

**Measurement of the Electron Charge Asymmetry in
Inclusive W Production in pp Collisions at
 $\sqrt{s} = 7$ TeV in the CMS Experiment**

Martyn Jarvis

Blackett Laboratory
Imperial College London

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Abstract

In this thesis, two measurements of the electron charge asymmetry in inclusive W boson production with the CMS detector are presented. The measurements are obtained from proton-proton collision data with $\sqrt{s} = 7$ TeV. The first measurement is performed with data corresponding to an integrated luminosity of 36 pb^{-1} collected by the CMS detector in 2010 and the second one uses data corresponding to 840 pb^{-1} collected during the first half of 2011.

In proton-proton collisions, more W^+ bosons are produced relative to W^- due to the prevalence of up-type quarks with respect to down-type valence quarks in the proton. A measurement of this asymmetry as a function of the boson rapidity can provide valuable information on the u/d ratio within the proton. Since the boson rapidity cannot be directly measured due to the longitudinal momentum carried by the undetected neutrino, the asymmetry is measured as a function of the pseudorapidity of the charged lepton, in this case the electron, from the W decay.

In both measurements, events are selected by requiring a single electron with tight selection criteria on quality of identification and measurement of the energy of the electron. The signal yield is extracted using extended maximum likelihood fits to the missing transverse energy spectrum using a set of reference template shapes for the signal, electroweak background and QCD background. The templates are obtained using Monte Carlo simulation, corrected with information from collision data events (for the signal and electroweak backgrounds), and a control sample of events obtained from an inverted selection (for the QCD background).

In the first measurement the charge asymmetry is measured in 6 bins of the absolute value of the electron's pseudorapidity and compared with predictions from theory. The statistical error ranges from 0.006 to 0.010. The increased amount of data in the second measurement allows the results to be presented in 11 bins of the absolute value of the electron's pseudorapidity. The statistical error has been reduced and ranges from 0.003 to 0.004 and the global error is in the range 0.006 to 0.014.

Declaration

This thesis contains the work for two measurements of the electron charge asymmetry that were performed with data from the CMS experiment taken in 2010 and 2011. The results of the measurements were approved for the CMS collaboration and are published in [1, 2]. The measurements are also documented in the analysis notes [3, 4].

The work in Chapters 6 and 7 is mine with the exception of Section 6.2.2 which was provided to me and Sections 6.3 and 7.3 which were either performed by others or in collaboration with others.

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Martyn Jarvis

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Chapter 1

Introduction

The Standard Model (SM) of particle physics is a quantum field theory that describes the dynamics of elementary particles and their interactions through the electromagnetic, strong and weak forces that has been tested with a high degree of precision. The SM predicts the existence of the Higgs boson, which may be the particle discovered by the Large Hadron Collider (LHC) experiments and announced on the fourth of July last year [5, 6].

The LHC at European Laboratory for Particle Physics (CERN) in Geneva is a particle accelerator designed to collide protons at 14 TeV with a luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This thesis is concerned with data collected by the Compact Muon Solenoid (CMS) experiment at the LHC, a general purpose detector with a range of goals including discovery of the Higgs boson and precise measurements of the SM.

The analysis presented in this thesis is a measurement of the electron charge asymmetry in inclusive W production. The asymmetric production of W bosons is an important observable; in proton-proton collisions the W^+ is produced at a higher rate than the W^- due to the excess of up-type quarks with respect to down-type quarks. Furthermore, the W^+ will tend to be produced at larger rapidities while the W^- is mostly produced at central rapidities. A measurement of the asymmetry as a function of the rapidity of the boson can provide important information on the parton densities of the colliding protons, specifically the u/d quark ratio. In the electron decay of the W boson, the longitudinal component of the neutrino momentum is lost so the boson's rapidity is unmeasurable. What is measurable is the electron charge asymmetry as a function of the

electron pseudorapidity.

This thesis is structured as follows. In Chapter 2 an overview of the constituent particles and the fundamental interactions of the SM is given. Chapter 3 describes the production of the W bosons and their decay to an electron and neutrino. Also shown are some theoretical predictions of the electron charge asymmetry for different parton distribution functions (PDFs). Chapter 4 introduces the LHC and the CMS detector and its sub-detectors. In Chapter 5, the particle reconstruction algorithms used in CMS are summarised with the electron reconstruction and identification methods described in detail. The measurement of the electron charge asymmetry with 36 pb^{-1} of data is presented in Chapter 6. The update to the measurement with 840 pb^{-1} is presented in Chapter 7. Chapter 8 provides a summary of the results.

Chapter 2

Standard Model

The Standard Model (SM) of particle physics is a quantum field theory that describes all known fundamental constituents of matter and their interactions through the strong, weak and electromagnetic forces. The theory was pieced together in the 60s and 70s and comprises the theories of quantum electrodynamics (QED), the Glashow-Weinberg-Salam theory of electroweak dynamics and quantum chromodynamics (QCD) [7–10].

The Standard Model is remarkable in its accuracy, describing every experimental test performed to a high degree of precision and accurately describes all processes that are observed in nature, with the exception of gravity and neutrino oscillations.

This chapter reviews the Standard Model of particle physics. The first section will introduce the matter constituents of the Standard Model; the leptons and quarks, and the final section will describe the fundamental interactions. The description follows the example given in reference [11] with additional insights from references [12–14].

2.1 Constituents of the Standard Model

Within the Standard Model, matter is described as being constructed from a small number of spin = $1/2$ particles called fermions that can interact via the electromagnetic, weak and strong forces. The fields corresponding to the fermions are described by the Dirac equation,

$$(i\gamma^\mu\partial_\mu - m)\psi(x) = 0 \tag{2.1}$$

where $\psi(x)$ is a four-component spinor, γ^μ are the Dirac matrices and m is the fermion mass.

The fermions are divided into two families called leptons and quarks. Each family of fermions can be further subdivided into three generations with particles progressively increasing in mass. The fermions of the Standard Model and some of their properties are summarised in Table 2.1.

	1st gen.	2nd gen.	3rd gen.	Q	colour
quarks	u	s	t	$+2/3 e$	R, G, B
	d	c	b	$-1/3 e$	
leptons	ν_e	ν_μ	ν_τ	0	-
	e^-	μ^-	τ	$-1e$	

Table 2.1: The fermions of the Standard Model. The charge is in units of elementary charge which is positive for the proton and negative for the electron.

2.1.1 Leptons

Each lepton generation contains a charged lepton and a corresponding light neutral particle called a neutrino. The charged leptons are the electron (e^-), the muon (μ^-) and the tau (τ^-). The neutrinos are the electron neutrino (ν_e), the muon neutrino (ν_μ) and the tau neutrino (ν_τ). For each lepton there is a corresponding anti-lepton with opposite charge, for example the positively charged positron. Therefore, in total there are 12 leptons. All leptons interact via the weak force, whereas only the charged leptons interact via the electromagnetic force.

The first generation of leptons is the most familiar containing the electron and the electron neutrino.

2.1.2 Quarks

There are six flavours of quark arranged into three generations. The first generation contains the up (u) and the down (d) quarks, the second generation contains the charm (c) and strange (s) quarks and the third generation, the top (t) and bottom (b) quarks, often called the truth and beauty quarks. Unlike leptons, quarks carry fractional charge;

within each generation there is a quark with a charge of $2/3 e$ and the other with a charge of $-1/3 e$.

As well as electric charge, quarks carry an additional charge called colour charge. The colour charge allows the quarks to interact via the strong force in addition to the electromagnetic and the weak forces. For each quark, there is a corresponding anti-quark which has opposite electric charge and colour charge. Including the anti-quarks and the possible colour charges there are a total of 36 quarks.

The first generation of quarks is the most familiar, containing the up and down-type quarks that are the constituents of the proton and neutron, which with the electron, form atoms and all normal matter.

2.2 Fundamental Forces

There are, as far as is known, four fundamental forces of nature, the strong, weak, electromagnetic and gravitational forces. Table 2.2 summarises the interactions and the theory that describes them in order of decreasing strength¹

Force	Strength	Theory	Mediator
Strong	$\mathcal{O}(10^0)$	Quantum Chromodynamics	Gluon
Electromagnetic	$\mathcal{O}(10^{-2})$	Quantum Electrodynamics	Photon
Weak	$\mathcal{O}(10^{-13})$	Electroweak Dynamics	W and Z
Gravitational	$\mathcal{O}(10^{-42})$	General Theory of Relativity	Graviton?

Table 2.2: The known four fundamental forces [13].

The Standard Model describes the strong, weak and electromagnetic interactions. Each force is mediated by exchange of integer spin intermediate particles called bosons. The constituent bosons of the Standard Model are summarised in Table 2.3. The final boson included in this table is the Higgs boson which is described later in this chapter.

Gravity is not included in the SM as a complete quantum theory of gravity has not yet been developed. However, the gravitational force is very weak when compared to the

¹The strength quoted in the table is a rough approximation as the ‘strength’ will depend on the source and distance of a force [13].

Name	Mass (GeV)	Charge
Photon (γ)	0	0
$W^\pm$	80.4	$\pm 1e$
Z	91.2	0
gluon (g)	0	0
Higgs (H)	≈ 125	0

Table 2.3: The boson content of the Standard Model.

other three forces so its contribution to particle interactions is negligible for the results presented in this thesis.

2.2.1 Quantum Electrodynamics

The classical theory for electromagnetism was formulated by Maxwell over a century ago, and a quantum theory of electrodynamics was realised by Tomonaga, Feynman and Schwinger in the 1940s.

The electromagnetic interaction is responsible for the interaction between charged particles. The interaction is mediated by the massless photon, which means that the electromagnetic interaction is effective over an infinite range. The fundamental process of Quantum Electrodynamics (QED) is shown in Figure 2.1. The fine structure constant, α , specifies the strength of the interaction between charged particles and photon, and is given by

$$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}. \quad (2.2)$$

The Standard Model describes all the interactions of known particles in terms of gauge theories. A gauge theory is a theory that is invariant under a set of gauge transformations. In electromagnetism the gauge transformations are complex phase transformations of the fields of the charged particles. Requiring local gauge invariance will require that a massless vector particle be introduced, the photon, that mediates the electromagnetic interaction.

The Lagrangian density for a free Dirac field, ψ , is given by,

$$\mathcal{L} = i\bar{\psi}\gamma_\mu\partial^\mu\psi - m\bar{\psi}\psi. \quad (2.3)$$

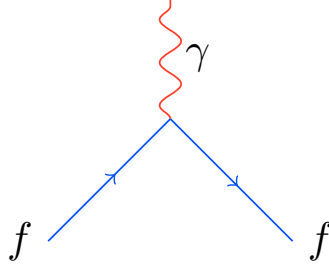


Figure 2.1: The elementary process for QED that all electromagnetic interactions can be reduced to, where f is a charged fermion and γ is a photon.

This Lagrangian is invariant under a ‘global’ phase transformation of the fermion field,

$$\psi(x) \rightarrow \psi'(x) = e^{i\omega} \psi(x), \quad (2.4)$$

$$\bar{\psi}(x) \rightarrow \bar{\psi}'(x) = e^{-i\omega} \bar{\psi}(x), \quad (2.5)$$

where ω is a global arbitrary parameter. The Lagrangian is said to exhibit global gauge invariance.

The family of transformations, $R = e^{i\omega}$, forms the Abelian group $U(1)$ which is the group of all unitary 1×1 matrices. Unitary refers to the property that $U^{-1} = U^\dagger$. Abelian refers to the property that all the elements in a group commute,

$$e^{-i\omega_1} e^{-i\omega_2} = e^{-i\omega_2} e^{-i\omega_1}. \quad (2.6)$$

If an infinitesimal transformation is considered then

$$\psi(x) \rightarrow e^{i\omega} \psi(x) \approx (1 + i\omega) \psi(x), \quad (2.7)$$

and it can be shown that the Lagrangian is unchanged by the transformation [14].

Global transformations introduce the problem that by making a transformation, it is

required that every space-time point must ‘know’ about that transformation. It would be preferable to require invariance under local transformations. More generally, the equation (2.4) can be rewritten as

$$\psi(x) \rightarrow e^{i\omega(x)}\psi(x), \quad (2.8)$$

where ω is now a function of the space time coordinate x . This is known as a local phase transformation. The infinitesimal transformation now becomes,

$$\psi(x) \rightarrow e^{i\omega(x)}\psi(x) \approx (1 + i\omega(x))\psi(x), \quad (2.9)$$

However, under this transformation the Lagrangian is now no longer invariant [14]. The gauge invariance can be restored if it is assumed that the fermion field interacts with a vector field, called a gauge field and denoted A_μ , with an interaction,

$$-e\bar{\psi}\gamma^\mu A_\mu\psi \quad (2.10)$$

where A_μ transforms under a gauge transformation as

$$-eA_\mu \rightarrow -e(A_\mu + \delta A_\mu(x)) \quad (2.11)$$

$$= -eA_\mu + \partial_\mu\omega(x) \quad (2.12)$$

and the new Lagrangian then becomes

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu(\partial_\mu + ieA_\mu) - m)\psi \quad (2.13)$$

$$= \bar{\psi}(i\gamma^\mu D_\mu - m)\psi \quad (2.14)$$

where the covariant derivative has been introduced,

$$D_\mu \equiv \partial_\mu + ieA_\mu. \quad (2.15)$$

The vector field, A_μ , couples with the electron, and can be identified as the physical photon field.

To complete the Lagrangian a kinetic term for the photon field should be added

which is quadratic in the derivative of the field. However, this term should not break the invariance under gauge transformations. This is achieved by defining the field strength tensor, $F_{\mu\nu}$,

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \quad (2.16)$$

which is gauge invariant. Therefore any term constructed only out of $F_{\mu\nu}$ may be added to the Lagrangian. A suitable term is $\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$ which is quadratic in the derivative of the field while remaining gauge invariant,

$$\mathcal{L} = \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi \quad (2.17)$$

Local gauge invariance has been restored with the introduction of the photon field. An interesting result is that the photon is required to be massless, as the introduction of a mass term for the photon, for example a term $\propto A_\mu A^\mu$, will break the gauge invariance.

2.2.2 Quantum Chromodynamics

The strong force is the force responsible for the interaction between particles that carry a colour charge: quarks and gluons. Unlike the electric charge, the colour charge can have three possible values, conventionally called ‘red’, ‘green’ and ‘blue’, as well as the corresponding anti-colour charges ‘anti-red’, ‘anti-green’ and ‘anti-blue’. The fundamental quark-gluon process of the strong force is shown in Figure 2.2. The strong force is mediated by eight massless gluons which themselves carry colour charge. This allows the gluons to self-interact which introduces gluon-gluon vertexes in addition to the quark-gluon vertex which are shown in Figure 2.3.

The coupling constant for the strong force, α_s , is given by,

$$\alpha_s = \frac{g_s^2}{4\pi} \approx 1, \quad (2.18)$$

which is approximately 100 times stronger than the electromagnetic force.

An interesting property of the strong force is that as the energy of the interaction increases the strength of the strong coupling decreases. This is known as asymptotic freedom; in high-energy experiments quarks appear to behave almost as free particles. However, at lower energies the coupling increases and quarks only appear in bound states.

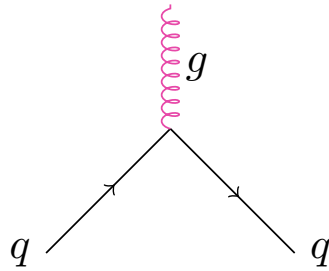


Figure 2.2: The quark-gluon vertex for QCD.



(a) Three-gluon vertex.

(b) Four-gluon vertex.

Figure 2.3: Fundamental gluon-gluon vertices.

This phenomenon is known as quark confinement.

The strong interaction is described by the theory of quantum chromodynamics (QCD). QCD follows from similar reasoning to QED, but with the Abelian $U(1)$ symmetry group replaced with the non-Abelian $SU(3)$ symmetry group of transformations on the quark colour fields.

Quarks form colour triplets under $SU(3)$ transformations for each quark flavour,

$$q_f = \begin{pmatrix} q_f^{red} \\ q_f^{green} \\ q_f^{blue} \end{pmatrix}. \quad (2.19)$$

The local gauge phase transformation under $SU(3)$ is given by,

$$q(x) \rightarrow e^{i\alpha_a(x)T_a} q(x), \quad (2.20)$$

where T_a are the generators of the $SU(3)$ group. The transformation breaks the invariance of the Lagrangian. In a similar way to the $U(1)$ transformation of QED, the gauge invariance can be restored by introducing the covariant derivative,

$$D_\mu \equiv \partial_\mu + igT_a G_\mu^a, \quad (2.21)$$

where eight gauge fields have been introduced, instead of the single field in QED. The gauge fields transform as,

$$G_\mu^a \rightarrow G_\mu^a - \frac{1}{g} \partial_\mu \alpha_a - f_{abc} \alpha_b G_\mu^c, \quad (2.22)$$

where the last term has been added to produce a gauge invariant Lagrangian due to the non-Abelian gauge transformation of $SU(3)$.

The final Lagrangian for QCD can now be written,

$$\mathcal{L} = \bar{q}(i\gamma^\mu \partial_\mu - m)q - g\bar{q}\gamma^\mu G_\mu^a - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}, \quad (2.23)$$

where the field strength tensor $G_a^{\mu\nu}$ is given by,

$$G_a^{\mu\nu} = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - gf_{abc}G_\mu^b G_\nu^c. \quad (2.24)$$

In a similar way to QED, the Lagrangian for interacting coloured quarks, q , and vector gluons, G_μ , results from the simple requirement of local colour phase invariance of the quark fields. Unlike the QED case, eight gauge fields are needed due to the three quark colour fields. Similar to QED, the gluons are required to be massless.

The field strength tensor, $G_a^{\mu\nu}$, introduces terms that are cubic and quadratic in G . These represent three and four vertex gluon interactions (Figure 2.3) and are a result of the non-Abelian nature of the $SU(3)$ group.

2.2.3 Weak Force

The weak interaction occurs between all fermions and is the interaction responsible for the radioactive decay of sub-atomic particles. Unlike the strong and electromagnetic forces, the weak force is mediated by the exchange of massive particles, the $W^\pm$ and Z bosons, which cause the weak interaction to have a very short range.

There are two kinds of weak interactions: charged and neutral, mediated by the W and the Z respectively.

The fundamental vertex for the neutral interaction is shown in Figure 2.4, where the Z interacts with any left-handed quark or lepton. The Z can mediate any process that can be mediated by the photon as well as processes involving neutrinos. The fundamental

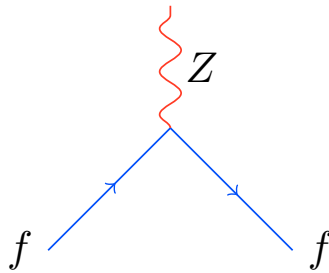


Figure 2.4: The fundamental vertex of neutral weak interaction.

vertices for the charged current are shown in Figure 2.5. The charged current has the

unique ability to change the flavour of quarks and leptons by the exchange of W bosons. The charged current will only interact with fermions of the same generation ($e^- \rightarrow \nu_e$ but never $e^- \rightarrow \nu_\mu$).

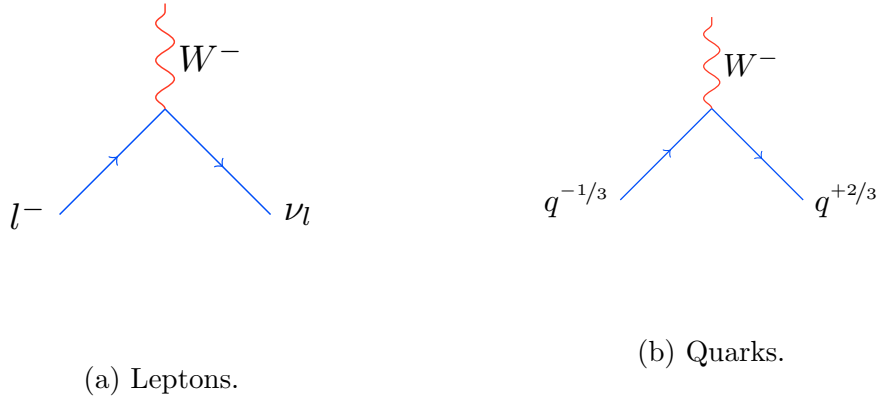


Figure 2.5: The fundamental vertices for charged weak interactions.

In a similar way to QCD, there is coupling of the W and Z bosons to one another as shown in Figure 2.6.

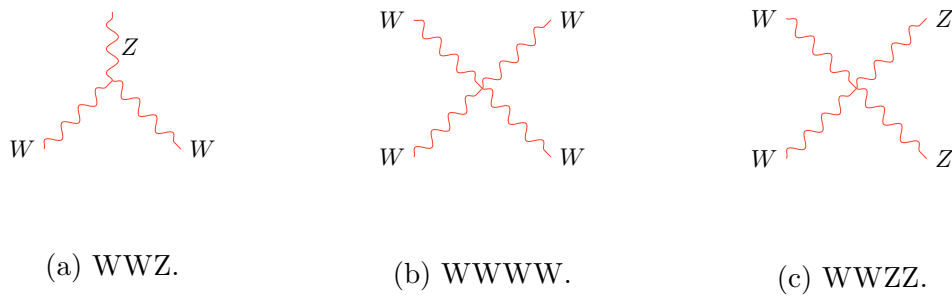


Figure 2.6: Direct couplings of the W and Z bosons to each other.

The weak interaction violates parity (P) and charge conjugation (C). A well known example of parity violation in weak interactions is the Wu experiment [15]. In the experiment, the β decay of nuclei (Cobalt-60) polarised by an external magnetic was

studied,

$$\begin{array}{ccccccc} \Rightarrow \Rightarrow & & \Rightarrow & \Rightarrow & & & \\ {}^{60}\text{Co} \rightarrow {}^{60}\text{Ni} + e^- + \bar{\nu}_e, & & & & & & \\ & & \leftarrow & \rightarrow & & & \end{array} \quad (2.25)$$

where the double arrows represent the spins and the single arrows represent the direction of the particle produced in the decay. The Cobalt-60 nuclei were aligned to the external magnetic field. By conservation of angular momentum, the neutrino and electron spins must be parallel and aligned with the magnetic field. By momentum conservation, the electron and neutrino must be produced in opposite directions which means that the electron and neutrino must have opposite helicity. By changing the direction of the magnetic field, the system undergoes a parity transformation

$$\begin{array}{ccccccc} \Leftarrow \Leftarrow & & \Leftarrow & \Leftarrow & & & \\ {}^{60}\text{Co} \rightarrow {}^{60}\text{Ni} + e^- + \bar{\nu}_e. & & & & & & \\ & & \leftarrow & \rightarrow & & & \end{array} \quad (2.26)$$

If parity was conserved then the electron would have no preference in direction. However, what was seen was that the electrons were preferentially emitted in the opposite direction to their spin. The weak interaction exhibits maximal parity violation. More generally, the $W^\pm$ boson is unique in that it only interacts with left-handed particles (or right-handed antiparticles).

2.2.4 Electroweak Interaction

The electromagnetic and weak interactions can be described by a unified theory known as the electroweak theory. The gauge group for the electroweak theory is given by,

$$U(1)_Y \times SU(2)_L. \quad (2.27)$$

The L subscript on $SU(2)$ indicates that the weak force couples to the left handed particles. The Y indicates that the $U(1)$ group is not the gauge group of QED but is that of the hypercharge which is connected to the electric charge (Q) and the charge associated with the weak interaction, called weak isospin (I), by the Gell-Mann-Nishijima

relation,

$$Q = I_3 + \frac{1}{2}Y. \quad (2.28)$$

The matter content of the theory are written as doublets or singlets. For the case of the leptons l_L is a left handed doublet,

$$l_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L, \quad (2.29)$$

and e_R is a right-handed singlet. For the case of the quarks, q_L is a left-handed doublet,

$$q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad (2.30)$$

and there are two right-handed singlets, the u_R and the d_R . In this description the left-handed fermions form isospin doublets and the right handed fermions are singlets. Therefore, under $SU(2)_L$ gauge transformations,

$$e_R \rightarrow e'_R = e_R \quad (2.31)$$

$$l_L \rightarrow l'_L = e^{-i\omega^a T^a} l_L \quad (2.32)$$

where T^a are the generators of $SU(2)_L$. The $SU(2)_L$ singlets are invariant so do not couple with the corresponding gauge bosons.

The matter fields transform under the $U(1)_Y$ gauge transformations as,

$$\psi \rightarrow \psi' = e^{-i\omega Y(\psi)} \psi \quad (2.33)$$

where Y is the hypercharge of the particle.

$$Y(l_L) = -\frac{1}{2}, \quad Y(e_R) = -1, \quad (2.34)$$

$$Y(q_L) = \frac{1}{6}, \quad Y(u_R) = \frac{2}{3}, \quad Y(d_R) = -\frac{1}{3}, \quad (2.35)$$

The Lagrangian for the electroweak interaction can be written as the sum of the gauge

boson and the fermion parts,

$$\mathcal{L}_{electroweak} = \mathcal{L}_{fermion} + \mathcal{L}_{gauge}. \quad (2.36)$$

The gauge part of the Lagrangian contains the kinetic terms and self interaction terms for the gauge fields,

$$\mathcal{L}_{gauge} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}W_{\mu\nu}^a W^{a\ \mu\nu} \quad (2.37)$$

where the first term contains the hypercharge field strength and the second term contains the $SU(2)_L$ field strength where the index, a , runs from 1 to 3.

$$\begin{aligned} B^{\mu\nu} &= \partial^\mu B^\nu - \partial^\nu B^\mu, \\ W_a^{\mu\nu} &= \partial^\mu W_a^\nu - \partial^\nu W_a^\mu + g\epsilon_{abc}W_b^\mu W_c^\nu. \end{aligned}$$

Four gauge fields have been introduced, three fields, W_μ^a , corresponding to the $SU(2)_L$ group and a single gauge field, B_μ , corresponding to the $U(1)_Y$ group. The physical W^+ and W^- bosons are superpositions of the W_μ^1 and W_μ^2 gauge fields,

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp W_\mu^2), \quad (2.38)$$

and the photon and Z boson are combinations of the B_μ and W_μ^3 gauge fields,

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}, \quad (2.39)$$

where θ_W is the Weinberg angle which is related to the coupling constants by

$$\begin{aligned} \sin \theta_W &= \frac{g'}{\sqrt{g^2 + g'^2}}, \\ \cos \theta_W &= \frac{g}{\sqrt{g^2 + g'^2}}. \end{aligned}$$

The fermion term has a lepton and a quark part,

$$\mathcal{L}_{fermion} = \mathcal{L}_{lepton} + \mathcal{L}_{quark}. \quad (2.40)$$

The quark and lepton Lagrangians are given by,

$$\begin{aligned}\mathcal{L}_{lepton} &= \bar{l}_L i\gamma^\mu \mathbf{D}_\mu l_L + \bar{e}_R i\gamma^\mu D_\mu e_R, \\ \mathcal{L}_{quark} &= \bar{q}_L i\gamma^\mu \mathbf{D}_\mu q_L + \bar{u}_R i\gamma^\mu D_\mu u_R + \bar{d}_R i\gamma^\mu D_\mu d_R,\end{aligned}$$

where the covariant derivative has again been introduced. The covariant derivative depends on the fermion field on which it acts. The covariant derivative for the left-handed fermion, for example, is given by,

$$\mathbf{D}_\mu = \partial_\mu + igT^a W_\mu^a + ig'Y(l^L)B_\mu, \quad (2.41)$$

whereas the covariant derivative for the right-handed fermion, for example a down quark, d_R , is given by,

$$D_\mu = \partial_\mu + ig'Y(d^R)B_\mu, \quad (2.42)$$

where g' and g are the two coupling constants, T^a are the three generators of $SU(2)_L$ group and W_μ^a and B_μ are the four gauge fields in the theory.

Higgs Mechanism

The Lagrangian, as it has been written so far, does not include terms for the mass of any of the particles. Adding in mass terms by hand will break the gauge invariance rendering the theory meaningless [11]. Specifically, only a theory that is gauge invariant can be renormalised [7].

The symmetry needs to be broken in some natural way. Spontaneous symmetry breaking (SSB) is a method to break the symmetry by requiring that the Lagrangian of a system remains invariant under a transformation, but the ground state is not invariant.

An example of spontaneous symmetry breaking is a point mass in a potential,

$$V(r) = \mu^2 \vec{r} \cdot \vec{r} + \lambda(\vec{r} \cdot \vec{r})^2 \quad (2.43)$$

where λ is positive. This potential is radially symmetric. A point mass sits at $\vec{r} = 0$. If $\mu^2 > 0$, as shown in Figure 2.7a then $\vec{r} = 0$ is the ground state and the mass will remain at this point. If $\mu^2 < 0$ then the potential will look like that given in Figure 2.7b. The system remains symmetric, but $\vec{r} = 0$ is no longer the ground state. To fall to the ground

state the mass has to “choose” a direction to fall. The choice will break the symmetry of the system; the potential remains symmetric, but the ground state is not. This is an example of SSB.

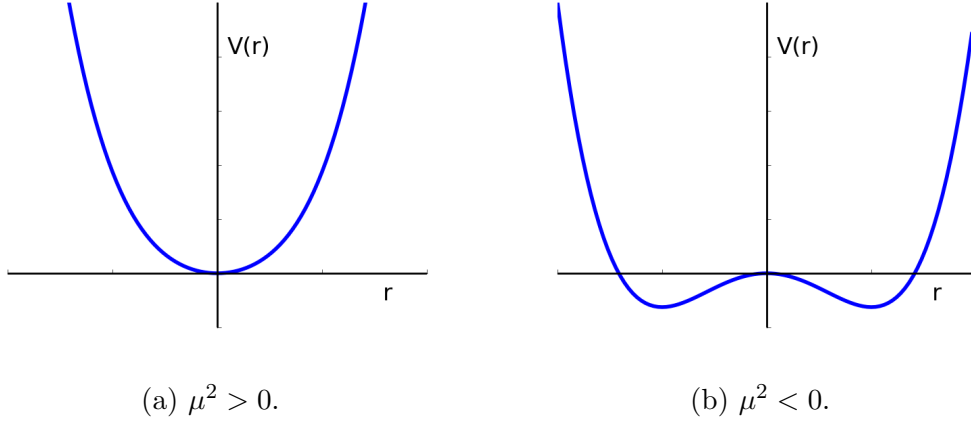


Figure 2.7: The potential $V(r) = \mu^2 \vec{r} \cdot \vec{r} + \lambda (\vec{r} \cdot \vec{r})^2$. For simplicity, the potential is shown for a single component of $\vec{r}$.

The application of SSB to the SM was studied by Brout, Englert, Higgs and others [16–19]. The result was a mechanism that spontaneously breaks the $SU(2)_L \times U(1)_Y$ symmetry called the Higgs mechanism².

The Higgs mechanism introduces four real scalar fields, that can be arranged in a complex doublet under $SU(2)$,

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad (2.44)$$

where,

$$\begin{aligned} \phi^+ &= \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2), \\ \phi^0 &= \frac{1}{\sqrt{2}}(\phi_3 + i\phi_4). \end{aligned}$$

²or the Brout-Englert-Higgs mechanism, or even the Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism.

The additional scalar part of the Lagrangian is,

$$\mathcal{L}_{scalar} = (D^\mu \Phi) (D_\mu \Phi) - V(\Phi), \quad (2.45)$$

where the potential is,

$$V(\Phi) = \mu^2 \Phi^\dagger \Phi + \lambda^2 (\Phi^\dagger \Phi)^2, \quad (2.46)$$

where λ and μ are free parameters. This Lagrangian is invariant under $SU(2)_L \times U(1)_Y$ transformations. By choosing $\lambda > 0$ and $\mu^2 < 0$ there are minima at

$$\Phi^\dagger \Phi = \frac{-\mu^2}{2\lambda}. \quad (2.47)$$

The potential at $\Phi = 0$ is unstable to small perturbations, and will fall to a lower energy ground state. The ground state does not have the same symmetry as the Lagrangian; by selecting a minimum the symmetry has become broken. An example choice of a minimum could be,

$$\phi_1 = \phi_2 = \phi_4 = 0, \quad (2.48)$$

and

$$\phi_3 = \frac{-\mu^2}{\lambda} \equiv v^2. \quad (2.49)$$

which results in a non-zero vacuum-expectation value,

$$\langle 0 | \Phi | 0 \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad (2.50)$$

Fluctuations around the vacuum-expectation value can be parametrised in terms of the real scalar field, H ,

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H \end{pmatrix} \quad (2.51)$$

where H is the physical Higgs field. The Lagrangian can be now written in terms of the

H field. The kinetic term, [11]

$$\begin{aligned} (D_\mu \Phi) (D^\mu \Phi) = & \frac{1}{2} (\partial_\mu H) (\partial^\mu H) + \frac{g^2 v^2}{4} W_\mu^+ W^{-\mu} \\ & + \frac{g^2 v^2}{8 \cos^2 \theta_W} Z_\mu Z^\mu + 0 A_\mu A^\mu \\ & + \text{interaction terms,} \end{aligned} \quad (2.52)$$

now includes mass terms for the gauge bosons,

$$M_W = \frac{1}{2} g v, \quad M_Z = \frac{1}{2} \frac{g v}{8 \cos^2 \theta_W}. \quad (2.53)$$

while the photon remains massless, $M_A = 0$.

The mechanism also introduces an additional boson with a mass $\sqrt{-2\mu^2}$, called the Higgs boson.

Fermion Masses and Yukawa Couplings

Another feature of the Higgs mechanism is that it also provides a way to introduce mass terms for the fermions, in a gauge invariant way, via the Yukawa coupling between the leptons and the Higgs field. The Lagrangian for this interaction for the electron can be written as,

$$\mathcal{L}_{yukawa} = -Y_e \bar{l}_L \Phi e_R + h.c. , \quad (2.54)$$

where Y_e is the coupling to the Higgs field known as the Yukawa coupling and h.c. stands for the hermitian conjugate. On substitution of Φ (from equation (2.51)), the Lagrangian for the Yukawa couplings becomes,

$$\mathcal{L}_{yukawa} = -\frac{Y_e}{\sqrt{2}} v (\bar{e}_L e_R + \bar{e}_R e_L) - \frac{Y_e}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R e_L) H \quad (2.55)$$

and if Y_e is chosen such that,

$$m_e = \frac{Y_e v}{\sqrt{2}} \quad (2.56)$$

then the Lagrangian simplifies to,

$$\mathcal{L}_{yukawa} = -m_e \bar{e} e - \frac{m_e}{v} \bar{e} e H \quad (2.57)$$

which represents a mass term for the electron and a coupling of the electron to the Higgs field proportional to the mass of the electron. All fermion masses can also be generated in a similar way [11, 14].

Higgs Boson Observation

On the fourth of July 2012, the two LHC experiments ATLAS and CMS both announced the discovery of a new boson that is compatible with the Standard Model Higgs boson [5, 6].

