Collaboration, “Search for the Standard-Model Higgs boson decaying to tau pairs in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV”, *CMS Physics Analysis Summary CMS-PAS-HIG-13-004* (2013).
- [6] CMS Collaboration, “Search for MSSM Neutral Higgs Bosons Decaying to Tau Pairs in pp Collisions”, *CMS Physics Analysis Summary CMS-PAS-HIG-13-021* (2013).
- [7] D. Griffiths, “Introduction to Elementary Particles”. Wiley, 2nd edition, 2008.
- [8] D. H. Perkins, “Introduction to High Energy Physics”. Cambridge University Press, 4th edition, 2000.
- [9] D. J. Gross and F. Wilczek, “Ultraviolet Behavior of Nonabelian Gauge Theories”, *Phys. Rev. Lett.* **30** (1973) 1343–1346, doi:10.1103/PhysRevLett.30.1343.
- [10] H. D. Politzer, “Reliable Perturbative Results for Strong Interactions?”, *Phys. Rev. Lett.* **30** (1973) 1346–1349, doi:10.1103/PhysRevLett.30.1346.

- [11] S. L. Glashow, “Partial Symmetries of Weak Interactions”, *Nucl. Phys.* **22** (1961) 579, doi:10.1016/0029-5582(61)90469-2.
- [12] S. Weinberg, “A model of leptons”, *Phys. Rev. Lett.* **19** (1967) 1264–1266.
- [13] A. Salam, “Weak and electromagnetic interactions”, in *Elementary particle physics: relativistic groups and analyticity*, N. Svartholm, ed., p. 367. Almqvist & Wiskell, Stockholm, 1968. Proceedings of the eighth Nobel symposium.
- [14] Gargamelle Neutrino Collaboration, “Observation of Neutrino Like Interactions Without Muon Or Electron in the Gargamelle Neutrino Experiment”, *Phys. Lett.* **B46** (1973) 138–140, doi:10.1016/0370-2693(73)90499-1.
- [15] UA1 Collaboration, “Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at $\sqrt{s} = 540$ GeV”, *Phys. Lett.* **B122** (1983) 103–116, doi:10.1016/0370-2693(83)91177-2.
- [16] UA2 Collaboration, “Observation of Single Isolated Electrons of High Transverse Momentum in Events with Missing Transverse Energy at the CERN anti-p p Collider”, *Phys. Lett.* **B122** (1983) 476–485, doi:10.1016/0370-2693(83)91605-2.
- [17] UA1 Collaboration, “Experimental Observation of Lepton Pairs of Invariant Mass Around 95 GeV/c² at the CERN SPS Collider”, *Phys. Lett.* **B126** (1983) 398–410, doi:10.1016/0370-2693(83)90188-0.
- [18] UA2 Collaboration, “Evidence for $Z^0 \rightarrow e^+ e^-$ at the CERN anti-p p Collider”, *Phys. Lett.* **B129** (1983) 130–140, doi:10.1016/0370-2693(83)90744-X.
- [19] Particle Data Group Collaboration, “Review of Particle Physics”, *Phys. Rev. D* **86** (2012) 010001, doi:10.1103/PhysRevD.86.010001.
- [20] I. J. R. Aitchison and A. J. G. Hey, “Gauge Theories in Particle Physics, 2 Volume Set”. Taylor & Francis, 3th edition, 2004.
- [21] P. W. Higgs, “Broken symmetries, massless particles and gauge fields”, *Phys. Lett.* **12** (1964) 132, doi:10.1016/0031-9163(64)91136-9.
- [22] P. W. Higgs, “Broken symmetries and the masses of gauge bosons”, *Phys. Rev. Lett.* **13** (1964) 508, doi:10.1103/PhysRevLett.13.508.