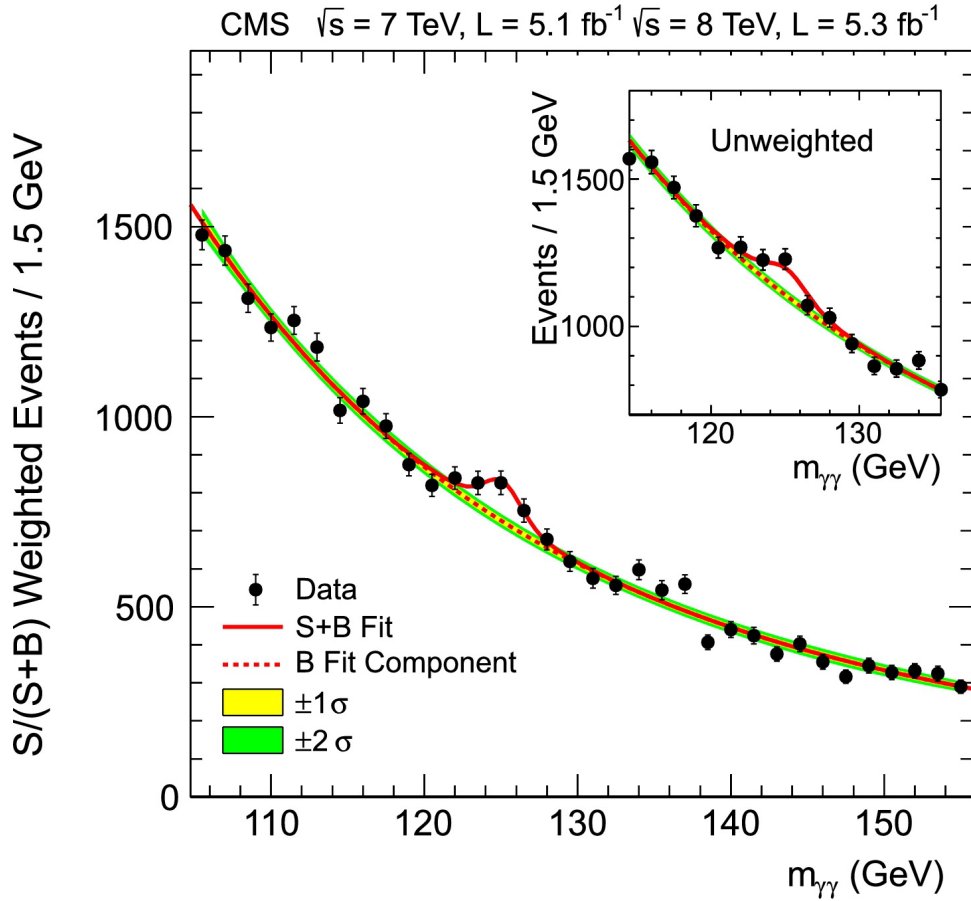


Figure 2.8: The diphoton invariant mass distribution observed in CMS data. Each event has been categorised and then weighted by the $S/(S + B)$ value of its category. The inset is the unweighted invariant mass distribution. A peak in the region of 125 GeV can clearly be seen. From [5].

The Higgs search was performed in many different decay channels over a wide mass

range from 100 up to 600 GeV. In the low-mass range, from 100 up to 160 GeV, a significant channel is the diphoton channel, where the Higgs decays to a pair of photons via a top or W loop. Figure 2.8 shows the diphoton invariant mass distribution measured in CMS. A peak in the region of 125 GeV can clearly be seen. After combining the observations in each of the channels, an excess of events was observed above what would be expected from only background events, with a local significance of 5.0σ at a mass near 125 GeV.

Chapter 3

W Bosons at the LHC

W boson production is an important process for physics studies at the LHC, not only for accurate measurements of the Standard Model, but also as a background to many processes from new physics. At the LHC, W bosons are produced at a high rate while offering a clean experimental signal with a final state consisting of, in the case of a leptonically decaying W, a single high p_T lepton with a large amount of missing transverse energy due to the neutrino in the event. The production of W bosons provides important information on the interacting partons within the colliding hadrons [20, 21].

This chapter will first describe the asymmetric production of W^+ and W^- bosons. The next section will describe the leptonic decay of the W and describe the electron charge asymmetry observable. The final section will show some theoretical predictions of the electron charge asymmetry.

3.1 W Boson Production

The dominant production process for a W boson at a proton-proton collider is given in equation (3.1), and shown in Figure 3.1.

$$h_1(p_1) + h_2(p_2) \rightarrow W + X \rightarrow \ell\nu_\ell + X. \quad (3.1)$$

The W boson is produced in the collision of a quark and an anti-quark from the two incoming protons, h_1 and h_2 , with momenta p_1 and p_2 ¹. X represents the accompanying

¹In this thesis, $p_1 = p_2 = 3.5$ TeV.

final state.

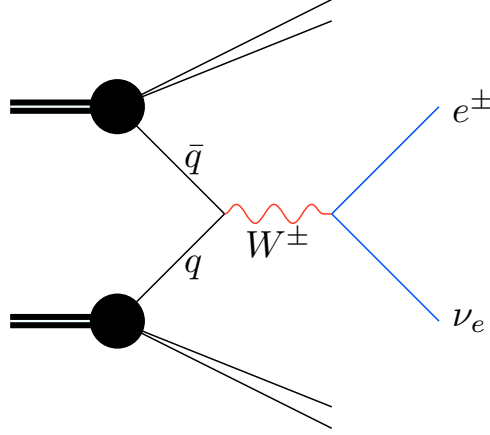


Figure 3.1: Diagram of a W boson production and leptonic decay at a hadron-hadron collider.

The W production cross section can be given by the convolution of the cross section at the parton level, and the parton distribution functions (PDF) of the protons,

$$d\sigma_{(h_1 h_2 \rightarrow W^\pm)}(p_1, p_2; Q^2) = \sum_{a,b} \int_0^1 dx_1 \int_0^1 dx_2 f_a^{h_1}(x_1, Q^2) f_b^{h_2}(x_2, Q^2) d\hat{\sigma}_{(ab \rightarrow W^\pm)}(x_1 p_1, x_2 p_2; Q^2), \quad (3.2)$$

where $\sum_{a,b}$ represents the sum over the initial parton states a and b , $f_a^h(x, Q^2)$ represents the proton PDF and $d\hat{\sigma}_{(ab \rightarrow W^\pm)}(x_1 p_1, x_2 p_2; Q^2)$ represents the partonic sub-process cross section. The ability to separate the complicated QCD process into a short-range perturbatively-calculable hard-scattering process and long-range experimentally-measurable parton densities is given by factorisation theorems.

Partonic Sub-Process

At leading order (LO) the process for a W^+ is

$$u + \bar{d} \rightarrow W^+ \rightarrow \ell^+ \nu_\ell \quad (3.3)$$

and for a W^- :

$$\bar{u} + d \rightarrow W^- \rightarrow \ell^- \bar{\nu}_\ell \quad (3.4)$$

Tree-level Feynman diagrams representing these processes are shown in Figure 3.2. At the LHC (a proton-proton collider), one parton is most likely to be a valence quark with a high fraction of the proton's momentum, and the other parton will tend to be a sea anti-quark with a lower fraction of the momentum than the quark. The difference in momentum of the partons causes the W bosons to tend to be produced at high rapidities.

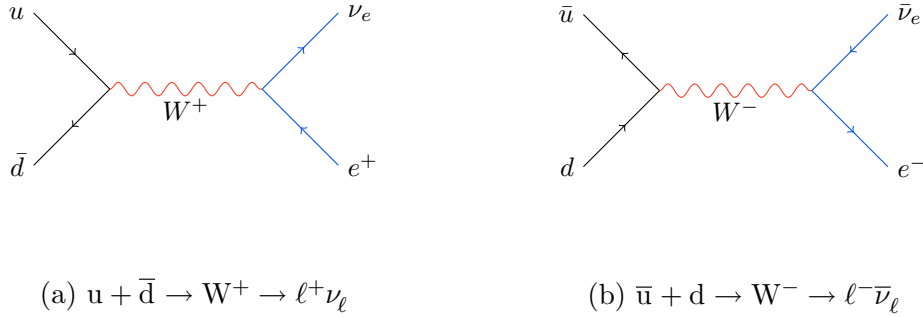


Figure 3.2: Tree-level diagrams for W^+ and W^- boson production and electron decay at a hadron-hadron collider.

Proton Parton Distribution Function

The proton PDF represents the number density of parton a that has a fraction between x and $x + dx$ of the momentum of the colliding hadron h at a resolution scale Q^2 .

The PDFs are obtained from global fits to experimental data [22]. Figure 3.3 (right) shows the proton PDF at $Q^2 \approx M_W^2$ from the MSTW group. The anti-quark parton densities $\bar{u}(x, Q^2)$ and $\bar{d}(x, Q^2)$ are relatively similar especially at the LHC energies, where the parton momentum fraction, x , tends to be small. However, the PDF for the

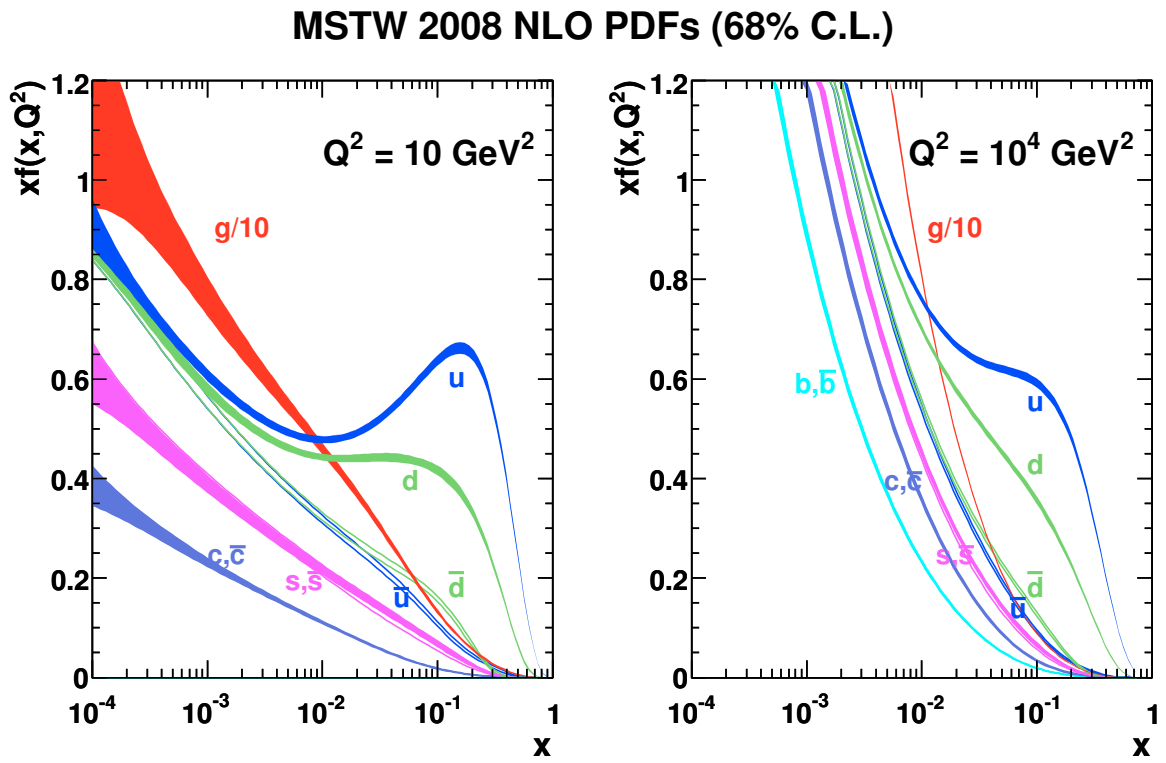


Figure 3.3: Proton PDFs at $Q^2 = 10 \text{ GeV}^2$ (left) and $Q^2 = 10^4 \text{ GeV}^2$ (right) from [22].

valence quarks in the proton differ, the up-type quark dominates over the down-type quark. This is due to the excess of up-type valence quarks with respect to down-type valence quarks in the proton (uud). This can be seen in the ratio of the up-type and the down-type PDFs,

$$R_{ud}(x, Q^2) = \frac{u(x, Q^2)}{d(x, Q^2)} > 1, \quad (3.5)$$

where $u(x, Q^2)$ are the up and down quark PDFs. Figure 3.4 shows the ratio of the up-type and down-type quarks. The ratio $R \approx 1$ for $x \ll 1$. This is due to the equal number of up-type and down-type sea quarks in the proton. The equal number of sea quarks, and the unequal number of valence quarks has the effect that if an up-type quark is picked at random from the proton, it is more likely to be a higher momentum valence quark, than if a down-type quark is picked. Therefore, an up-type quark will tend to have a greater fraction of the proton's momentum than a down-type quark.

3.1.1 W Boson Rapidity Distribution

The rapidity of a particle is defined as,

$$y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right), \quad (3.6)$$

where p_L is the longitudinal component (the component along the beam axis) of the momentum of the particle. It represents the boost along the beam axis required to go from the lab frame to the frame where the particle is produced perpendicular to the beam axis.

The rapidity distributions, y_W , for W^+ and W^- bosons produced at the LHC are shown in Figure 3.5. The W^+ cross section is greater than the W^- cross section. This is a consequence of the different production processes for W^+ and W^- bosons (shown in equation (3.3) and equation (3.4) respectively) and the PDF for the valence quarks in the proton differing as seen in Figure 3.4. The up-type quark PDF dominates over the down-type which leads to a greater W^+ production rate than W^- .

It is also seen in Figure 3.5 that the W^- tends to be produced more centrally whereas the W^+ can be produced at larger rapidities. This is due to up-type quarks tending to carry a greater fraction of the proton's momentum, x , than the down-type quarks as seen

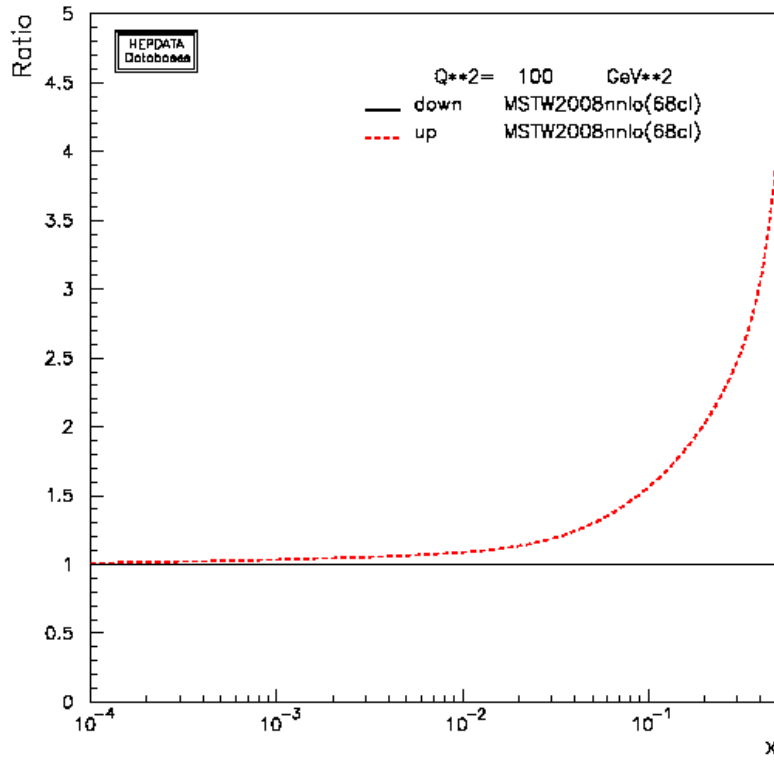


Figure 3.4: Ratio of up quarks to down quarks, R_{ud} at $Q^2 = 100 \text{ GeV}^2$. Generated from [23] using the MSTW2008nlo PDF sets [22].

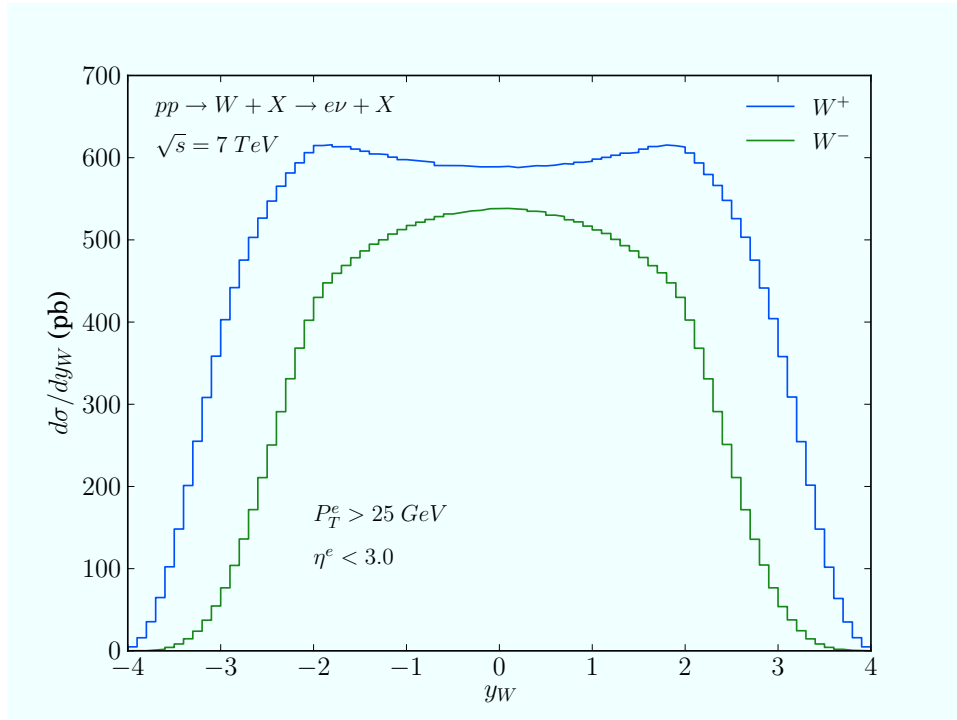


Figure 3.5: The rapidity distribution for W^+ and W^- bosons in $\sqrt{s} = 7 \text{ TeV}$ proton-proton collisions at the LHC. Generated with the MSTW2008nlo PDF set [22] interfaced with the MCFM generator tool [24].

in Figure 3.4.

The momentum fraction, x , of the interacting quarks is correlated with the rapidity of the W boson. Therefore, the ratio of u and d quarks as a function of momentum fraction, x , is directly related to the difference in the W^+ and W^- production cross sections as a function of the boson rapidity.

Therefore a measurement of the asymmetric production of W bosons, as a function of the rapidity of the boson, at the LHC provides important information on the ratio of the up-type and down-type quark parton densities as a function of x ($R_{ud}(x, Q^2)$) within the proton [21].

3.1.2 W Boson Charge Asymmetry

The $W^\pm$ boson charge asymmetry is defined as,

$$A_W(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W}, \quad (3.7)$$

where y_W is the boson rapidity, and $d\sigma(W^\pm)/dy_W$ is the $W^\pm$ production cross section at a fixed y_W . If $d\sigma(W^+) > d\sigma(W^-)$ then $A_W(y_W) > 0$, else if $d\sigma(W^+) < d\sigma(W^-)$ then $A_W(y_W) < 0$, and for symmetric $W^\pm$ boson production, $A_W(y_W) = 0$,

The prediction for the W boson charge asymmetry as a function of the boson rapidity is shown in Figure 3.6. $A_W(y_W) > 0$ and increases as the rapidity increases.

W bosons are identified by their decay to a lepton plus neutrino, however at hadronic colliders the neutrino longitudinal momentum cannot be determined which means that the W rapidity, y_W , cannot be measured. Instead what is studied is the charge asymmetry in the leptons that result from the W boson decaying leptonically.

3.2 W Boson Decay

The W boson will decay to either a lepton and neutrino, or a pair of up and down quarks. The branching fractions for the various decays are shown in Table 3.1. This thesis will consider the electron decay of the W boson which will occur in approximately 11% of W boson decays.

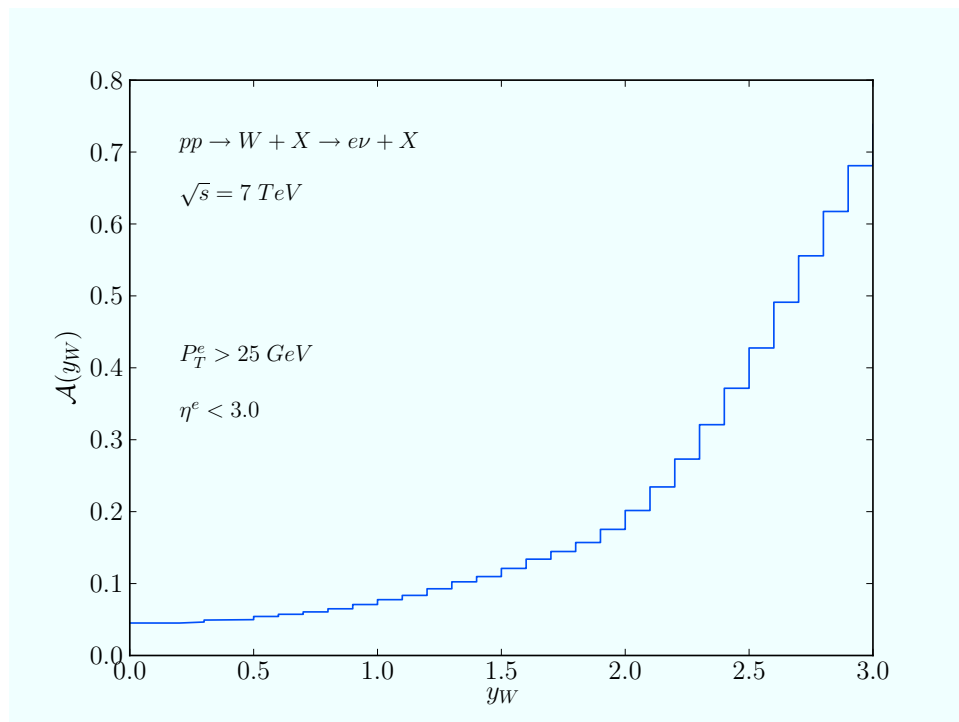


Figure 3.6: W boson charge asymmetry at LHC in $\sqrt{s} = 7 \text{ TeV}$ proton-proton collisions. Generated with the MSTW2008nlo PDF set [22] interfaced with the and the MCFM generator tool [24].

W ⁺ Decay Mode	Fraction (Γ_i/Γ)%
e ⁺ ν	10.75 ± 0.13
μ^+ ν	10.57 ± 0.15
τ^+ ν	11.25 ± 0.20
hadrons	67.60 ± 0.27

Table 3.1: Experimentally measured W⁺ decay modes. The decay modes of W⁻ are the charge conjugates of the W⁺. From [25].

3.2.1 Electron Pseudorapidity Distribution

The rapidity distributions of the charged leptons produced from $W^\pm$ decay are further complicated by the charge asymmetric decay of the $W^\pm$ boson. The asymmetric decay arises due to the $V - A$ coupling of the W boson to the annihilating $q\bar{q}$ pair and the decaying lepton pair.

At leading order (LO) the W^+ is produced in the annihilation of a u valance quark with a $\bar{d}$ sea-quark (equation (3.3)). If the parton masses are neglected the u is left-handed and the $\bar{d}$ is right-handed, as shown at the top of Figure 3.7.

In the W^+ decay the e^+ is right-handed and the ν_e is left-handed. Figure 3.7 shows that if the positron is produced in the same direction as the incoming $\bar{d}$ quark angular momentum is conserved and the decay is allowed. However the decay where the positron is produced in the same direction as the incoming u quark is forbidden. A similar argument holds true for W^- decays, where the e^- is produced preferentially in the direction of the d quark.

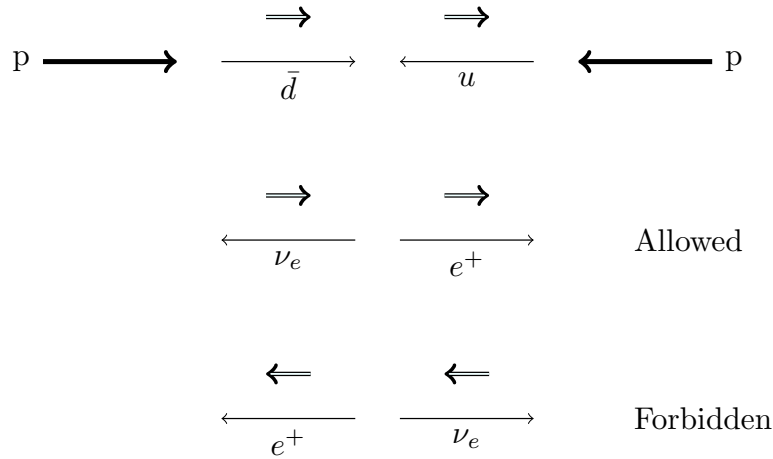


Figure 3.7: Preferred directions of electron spins in $W^+ \rightarrow e^+ \nu_e$ decay. The heavy arrows show the directions of the incoming protons, the thin arrows show the directions of the incoming quarks and the outgoing electron and neutrino. The double arrows show the spins. Modified from [26].

The distribution of the electron from $W^\pm$ decay in the massless limit is given by [12, 26],

$$\frac{1}{\sigma_{u\bar{d}}} \frac{d\sigma_{u\bar{d}}}{d\cos\theta_{\ell d}^*} = \frac{1}{\sigma_{d\bar{u}}} \frac{d\sigma_{d\bar{u}}}{d\cos\theta_{\ell d}^*} \propto (1 + \cos\theta_{\ell d}^*)^2 \quad (3.8)$$

where $\theta_{\ell d}^*$ is the scattering angle of the charged lepton with respect to the direction of the down-type quark or anti-quark, in the centre of mass system of the two quarks. The cross section is maximised when $\theta_{\ell d}^*$ is minimised and the charged lepton is produced in the same direction as the down-type quark.

The rapidity distribution of the electron is therefore a convolution of the electroweak correlations in equation (3.8) with the W rapidity described in Section 3.1.1. In proton-proton collisions the W^+ tends to be produced in the direction of the u. However, due to the electroweak correlations the charged lepton from the decaying W^+ will tend to be produced along the direction of the down-type quark and therefore will shift the rapidity distribution of the lepton to be more central. Similarly, W^- bosons tend to be produced more centrally, however the electroweak correlations will shift the charged lepton rapidity distribution to higher rapidities.

Figure 3.8 shows the Monte Carlo (MC) generated pseudorapidity distribution of electrons and positrons produced in $\sqrt{s} = 7$ TeV proton-proton collisions. The pseudorapidity is defined as

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right], \quad (3.9)$$

where θ is the polar angle. In the massless approximation, the pseudorapidity of the electron is equal to the rapidity.

3.2.2 Electron Charge Asymmetry

The electron asymmetry is defined in equation (3.10) analogously to the W boson asymmetry in equation (3.7), as the difference in the $W^+ \rightarrow e^+$ and $W^- \rightarrow e^-$ over the total $pp \rightarrow W(e\nu) + X$ cross section.

$$A_{the}(\eta) = \frac{\frac{d\sigma}{d\eta}(W^+ \rightarrow e^+\nu) - \frac{d\sigma}{d\eta}(W^- \rightarrow e^-\nu)}{\frac{d\sigma}{d\eta}(W^+ \rightarrow e^+\nu) + \frac{d\sigma}{d\eta}(W^- \rightarrow e^-\nu)} \quad (3.10)$$

The electron charge asymmetry has previously been studied in $p\bar{p}$ collisions by the

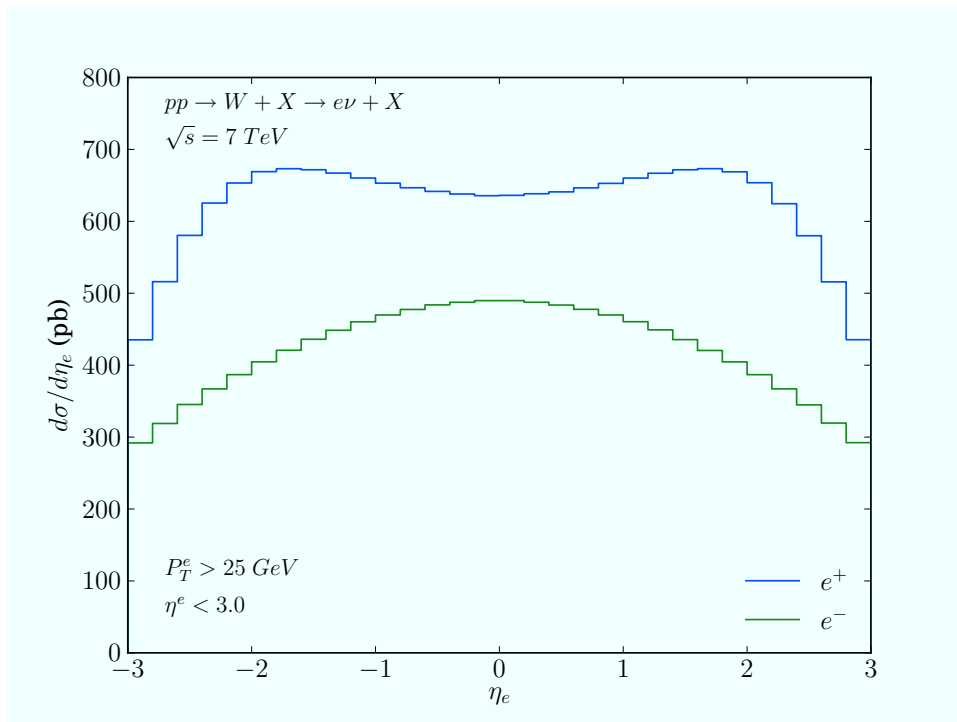


Figure 3.8: Electron and positron pseudorapidity, η_e , distributions in $\sqrt{s} = 7 \text{ TeV}$ proton-proton collisions. Generated with the MSTW2008nlo PDF set [22] interfaced with the MCFM generator tool [24].

CDF and D0 experiments at the Fermilab Tevatron collider [27, 28].

Figure 3.9 shows the electron charge asymmetry prediction for electron transverse momentum cuts of 25 GeV. The prediction was produced using the MSTW2008NLO PDF [22] set. Unlike the W asymmetry, the electron asymmetry turns over at $\eta \approx 2.25$. This effect is due to the electroweak correlations in the leptonic decay of the W boson.

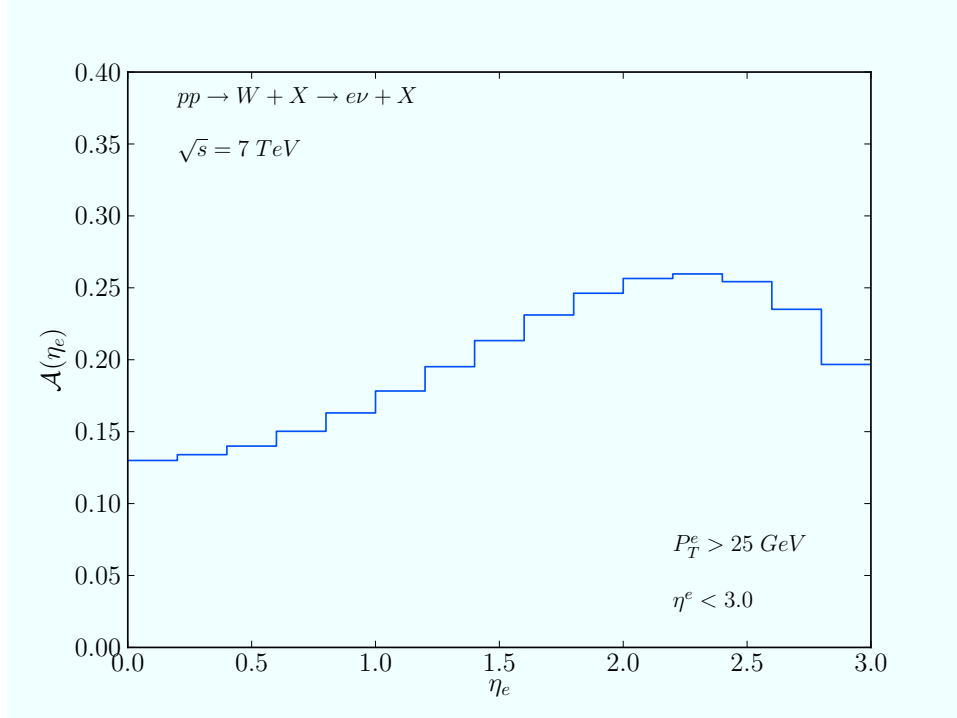


Figure 3.9: Electron charge asymmetry at LHC in $\sqrt{s} = 7$ TeV proton-proton collisions. Generated with the MSTW2008nlo PDF set [22] interfaced with the MCFM generator tool [24].

In an experiment, the cross section is not measured directly, instead what is measured are the electron and positron yields. The experimentally measured asymmetry is given by equation (3.11),

$$A_{exp}(\eta) = \frac{\frac{dN}{d\eta}(e^+) - \frac{dN}{d\eta}(e^-)}{\frac{dN}{d\eta}(e^+) + \frac{dN}{d\eta}(e^-)} \quad (3.11)$$

To get from the experimentally measured asymmetry to the lepton charge asymmetry, equation (3.12) must be used, which takes into account the experimental effects such as the luminosity ($\mathcal{L}$), high level trigger (ϵ_{HLT}), offline efficiency (ϵ_{off}) and the acceptance

(ϵ_{acc}) .

$$\frac{dN}{d\eta} = \mathcal{L} \frac{d\sigma}{d\eta} \epsilon_{HLT} \epsilon_{off} \epsilon_{acc} \quad (3.12)$$

As the asymmetry is a ratio, the luminosity, high level trigger and the offline efficiency can be cancelled out assuming that they are not asymmetric with respect to charge.

The acceptance cannot be cancelled, it is a function of transverse momentum of the electron, and these distributions will differ for e^- and e^+ . A correction due to acceptance effect could be included, but would be highly dependent on the choice of PDF set used to generate the corrections [27]. The measurements presented in this thesis do not correct for acceptance effects.

3.3 Theoretical Predictions of the Electron Charge Asymmetry

In this section predictions for the electron charge asymmetry are investigated in detail. The predictions are calculated using the MCFM [24] MC tool interfaced with the LHAPDF package [29]. LHAPDF provides an interface to many different PDF sets. For the following predictions, PDF sets from the MSTW [22] and CTEQ [30] collaborations are used.

Corrections for final state radiation (FSR) are not included in the predictions. In the measurements presented in the later chapters, FSR is considered as an additional contribution to the electron energy resolution and is corrected for, so the comparison of the measured asymmetry to the theoretical predictions is valid.

3.3.1 Uncertainty on Theoretical Predictions

The theoretical predictions of the electron charge asymmetry will have an error associated with the uncertainty on the PDF. The uncertainty on the PDF originates from the experimental errors on the data used in the global fits performed by each of the PDF collaborations.

Each PDF collaboration produces a set of PDFs that include the central value, or best fit to experimental data, and $2N$ error PDFs, where N is the number of free parameters

used in the global fit [31]. For each of the free parameters there is a PDF produced with the parameter at its upper error and another with the parameter at its lower error.

The uncertainty on the observable, in this case the lepton asymmetry, is found by producing $2N + 1$ theoretical predictions, one for each member of the PDF set. The predictions are then used to approximate the PDF uncertainty by using the ‘master equation’ [31, 32]. For the upper uncertainty,

$$\Delta A_{max}^+ = \sqrt{\sum_{i=1}^N [\max(A_i^+ - A_0, A_i^- - A_0, 0)]^2} \quad (3.13)$$

and for the lower uncertainty,

$$\Delta A_{max}^- = \sqrt{\sum_{i=1}^N [\max(A_0 - A_i^+, A_0 - A_i^-, 0)]^2} \quad (3.14)$$

where $A_i^\pm$ is the asymmetry prediction using the PDF with the positive/negative fluctuation of parameter i and A_0 is the prediction using the central value.

3.3.2 Prediction of the Electron Charge Asymmetry above 25 GeV

Figure 3.10 shows the theoretical predictions for the electron charge asymmetry for $p_T > 25$ GeV with PDF sets from the MSTW collaboration [22] and the CTEQ collaboration [30]. The uncertainty due to the PDFs is included. The predictions show a disagreement at low rapidities. The CTEQ prediction tends to be higher and the MSTW prediction lower. The disagreement is greater than the PDF uncertainty on the prediction.

3.3.3 Prediction of the Electron Charge Asymmetry above 30 GeV

Figure 3.11 shows the theoretical predictions for the electron charge asymmetry for $p_T > 30$ GeV with PDF sets from the MSTW collaboration [22] and the CTEQ collaboration [30]. Similar disagreement between the predictions at low rapidities is seen.

The asymmetry prediction at low rapidities is lower than the prediction with an electron cut at 25 GeV. The turning point in the asymmetry is also shifted to higher rapidities.

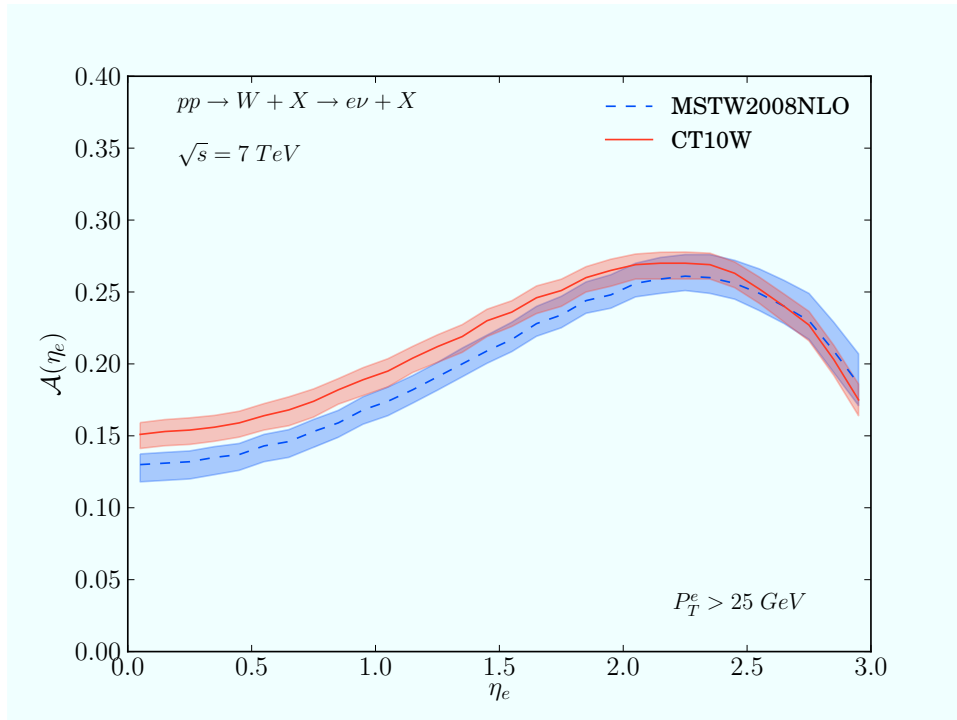


Figure 3.10: The theoretical electron charge asymmetry [33] for a $p_T > 25 \text{ GeV}$ with the PDF uncertainties for the MSTW08NLO [22] and CT10W [30] PDF sets. The uncertainties are 68% confidence level. The predictions are generated using the MCFM [24] generator.

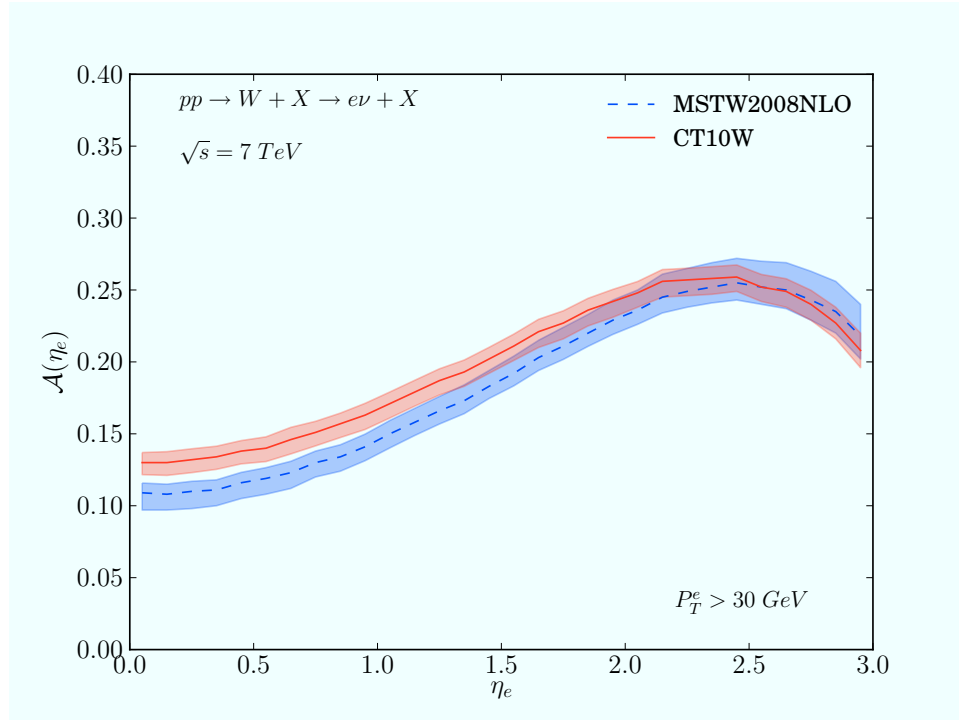


Figure 3.11: The theoretical electron charge asymmetry [33] for a $p_T > 30 \text{ GeV}$ with the PDF uncertainties for the MSTW08NLO [22] and CT10W [30] PDF sets. The uncertainties are 68% confidence level. The predictions are generated using the MCFM [24] generator.

Chapter 4

The LHC and the CMS Detector

4.1 Large Hadron Collider

The Large Hadron Collider (LHC) [34] is a circular synchrotron with a circumference of 27 km. It has been constructed in the existing tunnel 40-170 m beneath the border of France and Switzerland that was previously home to the LEP collider [35].

When operating at its design energy and luminosity it will collide beams of protons at a centre of mass energy of 14 TeV and a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. It is also designed to collide two 5.5 TeV beams of lead ions, and other species [34]. Table 4.1 summarises the machine parameters relevant to the CMS detector.

The main motivation for the LHC is to determine the mechanism that is responsible for electroweak symmetry breaking, of which the most favoured is the Higgs mechanism. The LHC is also designed to test the Standard Model at the TeV scale at high precision and to search for new particles predicted by theories beyond the Standard Model such as supersymmetric theories and theories involving extra dimensions. Figure 4.1 shows various cross sections for several physics processes as a function of the centre of mass energy. The cross section for many physics processes of interest, such as the Higgs cross section, σ_{Higgs} , are many orders of magnitude lower than the total inelastic cross section, σ_{tot} , and increase as a function of centre of mass energy. The large centre of mass energy and high luminosity of the LHC is needed to be able to probe the physics processes of interest with small cross sections.

The LHC is part of a larger accelerator complex as shown in Figure 4.2. Hydrogen gas

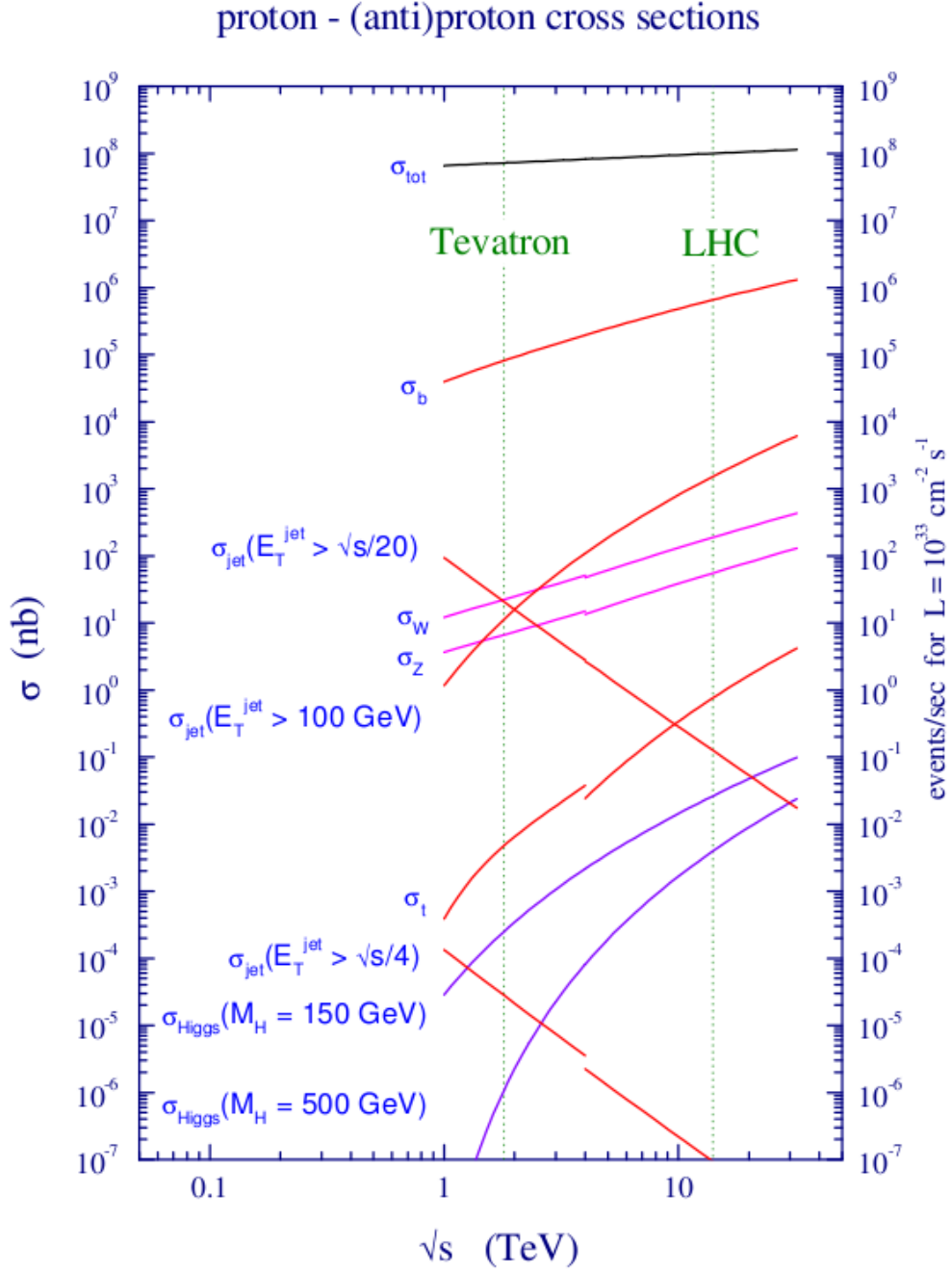


Figure 4.1: The theoretical production cross sections as a function of centre of mass energy for several Standard Model processes such as the b quark production cross section, σ_b , and the Higgs boson production cross sections, σ_{Higgs} . σ_{tot} is the total inelastic cross section. The cross sections that are of relevance to this thesis analysis are the W and Z boson cross sections σ_W and σ_Z respectively. From [32].

Parameter	p-p	Pb-Pb
Energy per nucleon (TeV)	7	2.36
Dipole field at 7 TeV (T)	8.33	8.33
Design luminosity ($\text{cm}^{-2} \text{s}^{-1}$)	10^{34}	10^{27}
Bunch separation (ns)	25	100
No. of bunches	2808	592
No. particles per bunch	1.15×10^{11}	1.15×10^{11}
β -value at IP (m)	0.55	0.5
RMS beam radius at IP (μm)	16.7	15.9
Luminosity lifetime (hr)	15	6
Average number of collisions/crossing	20	-

Table 4.1: The machine parameters relevant for the LHC detectors. From [36].

is first ionised to produce a cloud of protons, which are then accelerated by the LINAC2 linear accelerator to 50 MeV. Before being injected into the Proton Synchrotron (PS) the protons are injected into the Proton Synchrotron Booster (PSB) and accelerated to 1.4 GeV. In the PS the protons are grouped into bunches and the energy is increased to 25 GeV. The bunches are then accelerated in the Super Proton Synchrotron (SPS) to 450 GeV and then injected into the LHC.

There are four main experiments studying the collisions at the LHC. ALICE¹ is designed to study the quark gluon plasma that will be produced in the heavy ion collisions [37]. The LHCb² experiment is designed to study B-meson decays to measure CP violation [38]. ATLAS³ and CMS⁴ are general purpose detectors that are designed to search for a wide range of new physics [36, 39].

In addition there are two smaller special-purpose detectors. The LHCf⁵ is an experiment designed to measure the neutral particles emitted in the very forward region of LHC collisions. The goal of the experiment is to provide data for hadron interaction models that are used in the study of extremely high-energy cosmic-rays [40]. The goal of

¹A Large Ion Collider Experiment.

²Large Hadron Collider beauty.

³A Toroidal LHC Apparatus.

⁴Compact Muon Solenoid.

⁵Large Hadron Collider forward.

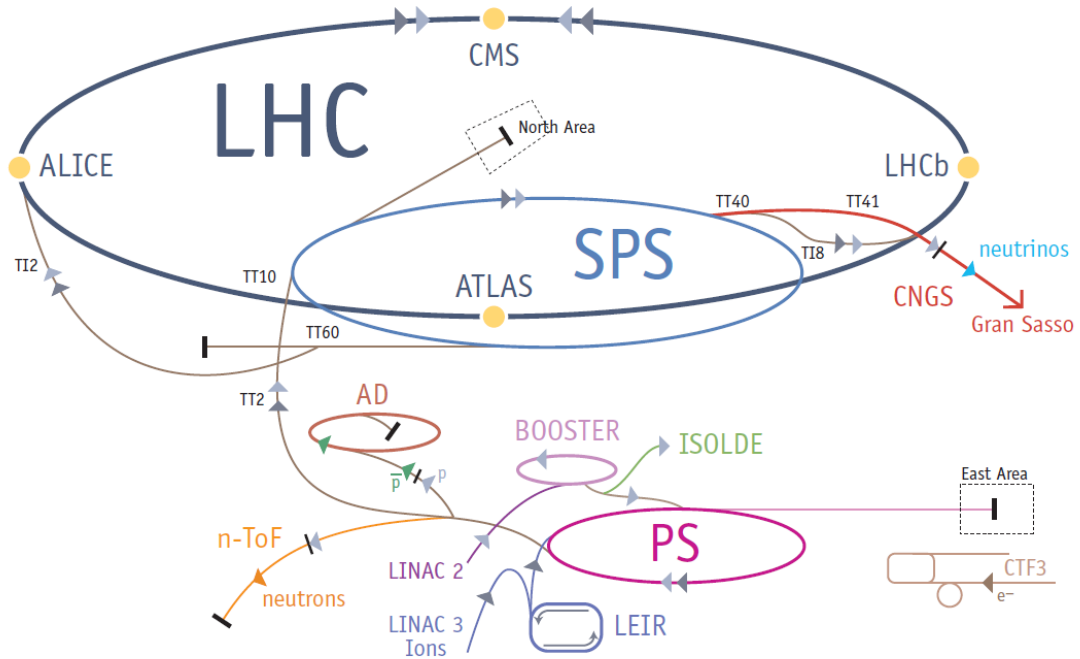


Figure 4.2: The LHC complex.

the TOTEM⁶ experiment is to measure the total proton-proton cross section and study the elastic and diffractive scattering at the LHC. The detector is located at either side of the CMS detector [41].

4.1.1 Operational History

In September 2008 the LHC was commissioned and the first beams were circulated. Before the first collisions could be delivered an interconnection between two of the dipole magnets failed. This led to a large amount of helium rapidly evaporating which caused considerable damage to the machine [42]. Due to this incident it was decided that, after the repairs, the LHC should be run at a lower centre of mass energy of 7 TeV until the quench protection system could be upgraded and the interconnections thoroughly verified for higher currents [43].

The LHC was repaired by the end of 2009 and the first collisions at a record energy of 2.36 TeV were delivered in November. From March to November 2010 the LHC operated

⁶TOTAL Elastic and diffractive cross section Measurement.

at 7 TeV delivering 46.4 pb^{-1} of proton-proton collisions of which 36.1 pb^{-1} was certified for analysis [35]. In November and December 2010 the LHC produced lead ion collisions at 2.36 TeV.

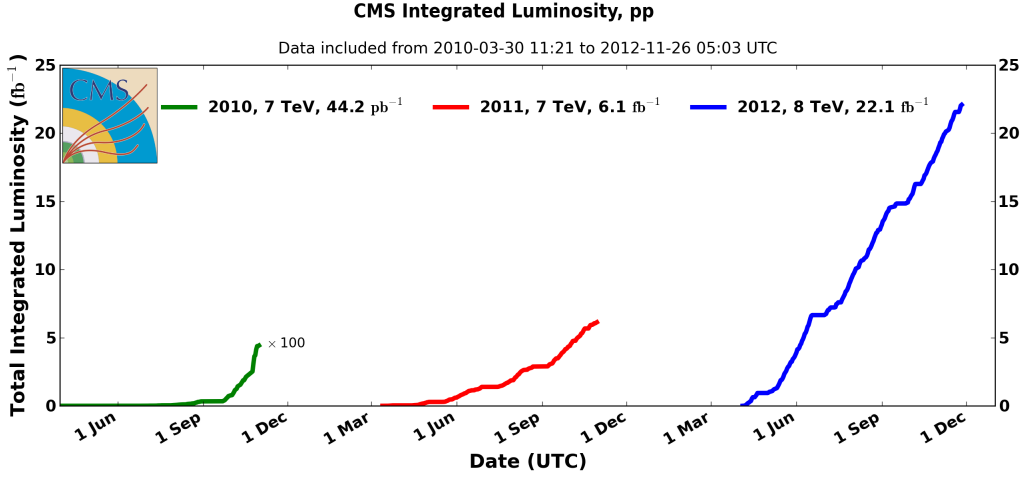


Figure 4.3: The luminosity delivered by LHC and recorded by CMS in 2010, 2011 and 2012. From [44].

The target for running in 2011 was to deliver 1 fb^{-1} of data. This was achieved by June. The target was increased to 5 fb^{-1} of data for 2011 which was achieved by October. In 2012 the LHC was operated at a centre of mass energy of 8 TeV and a total of 22.1 fb^{-1} of data was collected by December. The luminosity delivered by LHC and recorded in CMS in 2010, 2011 and 2012 is shown in Figure 4.3 [44].

The analysis presented in the following chapters is based on the 36.1 pb^{-1} of data from 2010 and 840 pb^{-1} of data from the first half of 2011.

4.2 CMS Detector

CMS [36] is one of the two general purpose detectors designed to study LHC collisions. The main design parameters for the CMS detectors are listed in Table 4.2.

The design goals of the CMS detector are:

- Good muon identification and momentum resolution and the ability to unambiguously assign charge to muons with $p_T < 1 \text{ TeV}$

Parameter	CMS
Total weight (tons)	12,500
Overall diameter (m)	15
Overall length (m)	20
Magnetic field for tracking (T)	4
Solid angle for energy measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 9.6$
Solid angle for precision measurements ($\Delta\phi \times \Delta\eta$)	$2\pi \times 5.0$
Total cost (CHF)	550×10^6

Table 4.2: Main design parameters of the CMS detector. From [45].

- Good charged particle momentum resolution and reconstruction in the tracker.
- Good electromagnetic energy resolution.
- Good resolution of missing transverse energy and dijet mass.

The design of CMS meets these requirements while overcoming significant experimental challenges. At design luminosity, approximately 1 billion inelastic events will occur in CMS every second, whereas CMS is limited to storing the data of only ≈ 100 events within that time. The detector must be able to reduce this rate with a trigger to accept events that are interesting from a physics perspective and reject events otherwise.

In addition to this challenge, each event of interest will have on average 20 inelastic events superimposed on it. This results in around 1000 charged particles produced every 25 ns, which require the detectors to have a high granularity with a good time resolution to ensure a low occupancy. The large flux of particles will also produce high radiation levels which required radiation hard detectors and electronics.

An overview of the detector is shown in Figure 4.4. Starting at the interaction point in the centre of the detector and moving radially outwards, CMS comprises the pixel tracker, the silicon microstrip tracker, the lead-tungstate electromagnetic calorimeter, the sampling brass-plate hadronic calorimeter, a 4 T superconducting solenoid magnet, an outer hadronic calorimeter and four muon chambers.

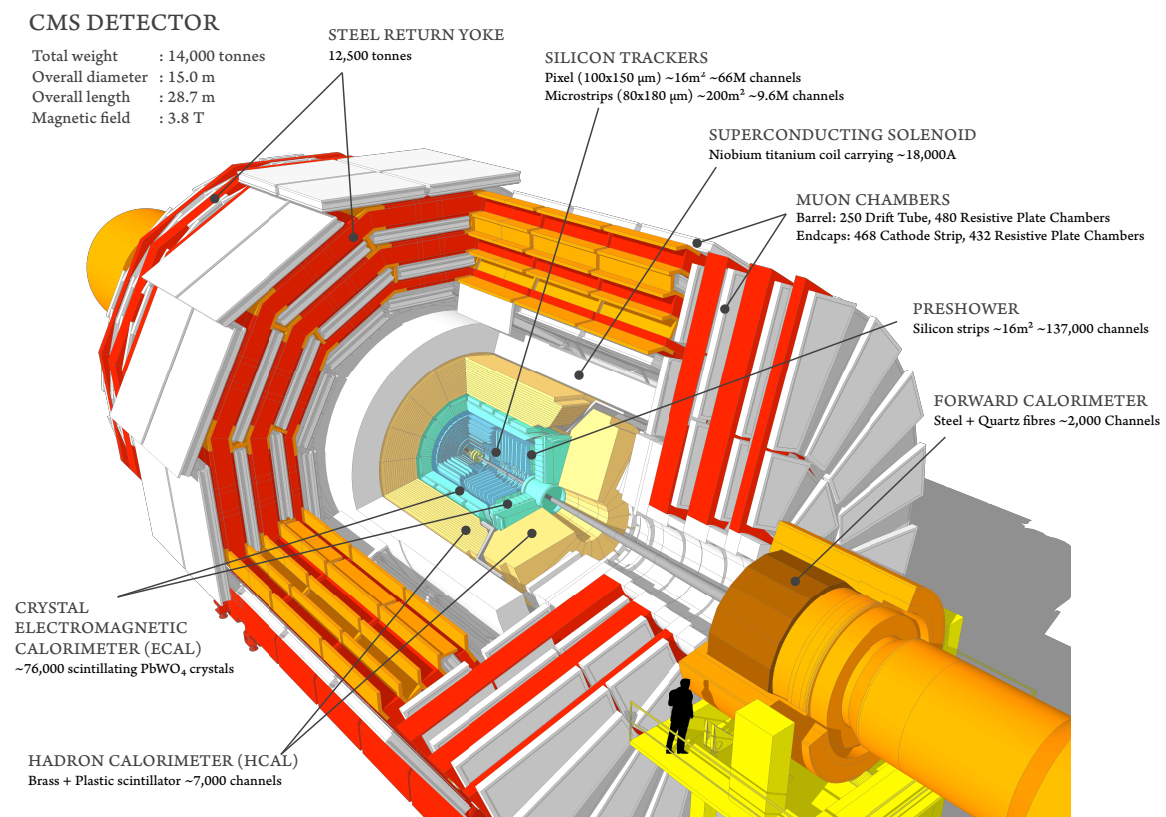


Figure 4.4: Diagram of the CMS detector. From [46].

4.2.1 Magnet

A large superconducting solenoid provides the basis for the design of the CMS detector, and is the main structural support for the detector components in the barrel region.

The superconducting magnet in CMS produces a 4 T field in a bore of 6 m diameter and 12.5 m length. While operating at full current the magnet stores 2.6 GJ of energy. A large magnetic field is needed to give CMS a large bending power and the ability to precisely measure the momentum of high-energy charged particles. The solenoid bore is large enough that the tracking detectors and the calorimetry can fit inside it [36].

The magnetic flux is returned through a 1.8 m thick saturated iron yoke which is interleaved with the muon detector.

4.2.2 Tracking

The inner tracker is designed to accurately and efficiently measure the trajectories of charged particles produced in collisions at the centre of CMS. The tracker is also required to be able to reconstruct secondary vertices from the decay of long-lived particles. At the design luminosity of the LHC it is expected that every 25 ns an average of 1000 particles will traverse the inner detector; therefore, it is required that the tracker has a high granularity and a fast response while remaining resilient to radiation damage.

A quadrant of the cross sections of the barrel part of the CMS tracker is shown in Figure 4.5. The tracker utilises silicon pixel detectors in the innermost layers where the particle flux is the highest. Outside of the pixel detector, the tracking detector comprises several layers of silicon microstrip detectors where the particle flux is smaller. The total active area of silicon in the CMS tracker is over 200 m² [36].

Pixel Tracker

The pixel tracker consists of three layers of hybrid silicon pixel detectors in the barrel region and two in the endcap region. The barrel layers are positioned at radii of 4.4, 7.3 and 10.2 cm and have a length of 53 cm. The two layers in each endcap are located at $|z| = 34.5$ and 46.5 cm with an inner radius of 6 cm and an outer radius of 15 cm.

A close up view of the pixel tracker is shown in Figure 4.6. Each pixel has a surface area of $100 \times 150 \mu\text{m}$ which results in an average particle occupancy of $\mathcal{O}(10^{-4})$ per pixel

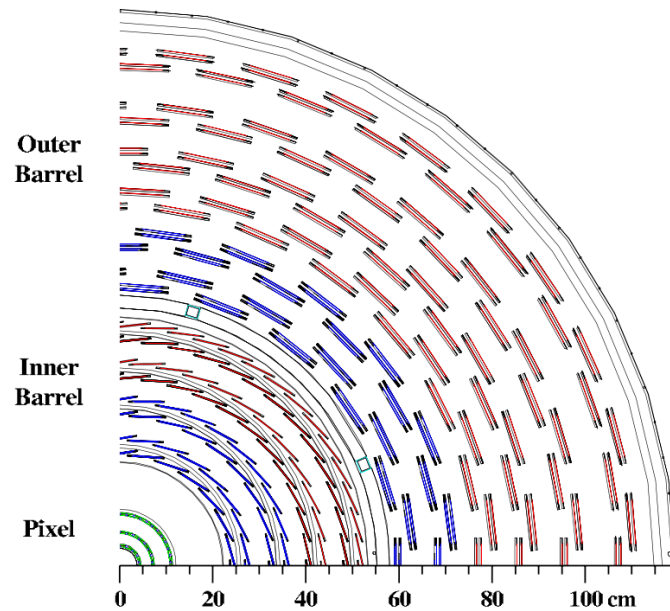


Figure 4.5: A quadrant of the cross section of the barrel part of the CMS tracker. From [47].

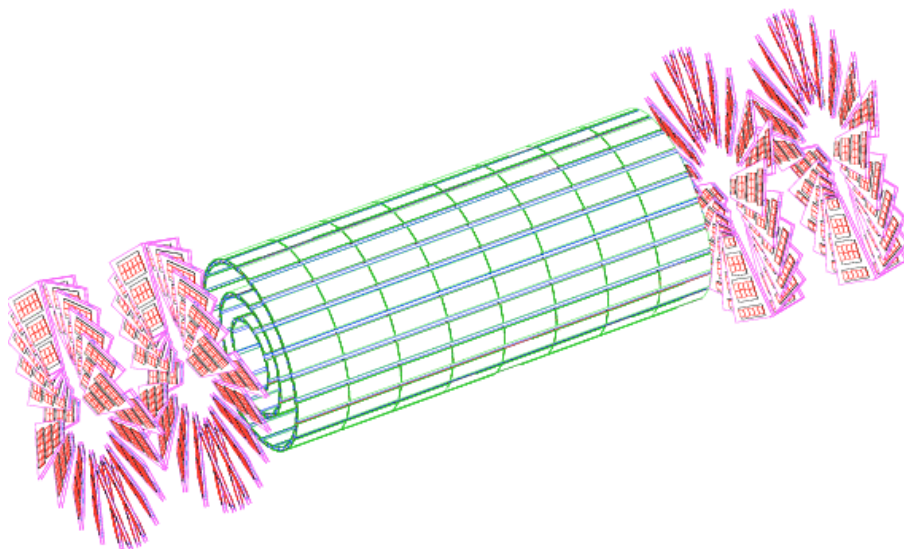


Figure 4.6: The layout of pixel detector in the CMS tracker. From [36].

per crossing.

Strip Tracker

The barrel strip tracker comprises two parts, the inner (TIB) and outer (TOB) trackers. The TIB is made of 4 layers and covers the longitudinal region $|z| < 65$ cm and the region $20 < r < 55$ cm in the radial direction. The TIB utilises microstrip detectors with a cell size of $10 \text{ cm} \times 80 \text{ }\mu\text{m}$ with an average occupancy of $\approx 2\text{-}3$ %.

The TOB is formed of 6 layers with a half-length of $|z| < 110$ cm. In this region the flux is low enough to allow for the use of larger pitch silicon microstrips with a cell size of $25 \text{ cm} \times 180 \text{ }\mu\text{m}$ with an average occupancy of ≈ 1 %.

The endcaps are separated into the Tracker End Cap (TEC) and the Tracker Inner Disks (TID). The TEC is split into nine disks and covers the region $120 \text{ cm} < |z| < 280$ cm. The TID comprises three rings and fills the gap between the TEC and the TIB.

4.2.3 Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL) is designed to measure the energy of electrons and photons with a high resolution. It has a fine lateral granularity to help with shower separation. It is a hermetic, homogeneous calorimeter comprising 61200 individual lead tungstate ($PbWO_4$) scintillation crystals in the barrel region ($|\eta| < 1.479$) closed by 7324 crystals in each of the two endcap parts ($1.479 < |\eta| < 3.0$) [48].

Lead tungstate crystals are ideally suited for this since the scintillation decay time is similar to the LHC bunch crossing time, with 80% of light being produced within 25 ns. They also have a short radiation length ($X_0 = 0.89$ cm) and Moliere radius (2.2 cm) as well as being radiation hard (up to 10 mrad).

A disadvantage to using lead tungstate is that the light output of the crystals is relatively low and changes with temperature. This is overcome by using photodetectors with an intrinsic gain and maintaining a stable temperature (within 0.1 °C).

Silicon avalanche photodiodes (APDs) are used to detect the scintillation light in the barrel and vacuum phototriodes (VPTs) are used in the endcap parts.

The barrel section of the ECAL (EB) surrounds the inner tracker. It comprises 36 identical supermodules that each cover a half length of the barrel ($0 < |\eta| < 1.479$) and 20° in ϕ . Each supermodule contains 1700 crystals arranged in a ϕ - η grid with

each crystal mounted in a “semi-projective” geometry, and aligned 3° off the nominal interaction vertex. The alignments in the longitudinal and transverse planes are shown in Figure 4.8 and Figure 4.7 respectively. The non-pointing geometry prevents particles escaping through the gaps between the crystals [48]. Each crystal has a cross section of $22 \times 22 \text{ mm}^2$ and a length of 230 mm ($25.8 X_0$).

The endcaps (EE) are formed of two “Dees”, semi-circular aluminium plates which support the “supercrystals”, 5×5 arrays of crystals. The crystals are mounted to point away from the nominal interaction vertex by a small angle in a similar way to the barrel. Unlike the barrel the crystals are arranged in an x - y grid. Installed in front of the endcap ECAL is a preshower system which helps with the rejection of π^0 [36].

Performance

Using a 100 GeV test beam, the energy resolution of the ECAL was found to be [36],

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2 \quad (4.1)$$

$$= \left(\frac{2\%}{\sqrt{E}}\right)^2 + \left(\frac{124 \text{ MeV}}{E}\right)^2 + (0.26\%)^2 \quad (4.2)$$

where S is the stochastic term, N is the noise term and C is the constant term. The measured ECAL energy resolution is shown in Figure 4.9. The stochastic term is due to the statistical fluctuations in the particles produced in the electromagnetic shower. The noise term is due to electronic noise and pile-up. The constant term is due to errors such as non-uniform signal generation and calibration errors [36].

4.2.4 Hadronic Calorimeter

The hadronic calorimeter (HCAL), in addition to the electromagnetic calorimeter, is designed to measure the energy of hadron jets and the missing transverse energy (E_T^{miss}) which are important signatures in many physics studies at the LHC.

The HCAL is a brass/scintillator sampling hadron calorimeter that covers the region up to $|\eta| < 3.0$. The scintillation light is channelled by wavelength shifting fibres, that are embedded in the scintillation tiles, to hybrid photodiodes that can operate in the high axial magnetic field [36].

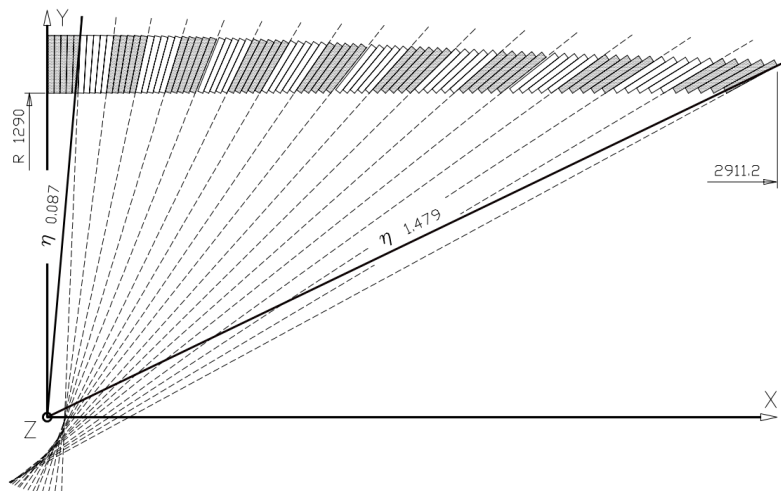


Figure 4.7: The crystal alignment in the longitudinal view. The dotted lines show the alignment of the edge of the crystals. A single supermodule is shown. From [48].

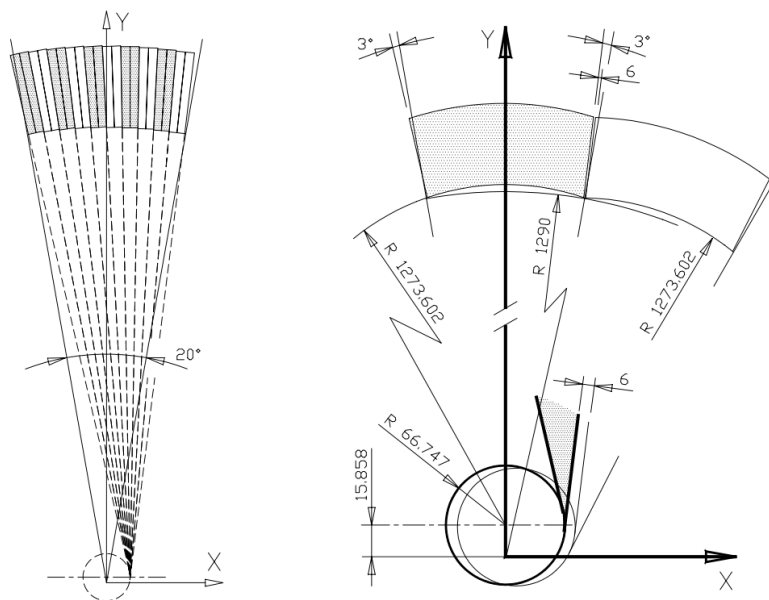


Figure 4.8: The tilt of the ECAL crystals in the transverse plane (left) and the alignment of the supermodules (right). The dotted lines show the alignment of the crystal edges. From [48].