- [23] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, “Global conservation laws and massless particles”, *Phys. Rev. Lett.* **13** (1964) 585, doi:10.1103/PhysRevLett.13.585.
- [24] P. W. Higgs, “Spontaneous symmetry breakdown without massless bosons”, *Phys. Rev.* **145** (1966) 1156, doi:10.1103/PhysRev.145.1156.
- [25] T. W. B. Kibble, “Symmetry breaking in non-Abelian gauge theories”, *Phys. Rev.* **155** (1967) 1554, doi:10.1103/PhysRev.155.1554.
- [26] “The LEP Electroweak Working Group”, March, 2012.
<http://lepewwg.web.cern.ch>.
- [27] LEP Working Group for Higgs boson searches, ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, “Search for the standard model Higgs boson at LEP”, *Phys. Lett.* **B565** (2003) 61–75, doi:10.1016/S0370-2693(03)00614-2, arXiv:hep-ex/0306033.
- [28] CDF Collaboration, D0 Collaboration, “Higgs Boson Studies at the Tevatron”, *Phys. Rev.* **D88** (2013) 052014, doi:10.1103/PhysRevD.88.052014, arXiv:1303.6346.
- [29] LHC Higgs Cross Section Working Group, “Handbook of LHC Higgs Cross Sections: 3. Higgs Properties”, doi:10.5170/CERN-2013-004, arXiv:1307.1347.
- [30] CMS Collaboration, “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC”, *Phys. Lett. B* **716** (2012) doi:10.1016/j.physletb.2012.08.021, arXiv:1207.7235.
- [31] ATLAS Collaboration, “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC”, *Phys. Lett. B* **716** (2012) doi:10.1016/j.physletb.2012.08.020, arXiv:1207.7214.
- [32] CMS Collaboration, “Precise determination of the mass of the Higgs boson and tests of compatibility of its couplings with the standard model predictions using proton collisions at 7 and 8 TeV”, arXiv:1412.8662.
- [33] ATLAS Collaboration, “Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector”, *Phys.Rev.* **D91** (2015), no. 1, 012006, doi:10.1103/PhysRevD.91.012006, arXiv:1408.5191.

- [34] ATLAS Collaboration, “Measurements of fiducial and differential cross sections for Higgs boson production in the diphoton decay channel at $\sqrt{s} = 8$ TeV with ATLAS”, *JHEP* **1409** (2014) 112, doi:10.1007/JHEP09(2014)112, arXiv:1407.4222.
- [35] ATLAS Collaboration, “Evidence for the Higgs-boson Yukawa coupling to tau leptons with the ATLAS detector”, arXiv:1501.04943.
- [36] CMS Collaboration, “Measurement of the properties of a Higgs boson in the four-lepton final state”, arXiv:1312.5353.
- [37] CMS Collaboration, “Measurement of Higgs boson production and properties in the WW decay channel with leptonic final states”, *JHEP* **1401** (2014) 096, doi:10.1007/JHEP01(2014)096, arXiv:1312.1129.
- [38] ATLAS Collaboration, “Evidence for the spin-0 nature of the Higgs boson using ATLAS data”, *Phys. Lett. B* **726** (2013) 120, doi:10.1016/j.physletb.2013.08.026, arXiv:1307.1432.
- [39] CMS Collaboration, “Constraints on the Higgs boson width from off-shell production and decay to Z-boson pairs”, *Phys.Lett.* **B736** (2014) 64, doi:10.1016/j.physletb.2014.06.077, arXiv:1405.3455.
- [40] ATLAS Collaboration, “Search for Invisible Decays of a Higgs Boson Produced in Association with a Z Boson in ATLAS”, *Phys.Rev.Lett.* **112** (2014) 201802, doi:10.1103/PhysRevLett.112.201802, arXiv:1402.3244.
- [41] CMS Collaboration, “Search for invisible decays of Higgs bosons in the vector boson fusion and associated ZH production modes”, *Eur.Phys.J.* **C74** (2014) 2980, doi:10.1140/epjc/s10052-014-2980-6, arXiv:1404.1344.
- [42] U. Amaldi, W. de Boer, and H. Furstenau, “Comparison of grand unified theories with electroweak and strong coupling constants measured at LEP”, *Phys. Lett.* **B260** (1991) 447–455, doi:10.1016/0370-2693(91)91641-8.
- [43] M. S. Carena and H. E. Haber, “Higgs boson theory and phenomenology”, *Prog. Part. Nucl. Phys.* **50** (2003) 63–152, doi:10.1016/S0146-6410(02)00177-1, arXiv:hep-ph/0208209.
- [44] S. P. Martin, “A Supersymmetry primer”, arXiv:hep-ph/9709356.