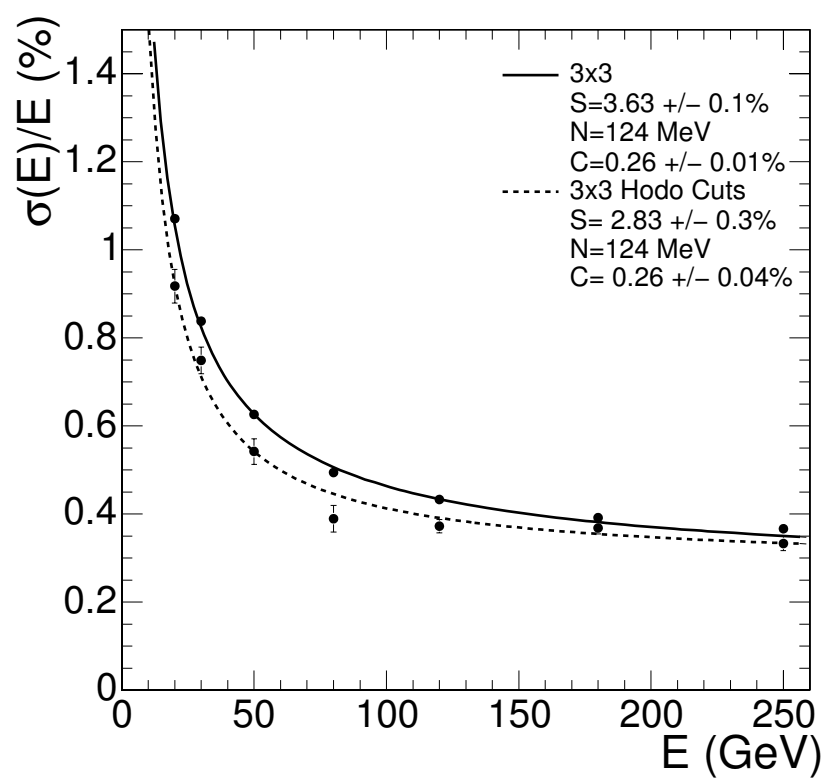


Figure 4.9: Energy resolution σ/E of ECAL as a function of electron energy E . From [36].

The barrel hadron calorimeter (HB) covers the region ($|\eta| < 1.4$) and the hadron endcap covers the region $1.4 < |\eta| < 3.0$.

The barrel hadron calorimeter is positioned between the ECAL and the inside of the solenoid magnet coil ($1.77 \text{ m} < r < 2.95 \text{ m}$). The strong constraints imposed by the dimensions of the solenoid magnet results in the HB having an insufficient amount of material to absorb the hadronic shower in the central region. To overcome this limitation the outer hadronic calorimeter (HO) or tail catcher, has been added around the solenoid magnet to increase the effective thickness of the hadron calorimetry to over 10 interaction lengths. This provides better protection against punch-through to the muon system.

The Forward Calorimeter

In the forward region ($|\eta| > 3$) energy measurements are made with the forward hadronic calorimeter, situated 11 m from the interaction point. The main role of the forward calorimeter is to improve the E_T^{miss} measurement and to tag jets in the forward direction.

The forward hadronic calorimeter is an iron/quartz-fibre calorimeter where the Cherenkov light is detected by photomultipliers. The calorimeter needs to be radiation hard due to the very large flux in the forward region. However, it is still expected that after 10 years of operation the light output will be reduced by about 30% due to the level of radiation [36].

Performance

Figure 4.10 shows the jet energy resolution for three parts of the HCAL measured in test beams. The granularity of the sampling in each region of the HCAL is such that the resolution is similar in each.

The performance of the missing transverse energy (E_T^{miss}) is shown in Figure 4.11 in QCD events. The E_T^{miss} resolution is $\sigma(E_T^{\text{miss}}) \approx 1.0\sqrt{E_T}\text{GeV}$ and the average E_T^{miss} is $\langle E_T^{\text{miss}} \rangle \approx 1.25\sqrt{E_T}\text{GeV}$ [36].

4.2.5 Muon System

The muon system lies outside of the CMS solenoid and the outer HCAL detectors. It is designed to have three functions; to identify muons, measure the momentum of muons and trigger on muons. To perform these functions the muon system consists of several

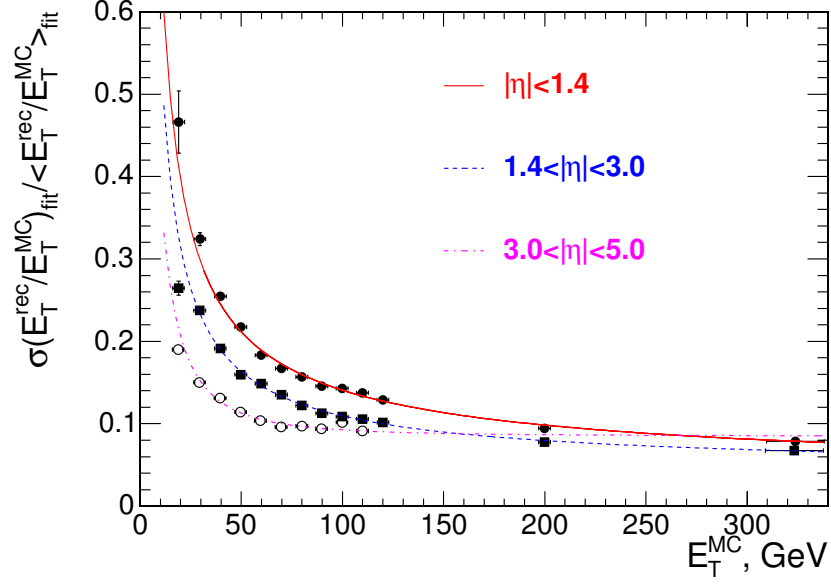


Figure 4.10: The jet transverse energy resolution as a function of jet transverse energy for barrel jets ($|\eta| < 1.4$), endcap jets ($1.4 < |\eta| < 3$) and forward jets ($3 < |\eta| < 5$). From [36].

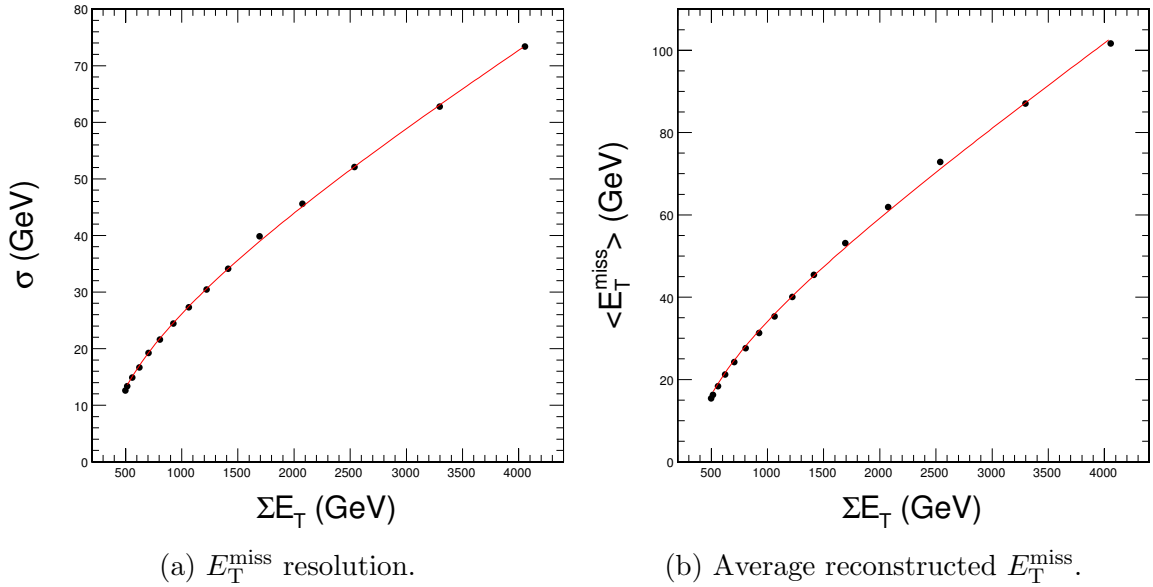


Figure 4.11: The missing transverse energy performance as a function of the $\sum E_T$ for QCD events with pile-up. From [36].

different types of detectors due to the different background rates and magnetic fields in each region of the detector. The layout of the CMS muon system is shown in Figure 4.12.

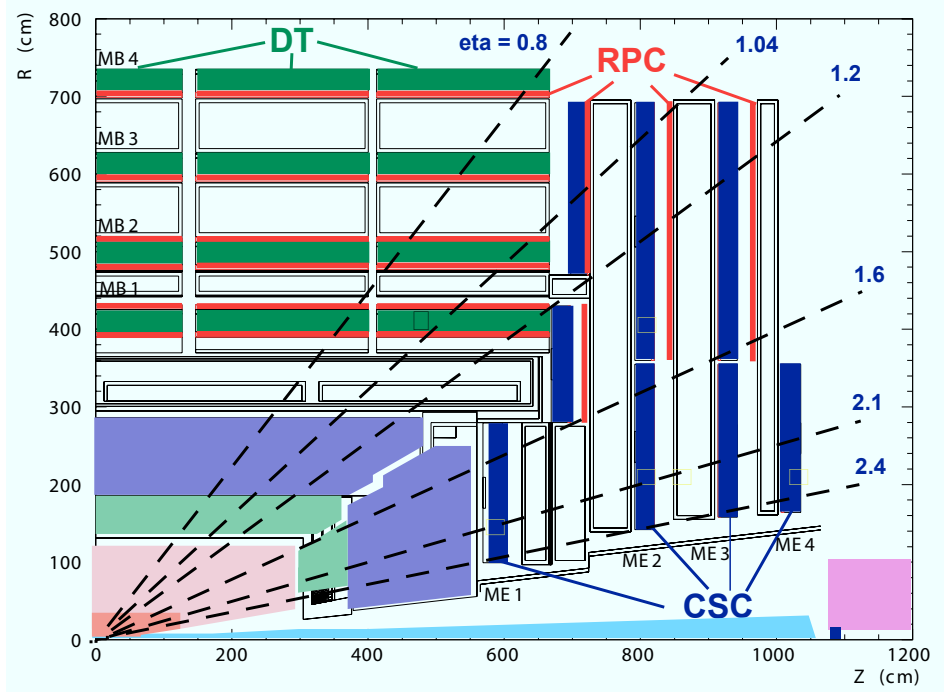


Figure 4.12: The layout of a quarter of the CMS muon system. From [36].

Drift Tubes

In the barrel region ($|\eta| < 1.2$) where the background rate is low and the residual magnetic field is small, aluminium drift tubes (DT) are used, arranged in four stations interleaved in the flux return plates. Each station contains 12 layers, eight to measure the coordinate in the r - ϕ plane and four to measure the z direction (except the fourth station which only measures the r - ϕ plane).

Cathode Strip Chambers

In the endcaps ($0.9 < |\eta| < 2.4$), where the muon and background rate is high and the magnetic field is also high, cathode strip chambers (CSC) are used. The CSCs are arranged in four stations in each endcap. Their faces are perpendicular to the beam line, and are placed between the flux return plates. The cathode strips of each chamber run

radially away from the beam line whereas the anode wires run perpendicular to the strips; both are read out which gives information on both the r - ϕ plane (from the cathode) and the η direction (from the anode). [36]

Resistive Plate Chambers

In addition to DT chambers and CSCs a complementary trigger system is also used consisting of resistive plate chambers (RPC) in the endcap and barrel regions. The RPCs are able to provide a fast and independent trigger over a large range ($|\eta| < 1.6$). In the barrel region, 6 layers of RPCs are used, 2 in each of the first 2 muon stations and 1 in each of the last 2 stations. In the endcap there is a layer of RPCs in each of the first 3 stations.

Alignment

An optical alignment system, that uses lasers and LEDs, measures the position of each muon station with respect to each other and the CMS inner tracker to ensure an accurate and high resolution measurement of the muon momentum. [36]

Performance

The performance of the muon system and inner tracker is shown in Figure 4.13. The best resolution for low-momentum muons is obtained from the measurement in the silicon tracker. However, as the momentum increases the best resolution is best obtained by combining information from both the inner tracker and the muon detector.

4.2.6 Trigger and Data Acquisition

At design luminosity, the high bunch crossing frequency of the LHC means that each crossing will contain an average of 20 superimposed inelastic events every 25 ns, a rate of 10^9 interactions per second. The size of an event is approximately 1 MB after zero-suppression. The total data output rate from CMS is ≈ 80 TB/s. These figures are many orders of magnitude larger than the storage and offline processing capability available to CMS, which corresponds to about 250 MB/s or about $\approx 10^2$ crossings written to the tape storage every second.

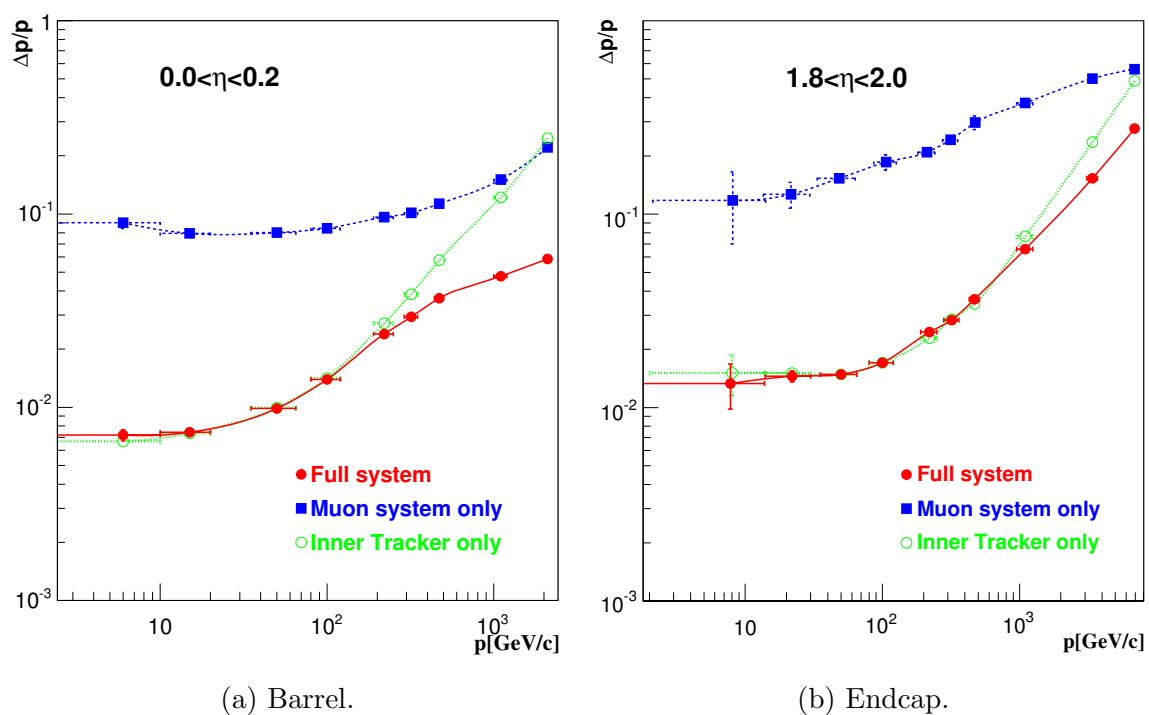


Figure 4.13: Muon transverse momentum resolution as a function of the muon momentum using only the muon system, only the tracker and both, for barrel muons ($|\eta| < 0.2$) and endcap muons ($1.8 < |\eta| < 2.0$). From [36].

The vast majority of events will contain only glancing inelastic collisions and may not be of interest from a physics perspective and can be discarded. It is the job of the trigger to reduce the rate of events by a factor of 10^6 by rejecting the uninteresting events while keeping as many interesting events as possible.

An overview of the DAQ and trigger is shown in Figure 4.14. The trigger is separated into two parts; the Level-1 trigger and the High Level Trigger. [36]

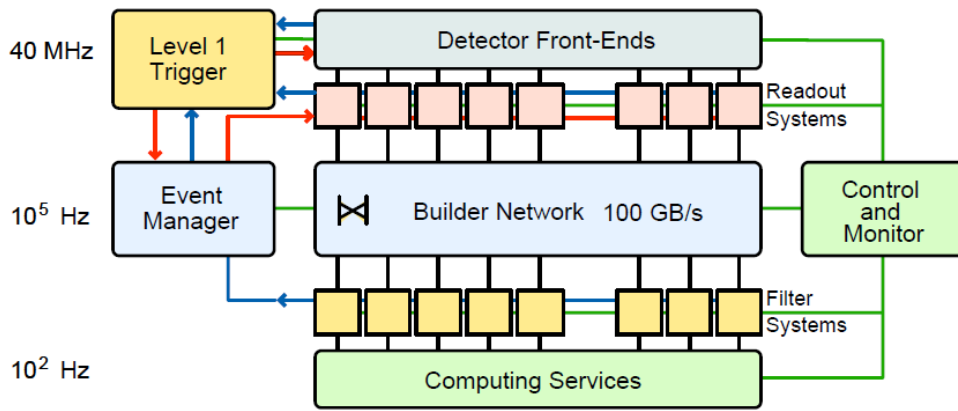


Figure 4.14: Overview of the architecture of the CMS DAQ and trigger. From [36].

Level-1 Trigger

The Level-1 trigger (L1) is designed to reduce the event rate from the bunch crossing frequency of 40 MHz to a maximum output rate of 100 kHz. The L1 trigger is implemented with custom-designed fast programmable electronics that take as input coarse data from the calorimeters and muon systems; the high resolution data are placed in pipe-lined memories awaiting a Level-1 decision. The reduced resolution and granularity data are used to form “trigger primitives”, such as isolated high energy electromagnetic deposits that pass a certain p_T or E_T threshold, upon which the L1 Trigger bases its decision. It also receives information on event-wide variables such as the total sum of transverse energy and the missing transverse energy.

High-Level Triggers

After a fixed time interval of $3.2\ \mu\text{s}$ the high resolution event data held in the pipeline memories are either read out or discarded depending on the decision at the Level-1 trigger. The data are transferred to a processor running the high-level trigger software.

The high-level trigger (HLT) is a software system which runs on a server farm with over one thousand commercial multicore processors with access to the complete event data allowing it to make more complex calculations. Objects are reconstructed in the HLT as they are needed and events are discarded as soon as possible to avoid wasting processing time. The decision to accept an event is based on the requirements on the datasets used in CMS analyses. A typical data-set requires a high p_T HLT-reconstructed object or an amount of missing transverse energy in the event. For example, the data-sets relevant to this thesis require a single high p_T electron, as is described in Section 6.1.1 and Section 7.1.1.

Computing

The CMS data are available in several different file formats that contain different levels of details [49],

- Raw data, is the output of the events that pass the HLT. The files contain the detector data, the L1 trigger results, the HLT trigger results and the higher-level objects that are created during the HLT process.
- Reconstructed (RECO) data, is the output of the reconstruction process. The files contain the reconstructed physics objects and reconstructed hits and clusters.
- Analysis Object Data (AOD), is the reduced event representation and contains only the reconstructed objects. This is the format that is used to perform physics analyses.

CMS utilises a distributed computing model called the “Grid”. The Grid consists of several clusters of computers distributed around the world and organised into several tiers [49]. Events that pass the HLT are sent to the primary Tier-0 centre where the raw data are stored on tape before undergoing prompt reconstruction. The reconstructed data are distributed to Tier-1 and Tier-2 centres at national laboratories and universities

around the world. The roles of the Tier-1 and Tier-2 sites are to run the physics analyses and to reprocess the data when updated calibrations are available. This is typically done once or twice a year.

Chapter 5

Physics Objects

In this chapter the algorithms used to reconstruct analysis objects and quantities from individual measurements from different parts of the CMS detector are described.

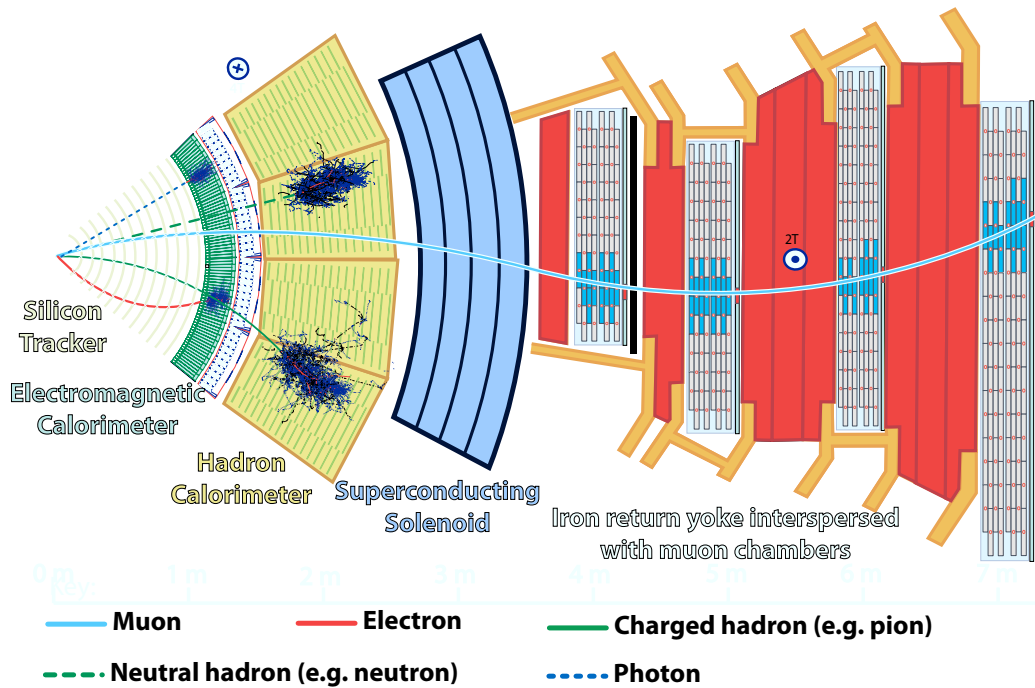


Figure 5.1: The path of different particles through a cross section of the CMS detector. From [50].

Figure 5.1 shows a cross section of CMS superimposed with the typical paths of several different particles and their interactions with the sub-detectors of CMS. This chapter describes how the information from each sub-detector is combined to identify and reconstruct the particles.

5.1 Electrons

Electrons are important physics objects in CMS as they provide easy-to-identify signatures and their energy can be measured with a good resolution. This section will describe the electron reconstruction algorithms used to produce electron candidates, and the identification variables used to discriminate between real electron candidates and their backgrounds.

5.1.1 Reconstruction

Electrons are reconstructed in CMS using information from the pixel detector, silicon strip tracker and the ECAL. The first step of the reconstruction is to collect together energy deposits in the ECAL. Next, the path of the electron through the tracker is reconstructed and matched to the energy deposits in the ECAL [51, 52].

Electron Clustering

In addition to ionisation energy losses and multiple Coulomb scattering, electrons will suffer large energy losses while traversing the inner detector by a process called bremsstrahlung. As electrons interact with the atomic nuclei, the nuclear electric field accelerates the electron, and the energy change appears in the form of a photon [12]. The photon may then undergo pair production, in the field of a nucleus, to produce an electron-positron pair. As the electron traverses the CMS tracker, the strong magnetic field causes the path to be curved in the azimuthal, ϕ , direction, so that the electron is accompanied by a “spray” of electromagnetic energy that is spread in the ECAL over a narrow strip in the ϕ direction. Figure 5.2 shows the fraction of energy radiated by bremsstrahlung for electrons of energy 10, 30 and 50 GeV [51].

To measure the electron energy, the separated deposits of energy need to be collected together, using “super-clustering” algorithms. In the barrel a “hybrid” algorithm is

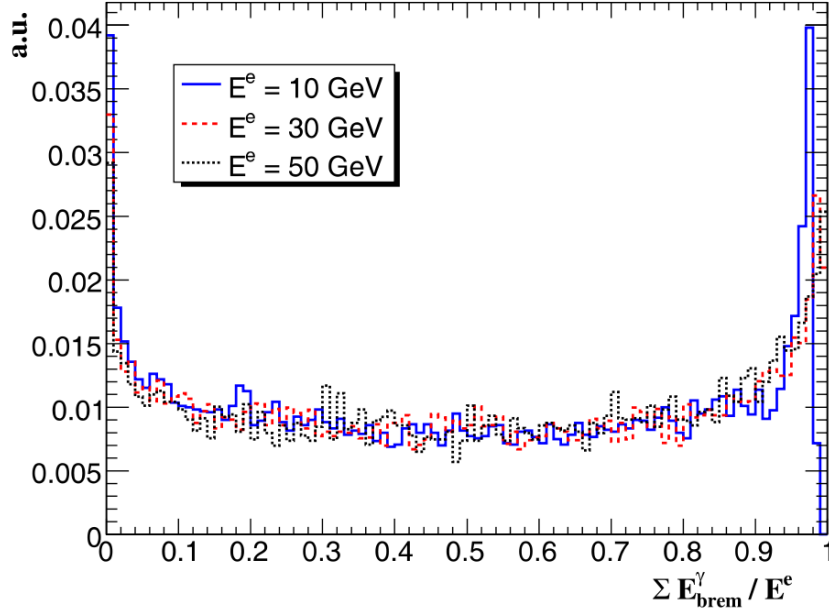


Figure 5.2: Distribution of the fraction of electron energy, E^e , radiated away as bremsstrahlung photons, ΣE_{brem}^γ . From [51].

used. The hybrid algorithm proceeds by identifying crystals with energies above a certain threshold, that will act as seeds. The algorithm then forms 5×1 or 3×1 crystal “dominos” in $\eta \times \phi$, centred on the seed crystal, depending on the energy within the domino. The dominos are then collected together in the ϕ direction, up to an angle of 0.3 rad, to form clusters of dominos, as demonstrated in Figure 5.3 [53]

A “multi5x5” algorithm is used in the ECAL endcaps. Energy is collected in 5×5 crystal arrays which are then collected together, if their position lies on a narrow ϕ road, to form superclusters [53].

Electron Seeding

The superclusters are then used to select seeds for the track reconstruction. Starting with a supercluster that passes a p_T threshold, the trajectory of the electron is propagated back through the magnetic field and matched to pairs or triplets of hits in the inner tracker that act as trajectory seeds. If the trajectory seeds fall within a window of the supercluster path under either charge hypothesis, they are selected and used to seed the track reconstruction. This ECAL-driven seeding is complemented by a tracker-driven

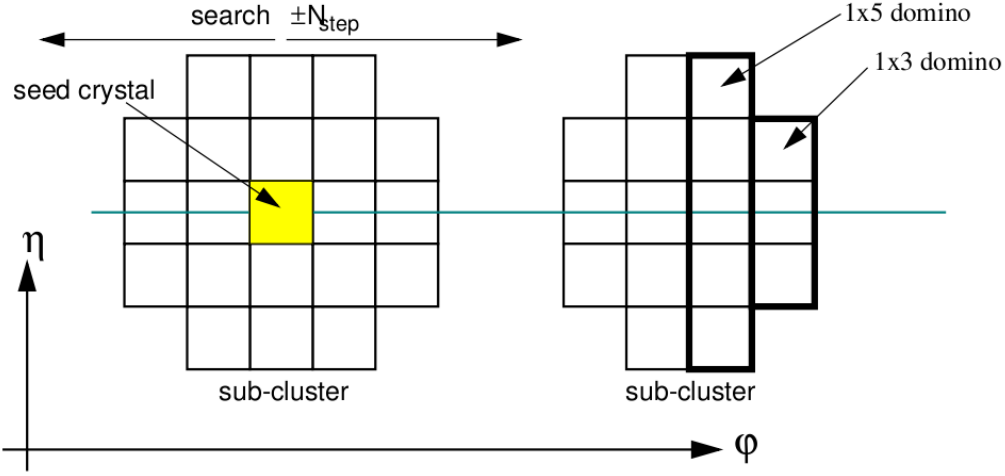


Figure 5.3: Demonstration of the clustering of dominos in the hybrid algorithm. From [53]. The algorithm starts on the seed crystal and clusters 3×1 and 5×1 dominos to form the first subcluster. The algorithm continues to search by stepping in ϕ and identifies a second subcluster.

seeding algorithm. This starts with high purity tracks and extrapolates them outwards to the ECAL, and is more effective for lower p_T electrons [51, 52].

Seeds from both of the algorithms are collected and merged into a single collection, which is then used to seed the electron track reconstruction.

Electron Track Reconstruction

The track reconstruction is based on a combinatorial Kalman filter [54], with the electron energy losses described using Bethe-Heitler modelling [55]. The track reconstruction starts from a trajectory seed, from which a tree of possible track candidates is built.

The Kalman filter has two steps, the propagation step and the update step. In the propagation step, track candidates are extrapolated to the next layer of the detector, while taking into account energy losses due to bremsstrahlung and Coulomb scattering. In the update step, the extrapolated track candidate is combined with the observed track hit in that layer and the track parameters are updated.

The collected hits are passed to the Gaussian Sum Filter (GSF) for a final fitting and estimation of the track parameters [47]. The GSF algorithm is similar to the Kalman filter but energy losses are now described by a weighted sum of Gaussian distributions [56].

5.1.2 Backgrounds to Prompt Electrons

In addition to prompt electrons, the electron candidates from the reconstruction algorithms will contain background signatures, either fake electrons or unwanted real electrons produced via some background process.

There are two main processes that may produce signatures in the detector that may be mistakenly identified as an electron and an additional two processes that may produce real electrons [57].

Charged hadrons that shower early in the ECAL

A charged pion will leave a track, that will appear similar to a non-radiating electron track. If the pion were to produce a hadronic shower early in the ECAL the energy deposits in the ECAL could be wrongly identified as an electromagnetic shower. As an example, the charge exchange process,

$$\begin{aligned}\pi^- + p &\rightarrow \pi^0 + n \\ &\rightarrow \gamma\gamma\end{aligned}\tag{5.1}$$

would be almost indistinguishable from an electron shower. The electron reconstruction algorithm would combine the track and electromagnetic shower to form an electron candidate [57].

$\pi^\pm\pi^0$ overlap

A charged pion within a jet will produce a charged track whereas a neutral pion will quickly decay to a pair of photons. If the electromagnetic clusters from the π^0 are matched to the track from the charged hadron, the electron reconstruction algorithm may form an electron candidate [57].

Electrons from hadronic decays

Heavy flavour quarks may decay semi-leptonically to produce real electrons. These electrons will tend to be less well isolated than prompt electrons from W decays [57].

Electrons from conversions

As stated previously, a neutral pion will quickly decay to a pair of photons. As the photons traverse the tracker material they may convert to produce a pair of real electrons [57, 58]. Figure 5.4 shows an example of a prompt electron and a pair of electrons from photon conversion. Electrons from photon conversions will appear to have a large distance of closest approach to the beam spot, d_0 . The electrons will also tend to have missing hits in the inner tracker close to the interaction point. There may also be a partner track nearby with opposite charge.

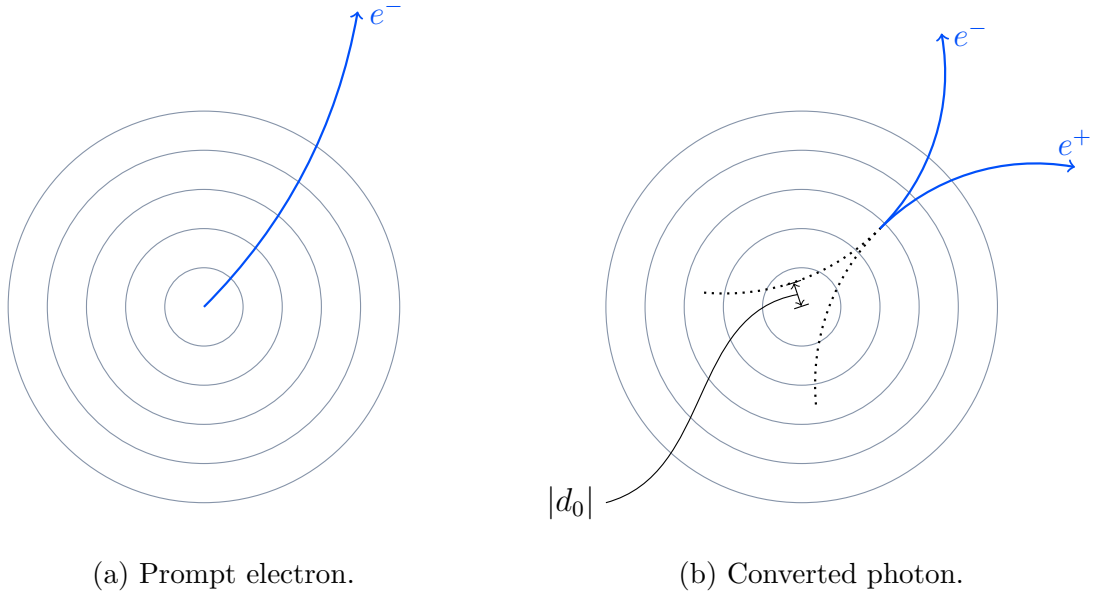


Figure 5.4: Tracks from an electron and a converted photon in the inner tracker. Modified from [58].

5.1.3 Electron Identification

Electron identification is based on a limited number of variables [59, 60].

Shape variable

$\sigma_{\eta\eta}$ is the width of the electron shower in the η direction,

$$\sigma_{\eta\eta} = \sum_{\text{crystals}} (\eta_i - \eta_s)^2 \frac{E_i}{E_{\text{seed cluster}}}. \quad (5.2)$$

where η_i and η_s are the crystal indices in the η direction of the i^{th} crystal and the seed crystal respectively. E_i is the energy deposited in the i^{th} crystal. This variable discriminates between electrons and jets, as a hadronic shower from a jet or a pair of photons from a π^0 will tend to produce a wider electromagnetic shower in the η direction than a prompt electron.

Hadronic energy

The variable H/E is the ratio of the energy deposited in the HCAL tower behind the electromagnetic seed cluster to the energy of that seed cluster. This variable offers some discrimination against early showering hadrons as some of the energy will tend to leak into the HCAL [60].

Angular separation of track and supercluster

$\Delta\phi$ and $\Delta\eta$ represent the angular separation between the trajectory of the reconstructed GSF track, extrapolated to the ECAL, and the ECAL supercluster in the ϕ and η direction respectively.

$$|\Delta\eta| \equiv |\eta_{\text{SC}} - \eta_{\text{track}}| \quad (5.3)$$

$$|\Delta\phi| \equiv |\phi_{\text{SC}} - \phi_{\text{track}}| \quad (5.4)$$

These variables provide discrimination against accidental matching to the track and supercluster [60].

Isolation quantities

For the calorimeter quantities, the isolation is defined as the sum of energy in a cone of $\Delta R = 0.3$ centred on the supercluster, where ΔR is defined in equation (A.3) and the energy deposits associated with the electron have been removed, divided by the candidate electron p_T .

The track isolation is defined as the sum of the p_T of Kalman filter tracks in a cone of $\Delta R = 0.3$ centred on the candidate electron, divided by the candidate electron p_T .

Isolation offers very good discrimination between electrons and hadrons, as hadrons that are mistakenly identified as an electron will tend to be accompanied by other particles, whereas prompt electrons will usually be well isolated [57, 60].

Conversion rejection

Three further variables are included to reject electrons that are produced from photon conversions. They are the number of missing hits, $\Delta \cot \theta$ and *dist*.

The number of missing hits is simply the number of layers in the inner tracker where an expected hit from the track reconstruction is not detected by the detector.

The other two variables are based on conversion partner tracks. Conversion partner tracks are track candidates that are within a cone of $\Delta R < 0.3$ around the electron candidate track, and have an opposite charge. $\Delta \cot \theta$ is defined as,

$$\Delta \cot \theta \equiv \cot(\theta_{KF}) - \cot(\theta_{GSF}), \quad (5.5)$$

where θ_{KF} and θ_{GSF} are the polar angle of the conversion partner track and the GSF track of the electron respectively. The *dist* variable is the distance between the two tracks at the point where they are parallel to one another in the $x - y$ plane as shown in Figure 5.5 [58, 60].