- [45] R. Barbieri and G. Giudice, “Upper bounds on supersymmetric particle masses”, *Nuclear Physics B* **306** (1988), no. 1, 63 – 76, doi:[http://dx.doi.org/10.1016/0550-3213\(88\)90171-X](http://dx.doi.org/10.1016/0550-3213(88)90171-X).
- [46] S. Dimopoulos and H. Georgi, “Softly Broken Supersymmetry and SU(5)”, *Nucl.Phys.* **B193** (1981) 150, doi:[10.1016/0550-3213\(81\)90522-8](http://dx.doi.org/10.1016/0550-3213(81)90522-8).
- [47] M. Carena, S. Heinemeyer, C. Wagner et al., “Suggestions for improved benchmark scenarios for Higgs boson searches at LEP-2”, [arXiv:hep-ph/9912223](https://arxiv.org/abs/hep-ph/9912223).
- [48] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, LEP Working Group for Higgs Boson Searches Collaboration, “Search for neutral MSSM Higgs bosons at LEP”, *Eur.Phys.J.* **C47** (2006) 547–587, doi:[10.1140/epjc/s2006-02569-7](http://dx.doi.org/10.1140/epjc/s2006-02569-7), [arXiv:hep-ex/0602042](https://arxiv.org/abs/hep-ex/0602042).
- [49] Tevatron New Phenomena & Higgs Working Group Collaboration, “Combined CDF and D0 Upper Limits on MSSM Higgs Boson Production in tau-tau Final States with up to 2.2 fb⁻¹”, [arXiv:1003.3363](https://arxiv.org/abs/1003.3363).
- [50] ATLAS Collaboration, “Search for neutral Higgs bosons of the minimal supersymmetric standard model in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, *JHEP* **1411** (2014) 056, doi:[10.1007/JHEP11\(2014\)056](http://dx.doi.org/10.1007/JHEP11(2014)056), [arXiv:1409.6064](https://arxiv.org/abs/1409.6064).
- [51] M. Carena, S. Heinemeyer, O. Stal et al., “MSSM Higgs Boson Searches at the LHC: Benchmark Scenarios after the Discovery of a Higgs-like Particle”, *Eur.Phys.J.* **C73** (2013), no. 9, 2552, doi:[10.1140/epjc/s10052-013-2552-1](http://dx.doi.org/10.1140/epjc/s10052-013-2552-1), [arXiv:1302.7033](https://arxiv.org/abs/1302.7033).
- [52] J. P. Miller, E. de Rafael, and B. L. Roberts, “Muon (g-2): Experiment and theory”, *Rept.Prog.Phys.* **70** (2007) 795, doi:[10.1088/0034-4885/70/5/R03](http://dx.doi.org/10.1088/0034-4885/70/5/R03), [arXiv:hep-ph/0703049](https://arxiv.org/abs/hep-ph/0703049).
- [53] BaBar Collaboration, “Exclusive Measurements of $b \rightarrow s\gamma$ Transition Rate and Photon Energy Spectrum”, *Phys.Rev.* **D86** (2012) 052012, doi:[10.1103/PhysRevD.86.052012](http://dx.doi.org/10.1103/PhysRevD.86.052012), [arXiv:1207.2520](https://arxiv.org/abs/1207.2520).
- [54] ATLAS Collaboration, “Measurements of the properties of the Higgs-like boson in the two photon decay channel with the ATLAS detector using 25 fb⁻¹ of proton-proton collision data”, Technical Report ATLAS-CONF-2013-012, CERN, Geneva, (Mar, 2013).

- [55] ATLAS Collaboration, “Measurement of Higgs boson production in the diphoton decay channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector”, *Phys.Rev.* **D90** (2014), no. 11, 112015, doi:10.1103/PhysRevD.90.112015, arXiv:1408.7084.
- [56] A. Djouadi and J. Quevillon, “The MSSM Higgs sector at a high M_{SUSY} : reopening the low $\tan\beta$ regime and heavy Higgs searches”, *JHEP* **1310** (2013) 028, doi:10.1007/JHEP10(2013)028, arXiv:1304.1787.
- [57] ATLAS Collaboration, “Search For Higgs Boson Pair Production in the $\gamma\gamma b\bar{b}$ Final State using pp Collision Data at $\sqrt{s} = 8$ TeV from the ATLAS Detector”, *Phys.Rev.Lett.* **114** (2015), no. 8, 081802, doi:10.1103/PhysRevLett.114.081802, arXiv:1406.5053.
- [58] CMS Collaboration, “Search for resonant HH production in 2gamma+2b channel”, Technical Report CMS-PAS-HIG-13-032, CERN, Geneva, (2014).
- [59] CMS Collaboration, “Search for di-Higgs resonances decaying to 4 bottom quarks”, Technical Report CMS-PAS-HIG-14-013, CERN, Geneva, (2014).
- [60] ATLAS Collaboration, “Search for a CP-odd Higgs boson decaying to Zh in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector”, arXiv:1502.04478.
- [61] CMS Collaboration, “Search for a pseudoscalar boson decaying into a Z boson and the 125 GeV Higgs boson in llbb final states”, arXiv:1504.04710.
- [62] S. Heinemeyer, “LHCHXSWG - unpublished note”, Accessed March, 2015. <https://twiki.cern.ch/twiki/pub/LHCPhysics/HXSWG3LowTanB/benchmark5-v0.pdf>.
- [63] A. Djouadi, L. Maiani, A. Polosa et al., “Fully covering the MSSM Higgs sector at the LHC”, arXiv:1502.05653.
- [64] L. Evans and P. Bryant, “LHC Machine”, *JINST* **3** (2008) S08001, doi:10.1088/1748-0221/3/08/S08001.
- [65] LEP Injector Study Group, “LEP design report, volume I: The LEP injector chain; LEP design report, volume II: The LEP Main Ring”. CERN, Geneva, 1983.
- [66] ALICE Collaboration, “The ALICE experiment at the CERN LHC”, *JINST* **3** (2008) S08002, doi:10.1088/1748-0221/3/08/S08002.

- [67] ATLAS Collaboration, “The ATLAS Experiment at the CERN Large Hadron Collider”, *JINST* **3** (2008) S08003, doi:10.1088/1748-0221/3/08/S08003.
- [68] CMS Collaboration, “The CMS experiment at the CERN LHC”, *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.
- [69] LHCb Collaboration, “The LHCb Detector at the LHC”, *JINST* **3** (2008) S08005, doi:10.1088/1748-0221/3/08/S08005.
- [70] W. J. Stirling. private communication.
- [71] CMS Collaboration, “CMS Luminosity - Public Results”,
<http://twiki.cern.ch/twiki/bin/view/CMSPublic/LumiPublicResults> (Accessed March, 2015).
- [72] T. Sakuma and T. McCauley, “Detector and Event Visualization with SketchUp at the CMS Experiment”, *Journal of Physics: Conference Series* **513** (2014), no. 2, 022032.
- [73] R. Fruhwirth, “Application of Kalman filtering to track and vertex fitting”, *Nucl. Instrum. Meth.* **A262** (1987) 444–450, doi:10.1016/0168-9002(87)90887-4.
- [74] CMS Collaboration, “CMS Physics: Technical Design Report Volume 1: Detector Performance and Software”, *CERN/LHCC* (2006).
- [75] USCMS, ECAL/HCAL Collaboration, “The CMS barrel calorimeter response to particle beams from 2-GeV/c to 350-GeV/c”, *Eur. Phys. J.* **C60** (2009) 359–373, doi:10.1140/epjc/s10052-009-1024-0.
- [76] CMS Collaboration, “Data Parking and Data Scouting at the CMS Experiment”, *CMS Performance Note* **CMS-DP-2012-022** (2012).
- [77] “Worldwide LHC Computing Grid”, <http://lcg.web.cern.ch/LCG/public/>.
- [78] K. Rose, “Deterministic Annealing for Clustering, Compression, Classification, Regression, and related Optimization Problems”, *Proceedings of the IEEE* **86** (1998) 2210.
- [79] R. Fruhwirth, W. Waltenberger, and P. Vanlaer, “Adaptive vertex fitting”, *J. Phys.* **G34** (2007) N343, doi:10.1088/0954-3899/34/12/N01.
- [80] CMS Collaboration, “Tracking and Primary Vertex Results in First 7 TeV Collisions”, *CMS Physics Analysis Summary* **CMS-PAS-TRK-10-005** (2010).