Electron identification working points

Several sets of cuts have been produced for CMS analyses. Each set of cuts has been optimised for a specific efficiency value, or working point [57, 59, 61]. The cut values are summarised in Table 5.1. The cuts can be split into three categories, ID Cuts, isolation cuts and conversion rejection cuts. Different sets of cut values are used for electrons in

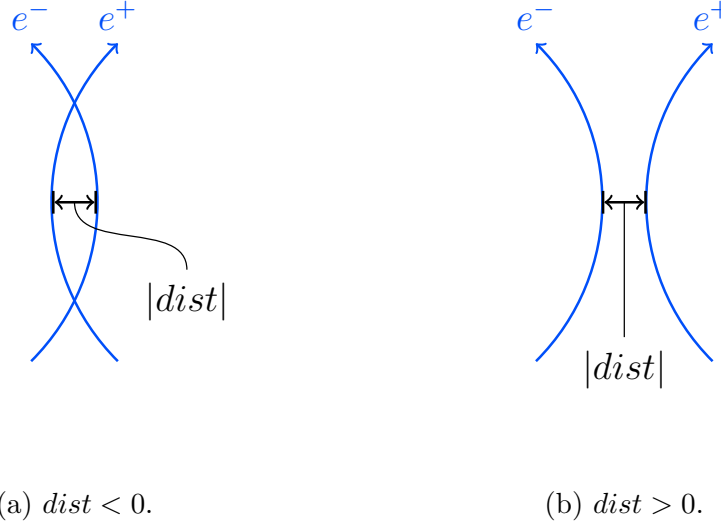


Figure 5.5: $dist$ is the distance between the two tracks where they are parallel. $dist$ is defined to be negative in the case that the tracks overlap and positive otherwise. Modified from [58].

the ECAL barrel and endcap. The cut values are obtained by simultaneous optimisation for an electron with $E_T = 25$ GeV. Although the efficiency and background rejection of the cuts is dependent on the E_T of the electron, the cut values obtained are found to be effective in the range 15-100 GeV [57, 59].

5.1.4 Charge Identification

The charge of an electron can be identified by studying how the electron trajectory is bent in the magnetic field as the electron passes through the silicon tracker. This can be made difficult by conversion of bremsstrahlung photons when they are radiated early.

Within CMS, three methods of charge identification have been developed based on the GSF track charge, the general track charge and the supercluster charge [52].

The GSF track charge is simply the sign of the curvature of the GSF fit of the electron track. The general track charge is found by matching the GSF track with a general Kalman filter track by asking for shared hits in the pixel tracker; the charge is the sign of the curvature of the Kalman filter track. The supercluster charge is obtained by finding the sign of the ϕ difference between the supercluster position and the first hit

Efficiencies	95%	90%	85%	80%	70%	60%
<i>Conversion Rejection Cuts</i>						
Missing Hits $\leq$	1	1	1	0	0	0
$ \text{Dist} $ (cm)	N/A	0.02	0.02	0.02	0.02	0.02
$ \Delta \cot \theta $	N/A	0.02	0.02	0.02	0.02	0.02
Barrel						
<i>Relative Isolation Cuts</i>						
Track	0.15	0.12	0.09	0.09	0.05	0.04
ECAL	—	0.09	0.08	0.07	0.06	0.04
HCAL	0.12	0.10	0.10	0.10	0.03	0.03
<i>Electron ID Cuts</i>						
$\sigma_{i\eta i\eta}$	0.01	0.01	0.01	0.01	0.01	0.01
$\Delta\phi$	—	—	0.06	0.06	0.03	0.025
$\Delta\eta$	0.007	0.007	0.006	0.004	0.004	0.004
H/E	0.15	0.12	0.04	0.04	0.025	0.025
End Cap						
<i>Relative Isolation Cuts</i>						
Track	0.08	0.05	0.05	0.04	0.025	0.025
ECAL	0.06	0.06	0.05	0.05	0.025	0.02
HCAL	0.05	0.03	0.025	0.025	0.02	0.02
<i>Electron ID Cuts</i>						
$\sigma_{i\eta i\eta}$	0.03	0.03	0.03	0.03	0.03	0.03
$\Delta\phi$	—	—	0.04	0.03	0.02	0.02
$\Delta\eta$	0.01	0.009	0.007	0.007	0.005	0.005
H/E	0.07	0.05	0.025	0.025	0.025	0.025

Table 5.1: Electron selection variables and corresponding cut values for several different efficiency working points [57, 59, 61].

of the electron track.

At the Z peak, an incorrect charge identification rate of 3 % [52] is measured when using the electron trajectory from the GSF fit. A sample with improved charge identification can be obtained by using a majority method, that combines the three measurements and assigns the sign from the two estimates out of three that are in agreement. A sample with even greater improved charge identification can be obtained by requiring that all three methods for assigning charge are in agreement and discarding the event otherwise [52].

5.2 Muons and Taus

Muons and taus are not used in the analyses presented in this thesis. Their reconstruction is only briefly described here. Muons are reconstructed from information in the muon chambers and the silicon tracker. Full details of the muon reconstruction are described in reference [62].

Taus may decay leptonically or hadronically. Leptonically decaying taus will decay to muons or electrons and may be indistinguishable from prompt leptons. The reconstruction algorithms for taus are described in reference [63].

5.3 Missing Energy

Neutrinos are weakly interacting neutral particles that escape the detector without being directly detected by any of the detector components. Instead they can be indirectly detected by measuring the total momentum of the reconstructed particles in an event. An imbalance in the total momentum of the event can be assigned to undetected particles. This is called the missing energy in the event.

In a hadron collider, the initial longitudinal momentum in the parton interaction is not known, so only the kinematic quantities in the transverse plane are usually considered. One of these is the missing transverse energy, E_T^{miss} , and is defined as the magnitude of the negative vector sum of the momentum of all final state particles in an event,

$$\vec{E}_T^{\text{miss}} = - \sum_i^{\text{particles}} \vec{p}_T^i, \quad (5.6)$$

where $E_T^{\text{miss}} = |\vec{E}_T^{\text{miss}}|$. There are several ways of measuring missing transverse energy. Calo E_T^{miss} is measured by creating pseudo-particles from the energies and direction of the deposits in the calorimeter towers. The muons are included by adding their p_T to the calculation and removing their energy deposited in the calorimeters. The calo E_T^{miss} is then the sum of the transverse energy of the pseudo-particles. Track E_T^{miss} extends calo E_T^{miss} to include the track p_T in the calculation. The corresponding energy deposited in the calorimeters by each track is removed. Particle flow E_T^{miss} (PFMET) is the sum of the transverse energies of all the reconstructed particle flow particles (see Section 5.3.1) [64].

5.3.1 Particle Flow at CMS

The particle-flow event reconstruction attempts to reconstruct and identify all stable particles in an event by combining information from all CMS sub-detectors. The particle reconstruction and identification starts with collecting information from each sub-detector to form elements such as tracks and energy clusters in the calorimeters. These basic ‘elements’ are then combined to form blocks which are then interpreted in terms of particles by the particle flow algorithm. A list of individual particles is then returned from the algorithm which can be used to study the event in greater detail by, amongst other things, building jets, tagging b quarks and calculating missing transverse energy [64].

The first step of the particle-flow reconstruction algorithm is to collect the fundamental elements. The elements consist of charged particle tracks from the tracker, clusters of energy deposition in the calorimeters and muon tracks.

As a particle traverses the detector it may interact with many CMS sub-detectors creating several particle-flow elements. A link algorithm is used to connect the elements together to form blocks that typically contain 1, 2 or 3 elements. The algorithm returns a distance between the elements as a measure of the quality of the link. The final step of the particle flow algorithm is to reconstruct and identify particles from each block of linked elements [64].

Once the event has been fully reconstructed with the particle flow technique the missing transverse energy in the event is computed by summing up the transverse momentum of all the reconstructed particles [64].

5.4 Jets

Jets are reconstructed from information in the tracker and the calorimeters. Jets are clustered using an anti- k_t algorithm [65] with a size of $R = 0.5$ [66].

There are four collections of jets produced by the event reconstruction algorithms at CMS, Calorimeter (Calo) jets, Particle Flow (PF) Jets, Jet Plus Tracks (JPT) jets and track jets [66]. Calo jets are jets reconstructed from energy deposits in the ECAL and HCAL. JPT jets extend the Calo jets to include information from the tracker to give an enhanced p_T resolution. PF jets are produced by the particle flow algorithm [64]. Track jets are reconstructed from tracks in the silicon tracker [66].

Chapter 6

Measurement of the Electron Charge Asymmetry with 36 pb^{-1}

In this chapter the measurement of the electron charge asymmetry is presented. The analysis is performed on the full 2010 dataset, which corresponds to a luminosity of 36.1 pb^{-1} at $\sqrt{s} = 7 \text{ TeV}$ [1, 4].

The results are presented in 6 bins of absolute value of pseudorapidity with a fixed width of 0.4. To avoid the gap between the ECAL barrel and the ECAL endcap the region $1.4 < |\eta| < 1.6$ is excluded.

6.1 Event Selection

The event selection is performed on single electron datasets formed of events that are selected using various single photon and single electron triggers. From these datasets, electrons are selected that pass a limited number of cuts. Events that contain only a single electron are then selected for the analysis.

6.1.1 Trigger

Several high-level triggers (HLT) were used to select the events due to the increasing luminosity during the LHC 2010 run. In the initial runs, events were selected using only a single photon trigger. As the instantaneous luminosity was increased and these triggers became prescaled, it was necessary to use electron triggers to select events. As the

luminosity increased even further, it was necessary to use electron triggers that included cuts on certain electron ID variables.

In the following analysis, a control region is obtained by inverting the selection on the $\Delta\phi$ and $\Delta\eta$ variables (see Section 5.1.3). To ensure that this inverted selection is effective and will actually select events, it is necessary to avoid using triggers that apply a selection on these variables.

The triggers used to select the events are summarised in Table 6.1 where “HLT_EleX” indicates a high-level trigger selection requiring an electron with $p_T > X$ GeV. “Photon” in the name indicates that the selection was applied to ECAL superclusters rather than a reconstructed electron. “SW” stands for small window, where window refers to the electron pixel-matching window. “Cleaned” indicates that spikes in the ECAL have been removed.

“CaloEleId” and “TighterCaloIdIso” represent increasingly tighter selection based on the shower shape ID and isolation variables from only the ECAL, and not the $\Delta\phi$ or $\Delta\eta$ variables.

“TightEleId” indicates a tight selection based on all ID variables. This nullifies the inverted cuts used for the control region but it was the only trigger available for these runs without a prescale applied. To compensate for the missing events in the control region, a looser prescaled trigger was also applied in these runs.

Run Ranges	Trigger String
132440-137028	HLT_Photon10_L1R
138564-140401	HLT_Photon15_Cleaned_L1R
141956-144114	HLT_Ele15_SW_CaloEleId_L1R
146428-147116	HLT_Ele17_SW_CaloEleId_L1R
147196-148102	HLT_Ele17_SW_TightEleId_L1R
	HLT_Ele17_SW_L1R (prescaled)
148822-149063	HLT_Ele22_SW_TighterCaloIdIso1_L1R_v1
149181-149442	HLT_Ele22_SW_TighterCaloIdIso1_L1R_v2

Table 6.1: The triggers used to select the data used in this analysis.

6.1.2 Electron Selection

The available high-level triggers place a lower limit on the electron p_T threshold. To avoid a changing HLT efficiency caused by the trigger-turn-on efficiency curve the electron p_T is required to be greater than 25 GeV in the analysis. The results are presented with an electron p_T cut of 25, 30 and 35 GeV.

Electron candidates are identified using a cut-based approach on a limited number of variables [59]. The cut values used correspond to the 80% working point from Table 5.1, and are summarised again in Table 6.2. The 80% working point was chosen as a compromise between ensuring high-enough statistical accuracy while maintaining a high-enough purity of the sample.

Selection Variable	Cut Value	
	Barrel	Endcap
<i>ID Cuts</i>		
H/E	0.04	0.025
$\Delta\phi$	0.06	0.03
$\Delta\eta$	0.004	0.007
$\sigma_{\eta\eta}$	0.01	0.03
<i>Isolation Cuts</i>		
ISO_{trk}/E_T	0.09	0.04
ISO_{ecal}/E_T	0.07	0.05
ISO_{hcal}/E_T	0.10	0.025
<i>Conversion Rejection Cuts</i>		
Missing Hits	≤ 0	
Dist (cm) Dcot	> 0.02	

Table 6.2: The electron selection variables and corresponding cut values [61].

Incorrectly assigning the charge of an electron will lead to a dilution of the measured charge asymmetry. An additional requirement is applied to the charge of the reconstructed electron to reject events where the true charge is difficult to determine. The methods for assigning a charge to an electron are described in Section 5.1.4. The methods are based on the GSF electron charge, the general track charge and the supercluster charge. Electron candidates are only selected if all of the three methods agree on the

charge assignment.

The incorrect charge assignment rate can be measured at the Z peak by comparing the same sign $Z \rightarrow e^\pm e^\pm$ yield to the opposite sign $Z \rightarrow e^- e^+$ yield. Figure 6.1 show these Z yields using only the GSF track charge (red) and also requiring a unanimous assignment of charge from all three methods (blue).

The incorrect charge assignment rate from the GSF track charge alone is about 3%. By requiring that all three methods for assigning the charge agree, and vetoing events otherwise, the incorrect assignment rate can be reduced by a factor of 8 with only a 5% loss in efficiency [4].

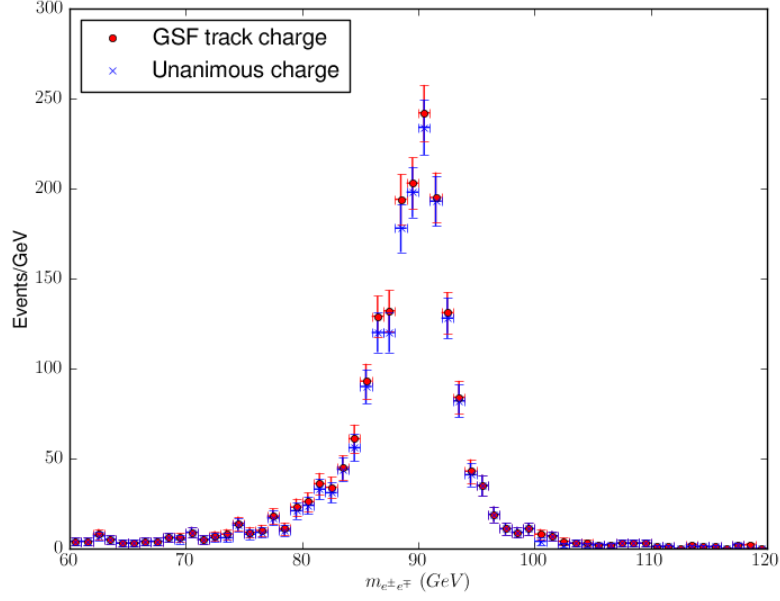
6.1.3 Event Selection

An event is selected if it contains a single electron that passes all the electron selection requirements. To remove Drell-Yan events, an event is vetoed if it contains a second electron passing a loose selection with $p_T > 15$ GeV. Events are also vetoed if they contain an isolated muon with $p_T > 15$ GeV.

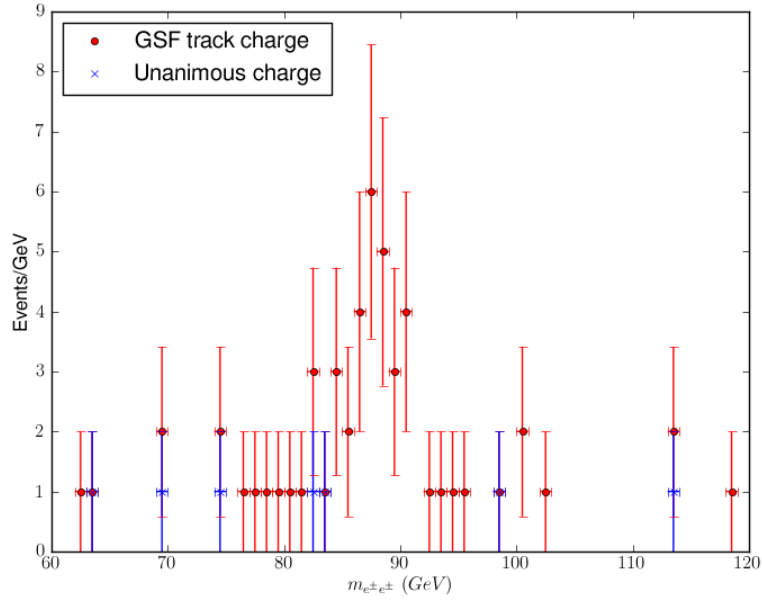
The expected composition of the selected events is measured from the MC simulation samples. With a p_T cut of 25 GeV it is expected that 65% of selected events are signal events, and of the remaining 35% background events, the majority are from QCD backgrounds with a small number from electroweak processes, which are mostly Drell-Yan (DY) events.

The particle flow E_T^{miss} distribution for the events that pass the event selection, with an electron cut of $p_T > 25$ GeV and $|\eta| < 2.4$ is shown in Figure 6.2. There are two obvious peaks in the distribution. The peak at $E_T^{\text{miss}} \approx 40$ GeV is the $W \rightarrow e\nu_e$ signal region. This region also contains $W \rightarrow \tau\nu_\tau$ backgrounds. The peak at $E_T^{\text{miss}} \approx 10$ GeV is the background region that contains the QCD and DY background events.

The number of selected events that pass the event selection are shown in Table 6.3. To obtain a measurement of the asymmetry from the selected events it is necessary to extract the signal yield from each pseudorapidity/charge bin.



(a) Opposite sign Z peak.



(b) Same sign Z peak.

Figure 6.1: $Z \rightarrow ee$ peak. One electron is required to be in the barrel to pass the electron selection and to have a fraction of energy loss by radiation less than 0.3; the second electron is required only to pass the electron selection [4].

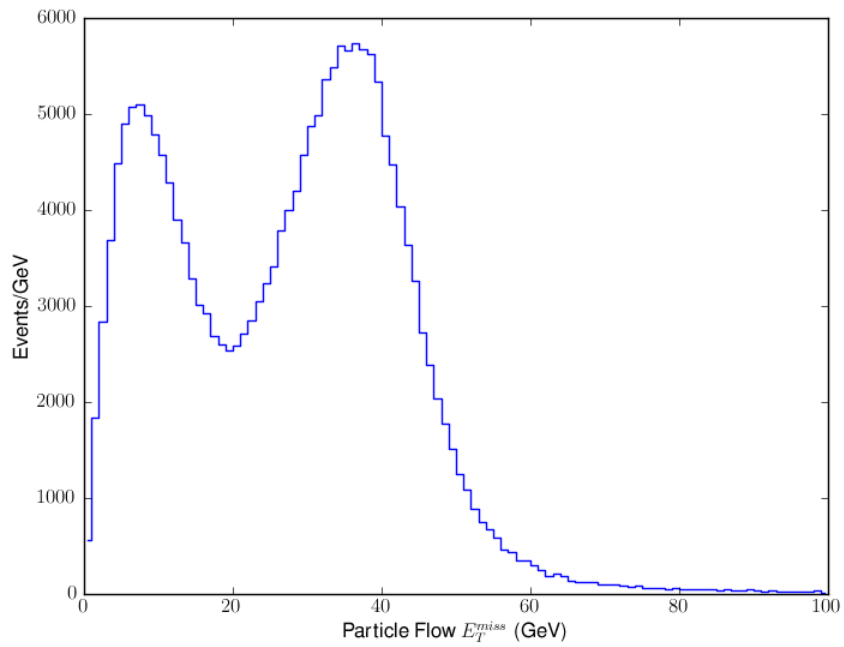


Figure 6.2: Particle Flow E_T^{miss} distribution for selected events with an electron cut of $p_T > 25$ GeV and $|\eta| < 2.4$ [4].

$ \eta $ range	Charge	Selected Events		
		$p_T > 25$ GeV	$p_T > 30$ GeV	$p_T > 35$ GeV
$0.0 < \eta < 0.4$	+	18956	14232	9885
	−	15060	11505	8105
$0.4 < \eta < 0.8$	+	20118	14966	10345
	−	15736	11780	8307
$0.8 < \eta < 1.2$	+	20681	15091	10184
	−	16167	11735	8112
$1.2 < \eta < 1.4$	+	10646	7606	5161
	−	8226	5871	4067
$1.6 < \eta < 2.0$	+	16426	11877	7814
	−	11678	8578	5886
$2.0 < \eta < 2.4$	+	18885	13239	8726
	−	13226	9227	6184

Table 6.3: Number of events passing the event selection for lepton momentum cuts of $p_T > 25$ GeV, $p_T > 30$ GeV and $p_T > 35$ GeV [4].

6.2 Signal Yield Extraction Method

The number of signal and background events in each bin is extracted using a maximum likelihood fit to the E_T^{miss} distribution using two fixed templates shapes [67], similar to the method used in the measurement of the W cross section [68]. The first template is the sum of the $W \rightarrow e\nu$ signal and the electroweak background shapes, and the second template is the sum of the QCD plus $\gamma + jet$ processes.

6.2.1 QCD E_T^{miss} Shape

The E_T^{miss} distribution for the QCD and $\gamma + jet$ background is obtained from a control. The control sample is selected by requiring that the electrons pass the isolation and H/E cuts but fail the $\Delta\phi$ and $\Delta\eta$ cuts as shown in Table 6.4.

To validate the anti-selection used, QCD Monte Carlo (MC) simulation samples are used. The distribution of QCD MC events passing the event selection is compared to the anti-selected MC events. This is shown for each pseudorapidity bin in Figure 6.3. The agreement is seen to be good with little signal contamination in the control region.

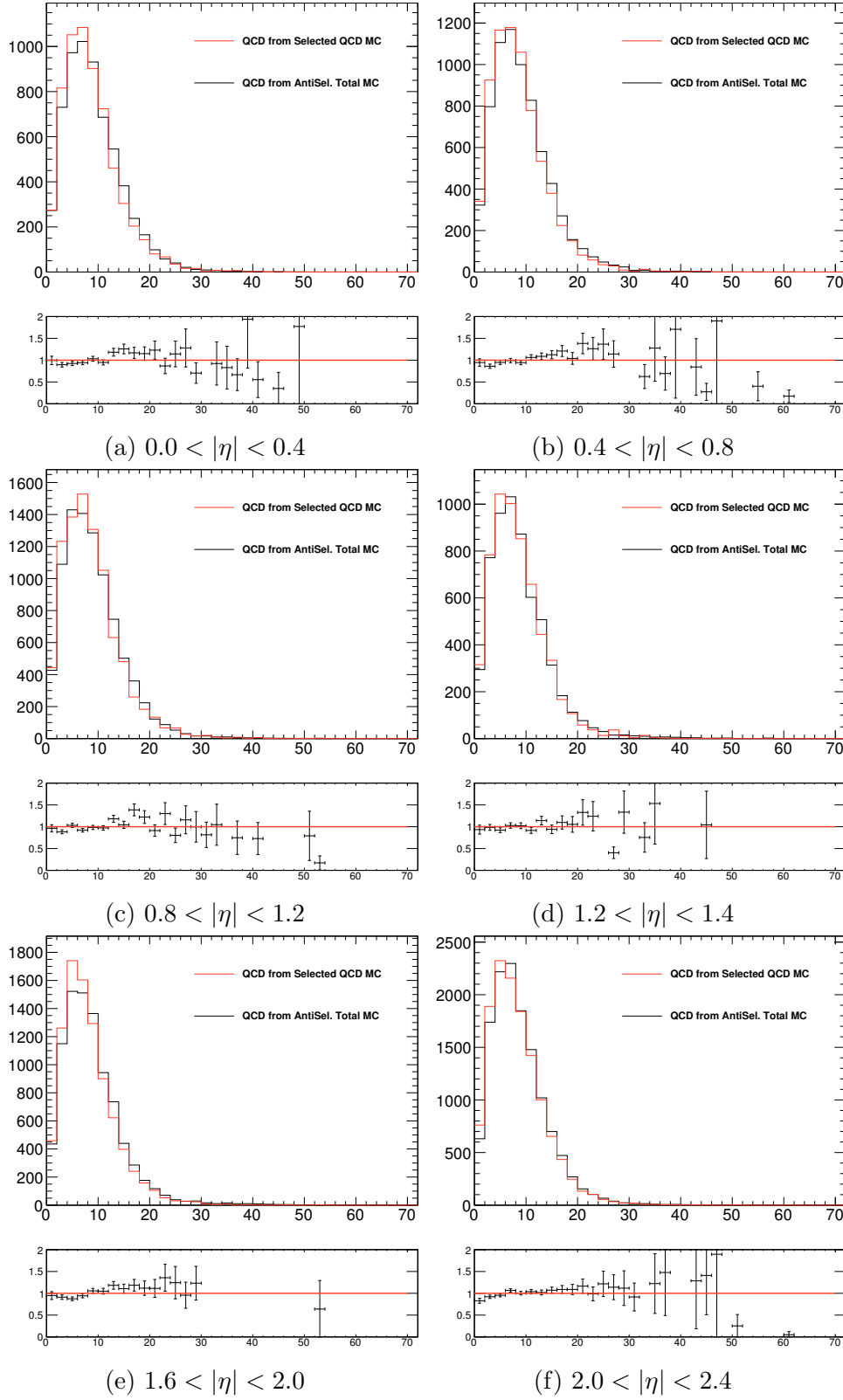


Figure 6.3: The E_T^{miss} distribution in data and background anti-selected MC simulated events and selected QCD and $\gamma + \text{jet}$ background MC simulated events in each pseudo-rapidity bin [4].

Selection Variable	Cut Value	
	Barrel	Endcap
H/E	0.04	0.025
$\Delta\phi$	> 0.06	> 0.04
$\Delta\eta$	> 0.007	> 0.009
ISO_{trk}/E_T	0.09	0.04
ISO_{ecal}/E_T	0.07	0.05
ISO_{hcal}/E_T	0.10	0.025

Table 6.4: Electron anti-selection variables and corresponding cut values. The $\Delta\phi$ and $\Delta\eta$ cuts are inverted [4].

6.2.2 Signal E_T^{miss} Shape from Boson Recoil

The E_T^{miss} in signal events arises from the unmeasured neutrino in the event. The signal E_T^{miss} shape is derived from MC simulations with an event-by-event correction applied to account for differences in the E_T^{miss} scale and resolution between data and MC. The correction is based on the hadronic recoil distribution measured in data. The recoil response and resolution in $Z \rightarrow \ell\ell$ data events is measured as a function of the p_T of the boson. This is combined with information from the W and Z MC simulation to derive a correction to the simulated E_T^{miss} as a function of W boson's p_T [68, 69].

The transverse recoil vector, $\vec{U}$, is calculated from the reconstructed transverse missing energy, $\vec{E}_T^{\text{miss}}$, and the electron p_T vectors,

$$\vec{U} = -\vec{E}_T^{\text{miss}} - \vec{p}_T^e \quad (6.1)$$

$$\vec{U} = -\vec{E}_T^{\text{miss}} - \sum_i \vec{p}_T^{e_i} \quad (6.2)$$

for W events and Z events respectively. $\vec{U}$ is split into components that are parallel (U_1) and perpendicular (U_2) to the true boson p_T direction. In Z data events the true boson p_T is not known and is reconstructed from the p_T of the two electrons.

The hadronic activity that balances the p_T of the boson will lie mostly in the U_1 direction whereas U_2 will be mostly formed from other sources. Figure 6.4 shows the decomposition of $\vec{U}$ into U_1 and U_2 in W events [69].

U_1 and U_2 are measured in Z data, Z MC simulation and W MC simulation and are

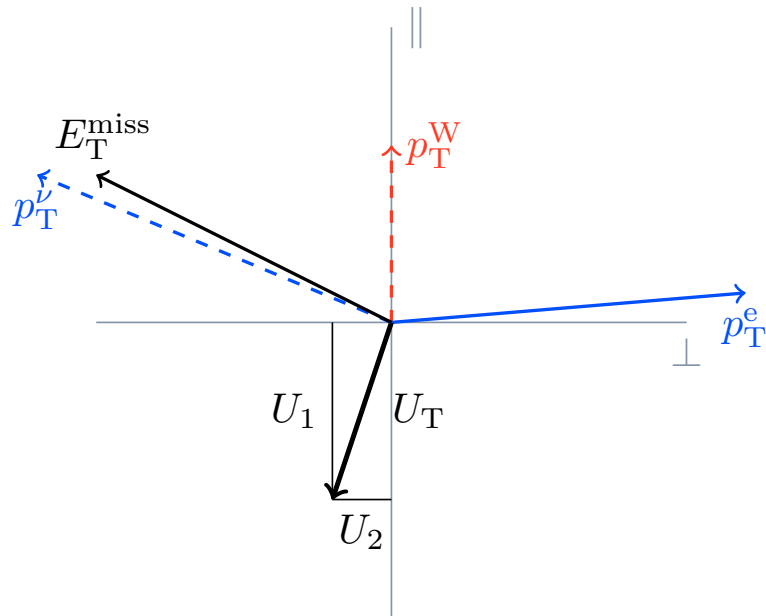


Figure 6.4: The decomposition of $\vec{U}$ for W events. Modified from [69].

then binned in units of the boson p_T . In each p_T^Z bin the U_1 and U_2 distributions are fitted with a Gaussian. A linear function, $f_i(p_T^Z)$, is fit to the distribution of the Gaussian means to produce a response curve for both data and MC. A second order polynomial, $\sigma_i(p_T^Z)$, is then fit to the distribution of the Gaussian widths to produce a resolution curve for both data and MC [69].

The fitting procedure results in two response functions, $f_i(p_T)$, and two resolution functions, $\sigma_i(p_T)$, for Z data, Z MC events and the W MC events. The functions are then used to define a set of W MC corrected functions,

$$f_i^{corr}(p_T^W) = \frac{f_i^{Z \text{ data}}(p_T^Z)}{f_i^{Z \text{ MC}}(p_T^Z)} f_i^{W \text{ MC}}(p_T^W) \quad (6.3)$$

$$\sigma_i^{corr}(p_T^W) = \frac{\sigma_i^{Z \text{ data}}(p_T^Z)}{\sigma_i^{Z \text{ MC}}(p_T^Z)} \sigma_i^{W \text{ MC}}(p_T^W) \quad (6.4)$$

The corrected recoil response and resolution curves are then used to correct the W MC E_T^{miss} . For each W MC event, the generator level p_T of the boson is found, and the values for the response, $f_i^{corr}(p_T^W)$, and resolution curves, $\sigma_i^{corr}(p_T^W)$, are looked up. A Gaussian is defined with these values and then sampled to determine the new recoil components U_i ,

$$U_i \sim \text{Gaus}(f_i^{corr}(p_T^W), \sigma_i^{corr}(p_T^W)). \quad (6.5)$$

The components are then combined to form the new corrected recoil vector $\vec{U}'$ which is then combined with the electron vector to form the corrected E_T^{miss} [69].

The modelling of the $W \rightarrow \ell \nu$ E_T^{miss} with boson recoil is described in detail in reference [69]. Ntuples containing $W \rightarrow e^- \nu$ simulation with the recoil corrected E_T^{miss} were provided from reference [68].

6.2.3 Electroweak E_T^{miss} Shape

The electroweak background processes that can produce a single isolated electron which are considered in this analysis are:

- $Z \rightarrow e^- e^+$, where one of the electrons falls outside the geometric acceptance or is not detected,

- $Z \rightarrow \tau^- \tau^+$, where one of the taus decays to an electron and the other decays hadronically, or semi-leptonically and the lepton is not detected,
- $W \rightarrow \tau \nu$, where the tau decays to an electron,
- $t\bar{t}$, where an electron is produced.

The E_T^{miss} distributions for the electroweak background were obtained from PYTHIA [70] MC simulations for each pseudorapidity/charge bin. The MC samples used are summarised in Table C.1. The scale of the electroweak shape is fixed to the signal E_T^{miss} shape by the ratio obtained from MC samples.

6.2.4 Fit Results

The results of the extended maximum likelihood fits to each pseudorapidity/charge bin are shown the appendix in Figure B.1 and Figure B.2 and the χ^2 of each fit is included in Table 6.5.

$ \eta $ range	Charge	χ^2/ndof of Fit
$0.0 < \eta < 0.4$	+	0.86
	−	0.84
$0.4 < \eta < 0.8$	+	0.99
	−	1.36
$0.8 < \eta < 1.2$	+	1.05
	−	1.13
$1.2 < \eta < 1.4$	+	0.97
	−	1.30
$1.6 < \eta < 2.0$	+	1.38
	−	1.61
$2.0 < \eta < 2.4$	+	1.44
	−	1.11

Table 6.5: χ^2/ndof of the fits in each pseudorapidity bin [4].

6.2.5 Validation of Signal Extraction Method on Simulation

The signal yield extraction procedure was validated using pseudo-data experiments. 1000 pseudo-data experiments were generated with the number of events expected in 36.1 pb^{-1} of data. The signal yields are extracted in each experiment and the asymmetry is calculated. The distribution of asymmetries is then fitted with a Gaussian. The measured asymmetry for the 1000 pseudo-data experiments distribution for each pseudorapidity bin is shown in Figure 6.5.

The width of the Gaussian is the statistical uncertainty on the measurement. The statistical uncertainty can also be estimated from the following formula

$$\sigma_A = \frac{2 \times \sqrt{(N^+ \sigma_{N^-})^2 + (N^- \sigma_{N^+})^2}}{(N^+ + N^-)^2}. \quad (6.6)$$

where σ_A is the statistical uncertainty on the asymmetry measurement in a given pseudorapidity bin, $N^\pm$ is the measured signal yield in a given pseudorapidity/charge bin and $\sigma_{N^\pm}$ is the statistical uncertainty on the measured signal yield in each bin.

The uncertainty from equation (6.6) evaluated with MC truth values, and the uncertainty measured from pseudo-data experiments for an integrated luminosity of 36.1 pb^{-1} are summarised in Table 6.6, and are in good agreement.

$ \eta $ range	σ_A from equation (6.6).	σ_A from pseudo-data exp.
$0.0 < \eta < 0.4$	0.0064	0.0062
$0.4 < \eta < 0.8$	0.0064	0.0064
$0.8 < \eta < 1.2$	0.0065	0.0065
$1.2 < \eta < 1.4$	0.0096	0.0104
$1.6 < \eta < 2.0$	0.0076	0.0079
$2.0 < \eta < 2.4$	0.0077	0.0077

Table 6.6: Expected statistical error from MC simulation and pseudo-data experiments as a function of pseudorapidity, for an integrated luminosity of 36 pb^{-1} [4].

The distributions of the asymmetry measurements in each pseudo-data experiment are shown in Figure 6.5. The true MC value of the asymmetry is shown with a vertical line, and the Gaussian fit is also shown. The results show good agreement with the true

value which implies an unbiased measurement.