- [81] E. Meschi, T. Monteiro, C. Seez et al., “Electron Reconstruction in the CMS Electromagnetic Calorimeter”, *CMS Note* **CMS-NOTE-2001-034** (2001).
- [82] CMS Collaboration, “Performance of electron reconstruction and selection with the CMS detector in proton-proton collisions at $\sqrt{s} = 8\text{TeV}$ ”, (2015).
[arXiv:1502.02701](#). Submitted to *JINST*.
- [83] W. Adam, R. Frühwirth, A. Strandlie et al., “Reconstruction of Electrons with the Gaussian-Sum Filter in the CMS Tracker at the LHC”, *CMS Note* **CMS-NOTE-2005-001** (2005).
- [84] S. Baffioni, C. Charlot, F. Ferri et al., “Electron reconstruction in CMS”, *Eur. Phys. J.* **C49** (2007) 1099–1116, [doi:10.1140/epjc/s10052-006-0175-5](#).
- [85] A. Hocker, J. Stelzer, F. Tegenfeldt et al., “TMVA - Toolkit for Multivariate Data Analysis”, *PoS ACAT* (2007) 040, [arXiv:physics/0703039](#).
- [86] CMS Collaboration, “Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7\text{ TeV}$ ”, *JINST* **7** (2012) P10002,
[doi:10.1088/1748-0221/7/10/P10002](#), [arXiv:1206.4071](#).
- [87] CMS Collaboration, “Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and MET”, *CMS Physics Analysis Summary* **CMS-PAS-PFT-09-001** (2009).
- [88] CMS Collaboration, “Commissioning of the Particle-flow Event Reconstruction with the first LHC collisions recorded in the CMS detector”, *CMS Physics Analysis Summary* **CMS-PAS-PFT-10-001** (2010).
- [89] CMS Collaboration, “Commissioning of the Particle-Flow reconstruction in Minimum-Bias and Jet Events from pp Collisions at 7 TeV”, *CMS Physics Analysis Summary* **CMS-PAS-PFT-10-002** (2010).
- [90] G. P. Salam, “Towards Jetography”, *Eur. Phys. J.* **C67** (2010) 637–686,
[doi:10.1140/epjc/s10052-010-1314-6](#), [arXiv:0906.1833](#).
- [91] M. Cacciari, G. P. Salam, and G. Soyez, “The anti- k_t jet clustering algorithm”, *JHEP* **04** (2008) 063, [doi:10.1088/1126-6708/2008/04/063](#),
[arXiv:0802.1189](#).
- [92] M. Cacciari, G. P. Salam, and G. Soyez, “FastJet User Manual”, *Eur. Phys. J. C* **72** (2012) 1896, [doi:10.1140/epjc/s10052-012-1896-2](#), [arXiv:1111.6097](#).