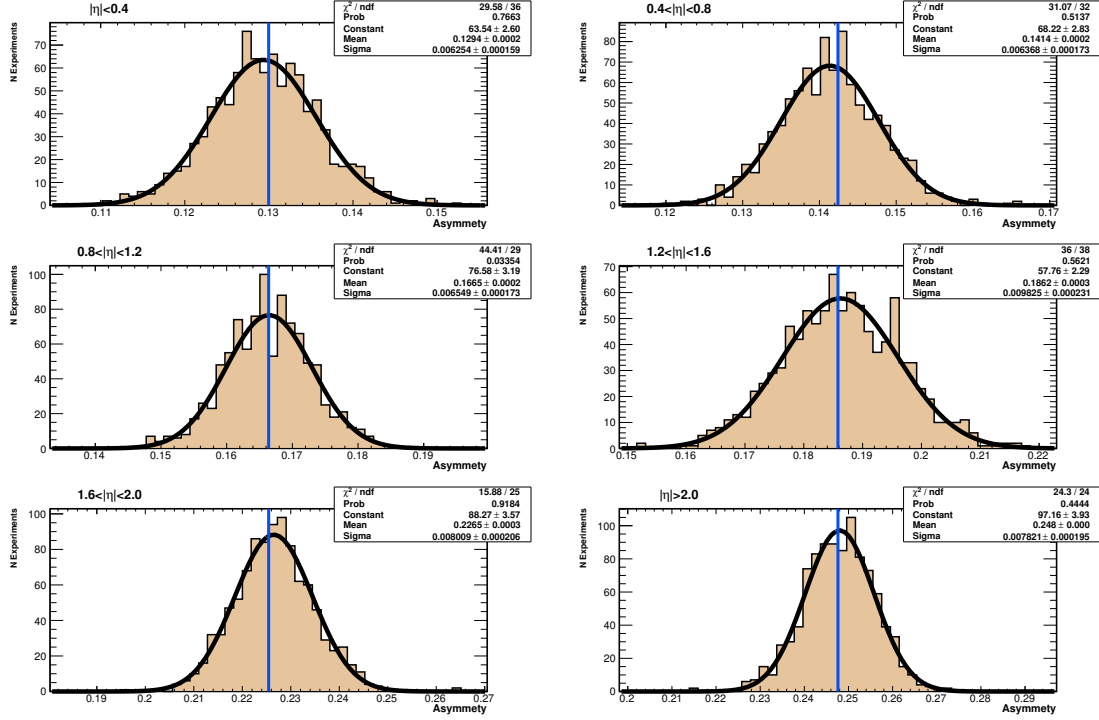


Figure 6.5: Measured asymmetry for 1000 pseudo-data experiments. The distribution of the measured asymmetry is fitted with a Gaussian [4].

6.3 Corrections to the Measured Asymmetry

After the signal extraction procedure the measured asymmetry is simply,

$$\mathcal{A}_{meas} = \frac{N_{meas}^+ - N_{meas}^-}{N_{meas}^+ + N_{meas}^-}, \quad (6.7)$$

where N_{meas}^+ and N_{meas}^- are number of positrons and electrons extracted with the fitting procedure. To compare with the theoretical value, the measured lepton asymmetry has to be corrected for three detector effects,

- charge-dependent reconstruction efficiency,

- incorrect charge assignment rate,
- electron energy resolution.

If the reconstruction efficiency of electrons is different to that of positrons then a bias will be introduced into the measured asymmetry, which will need to be taken into account in the calculation of the asymmetry.

The second experimental effect is due the incorrect charge assignment of electrons. The incorrect charge assignment rates, ω^+ and ω^- , are the rate at which electrons are incorrectly assigned a positive charge and identified as positrons and the rate that positrons are identified as electrons, respectively. The incorrect assignment induces a dilution factor to the asymmetry as a function of the electron pseudorapidity.

The true asymmetry at the reconstruction level is defined as,

$$\mathcal{A}_{reco} = \frac{N_{reco}^+ - N_{reco}^-}{N_{reco}^+ + N_{reco}^-}, \quad (6.8)$$

where N_{reco}^+ and N_{reco}^- are the true number of positrons and electrons with p_T greater than the threshold. N_{meas}^+ , N_{meas}^- and N_{reco}^+ , N_{reco}^- are related by the efficiency of electrons and positrons (ϵ^- and ϵ^+) and the incorrect charge assignment rates (ω^+ and ω^-),

$$N_{meas}^+ = \epsilon^+ ((1 - \omega^-)N_{reco}^+ + \omega^+ N_{reco}^-) \quad (6.9)$$

$$N_{meas}^- = \epsilon^- ((1 - \omega^+)N_{reco}^- + \omega^- N_{reco}^+). \quad (6.10)$$

The Equations (6.9) and (6.10) can then be inserted into the definition of the measured asymmetry, equation (6.7), to obtain,

$$\mathcal{A}_{meas} = \frac{\epsilon^+ ((1 - \omega^-)N_{reco}^+ + \omega^+ N_{reco}^-) - \epsilon^- ((1 - \omega^+)N_{reco}^- + \omega^- N_{reco}^+)}{\epsilon^+ ((1 - \omega^-)N_{reco}^+ + \omega^+ N_{reco}^-) + \epsilon^- ((1 - \omega^+)N_{reco}^- + \omega^- N_{reco}^+)}. \quad (6.11)$$

The above can be simplified by first assuming that the rate at which electrons are assigned a positive charge is the same as the rate at which positrons are assigned a negative charge, i.e. [4]

$$\omega^+ = \omega^- = \omega, \quad (6.12)$$

A further simplification is to introduce the relative detection efficiency, R , which is defined as the ratio of electron efficiency to the positron efficiency,

$$R = \epsilon^+ / \epsilon^-, \quad (6.13)$$

which can be substituted into equation (6.11),

$$\mathcal{A}_{meas} = \frac{N_{reco}^+(R - \omega(R + 1)) - N_{reco}^-(1 - \omega(R + 1))}{N_{reco}^+(R - \omega(R - 1)) + N_{reco}^-(1 + \omega(R - 1))} \quad (6.14)$$

$$= \frac{(1 + \mathcal{A}_{reco})(R - \omega(R + 1)) - (1 - \mathcal{A}_{reco})(1 - \omega(R + 1))}{(1 + \mathcal{A}_{reco})(R - \omega(R + 1)) - (1 - \mathcal{A}_{reco})(1 + \omega(R - 1))} \quad (6.15)$$

$$= \frac{\mathcal{A}_{reco}(R + 1)(1 - 2\omega) + (R - 1)}{\mathcal{A}_{reco}(R - 1)(1 - 2\omega) + (R - 1)}, \quad (6.16)$$

which can then be inverted to derive $\mathcal{A}_{reco}$ as a function of the measured asymmetry ($\mathcal{A}_{meas}$), the relative efficiency (R) and the incorrect charge assignment rate (ω),

$$\mathcal{A}_{reco} = \frac{1}{1 - 2\omega} \frac{\mathcal{A}_{meas}(R + 1) - (R - 1)}{(R + 1) - \mathcal{A}_{meas}(R - 1)} \quad (6.17)$$

$$\approx \frac{1}{1 - 2\omega} \left(\mathcal{A}_{meas} - \frac{(R - 1)(1 - \mathcal{A}_{meas}^2)}{2} \right) \quad (6.18)$$

The measurements of the parameters R and ω , as well as the uncertainties, are detailed in the following sections.

The electron energy resolution and energy scale can also introduce a systematic bias on the asymmetry due to the effect of the transverse momentum cut applied to the electrons. The largest source of the electron energy scale is the radiation-induced change to the ECAL crystal transparency. To correct for this effect, energy scale and resolution corrections are derived using a $Z \rightarrow ee$ mass distribution. The results are presented in the following sections.

6.3.1 Relative Efficiency

If the reconstruction efficiency of electrons is different to that of positrons then the measured asymmetry will be diluted and will need to be corrected.

The efficiency for electrons and positrons is measured using the tag and probe method

[71] with a sample of $Z \rightarrow ee$ events from the same datasets used in the analysis. The $Z \rightarrow ee$ events offer a high purity source of unbiased electrons with which to measure the efficiencies.

From the sample of $Z \rightarrow ee$ events a “tag” electron is selected with strict selection criteria. A “probe” electron is selected with the same electron selection described earlier. The invariant mass of the tag-probe pair is required to be $60 \text{ GeV} < M_{ee} < 120 \text{ GeV}$ to ensure a high purity sample.

Efficiencies can then be calculated by measuring the signal yield in events with one tag electron and one probe passing the selection (tag & pass) and events where the probe electron fails the selection (tag & fail). The signal yield is extracted using a simultaneous maximum likelihood fit to both the tag & pass and the tag & fail samples.

For this analysis the efficiencies are measured in two parts:

- GSF tracking efficiency, ϵ_{GSF} .
- Identification efficiency, including conversion rejection, unanimous charge assignment and HLT request, ϵ_{ID} .

The ratios $R_{GSF} = \epsilon_{GSF}^+/\epsilon_{GSF}^-$ and $R_{ID} = \epsilon_{ID}^+/\epsilon_{ID}^-$ are found and the overall efficiency ratio is given by $R = R_{GSF}R_{ID}$. Table 6.7 shows the GSF tracking efficiency and identification efficiency as a function of the charge.

$ \eta $ range	Charge	ϵ_{GSF}	ϵ_{ID}	R
$0.0 < \eta < 1.4$	+	98.8 ± 0.5	84.1 ± 0.8	1.007 ± 0.015
	−	98.4 ± 0.5	83.8 ± 0.8	
$1.6 < \eta < 2.4$	+	98.3 ± 0.7	70.7 ± 1.4	0.99 ± 0.03
	−	97.8 ± 0.7	71.5 ± 1.4	
$0.0 < \eta < 2.4$	+	98.5 ± 0.4	80.3 ± 0.7	1.007 ± 0.014
	−	97.8 ± 0.4	80.3 ± 0.7	

Table 6.7: GSF track reconstruction and electron identification efficiency as a function of charge in the barrel and endcap separately and the full inclusive range [4].

The main systematic errors on the efficiency measurements are the energy scale and the signal shape used to extract the signal yield. Fortunately, these errors will cancel in

the calculation of the ratio R , such that the effects of the energy scale and signal shape are negligible when compared to the statistical uncertainty of the measurement. Only the statistical uncertainty is therefore propagated to the error in the ratio σ_R .

The value of R is measured in the barrel and endcap separately as well as inclusively across the range $0 < |\eta| < 2.4$. The relative efficiency is found to be statistically compatible with 1 so the measured asymmetry is not corrected for this effect.

The statistical errors on the relative efficiency are taken as a source of systematic uncertainty and is propagated to the asymmetry. The inclusive electron efficiency ratio is found to be 1.007 ± 0.014 . The systematic error assigned in each bin is 0.070.

6.3.2 Incorrect Charge Assignment

The incorrect charge assignment rate, ω , is the rate at which electrons are wrongly assigned a positive charge and identified as positrons, and vice versa. The effect of incorrectly assigning the charge is to dilute the measured asymmetry.

The main mechanism responsible for the incorrect assignment of charge is the conversion of bremsstrahlung photons close to the initial track, which the GSF track reconstruction then incorrectly reconstructs.

The rate of incorrect charge assignment is obtained from $Z \rightarrow ee$ samples, selected from real data with the same selection as used in the analysis. The rate is measured by comparing the same sign Z yield ($Z \rightarrow e^\pm e^\pm$) to the opposite sign Z yield ($Z \rightarrow e^- e^+$). It was found that the rate at which electrons are reconstructed as positrons is the same as the rate of positrons reconstructed as electrons. The total Z yield from this sample is 6834 opposite-sign Z candidates and 21 same-sign Z candidates. The sample is split into 21 sub-samples, representing combinations of the 6 pseudorapidity bins of the two electrons.

For each Z event with two electrons in pseudorapidity bin i and j respectively the probability of an event being same sign or opposite sign can be written,

$$p(q_i q_j) = \begin{cases} (1 - \omega_i)(1 - \omega_j) + \omega_i \omega_j & \text{if } q_i q_j = -1 \\ \omega_i (1 - \omega_j) + \omega_j (1 - \omega_i) & \text{if } q_i q_j = +1 \end{cases}, \quad (6.19)$$

where ω_i, ω_j are the incorrect charge assignment rates and q_i, q_j are the charges of the

electrons.

The incorrect charge assignment rates in each of the 6 pseudorapidity bins can then be determined by a simultaneous fit to each of the 21 sub-samples. The results are shown in Table 6.8. The charge asymmetry is corrected for these values. The statistical error on the measurement of ω is then propagated to the charge asymmetry as a systematic uncertainty, $\sigma(\mathcal{A})_{\text{misch}}$.

η range	$\omega \times 10^{-3}$	$\sigma(\mathcal{A})_{\text{misch}} \times 10^{-3}$		
		$p_{\text{T}} > 25 \text{ GeV}$	$p_{\text{T}} > 30 \text{ GeV}$	$p_{\text{T}} > 35 \text{ GeV}$
$0.0 < \eta < 0.4$	0^{+8}	0.2	0.2	0.2
$0.4 < \eta < 0.8$	8^{+8}_{-8}	0.3	0.2	0.2
$0.8 < \eta < 1.2$	11^{+10}_{-8}	0.3	0.3	0.3
$1.2 < \eta < 1.4$	34^{+21}_{-15}	0.8	0.7	0.6
$1.6 < \eta < 2.0$	41^{+20}_{-15}	0.9	0.8	0.7
$2.0 < \eta < 2.4$	25^{+21}_{-15}	1.0	1.0	0.9

Table 6.8: Incorrect charge assignment rate and systematic error on the charge asymmetry [4].

6.3.3 Lepton Energy Scale and Resolution

The energy resolution and scale of the electrons can introduce a systematic error on the asymmetry due to the effect of the transverse momentum cut applied to the electrons. The largest source of bias in the electron energy scale is the changing transparency of the ECAL crystals caused by the changing level of radiation during the LHC 2010 run. Final state radiation (FSR) is considered as an additional contribution to the electron energy resolution so is corrected for by the following method. However, this effect is small as most FSR photons will tend to be collected in the electron supercluster.

To correct for this effect, a set of ad-hoc energy scale and resolution corrections are derived using a $Z \rightarrow ee$ mass distribution. The corrections are parametrised by six energy scale factors, s_i , and six resolutions, σ_i , one for each pseudorapidity bin in the asymmetry measurement. The scale factors represent the average factor by which the p_{T} of each MC electron should be corrected to match what is observed in data. The resolution factors represent the difference between the resolution in data and MC. It is

the additional smearing that would need to be applied to reconstruction level MC to match the observed resolution in data.

A sample of $Z \rightarrow ee$ events is split into 21 categories which correspond to all combinations of pseudorapidity bins of the two electrons. A mass template is obtained in each category from MC simulation where the ECAL calibration is taken to be perfect. A simultaneous fit to the $Z \rightarrow ee$ mass is performed in each of the 21 categories to determine the six energy scale factors, s_i , and the six resolutions, σ_i .

In each category ($category_{ij}$) where one electron is in the i^{th} pseudorapidity bin and the other is in the j^{th} bin, the MC template mass shape is scaled by $\frac{1}{\sqrt{s_i s_j}}$ and smeared by an additional Gaussian with width of $\sqrt{\sigma_i^2 + \sigma_j^2}$.

The bias in the measured charge asymmetry introduced by the electron energy resolution is evaluated by measuring the difference in the generator level charge asymmetry and the asymmetry after simulation of the detector with a perfect ECAL calibration that has been scaled and smeared by the factors obtained in the fit.

Table 6.9 contains the bias values due to the electron resolution for different electron p_T cuts. A conservative uncertainty of 1% is assigned to the electron energy after the scale corrections [4]. A systematic error is then estimated by measuring the difference of the measured charge asymmetry with and without the additional 1% scale factor. The systematic error due to the additional scale factors is summarised in Table 6.10.

η range	$p_T > 25$ GeV	$p_T > 30$ GeV	$p_T > 35$ GeV
$0.0 < \eta < 0.4$	0.4	0.5	-0.3
$0.4 < \eta < 0.8$	0.5	0.9	-1.0
$0.8 < \eta < 1.2$	1.9	0.9	3.2
$1.2 < \eta < 1.4$	4.3	3.7	2.4
$1.6 < \eta < 2.0$	3.2	5.0	4.3
$2.0 < \eta < 2.4$	4.2	5.2	2.7

Table 6.9: Bias values due to the electron resolution for different electron p_T cuts. All unit in $\times 10^{-3}$ [4].

η range	$p_T > 25$ GeV	$p_T > 30$ GeV	$p_T > 35$ GeV
$0.0 < \eta < 0.4$	1.0	0.5	1.4
$0.4 < \eta < 0.8$	0.7	1.5	4.4
$0.8 < \eta < 1.2$	0.2	2.4	3.1
$1.2 < \eta < 1.4$	1.9	2.7	4.6
$1.6 < \eta < 2.0$	2.4	1.7	2.8
$2.0 < \eta < 2.4$	1.6	1.7	4.4

Table 6.10: Systematic error due to the additional scale factor of 1% on the energy. All unit in $\times 10^{-3}$ [4].

6.4 Other Systematic Effects

There are several over systematic effects that must be evaluated and taken into account for the measurements.

Bin-to-bin migrations in pseudorapidity have a negligible effect on the asymmetry as the position resolution is small when compared to the size of the bins and the pseudorapidity distributions of electrons and positrons are not steeply falling in the region of interest, $0 < |\eta| < 2.4$.

The signal extraction procedure may introduce some biases into the measured asymmetry. A bias may be introduced into the measurement if there is a difference between the E_T^{miss} templates used and the true E_T^{miss} distribution. The systematic uncertainties due to the signal extraction method are evaluated by varying the templates used within certain uncertainties.

6.4.1 Signal Extraction Method

The systematic uncertainty due to the signal extraction method is evaluated by considering the error introduced by each E_T^{miss} template shape used in the fit separately.

Background E_T^{miss} Shape

The QCD and $\gamma + jet$ E_T^{miss} template shape is obtained from a control sample of events by anti-selecting electrons. This may introduce a systematic bias to the measurement if

there is a difference between the anti-selected QCD and $\gamma + jet$ E_T^{miss} samples and the selected QCD and $\gamma + jet$ samples.

The systematic uncertainty due to the QCD and $\gamma + jet$ E_T^{miss} shape is evaluated by varying the set of cuts in the anti-selection that is used to obtain the control sample by $\pm 10\%$. The effect that this has on the asymmetry is taken as a measure of the systematic uncertainty.

For each variation on the anti-selection, 500 pseudo-data experiments are generated using the signal and background E_T^{miss} shapes from MC samples with the number of events that are expected in 36.1 pb^{-1} of data. The distribution of the measured asymmetry in each pseudo-data experiment is then fitted with a Gaussian. The effect that changing the anti-selection has on the mean of the Gaussian is studied, the maximum distance from the asymmetry measured with the nominal anti-selection is taken as an estimate of the systematic uncertainty. The effect of changing the anti-selection used on the result with real data is also studied. The assigned systematic error due to the background is summarised in Table 6.11 for each pseudorapidity bin.

$ \eta $ range	$\sigma(\mathcal{A}) \times 10^{-3}$	
	MC	Data
$0.0 < \eta < 0.4$	0.8	1.2
$0.4 < \eta < 0.8$	0.7	0.9
$0.8 < \eta < 1.2$	0.8	2.1
$1.2 < \eta < 1.4$	1.2	2.5
$1.6 < \eta < 2.0$	0.6	1.0
$2.0 < \eta < 2.4$	2.2	1.3

Table 6.11: Maximum distance between the asymmetry measured with many different anti-selections and the asymmetry measured with the chosen anti-selection in MC pseudo-data and real data for each η bin [4].

Signal E_T^{miss} Shape from Boson Recoil

The signal E_T^{miss} shape is constructed using information from the boson recoil. There are three main sources of uncertainty due to the signal template.

The first source of systematic uncertainty is from the uncertainty in the recoil corrections. To evaluate the effect of the uncertainties of the recoil method, the upper and

lower limits on the corrections are used to generate different templates, and the effect on the measured asymmetry is evaluated as a measure of the systematic uncertainty.

The second source of systematic uncertainty is from the effect the energy scale has on the recoil corrections. Any differences in the energy scale of the electrons between data and MC must be taken into account to ensure accurate E_T^{miss} predictions. The MC energy scale corrections were determined from Z data and applied to the Z MC before calculating the recoil components [69].

The final source of uncertainty is due to the uncertainty of the PDF set used to generate the events that the recoil corrections are applied to. The recoil method uses generator level MC simulation as an input to the template shape. To evaluate the effect of the generator used, templates are generated with the CTEQ 6.6 [30] PDF set. The PDF set contains the central PDF and 44 error PDFs, which contain the 95 % CL for each of the 22 free parameters in the PDF. The maximum changes in the asymmetry with respect to the central value for each parameter are combined using the prescription in Section 3.3 and taken as a measure of the systematic uncertainty.

The systematic uncertainties due to the signal E_T^{miss} shape used in the signal extraction method are summarised in Table 6.12.

$ \eta $ range	Recoil Corr.	$\sigma(\mathcal{A}) \times 10^{-3}$			
		Energy Scale	PDF	Combined	
$0.0 < \eta < 0.4$	0.4	0.2	1.0	1.1	
$0.4 < \eta < 0.8$	0.6	0.3	1.5	1.6	
$0.8 < \eta < 1.2$	0.5	0.2	1.5	1.6	
$1.2 < \eta < 1.4$	0.9	0.5	2.0	2.2	
$1.6 < \eta < 2.0$	1.1	0.4	2.0	2.3	
$2.0 < \eta < 2.4$	0.7	0.3	2.0	2.1	

Table 6.12: Systematic uncertainty due to the signal E_T^{miss} shape used in the signal extraction method assigned to each η bin [4].

Electroweak E_T^{miss} Shape

The electroweak shape is also generated from MC samples. During the fitting procedure, the electroweak shape is fixed to the $W \rightarrow e\nu$ signal shape according to the cross section

taken from the MC samples. To estimate the effect that the uncertainty in the cross section has on the asymmetry measurement, the electroweak background is artificially varied by $\pm 20\%$ and the effect on the asymmetry is measured. Even with an overestimation of the uncertainty on the cross section, the effect on the asymmetry is found to be small.

The systematic uncertainties due to the electroweak E_T^{miss} shape used in the signal extraction method are summarised in Table 6.13.

$ \eta $ range	$\sigma(\mathcal{A}) \times 10^{-4}$
$0.0 < \eta < 0.4$	0.0
$0.4 < \eta < 0.8$	0.3
$0.8 < \eta < 1.2$	0.1
$1.2 < \eta < 1.4$	0.1
$1.6 < \eta < 2.0$	0.0
$2.0 < \eta < 2.4$	0.3

Table 6.13: Systematic uncertainty due to the electroweak E_T^{miss} shape used in the signal extraction method assigned to each η bin [4].

6.4.2 Systematic Uncertainty Summary

The summary of the systematic uncertainties due to the relative efficiency of electrons and positrons, the electron energy scale and resolution, the signal yield method and the incorrect assignment of charge are given in Table 6.14.

6.5 Results

The measurement of the electron charge asymmetry is presented with three different p_T cuts of 25, 30 and 35 GeV. The higher p_T cuts select a subset of events that will have a pseudorapidity closest to the W boson rapidity and enables the testing of PDF predictions in a more constrained region of phase space [1].

The results of the electron charge asymmetry with a p_T cut of 25 GeV, 30 GeV and 35 GeV are summarised in Table 6.15, Table 6.16 and Table 6.17.

		$\sigma(\mathcal{A}) \times 10^{-3}$			
	Relative Efficiency	Electron Scale/Res	Signal Estimation	Charge MisID	Total
$p_T > 25 \text{ GeV}$					
$0.0 < \eta < 0.4$	7.0	1.1	1.6	0.2	7.3
$0.4 < \eta < 0.8$	7.0	0.9	1.9	0.3	7.3
$0.8 < \eta < 1.2$	7.0	1.9	2.6	0.3	7.7
$1.2 < \eta < 1.4$	7.0	4.7	3.3	0.8	9.0
$1.6 < \eta < 2.0$	7.0	4.0	2.5	0.9	8.5
$2.0 < \eta < 2.4$	7.0	4.5	2.5	1.0	8.7
$p_T > 30 \text{ GeV}$					
$0.0 < \eta < 0.4$	7.0	0.7	1.6	0.2	7.2
$0.4 < \eta < 0.8$	7.0	1.7	1.9	0.2	7.5
$0.8 < \eta < 1.2$	7.0	2.6	2.6	0.3	7.9
$1.2 < \eta < 1.4$	7.0	4.6	3.3	0.7	9.1
$1.6 < \eta < 2.0$	7.0	5.3	2.5	0.8	9.2
$2.0 < \eta < 2.4$	7.0	5.5	2.5	1.0	9.3
$p_T > 35 \text{ GeV}$					
$0.0 < \eta < 0.4$	7.0	1.4	1.6	0.2	7.3
$0.4 < \eta < 0.8$	7.0	4.5	1.9	0.2	8.5
$0.8 < \eta < 1.2$	7.0	4.4	2.6	0.3	8.7
$1.2 < \eta < 1.4$	7.0	5.2	3.3	0.6	9.3
$1.6 < \eta < 2.0$	7.0	5.1	2.5	0.7	9.4
$2.0 < \eta < 2.4$	7.0	5.2	2.5	0.9	9.4

Table 6.14: Summary of the systematic errors [4].

Figure 6.6, Figure 6.7 and Figure 6.8 show a comparison of the experimental results to predictions from CTEQ10W PDF model [30] and MSTW08NNLO PDF model [22]. The predictions are obtained using the MCFM [24] MC tool and the uncertainties are obtained by using the prescription outlined in Section 3.3.

The data suggest the asymmetry has a flatter pseudorapidity dependence than the PDF models studied. At more central rapidities the CTEQ prediction is favoured but at higher rapidities the MSTW is favoured by the experimental data. The combined statistical and systematic uncertainty on the experimental results is comparable to the PDF uncertainty on the theoretical predictions.

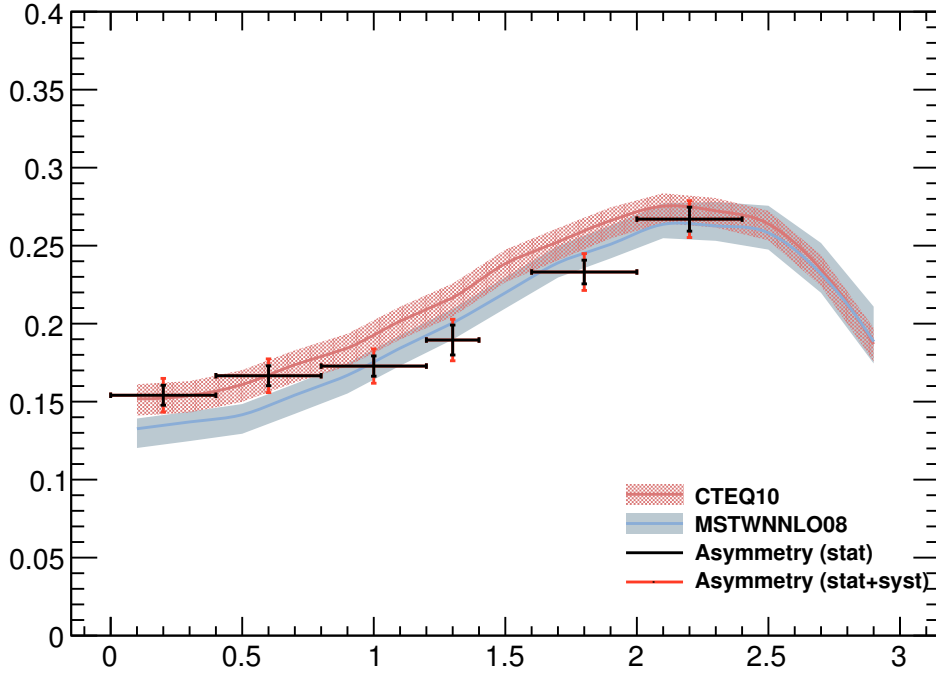


Figure 6.6: Measured electron charge asymmetry with predictions from CTEQ10W and MSTW08NNLO with a p_T cut of 25 GeV [4].

$ \eta $ range	$\langle \eta \rangle$	Data	CTEQ6.6	MSTW
$0.0 < \eta < 0.4$	0.2	$0.154 \pm 0.006 \pm 0.007$	$0.150^{+0.006}_{-0.005}$	$0.130^{+0.002}_{-0.003}$
$0.4 < \eta < 0.8$	0.6	$0.167 \pm 0.006 \pm 0.007$	$0.168^{+0.006}_{-0.006}$	$0.146^{+0.002}_{-0.003}$
$0.8 < \eta < 1.2$	1.0	$0.173 \pm 0.007 \pm 0.008$	$0.194^{+0.005}_{-0.007}$	$0.174^{+0.003}_{-0.003}$
$1.2 < \eta < 1.4$	1.3	$0.190 \pm 0.010 \pm 0.009$	$0.222^{+0.005}_{-0.009}$	$0.198^{+0.003}_{-0.003}$
$1.6 < \eta < 2.0$	1.8	$0.233 \pm 0.008 \pm 0.009$	$0.267^{+0.005}_{-0.011}$	$0.245^{+0.004}_{-0.002}$
$2.0 < \eta < 2.4$	2.2	$0.267 \pm 0.008 \pm 0.009$	$0.282^{+0.004}_{-0.011}$	$0.262^{+0.004}_{-0.002}$

Table 6.15: Measured electron charge asymmetry with a p_T cut of 25 GeV with predictions from CTEQ6.6 and MSTW PDFs. The uncertainties on the measured asymmetry are statistical and systematic respectively and the uncertainties on the predictions are due to the uncertainties on the PDFs [4].

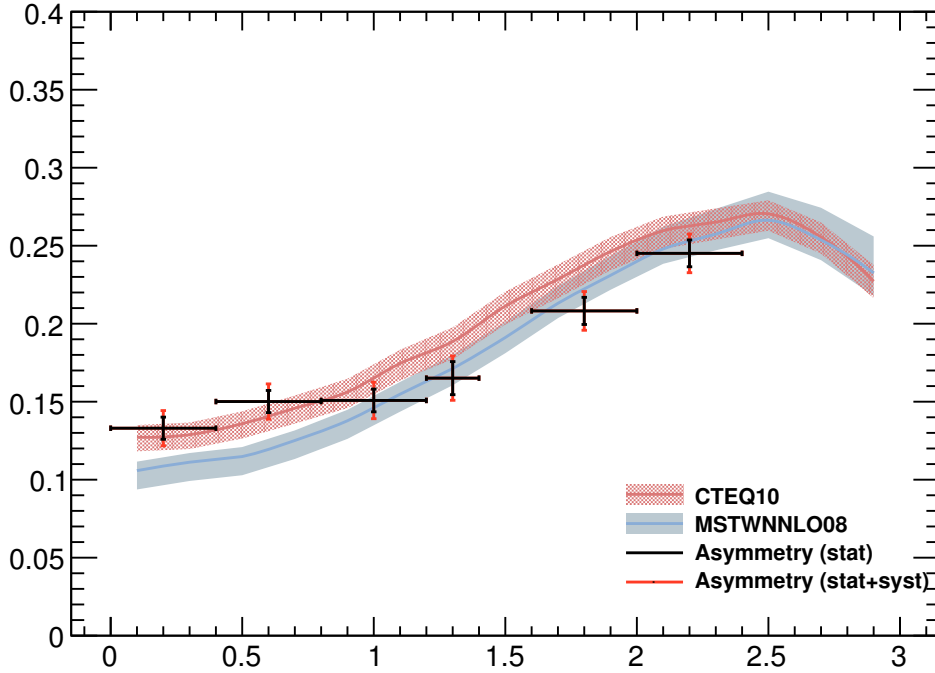


Figure 6.7: Measured electron charge asymmetry with predictions from CTEQ10W and MSTW08NNLO with a p_T cut of 30 GeV [4].

$ \eta $ range	$\langle \eta \rangle$	$p_T > 30 \text{ GeV}$	
		Data	Prediction
$0.0 < \eta < 0.4$	0.2	$0.133 \pm 0.007 \pm 0.007$	$0.133^{+0.006}_{-0.003}$
$0.4 < \eta < 0.8$	0.6	$0.150 \pm 0.007 \pm 0.008$	$0.150^{+0.003}_{-0.003}$
$0.8 < \eta < 1.2$	1.0	$0.151 \pm 0.007 \pm 0.008$	$0.171^{+0.004}_{-0.003}$
$1.2 < \eta < 1.4$	1.3	$0.165 \pm 0.011 \pm 0.009$	$0.195^{+0.003}_{-0.005}$
$1.6 < \eta < 2.0$	1.8	$0.208 \pm 0.009 \pm 0.009$	$0.242^{+0.006}_{-0.006}$
$2.0 < \eta < 2.4$	2.2	$0.245 \pm 0.009 \pm 0.009$	$0.263^{+0.007}_{-0.008}$

Table 6.16: Measured electron charge asymmetry with a p_T cut of 30 GeV with predictions from CTEQ6.6 PDF. The uncertainties on the measured asymmetry are statistical and systematic respectively and the uncertainties on predictions are due to the uncertainties on the PDFs [4].

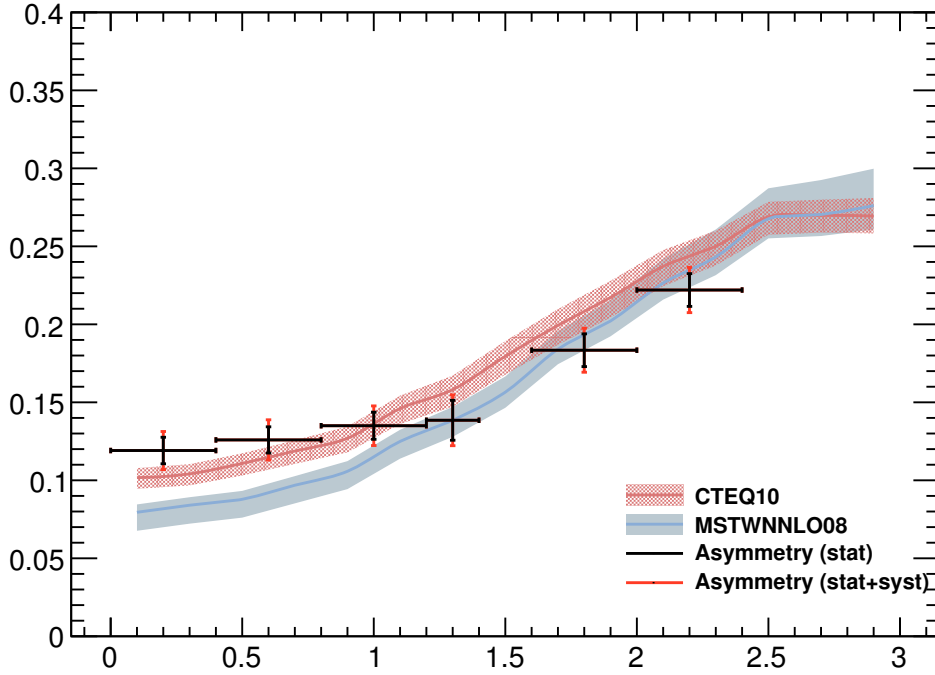


Figure 6.8: Measured electron charge asymmetry with predictions from CTEQ10W and MSTW08NNLO with a p_T cut of 35 GeV [4].

$ \eta $ range	$\langle \eta \rangle$	$p_T > 35 \text{ GeV}$	
		Data	Prediction
$0.0 < \eta < 0.4$	0.2	$0.119 \pm 0.009 \pm 0.007$	$0.115^{+0.003}_{-0.002}$
$0.4 < \eta < 0.8$	0.6	$0.126 \pm 0.008 \pm 0.009$	$0.127^{+0.002}_{-0.003}$
$0.8 < \eta < 1.2$	1.0	$0.135 \pm 0.009 \pm 0.009$	$0.150^{+0.003}_{-0.004}$
$1.2 < \eta < 1.4$	1.3	$0.139 \pm 0.013 \pm 0.009$	$0.169^{+0.004}_{-0.004}$
$1.6 < \eta < 2.0$	1.8	$0.183 \pm 0.011 \pm 0.009$	$0.217^{+0.006}_{-0.007}$
$2.0 < \eta < 2.4$	2.2	$0.222 \pm 0.011 \pm 0.009$	$0.243^{+0.008}_{-0.009}$

Table 6.17: Measured electron charge asymmetry with a p_T cut of 35 GeV with predictions from CTEQ6.6 PDF. The uncertainties on the measured asymmetry are statistical and systematic respectively and the uncertainties on predictions are due to the uncertainties on the PDFs [4].

Chapter 7

Update to the electron charge asymmetry measurement with 840 pb⁻¹

The measurement detailed in the previous chapter was performed with 36 pb⁻¹ of data from the full 2010 dataset. In this chapter, the update to the measurement of the electron charge asymmetry in inclusive $pp \rightarrow W(e\nu) + X$ production with 840 pb⁻¹ is presented [2,3]. The data were collected with the CMS detector from collisions from the first 2011 LHC run (Run A) and correspond to a nearly 25 times increase in statistics over the 2010 measurement.

The majority of the 2011 analysis is identical to the 2010 analysis, however small changes to the methodology have been implemented due to changes in the instantaneous luminosity and the increased amount of data in the 2011 LHC run.

The results are presented in 11 bins of absolute value of pseudorapidity with a fixed width of 0.2. To avoid the gap between the ECAL barrel and ECAL endcap the region $1.4 < |\eta| < 1.6$ is excluded.

7.1 Event Selection

7.1.1 Trigger

The triggers used in the updated measurement are summarised in Table 7.1 with the run ranges to which they are applied. Due to the increased instantaneous luminosity in the 2011 Run A, the identification and isolation cuts applied to the trigger have been tightened. The p_T cut applied to the electron was increased, first to 27 GeV and then in later runs to 32 GeV.

Run Ranges	Trigger
160404-161176	HLT_Ele27_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_v1
161217-163261	HLT_Ele32_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_v1
163270-163869	HLT_Ele32_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_v2
165088-165633	HLT_Ele32_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_v3
165970-166967	HLT_Ele32_CaloIdVT_CaloIsoT_TrkIdT_TrkIsoT_v4

Table 7.1: Triggers used to select the data used in this measurement.

7.1.2 Electron Selection

The electron transverse momentum cut is increased to 35 GeV due to the constraints imposed by the high-level triggers available. This is the only change to the electron selection with respect to the 2010 analysis, detailed in Table 6.2.

7.1.3 Event Selection

The event selection remains the same with respect to the 2010 measurement. An event is selected if it contains a single electron that passes all electron selections and it is vetoed if it contains a second charged lepton with $p_T > 15$ GeV.

The particle flow E_T^{miss} distribution for the events that pass the event selection, with $p_T > 35$ GeV and $|\eta| < 2.4$ is shown in Figure 7.1. The numbers of selected events that pass the event selection are shown in Table 7.2. The expected composition of the selected events, derived from MC simulations, is shown in Table 7.3.

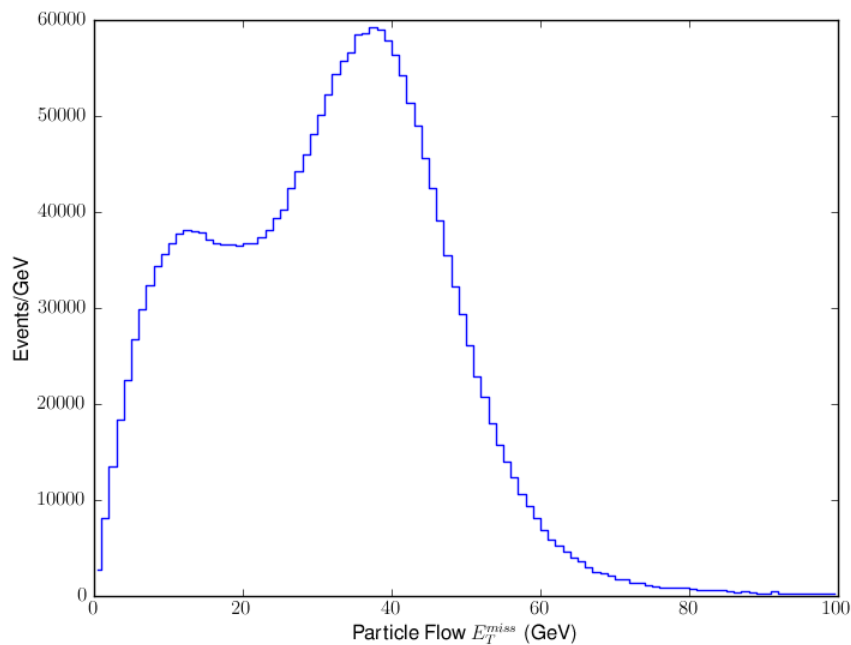


Figure 7.1: Particle Flow E_T^{miss} distribution for selected events that pass a transverse momentum cut of 35 GeV.

$ \eta $ range	Selected Positrons	Selected Electrons
$0.0 < \eta < 0.2$	108235	90860
$0.2 < \eta < 0.4$	112870	93996
$0.4 < \eta < 0.6$	114148	94721
$0.6 < \eta < 0.8$	117099	95295
$0.8 < \eta < 1.0$	116956	94580
$1.0 < \eta < 1.2$	113336	90755
$1.2 < \eta < 1.4$	115265	91572
$1.6 < \eta < 1.8$	92137	70205
$1.8 < \eta < 2.0$	105596	80921
$2.0 < \eta < 2.2$	112419	86240
$2.2 < \eta < 2.4$	121224	102111

Table 7.2: Number of events passing the event selection for a lepton momentum cut of $p_T > 35$ GeV [3].

$p_T > 35 \text{ GeV}$		
Signal	$W \rightarrow e\nu$	76.2%
Electroweak	$Z \rightarrow \tau\tau$	0.2%
	$Z \rightarrow ee$	6.4%
	$W \rightarrow \tau\nu$	0.8%
	$t\bar{t}$	0.4%
	Total	7.8%
QCD	Total	16.0%

Table 7.3: Composition of selected events for a lepton momentum cut of $p_T > 35 \text{ GeV}$. Numbers are evaluated using simulation [3].

7.2 Signal Yield Extraction Method

The number of signal and background events in each bin is extracted using a fit to the E_T^{miss} distribution using two templates: the sum of the $W \rightarrow e\nu$ signal and the electroweak background shapes, and the QCD plus $\gamma + jet$ processes.

The QCD and $\gamma + jet$ background distribution is obtained from a control sample of events that pass an anti-selection described in Table 6.4. The E_T^{miss} distributions for the electroweak background were obtained from MadGraph [72] MC simulations with the Z2 tune. The MC samples used are summarised in Table C.2. The scale of the electroweak The signal E_T^{miss} shape is obtained by modelling the recoil of the W boson.

7.2.1 Signal E_T^{miss} Shape from Boson Recoil

The E_T^{miss} shape for signal is obtained by modelling the recoil of the W boson. The recoil response and resolution is measured in $Z \rightarrow ee$ data events, and W and ZMC simulations to derive a correction to E_T^{miss} as a function of W p_T [68, 69].

The methodology in deriving the details is described in Section 6.2.2. The Gaussian used to fit the recoil components was modified to a double Gaussian. The corrections were obtained by selecting $Z \rightarrow ee$ events using the same selection criteria as the analysis, but with the requirement of two electrons instead of one.

7.2.2 Fit on Real Data

The results of the extended maximum likelihood fits to each pseudorapidity/charge bin are shown in Figures B.3, B.4, B.5 and B.6 in the appendix. The signal yield in each bin is summarised in Table 7.4 and the uncorrected asymmetry values are shown in Table 7.5.

$ \eta $ range	Charge	N_{QCD} fitted events	$N_{W \rightarrow e\nu}$ fitted events
$0.0 < \eta < 0.2$	+	12794.5 ± 202.6	89698.3 ± 330.5
	−	12926.1 ± 194.3	72369.8 ± 297.6
$0.2 < \eta < 0.4$	+	13773.9 ± 209.6	93109.0 ± 337.7
	−	14071.4 ± 199.8	74215.4 ± 302.0
$0.4 < \eta < 0.6$	+	14803.9 ± 212.9	93211.7 ± 338.1
	−	14554.2 ± 203.5	74360.3 ± 303.4
$0.6 < \eta < 0.8$	+	15484.5 ± 217.0	94943.5 ± 341.0
	−	15523.8 ± 206.4	73764.2 ± 302.2
$0.8 < \eta < 1.0$	+	17177.5 ± 221.7	92971.3 ± 338.1
	−	16871.6 ± 210.5	71476.6 ± 298.3
$1.0 < \eta < 1.2$	+	20001.2 ± 229.9	86449.0 ± 329.0
	−	19930.1 ± 218.4	64643.8 ± 286.6
$1.2 < \eta < 1.4$	+	24214.9 ± 243.7	83718.6 ± 326.6
	−	24425.4 ± 233.0	60683.8 ± 281.4
$1.6 < \eta < 1.8$	+	15759.0 ± 228.6	68726.0 ± 302.3
	−	16093.2 ± 220.1	47154.5 ± 256.2
$1.8 < \eta < 2.0$	+	23809.6 ± 241.7	73116.7 ± 305.0
	−	23135.2 ± 234.7	49577.2 ± 257.0
$2.0 < \eta < 2.2$	+	33773.0 ± 261.7	69872.7 ± 299.1
	−	32104.6 ± 253.1	45913.9 ± 248.8
$2.2 < \eta < 2.4$	+	61794.8 ± 309.3	52495.9 ± 269.8
	−	60449.1 ± 306.6	34746.0 ± 228.7

Table 7.4: The signal and QCD background yields with the corresponding statistical uncertainty [3].

$ \eta $ range	$\mathcal{A}_{exp}(\times 10^{-3})$
$0.0 < \eta < 0.4$	106.9 ± 2.7
$0.2 < \eta < 0.4$	112.9 ± 2.7
$0.4 < \eta < 0.6$	112.5 ± 2.7
$0.6 < \eta < 0.8$	125.5 ± 2.7
$0.8 < \eta < 1.0$	130.7 ± 2.7
$1.0 < \eta < 1.2$	144.3 ± 2.9
$1.2 < \eta < 1.4$	159.5 ± 3.0
$1.6 < \eta < 1.8$	186.1 ± 3.4
$1.8 < \eta < 2.0$	191.8 ± 3.2
$2.0 < \eta < 2.2$	206.9 ± 3.3
$2.2 < \eta < 2.4$	203.4 ± 4.1

Table 7.5: Uncorrected values ($\times 10^{-3}$) of the charge asymmetry for an integrated luminosity of 840 pb^{-1} [3].

7.3 Corrections

To compare with the theoretical value, the measured lepton asymmetry has to be corrected for the charge-dependent reconstruction efficiency, the incorrect charge assignment rate and the effect of the electron energy resolution.

7.3.1 Relative Efficiency

The relative efficiency is again measured using a tag and probe method [71]. The GSF tracking efficiency, identification efficiency and the HLT efficiency are measured individually for each bin of pseudorapidity and for electrons and positrons separately.

The GSF tracking efficiency, identification efficiency and the HLT efficiency are summarised in Table 7.6 in each pseudorapidity bin, as well as inclusively across the range $0 < |\eta| < 2.4$.

The main systematic errors on the measurements of the efficiencies are the energy scale and the signal shape. It was verified that these systematic effects cancel in the measurement of the ratio of the efficiencies, R , and are negligible with respect to the statistical error on the measurement [3]. Only the statistical error on the measurement is propagated to the error on the measurement of the ratio of the efficiencies. Unlike in the

previous chapter the statistical error on the measurement of R in each pseudorapidity bin is propagated to the asymmetry as a systematic error.

7.3.2 Incorrect Charge Assignment

The rate that electrons and positrons are incorrectly assigned charge is measured in data from the same-sign and opposite-sign Z yields using the same electron selection as in the asymmetry measurement.

The $Z \rightarrow ee$ sample is split into 66 sub-samples, representing the combinations of pseudorapidity bins of the two electrons. For each Z event with two electrons in pseudorapidity bin i and j respectively, the probability of an event being same-sign or opposite-sign is given by the equation (6.19). The incorrect charge rates, ω_i , are extracted from a simultaneous fit to the 66 samples. The resulting values of ω are shown in Table 7.7. The statistical uncertainty on ω is propagated to the measurement of the asymmetry as a systematic uncertainty.

7.3.3 Lepton Energy Scale and Resolution

The effect of the electron energy resolution on the asymmetry measurement is studied using a MC study. A correction to the asymmetry can be evaluated by comparing the asymmetry measured at the generator level and the asymmetry measured in MC after the simulation of detector effects.

The correction relies on the simulation reproducing the energy scale and resolution of the electrons perfectly. Unfortunately the simulation does not take into account all the detector effects present in real data, so additional residual corrections to the simulated electron p_T distributions are necessary, similar to the ad-hoc corrections in Section 6.3.3. An additional Gaussian smearing of the p_T distribution (σ_{corr}) and electron energy scale corrections (k_{corr}) for each pseudorapidity bin are applied [73].

The values for k_i and σ_i are obtained from the $Z \rightarrow ee$ mass distribution. The $Z \rightarrow ee$ sample is again split into 66 sub-samples for the combinations of pseudorapidity bins of the two electrons for real data and MC. The $Z \rightarrow ee$ mass distribution is then fitted with a Breit-Wigner function convoluted with a Crystal Ball function that represents the resolution function, instead of the simple Gaussian used previously. The width and the mass of the Breit-Wigner function are taken from the PDG values [25]. The resolution

$ \eta $ range	Charge	ϵ_{GSF}	ϵ_{ID}	ϵ_{HLT}	R
$0.0 < \eta < 0.2$	+	98.5 ± 0.2	83.6 ± 0.4	97.9 ± 0.2	1.003 ± 0.009
	-	98.4 ± 0.2	83.5 ± 0.5	97.8 ± 0.2	
$0.2 < \eta < 0.4$	+	98.9 ± 0.2	82.6 ± 0.5	97.9 ± 0.2	0.998 ± 0.009
	-	98.8 ± 0.2	82.8 ± 0.5	98.0 ± 0.2	
$0.4 < \eta < 0.6$	+	98.9 ± 0.2	83.6 ± 0.5	98.1 ± 0.2	0.995 ± 0.009
	-	99.0 ± 0.2	84.1 ± 0.5	97.9 ± 0.2	
$0.6 < \eta < 0.8$	+	98.7 ± 0.2	83.7 ± 0.5	98.4 ± 0.2	0.999 ± 0.009
	-	98.7 ± 0.2	84.0 ± 0.5	98.2 ± 0.2	
$0.8 < \eta < 1.0$	+	98.6 ± 0.2	84.3 ± 0.5	97.3 ± 0.2	0.998 ± 0.009
	-	98.3 ± 0.2	84.4 ± 0.5	97.7 ± 0.2	
$1.0 < \eta < 1.2$	+	98.2 ± 0.2	82.6 ± 0.5	97.6 ± 0.2	1.010 ± 0.010
	-	98.2 ± 0.2	81.7 ± 0.5	97.7 ± 0.2	
$1.2 < \eta < 1.4$	+	97.4 ± 0.2	79.4 ± 0.5	97.3 ± 0.2	1.005 ± 0.011
	-	97.5 ± 0.2	78.8 ± 0.6	97.5 ± 0.2	
$1.6 < \eta < 1.8$	+	97.3 ± 0.3	62.3 ± 0.7	97.1 ± 0.3	1.032 ± 0.019
	-	96.9 ± 0.3	61.2 ± 0.7	96.2 ± 0.4	
$1.8 < \eta < 2.0$	+	97.3 ± 0.3	62.1 ± 0.8	97.6 ± 0.3	0.976 ± 0.018
	-	97.4 ± 0.3	63.7 ± 0.8	97.4 ± 0.3	
$2.0 < \eta < 2.2$	+	97.5 ± 0.3	58.6 ± 0.9	98.5 ± 0.3	0.966 ± 0.021
	-	97.3 ± 0.3	60.7 ± 0.8	98.6 ± 0.3	
$2.2 < \eta < 2.4$	+	95.9 ± 0.4	55.1 ± 1.0	97.5 ± 0.4	0.967 ± 0.026
	-	96.5 ± 0.4	56.3 ± 1.0	98.0 ± 0.4	
$0.0 < \eta < 1.4$	+	98.42 ± 0.07	82.9 ± 0.2	97.82 ± 0.08	0.999 ± 0.004
	-	98.51 ± 0.07	82.9 ± 0.2	97.82 ± 0.08	
$1.6 < \eta < 2.4$	+	97.12 ± 0.15	60.1 ± 0.4	97.63 ± 0.17	0.987 ± 0.010
	-	97.12 ± 0.15	61.0 ± 0.4	97.42 ± 0.17	
$0.0 < \eta < 2.4$	+	98.09 ± 0.06	77.41 ± 0.17	97.76 ± 0.07	0.999 ± 0.003
	-	98.16 ± 0.06	77.49 ± 0.17	97.73 ± 0.07	

Table 7.6: GSF tracking, identification and HLT efficiency as a function of charge [3].

η range	$\omega \times 10^{-4}$
$0.0 < \eta < 0.2$	1 ± 1
$0.2 < \eta < 0.4$	1 ± 1
$0.4 < \eta < 0.6$	1 ± 1
$0.6 < \eta < 0.8$	2 ± 1
$0.8 < \eta < 1.0$	4 ± 2
$1.0 < \eta < 1.2$	3 ± 2
$1.2 < \eta < 1.4$	3 ± 2
$1.6 < \eta < 1.8$	17 ± 4
$1.8 < \eta < 2.0$	12 ± 4
$2.0 < \eta < 2.2$	26 ± 7
$2.2 < \eta < 2.4$	7 ± 7

Table 7.7: Incorrect charge assignment rates and related systematic uncertainties [3].

of the Crystal Ball function is defined as,

$$\sigma_{ij} = \sqrt{\sigma_i^2 + \sigma_j^2}, \quad (7.1)$$

where σ_i is the resolution in each individual pseudorapidity bin. The mean value of the Crystal Ball function is defined as,

$$m_{0_{ij}} = m_Z^{PDG} \left(\sqrt{k_i k_j} - 1 \right), \quad (7.2)$$

where k_i is the scale factor in each pseudorapidity bin. The 11 scale factors k_i and the 11 additional smearing factors σ_i for each pseudorapidity bin are obtained from a simultaneous fit to each of the mass distributions from 66 sub-samples to both MC and data.

To have a good agreement between data and simulation the simulated p_T distribution of the leptons must be smeared with a Gaussian of width,

$$\sigma_i^{corr} = \sqrt{(\sigma_i^{data})^2 - (\sigma_i^{MC})^2}, \quad (7.3)$$

and then scaled by a factor,

$$k_i^{corr} = \frac{k_i^{data}}{k_i^{MC}}, \quad (7.4)$$

The values of the residual corrections, obtained with this method are given in Table 7.8.

A MC sample of $W \rightarrow e\nu_e$ events is used to evaluate the corrections introduced by the effect of the energy scale and resolution for each pseudorapidity bin. The generator level electron p_T is first smeared by the nominal p_T resolution of the simulated sample after the simulation of detector effects. It is then smeared and scaled according to the residual energy corrections, σ^{corr} and k^{corr} . The p_T cut is then applied to the generator and corrected samples, and the asymmetry corrections are obtained by comparing the number of events that pass the threshold in either sample.

There are three sources of systematic uncertainty that affect the evaluated correction, the PDF uncertainty on the generated p_T spectra, the modelling of FSR and the uncertainty on the residual correction. The PDF uncertainty is evaluated by generating a p_T spectrum for each error PDF in the PDF set and summing in quadrature the variations. The energy scale correction will have the effect of correcting for final state radiation in the event. The uncertainty on the correction is evaluated using a prescribed method [74]. The uncertainty on the residual correction is evaluated by scaling and smearing the p_T spectra within the uncertainty taking the maximum distance from a central value as the uncertainty.

The correction factor introduced by the electron energy scale and resolution and the accompanying uncertainties are described in Table 7.9.

7.3.4 Correction Factors

The summary of each of the correction factors applied to the asymmetry measurement in each pseudorapidity bin is given in Table 7.10. At central pseudorapidities the corrections are small, but at larger pseudorapidities the corrections due to the incorrect charge assignment become larger.

7.4 Systematic Uncertainties

The systematic uncertainties due to the relative efficiency, the incorrect charge assignment and the electron energy scale and resolution are included in the uncertainties on the correction factors applied to the asymmetry that were described in the preceding section.

η bin	σ_{DATA} GeV	σ_{MC} GeV	σ_{corr} GeV	k_{DATA}	k_{MC}	k_{corr}
$0.0 < \eta < 0.2$	1.08 ± 0.03	0.83 ± 0.03	0.70 ± 0.06	1.0007 ± 0.0003	1.0012 ± 0.0003	0.9995 ± 0.0004
$0.2 < \eta < 0.4$	1.01 ± 0.03	0.85 ± 0.02	0.54 ± 0.07	1.0036 ± 0.0003	1.0020 ± 0.0003	1.0016 ± 0.0004
$0.4 < \eta < 0.6$	1.16 ± 0.03	0.95 ± 0.02	0.67 ± 0.06	1.0019 ± 0.0003	1.0006 ± 0.0003	1.0013 ± 0.0004
$0.6 < \eta < 0.8$	1.16 ± 0.03	0.98 ± 0.02	0.61 ± 0.07	1.0039 ± 0.0003	1.0008 ± 0.0003	1.0031 ± 0.0004
$0.8 < \eta < 1.0$	1.28 ± 0.03	1.13 ± 0.02	0.61 ± 0.08	1.0003 ± 0.0004	0.9987 ± 0.0003	1.0016 ± 0.0005
$1.0 < \eta < 1.2$	1.68 ± 0.03	1.42 ± 0.02	0.90 ± 0.07	0.9906 ± 0.0004	0.9941 ± 0.0003	0.9964 ± 0.0005
$1.2 < \eta < 1.4$	2.02 ± 0.03	1.62 ± 0.02	1.21 ± 0.06	0.9859 ± 0.0005	0.9962 ± 0.0004	0.9896 ± 0.0006
$1.6 < \eta < 1.8$	2.78 ± 0.04	2.26 ± 0.03	1.62 ± 0.08	0.9977 ± 0.0007	0.9797 ± 0.0005	1.0184 ± 0.0009
$1.8 < \eta < 2.0$	2.38 ± 0.04	1.83 ± 0.03	1.53 ± 0.07	0.9976 ± 0.0006	0.9768 ± 0.0005	1.0213 ± 0.0008
$2.0 < \eta < 2.2$	2.16 ± 0.04	1.49 ± 0.03	1.56 ± 0.06	0.9922 ± 0.0006	0.9837 ± 0.0005	1.0087 ± 0.0008
$2.2 < \eta < 2.4$	2.21 ± 0.04	1.39 ± 0.04	1.72 ± 0.06	0.9510 ± 0.0008	0.9881 ± 0.0005	0.9625 ± 0.0009

Table 7.8: Scale and residual smearing factors measured in $Z \rightarrow ee$ data [3].

η range	Correction factor	Stat. Error	PDF Syst. Error	FSR Syst. Error	Scale Syst. Error
$0.0 < \eta < 0.2$	-1.1	0.1	0.3	0.1	0.0
$0.2 < \eta < 0.4$	0.2	0.1	0.6	0.0	0.0
$0.4 < \eta < 0.6$	-0.4	0.1	0.3	0.0	0.0
$0.6 < \eta < 0.8$	-0.9	0.1	0.3	0.0	0.0
$0.8 < \eta < 1.0$	-0.9	0.1	0.6	0.0	0.0
$1.0 < \eta < 1.2$	-1.4	0.1	1.0	0.0	0.0
$1.2 < \eta < 1.4$	-3.5	0.1	0.8	0.0	0.1
$1.6 < \eta < 1.8$	-2.5	0.1	0.8	0.0	0.0
$1.8 < \eta < 2.0$	-4.4	0.1	1.6	0.0	0.0
$2.0 < \eta < 2.2$	-0.2	0.1	2.6	0.0	0.1
$2.2 < \eta < 2.4$	-3.5	0.1	2.4	0.0	0.2

Table 7.9: Bias in the charge asymmetry introduced by the electron energy scale and resolution. All values are in units $\times 10^{-3}$ [3].

η range	$\mathcal{A}_M$	Rel. Eff MisCharge Correction	Energy Resolution Correction	$\mathcal{A}_C$
$0.0 < \eta < 0.4$	106.9	-1.5 ± 4.5	-1.1 ± 0.3	104.3
$0.2 < \eta < 0.4$	112.9	$+1.0 \pm 4.4$	0.2 ± 0.6	114.1
$0.4 < \eta < 0.6$	112.5	$+2.5 \pm 4.4$	-0.4 ± 0.3	114.6
$0.6 < \eta < 0.8$	125.5	$+0.5 \pm 4.4$	-0.9 ± 0.3	125.1
$0.8 < \eta < 1.0$	130.7	$+0.2 \pm 4.4$	-0.9 ± 0.6	130.0
$1.0 < \eta < 1.2$	144.3	-4.8 ± 4.9	-1.4 ± 1.0	138.1
$1.2 < \eta < 1.4$	159.5	-2.3 ± 5.4	-3.5 ± 0.8	153.7
$1.6 < \eta < 1.8$	186.1	-14.9 ± 9.2	-2.5 ± 0.8	168.7
$1.8 < \eta < 2.0$	191.8	$+12.0 \pm 8.7$	-4.4 ± 1.6	199.5
$2.0 < \eta < 2.2$	206.9	$+17.4 \pm 10.1$	-0.2 ± 2.6	224.1
$2.2 < \eta < 2.4$	203.4	$+16.1 \pm 12.5$	-3.5 ± 2.4	216.0

Table 7.10: Summary of the corrections ($\times 10^{-3}$) that are applied to the measured asymmetry [3].

7.4.1 Signal Extraction Method

Biases may be introduced into the measurement if there is a difference between the E_T^{miss} templates used and the true E_T^{miss} distribution. The systematic uncertainties due to the signal extraction method are evaluated in a similar way to the measurement described in the preceding chapter. The template shapes used in the signal yield extraction method are varied within certain uncertainties.

QCD E_T^{miss} Shape

The systematic uncertainty due to the QCD and $\gamma + \text{jet}$ E_T^{miss} shape is evaluated by varying the anti-selection that is used to obtain the control sample. The effect that changing the values of the inverted $\Delta\eta$ and $\Delta\phi$ cuts used in anti-selection has on the asymmetry is observed and the maximum distance from the measured asymmetry with the nominal anti-selection is used as a measure of the systematic uncertainty.

Table 7.11 summarises the systematic uncertainty due to the QCD E_T^{miss} shape for each pseudorapidity bin.

$ \eta $ range	$\sigma(\mathcal{A}) \times 10^{-3}$
$0.0 < \eta < 0.2$	1.0
$0.2 < \eta < 0.4$	1.9
$0.4 < \eta < 0.6$	2.2
$0.6 < \eta < 0.8$	1.8
$0.8 < \eta < 1.0$	0.5
$1.0 < \eta < 1.2$	1.5
$1.2 < \eta < 1.4$	1.4
$1.6 < \eta < 1.8$	2.5
$1.8 < \eta < 2.0$	1.3
$2.0 < \eta < 2.2$	0.6
$2.2 < \eta < 2.4$	1.6

Table 7.11: Maximum distance between the asymmetry measured with many different anti-selections and the asymmetry measured with the nominal anti-selection in MC pseudo-data for each η bin [3].

Signal E_T^{miss} Shape from Boson Recoil

The two sources of systematic error due to the signal E_T^{miss} shape are considered: the uncertainties on the recoil method and the uncertainty due to the choice of PDF used as an input to the recoil method.

The uncertainties on the recoil method corrections are propagated to the asymmetry measurement as systematic uncertainties. The corrections obtained from the recoil method vary between an upper and lower value [69]. The effect of these uncertainties on the asymmetry measurement is evaluated by using the upper and lower limits on the corrections to observe the effect that they have on the measured asymmetry, and use this as a measure of the systematic uncertainty.

The systematic uncertainty due to the PDF uncertainty used to generate the template shapes is evaluated by considering the PDF error sets. The CTEQ6.6 [30] error PDF sets have 45 individual PDFs which represent the central value PDF, 22 upper and 22 lower error PDF for each of the 22 parameters the CTEQ collaboration use in their global fits to data. The uncertainty is evaluated by generating template shapes for each of the parameters and measuring the effect of these templates on the measured asymmetry. The effects due to each parameter are combined using the prescription in Section 3.3 and taken as a measure of the systematic uncertainty.

The systematic uncertainty due to the signal E_T^{miss} signal shape is summarised in Table 7.12.

Electroweak E_T^{miss} Shape

The electroweak E_T^{miss} shape is obtained from MC samples. During the fitting procedure, the electroweak shape is fixed to the $W \rightarrow e\nu$ signal shape according to the cross section from NLO MC.

To estimate the effect of the uncertainty of the cross section has on the asymmetry measurement, the electroweak background is varied by the measured uncertainty on the relative W to Z cross sections of $\pm 2\%$. The effect on the asymmetry is measured and found to be negligible [3].

$ \eta $ range	$\sigma(\mathcal{A}) \times 10^{-3}$		
	Recoil Corr.	PDF	Combined
$0.0 < \eta < 0.2$	0.2	1.5	1.5
$0.2 < \eta < 0.4$	0.4	1.6	1.7
$0.4 < \eta < 0.6$	0.6	1.3	1.4
$0.6 < \eta < 0.8$	0.8	1.5	1.7
$0.8 < \eta < 1.0$	0.9	1.6	1.8
$1.0 < \eta < 1.2$	0.8	1.7	1.9
$1.2 < \eta < 1.4$	1.5	1.6	2.3
$1.6 < \eta < 1.8$	0.7	1.7	1.9
$1.8 < \eta < 2.0$	0.4	1.5	1.6
$2.0 < \eta < 2.2$	1.1	1.5	1.9
$2.2 < \eta < 2.4$	0.9	2.3	2.4

Table 7.12: Systematic uncertainty due to the signal E_T^{miss} shape used in the signal extraction method assigned to each η bin [3].

7.4.2 Systematic Uncertainty Summary

The summary of the systematic uncertainties due to the signal yield method, the electron energy scale and resolution, the incorrect assignment of charge and the relative efficiency of electrons and positrons are given in Table 7.13.

A full correlation matrix of the systematic errors in the measurement is presented in Table 7.14.

7.5 Results

The measured electron charge asymmetry results are summarised in Table 7.15 with both the statistical and systematic uncertainties included. The experimental results are compared with predictions from various PDF models obtained with the MCFM [24] MC tool. The MCFM MC tool has been interfaced with the CT10 [30], HERAPDF [75], NNPDF [76] and MSTW2008 [22] PDF models and the uncertainties are obtained by using the prescription outlined in Section 3.3.

The results are also presented in Figure 7.2. The experimental data are in agreement with the predictions from the CT10, NNPDF and HERAPDF pdf models whereas MSTW

	Signal Yield	Energy Scale and Res.	Charge MisId.	Efficiency Ratio
$0.0 < \eta < 0.2$	1.8	0.6	0.0	4.5
$0.2 < \eta < 0.4$	2.5	0.6	0.0	4.4
$0.4 < \eta < 0.6$	2.7	0.3	0.0	4.4
$0.6 < \eta < 0.8$	2.5	0.3	0.0	4.4
$0.8 < \eta < 1.0$	1.9	0.6	0.1	4.4
$1.0 < \eta < 1.2$	2.4	1.0	0.1	4.9
$1.2 < \eta < 1.4$	2.6	0.8	0.1	5.4
$1.6 < \eta < 1.8$	3.1	0.8	0.1	9.2
$1.8 < \eta < 2.0$	2.0	1.6	0.2	8.7
$2.0 < \eta < 2.2$	2.0	2.6	0.3	10.0
$2.2 < \eta < 2.4$	2.9	2.4	0.3	12.5

Table 7.13: Summary of the systematic uncertainties. All values are in units $\times 10^{-3}$ [3].

is systematically lower than the experimentally observed asymmetry in the more central regions. This is also demonstrated in Figure 7.3 which shows the ratio between the experimental results and the theoretical predictions from the four PDF models.

	[0,0,0,2]	[0,2,0,4]	[0,4,0,6]	[0,6,0,8]	[0,8,1,0]	[1,0,1,2]	[1,2,1,4]	[1,6,1,8]	[1,8,2,0]	[2,0,2,2]	[2,2,2,4]
[0,0,0,2]	23.7	2.6	2.2	2.5	2.7	2.9	2.9	2.9	2.8	3.1	4.2
[0,2,0,4]	2.6	26.2	2.6	2.9	3.1	3.3	3.4	3.2	3.0	3.9	4.7
[0,4,0,6]	2.2	2.6	26.6	2.6	2.8	2.9	3.2	2.9	2.5	3.3	4.1
[0,6,0,8]	2.5	2.9	2.6	25.6	3.3	3.4	3.7	3.3	2.8	3.7	4.7
[0,8,1,0]	2.7	3.1	2.8	3.3	23.3	3.9	4.2	3.7	3.4	4.6	5.6
[1,0,1,2]	2.9	3.3	2.9	3.4	3.9	30.8	4.5	4.1	4.0	5.7	6.8
[1,2,1,4]	2.9	3.4	3.2	3.7	4.2	4.5	36.5	4.3	3.7	5.8	6.7
[1,6,1,8]	2.9	3.2	2.9	3.3	3.7	4.1	4.3	94.9	3.8	5.1	6.2
[1,8,2,0]	2.8	3.0	2.5	2.8	3.4	4.0	3.7	3.8	82.4	6.2	7.0
[2,0,2,2]	3.1	3.9	3.3	3.7	4.6	5.7	5.8	5.1	6.2	110.7	10.3
[2,2,2,4]	4.2	4.7	4.1	4.7	5.6	6.8	6.7	6.2	7.0	10.3	171.0

Table 7.14: Correlation matrix for all the systematic errors. All the values are given in units $\times 10^{-6}$ [3].

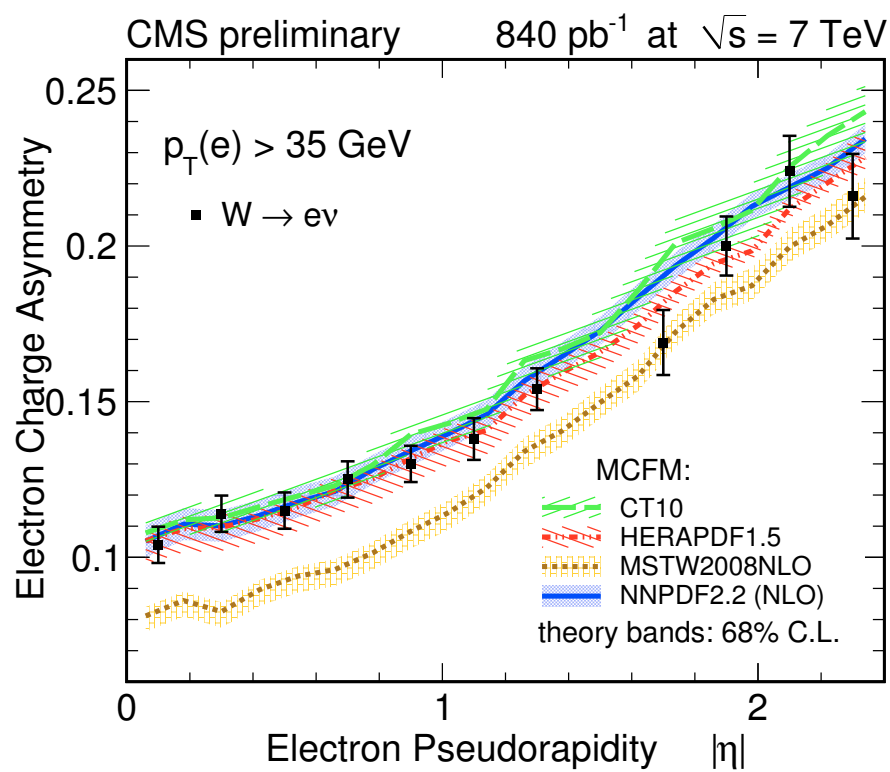


Figure 7.2: Measured electron charge asymmetry with predictions from CTEQ10, HERAPDF15, MSTW08NNLO and NNPDF2.2.