- [93] CMS Collaboration, “Pileup Jet Identification”, *CMS Physics Analysis Summary CMS-PAS-JME-13-005* (2013).
- [94] CMS Collaboration, “Determination of jet energy calibration and transverse momentum resolution in CMS”, *JINST* **6** (2011) 11002, doi:10.1088/1748-0221/6/11/P11002, arXiv:1107.4277.
- [95] CDF Collaboration, “The Dijet angular distribution in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV”, *Phys. Rev. Lett.* **69** (1992) 2896–2900, doi:10.1103/PhysRevLett.69.2896.
- [96] CMS Collaboration, “Identification of b-quark jets with the CMS experiment”, *JINST* **8** (2013) P04013, doi:10.1088/1748-0221/8/04/P04013, arXiv:1211.4462.
- [97] CMS Collaboration, “Performance of Missing Transverse Momentum Reconstruction Algorithms in Proton-Proton Collisions at $\sqrt{s} = 8$ TeV with the CMS Detector”, *CMS Physics Analysis Summary CMS-PAS-JME-12-002* (2013).
- [98] CMS Collaboration, “Performance of tau-lepton reconstruction and identification in CMS”, *JINST* **7** (2012) P01001, doi:10.1088/1748-0221/7/01/P01001, arXiv:1109.6034.
- [99] L. Bianchini, J. Conway, E. K. Friis et al., “Reconstruction of the Higgs mass in $H \rightarrow \tau\tau$ Events by Dynamical Likelihood techniques”, *J.Phys.Conf.Ser.* **513** (2014) 022035, doi:10.1088/1742-6596/513/2/022035.
- [100] B. Bullock, K. Hagiwara, and A. D. Martin, “Tau polarization and its correlations as a probe of new physics”, *Nucl. Phys. B* **395** (1993) 499, doi:10.1016/0550-3213(93)90045-Q.
- [101] J. Alwall, M. Herquet, F. Maltoni et al., “MadGraph 5: Going Beyond”, *JHEP* **06** (2011) 128, doi:10.1007/JHEP06(2011)128, arXiv:1106.0522.
- [102] S. Frixione, P. Nason, and C. Oleari, “Matching NLO QCD computations with parton shower simulations: the POWHEG method”, *JHEP* **11** (2007) 070, doi:10.1088/1126-6708/2007/11/070, arXiv:0709.2092.
- [103] S. Alioli, P. Nason, C. Oleari et al., “A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX”, *JHEP* **06** (2010) 043, doi:10.1007/JHEP06(2010)043, arXiv:1002.2581.

- [104] S. Alioli, K. Hamilton, P. Nason et al., “Jet pair production in POWHEG”, *JHEP* **04** (2011) 081, doi:10.1007/JHEP04(2011)081, arXiv:1012.3380.
- [105] T. Sjöstrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 physics and manual”, *JHEP* **05** (2006) 026, doi:10.1088/1126-6708/2006/05/026.
- [106] S. Jadach, J. H. Kühn, and Z. Was, “TAUOLA - a library of Monte Carlo programs to simulate decays of polarized tau leptons”, *Comput. Phys. Commun.* **64** (1991) 275, doi:10.1016/0010-4655(91)90038-M.
- [107] LHC Higgs Cross Section Working Group, “Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables”, doi:10.5170/CERN-2011-002, arXiv:1101.0593.
- [108] LHC Higgs Cross Section Working Group, “Handbook of LHC Higgs Cross Sections: 2. Differential Distributions”, doi:10.5170/CERN-2012-002, arXiv:1201.3084.
- [109] CMS Collaboration, “Measurements of Inclusive W and Z Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **1101** (2011) 080, doi:10.1007/JHEP01(2011)080, arXiv:1012.2466.
- [110] CMS Collaboration, “b-Jet Identification in the CMS Experiment”, *CMS Physics Analysis Summary* **CMS-PAS-BTV-11-004** (2012).
- [111] CMS Collaboration, “Performance of b tagging at $\sqrt{s} = 8$ TeV in multijet, $t\bar{t}$ and boosted topology events”, *CMS Physics Analysis Summary* **CMS-PAS-BTV-13-001** (2013).
- [112] D. de Florian, G. Ferrera, M. Grazzini et al., “Higgs boson production at the LHC: transverse momentum resummation effects in the $H \rightarrow 2\gamma$, $H \rightarrow WW \rightarrow \ell\nu\ell\nu$ and $H \rightarrow ZZ \rightarrow 4\ell$ decay modes”, *JHEP* **06** (2012) 132, doi:10.1007/JHEP06(2012)132, arXiv:1203.6321.
- [113] M. Grazzini and H. Sargsyan, “Heavy-quark mass effects in Higgs boson production at the LHC”, *JHEP* **1309** (2013) 129, doi:10.1007/JHEP09(2013)129, arXiv:1306.4581.
- [114] CMS Collaboration, “Performance of tau-lepton reconstruction and identification in CMS”, *JINST* **7** (2012) P01001, doi:10.1088/1748-0221/7/01/P01001, arXiv:1109.6034.

-
- [115] CMS Collaboration, “Measurement of the W^+W^- and ZZ production cross sections in pp collisions at $\sqrt{s} = 8$ TeV”, *Phys. Lett. B* **721** (2013) 190, doi:10.1016/j.physletb.2013.03.027, arXiv:1301.4698.
- [116] CMS Collaboration, “Measurement of the single-top-quark t -channel cross section in pp collisions at $\sqrt{s} = 7$ TeV”, *JHEP* **12** (2012) 035, doi:10.1007/JHEP12(2012)035, arXiv:1209.4533.
- [117] CMS Collaboration, “Absolute Calibration of the Luminosity Measurement at CMS: Winter 2012 Update”, *CMS Physics Analysis Summary CMS-PAS-SMP-12-008* (2012).
- [118] CMS Collaboration, “CMS Luminosity Based on Pixel Cluster Counting - Summer 2013 Update”, *CMS Physics Analysis Summary CMS-PAS-LUM-13-001* (2013).
- [119] K. Hamilton, P. Nason, and G. Zanderighi, “MINLO: Multi-Scale Improved NLO”, *JHEP* **10** (2012) 155, doi:10.1007/JHEP10(2012)155, arXiv:1206.3572.
- [120] S. Frixione and B. R. Webber, “Matching NLO QCD computations and parton shower simulations”, *JHEP* **06** (2002) 029, doi:10.1088/1126-6708/2002/06/029, arXiv:hep-ph/0204244.
- [121] R. Barlow and C. Beeston, “Fitting using finite Monte Carlo samples”, *Comput. Phys. Commun.* **77** (1993), no. 2, 219 – 228, doi:http://dx.doi.org/10.1016/0010-4655(93)90005-W.
- [122] ATLAS and CMS Collaborations, LHC Higgs Combination Group, “Procedure for the LHC Higgs boson search combination in Summer 2011”, Technical Report ATL-PHYS-PUB 2011-11, CMS NOTE 2011/005, CERN, (2011).
- [123] A. L. Read, “Presentation of search results: the CLs technique”, *J. Phys. G* **28** (2002) 2693, doi:10.1088/0954-3899/28/10/313.
- [124] G. Cowan, K. Cranmer, E. Gross et al., “Asymptotic formulae for likelihood-based tests of new physics”, *The European Physical Journal C* **71** (2011), no. 2, 1–19, doi:10.1140/epjc/s10052-011-1554-0.
- [125] CMS Collaboration, V. Khachatryan et al., “Search for neutral MSSM Higgs bosons decaying to a pair of tau leptons in pp collisions - analysis results twiki”.

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- [126] E. Schlieckau, “Measurement of Top-Quark Mass and Inclusive Top-Quark-Pair Production Cross Section in pp Collisions at $\sqrt{s}=7/8$ TeV with CMS”. PhD thesis, University of Hamburg, 2014.

List of Acronyms

BDT boosted decision tree

BSM beyond-the-standard-model

CL confidence level

CSC cathode strip chamber

CSV combined secondary vertex

DA deterministic annealing

DAQ data acquisition

DT drift tube

ECAL electromagnetic calorimeter

GSF Gaussian sum filter

HB hadron barrel

HCAL hadron calorimeter

HE hadron endcaps

HF hadron forward

HLT high-level trigger

HO hadron outer

HPS hadron plus strips

L1 Level-1

LHCHXSWG LHC Higgs Cross Section Working Group

LO leading order

MC	Monte Carlo
MPF	missing transverse energy projection fraction
MSSM	minimal supersymmetric standard model
NLO	next-to-leading order
NNLO	next-to-next-to-leading order
pdf	probability density function
PDF	parton distribution function
PF	particle flow
PS	Proton Synchrotron
PSB	Proton Synchrotron Booster
PU	pile-up
PV	Primary Vertex
QCD	Quantum Chromodynamics
RPC	resistive plate chamber
SPS	Super Proton Synchrotron
SM	standard model
SUSY	supersymmetry
TEC	tracker endcaps
TIB	tracker inner barrel
TID	tracker inner disks
TOB	tracker outer barrel
VBF	vector boson fusion
WLCG	Worldwide LHC Computing Grid