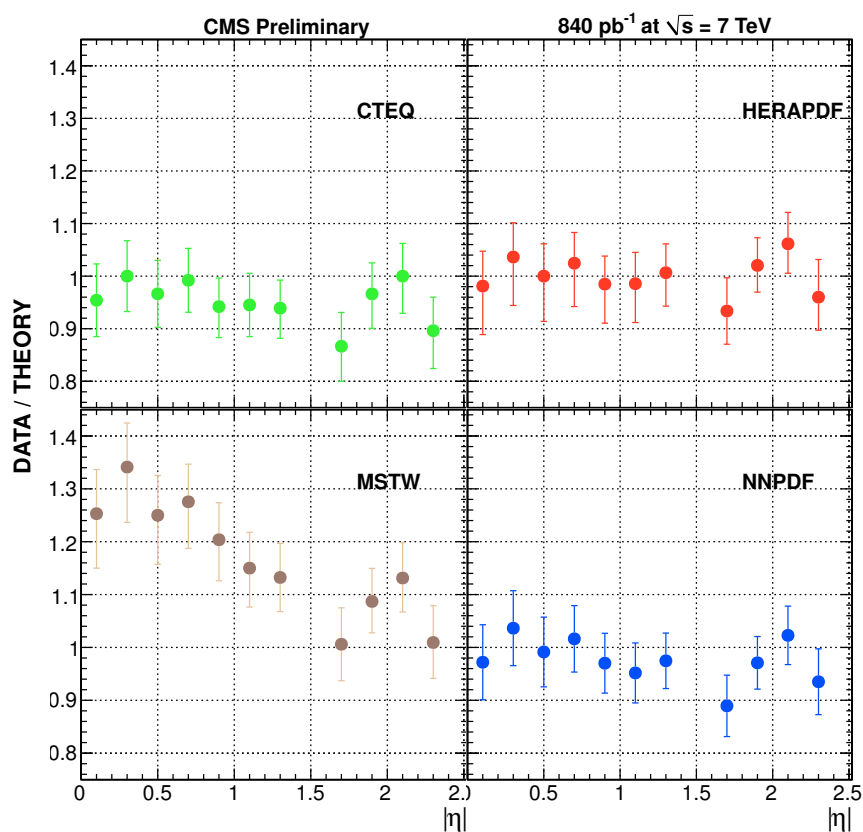


Figure 7.3: Ratio between the measured charge asymmetry and the predictions from CTEQ(top-left), HERAPDF(top-right), MSTW(bottom-left), NNPDF(bottom-right). The error bars include both the uncertainties on the experimental results and the uncertainties on theoretical predictions [3].

$ \eta $ range	Data	CTEQ	HERAPDF	MSTW	NNPDF
$0.0 < \eta < 0.2$	$104 \pm 3 \pm 5$	109^{+5}_{-5}	106^{+4}_{-8}	83^{+3}_{-5}	107 ± 5
$0.2 < \eta < 0.4$	$114 \pm 3 \pm 5$	114^{+5}_{-5}	110^{+4}_{-8}	85^{+3}_{-5}	110 ± 5
$0.4 < \eta < 0.6$	$115 \pm 3 \pm 5$	119^{+5}_{-5}	115^{+4}_{-8}	92^{+3}_{-5}	116 ± 5
$0.6 < \eta < 0.8$	$125 \pm 3 \pm 5$	126^{+5}_{-5}	122^{+4}_{-8}	98^{+3}_{-5}	123 ± 5
$0.8 < \eta < 1.0$	$130 \pm 3 \pm 5$	138^{+5}_{-6}	132^{+4}_{-8}	108^{+4}_{-5}	134 ± 5
$1.0 < \eta < 1.2$	$138 \pm 3 \pm 6$	146^{+6}_{-6}	140^{+5}_{-8}	120^{+4}_{-5}	145 ± 5
$1.2 < \eta < 1.4$	$154 \pm 3 \pm 6$	164^{+6}_{-7}	153^{+5}_{-7}	136^{+5}_{-5}	158 ± 5
$1.6 < \eta < 1.8$	$169 \pm 3 \pm 10$	195^{+8}_{-9}	181^{+5}_{-5}	168^{+5}_{-5}	190 ± 4
$1.8 < \eta < 2.0$	$200 \pm 3 \pm 9$	207^{+8}_{-10}	196^{+4}_{-3}	184^{+6}_{-5}	206 ± 4
$2.0 < \eta < 2.2$	$224 \pm 3 \pm 11$	224^{+8}_{-11}	211^{+5}_{-3}	198^{+6}_{-5}	219 ± 4
$2.2 < \eta < 2.4$	$216 \pm 4 \pm 13$	241^{+8}_{-12}	225^{+9}_{-4}	214^{+6}_{-5}	231 ± 5

Table 7.15: Measured electron charge asymmetry with predictions from CTEQ6.6, HERAPDF, NNPDF and MSTW PDFs. Uncertainties on measured asymmetry are statistical and systematic respectively and the uncertainties on predictions are due to the uncertainties on the PDFs. All units are $\times 10^{-3}$ [3].

Chapter 8

Conclusion

The electron charge asymmetry in inclusive W production has been measured using an initial data sample corresponding to an integrated luminosity of 36 pb^{-1} of data and updated with a larger data sample corresponding to an integrated luminosity of 840 pb^{-1} .

The measurement has been performed with a template fitting method to the $E_{\text{T}}^{\text{miss}}$ spectrum of events selected using a simple cut based electron selection. The backgrounds have been modelled using control regions obtained with an inverted selection for the QCD contribution, as well as Monte Carlo simulations for the better understood background contributions. The signal has been modelled using a MC simulation corrected with a data-driven boson recoil method. The measurement was presented in bins of pseudorapidity. In the first measurement 5 bins were used and in the updated measurement the additional statistics available allowed the results to be presented in 11 bins. The results have been compared directly to predictions based on several PDF models.

The measurement of the electron charge asymmetry with 36 pb^{-1} of CMS data [4] was combined with a similar measurement in the muon channel [77] and published together [1]. The combined electron and muon asymmetry measurement is shown in Figure 8.1. The electron and muon measurements are in good agreement with each other.

In addition to the CMS measurements, similar charge asymmetry measurements were made with the LHCb and the ATLAS experiments. The combined results, in the muon channels, over a combined pseudorapidity range of $0.0 < |\eta| < 4.0$, are shown in Figure 8.2.

The precise measurement of the asymmetry in inclusive W production at the LHC

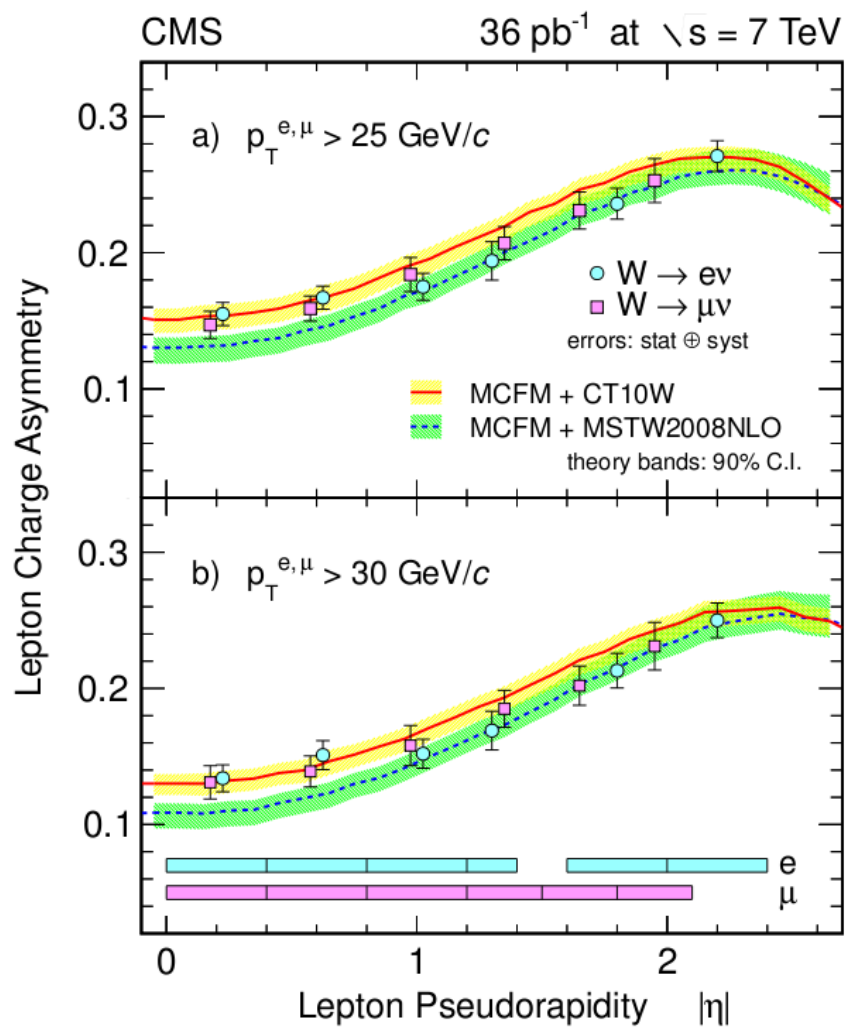


Figure 8.1: Comparison of the measured lepton charge asymmetry in the muon and electron channels with $p_T > 25 \text{ GeV}$ and $p_T > 30 \text{ GeV}$. The bin width is shown by the filled bars [1].

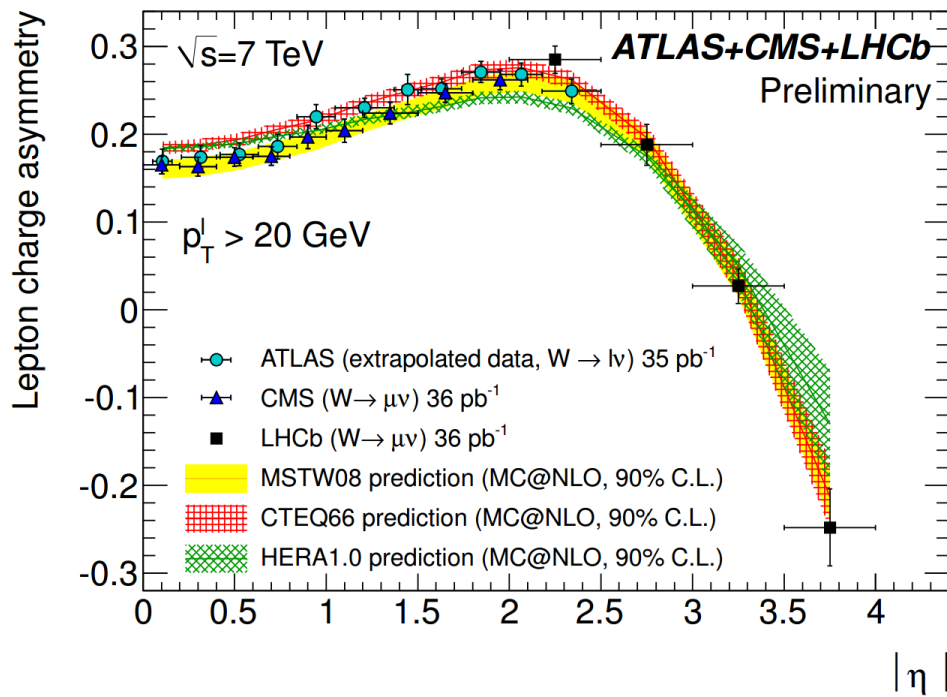


Figure 8.2: Combined measurements of the lepton charge asymmetry by the ATLAS, CMS and LHCb experiments with $p_T > 20$ GeV. From [78].

provides constraints for parton distribution functions [2]. For example, the NNPDF collaboration [76] have studied the impact of the 2010 LHC W lepton charge asymmetry data on their PDF sets [79]. Figure 8.3 shows a comparison of the up and down quark and anti-quark distributions before and after the combined LHC data have been added [79]. The lepton asymmetry measurements reduce the PDF uncertainties of the light quarks. This was the first use of LHC data in the production of PDF sets.

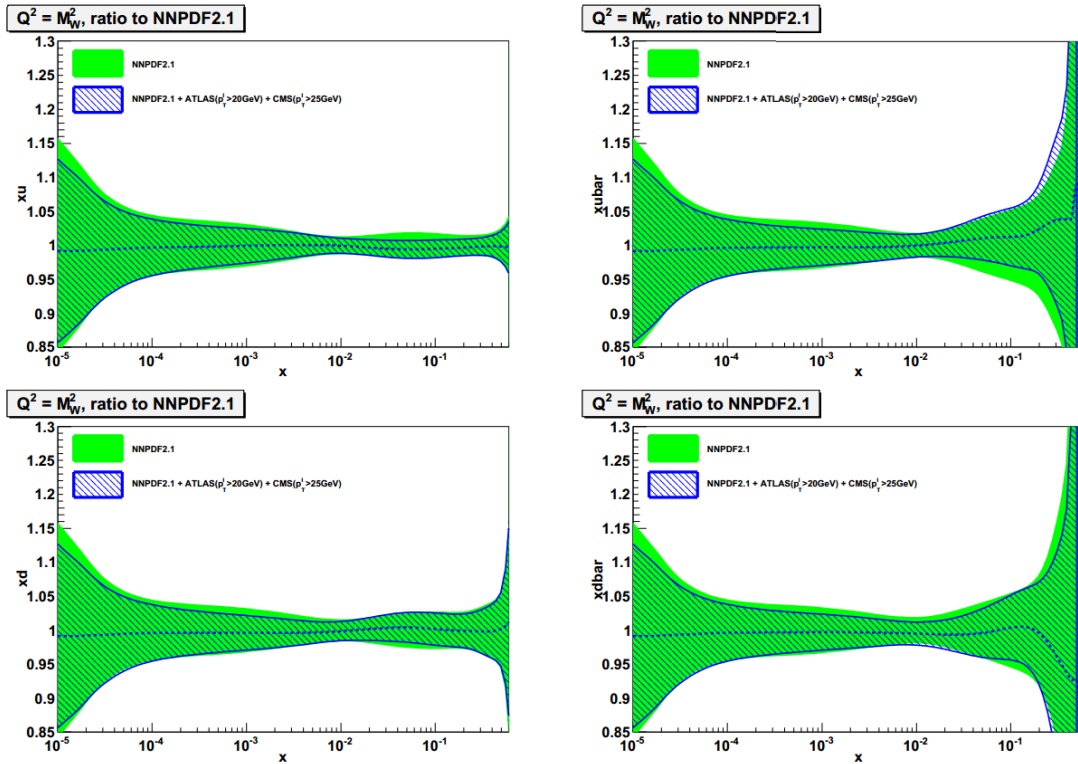


Figure 8.3: Comparison of the light quark and anti-quark distributions from the NNPDF2.1 NLO PDF set and the same distribution after reweighting to account for the combined LHC lepton charge asymmetry measurements with 36 pb^{-1} of data. The parton densities are normalised to the NNPDF2.1 central value. From [79].

The updated measurement of the electron charge asymmetry with an integrated luminosity of 840 pb^{-1} has also been used by PDF collaborations to examine the behaviour of their PDFs. The results continued to show some disagreement with the predictions generated using PDFs from the MSTW collaboration. The MSTW collaboration examined this in more detail [80], and saw that by extending their parametrisation using Chebyshev

polynomials, the agreement with the CMS asymmetry data can be significantly improved as shown in Figure 8.4.

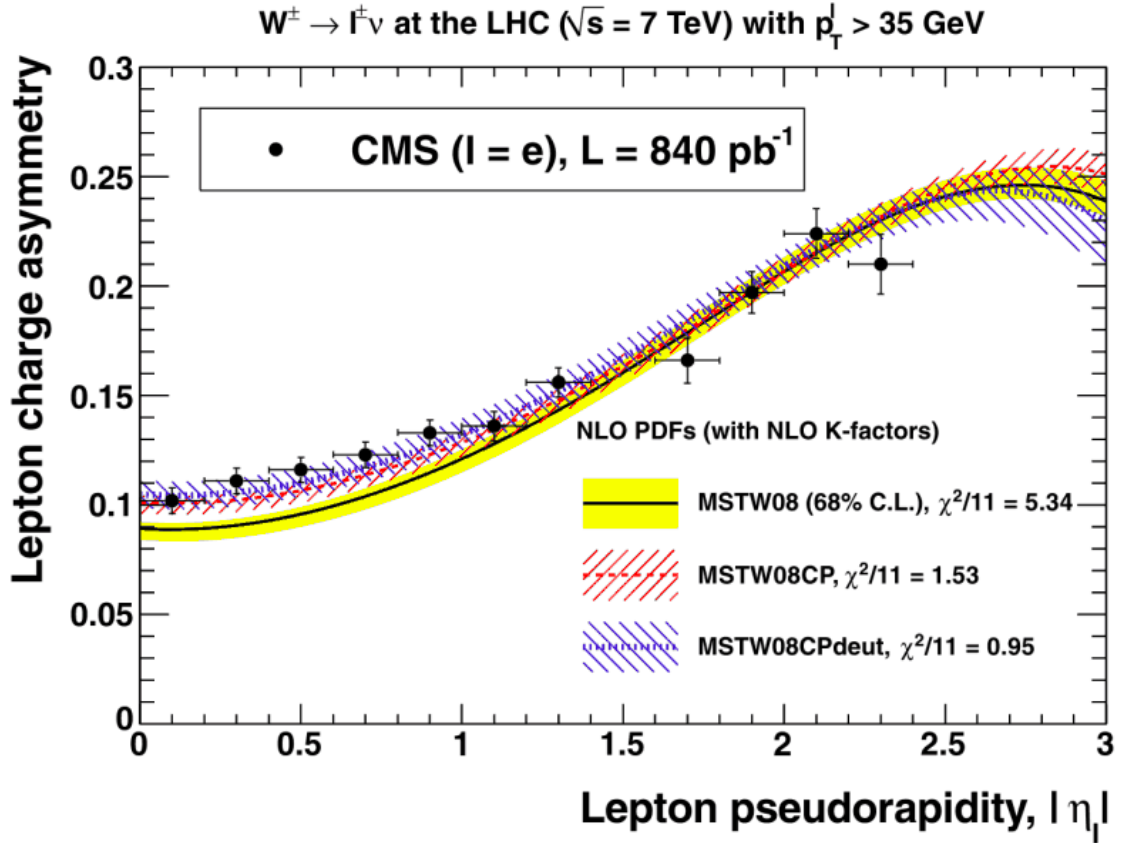


Figure 8.4: The CMS electron charge asymmetry results with the MSTW08 prediction and two predictions with different PDF parametrisation. The agreement between prediction and data is improved with the new parametrisation. From [80].

The measurements of the electron charge asymmetry are important inputs in to the global fits that are used to constrain the PDFs. Improved knowledge on PDFs has an impact on almost all measurements and searches that are performed at high energy hadron colliders.

Appendix A

Common Definitions and Conventions

A.1 Coordinate Conventions

The coordinate system of CMS is centred on the nominal interaction point. The x -axis points towards the centre of the LHC ring, the y -axis points vertically upwards and the z -axis points along the direction of the beamline, in the anti-clockwise direction when the LHC is viewed from above. The azimuth angle, ϕ , is the angle in the x - y plane with respect to the x -axis. The polar angle, θ , is measured from the z -axis.

The rapidity of a particle is defined as,

$$y = \frac{1}{2} \ln \left(\frac{E + p_L}{E - p_L} \right), \quad (\text{A.1})$$

where p_L is the longitudinal component (the component along the beam axis) of the momentum of the particle. It represents the boost along the beam axis required to go from the lab frame to the frame where the particle is produced perpendicular to the beam axis. The pseudorapidity is defined as

$$\eta = -\ln \left[\tan \left(\frac{\theta}{2} \right) \right], \quad (\text{A.2})$$

where θ is the polar angle. In the massless approximation, this is equal to the rapidity.

The variable ΔR is defined as:

$$(\Delta R)^2 = (\Delta\eta)^2 + (\Delta\phi)^2 \quad (\text{A.3})$$

In the LHC experiments the initial longitudinal momentum in the event is not known. Many of the kinematic quantities are considered only in the transverse (x - y) plane and denoted with a ‘T’ subscript, for example the transverse missing energy, $E_{\text{T}}^{\text{miss}}$, and the transverse momentum, p_{T} .

A.2 List of Acronyms

ALICE....	A Large Ion Collider Experiment
APD.....	Avalanche Photodiode
AS.....	Anti-Selection
ATLAS...	A Toroidal LHC ApparatuS
CERN....	European Organisation for Nuclear Research.
CMS.....	Compact Muon Solenoid
CPU.....	Central Processing Unit
CSC.....	Cathode Strip Chamber
CTEQ....	The Coordinated Theoretical-Experimental Project on QCD [30]
DAQ.....	Data Acquisition
DT.....	Drift Tube
DY.....	Drell-Yan
ECAL.....	Electromagnetic Calorimeter
$E_{\text{T}}^{\text{miss}}$	Missing Transverse Energy
EWSB....	Electroweak Symmetry Breaking
FSR.....	Final State Radiation.
GSF.....	Gaussian Sum Filter
HCAL....	Hadronic Calorimeter
HEP.....	High Energy Physics
HERAPDF	Hadron Elektron Ring Anlage PDF [75]
HF.....	Hadronic Calorimeter (Forward)
HLT.....	High Level Trigger

KF.....	Kalman Filter
L1	Level 1 Trigger
LEP	Large Electron-Positron Collider
LHAPDF .	Les Houches Accord PDF Interface [29]
LHCb.....	Large Hadron Collider Beauty.
LHC	Large Hadron Collider
LINAC2...	Linear Accelerator 2
MC	Monte Carlo
MCFM....	Monte Carlo for FeMtobarn processes [24]
MET.....	Missing Transverse Energy
MSTW....	Martin-Stirling-Thorne-Watt Parton Distribution Functions [22]
MVA.....	Multivariate Analysis
NNPDF...	Neural Network Parton Distribution Functions [76]
NP.....	New Physics
PDF	Parton Distribution Function
PF.....	Particle Flow
PFMET...	Particle Flow Missing Transverse Energy
PSB	Proton Synchrotron Booster
PS	Proton Synchrotron
PU.....	Pile Up
PV.....	Primary Vertex
QCD.....	Quantum ChromoDynamics
QED.....	Quantum ElectroDynamics
RPC.....	Resistive Plate Chamber
SM.....	Standard Model
SPS.....	Super Proton Synchrotron
SUSY.....	Supersymmetry
TEC.....	Tracker End Cap
TIB.....	Tracker Inner Barrel
TID.....	Tracker Inner Disk
TOB.....	Tracker Outer Barrel.
TP.....	Tag and Probe
VEV.....	Vacuum Expectation Value

VPT Vacuum Phototriode

Appendix B

Fits to the $E_{\text{T}}^{\text{miss}}$ Distributions

B.1 36 pb⁻¹

The following plots show the results of the fits to the $E_{\text{T}}^{\text{miss}}$ for each pseudorapidity/charge bin with 36 pb⁻¹ of data. The x -axis is the particle flow $E_{\text{T}}^{\text{miss}}$ (GeV) and the y -axis is the number of events. The results are for the $p_{\text{T}} > 25$ GeV cut.

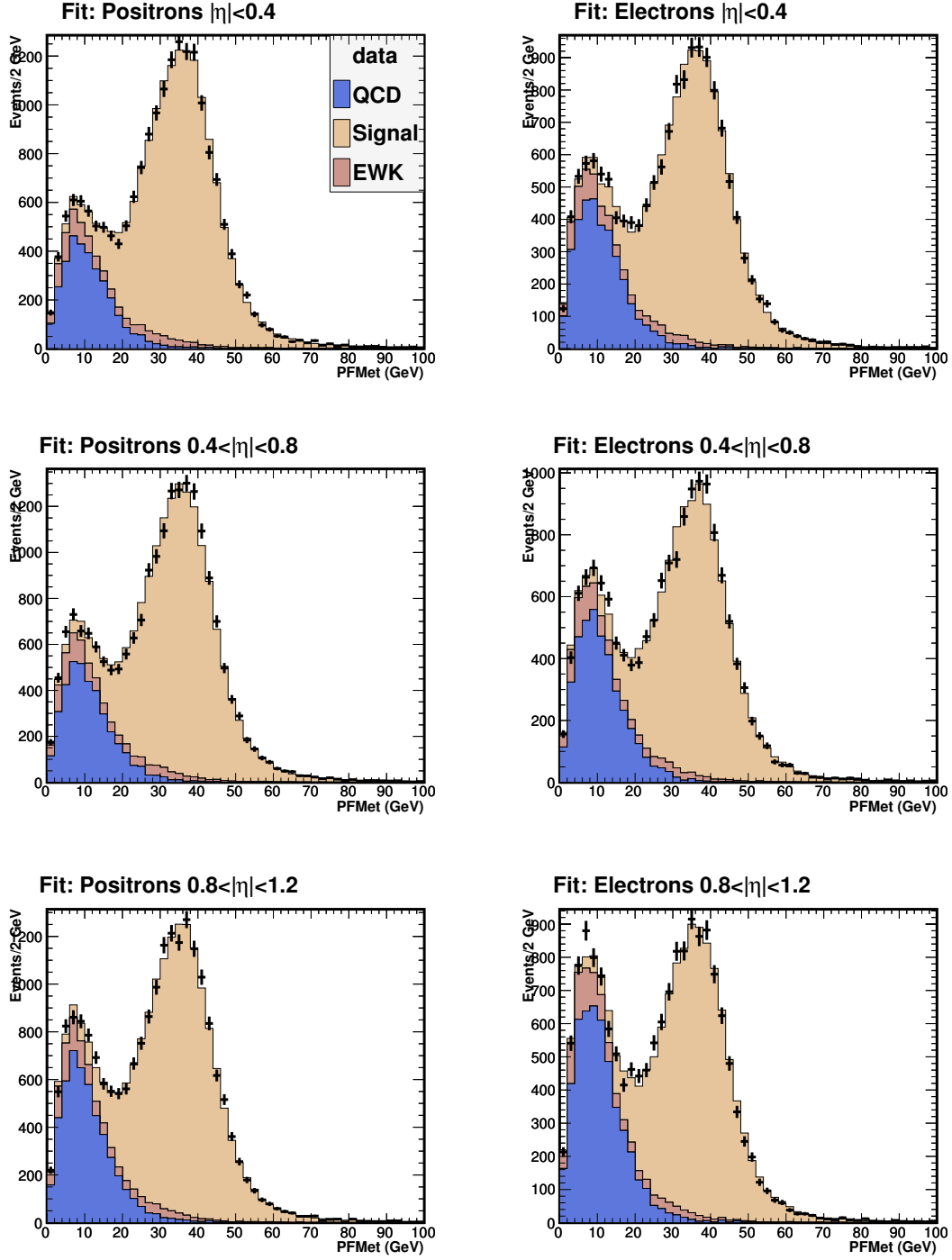


Figure B.1: The fit to E_T^{miss} for each pseudorapidity/charge bin. The x -axis is the particle flow E_T^{miss} (GeV) and the y -axis is the number of events (2GeV^{-1}).

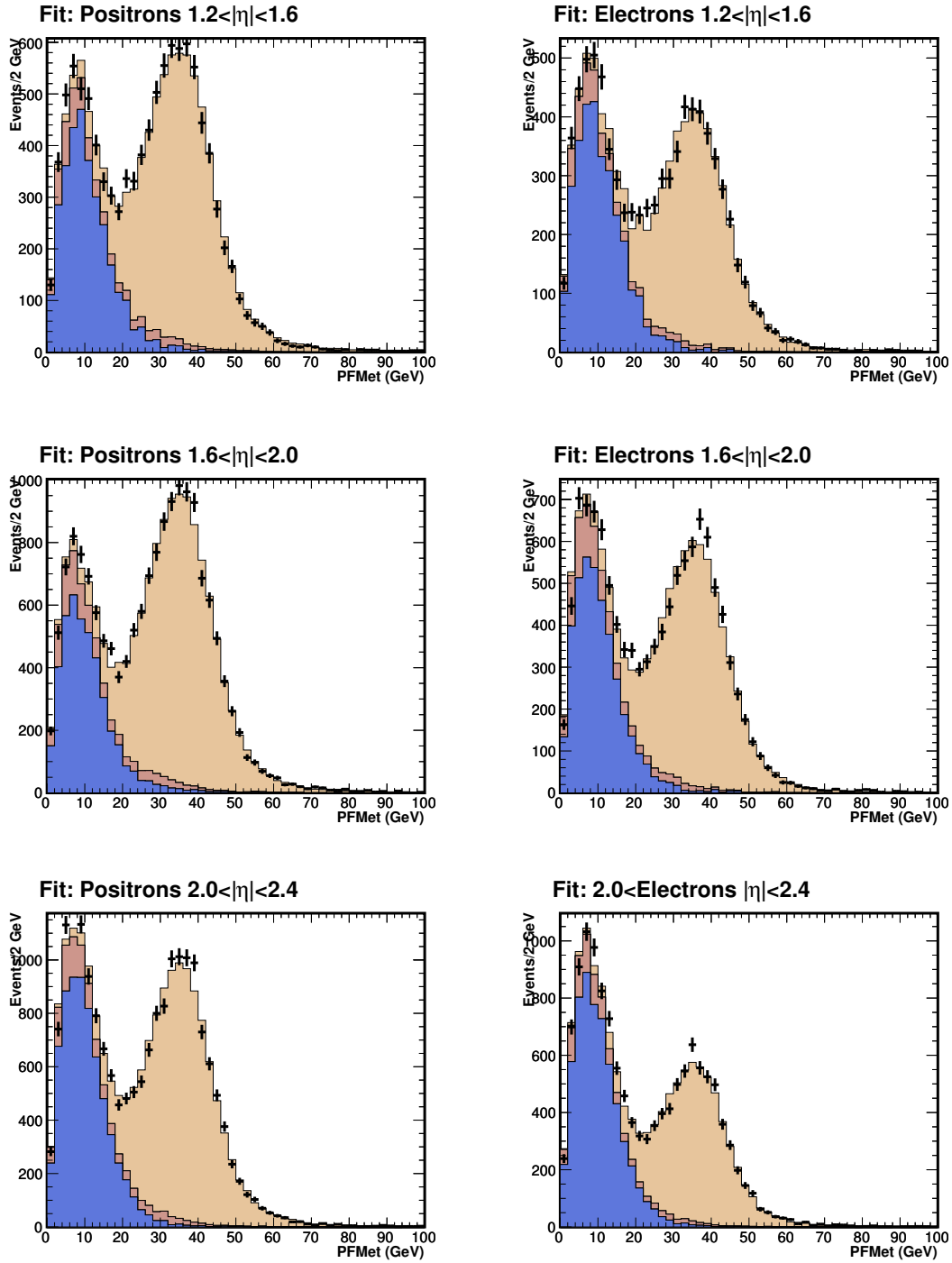


Figure B.2: The fit to E_T^{miss} for each pseudorapidity/charge bin. The x -axis is the particle flow E_T^{miss} (GeV) and the y -axis is the number of events (2GeV^{-1}).

B.2 840 pb⁻¹

The following plots show the results of the fits to the E_T^{miss} distribution in each pseudo-rapidity/charge bin with 840 pb⁻¹ of data. A p_T cut of 35 GeV is applied. The x -axis is the particle flow E_T^{miss} (GeV) and the y -axis is the number of events (GeV⁻¹).

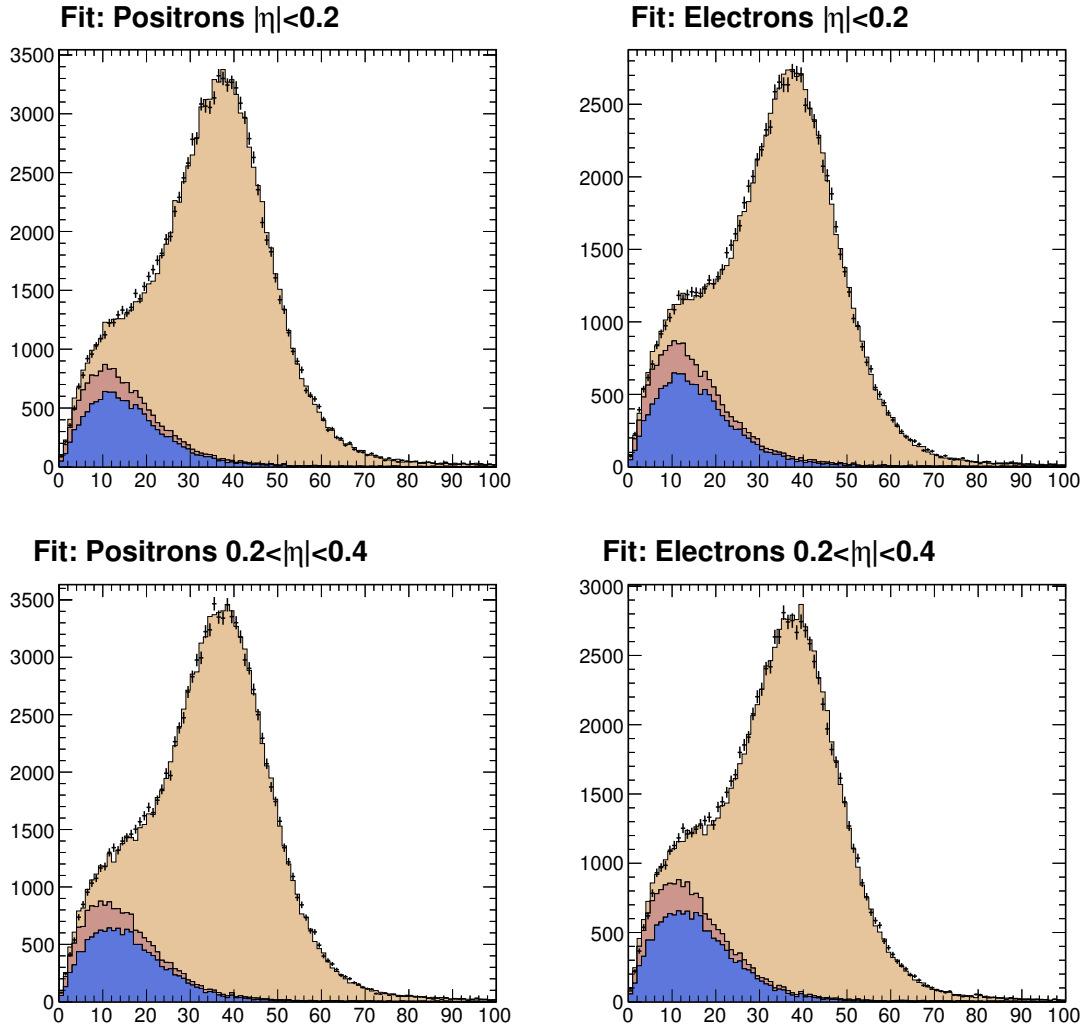


Figure B.3: The fit to E_T^{miss} for pseudorapidity bins 1,2 and 3. The x -axis is the particle flow E_T^{miss} (GeV) and the y -axis is the number of events (GeV⁻¹).

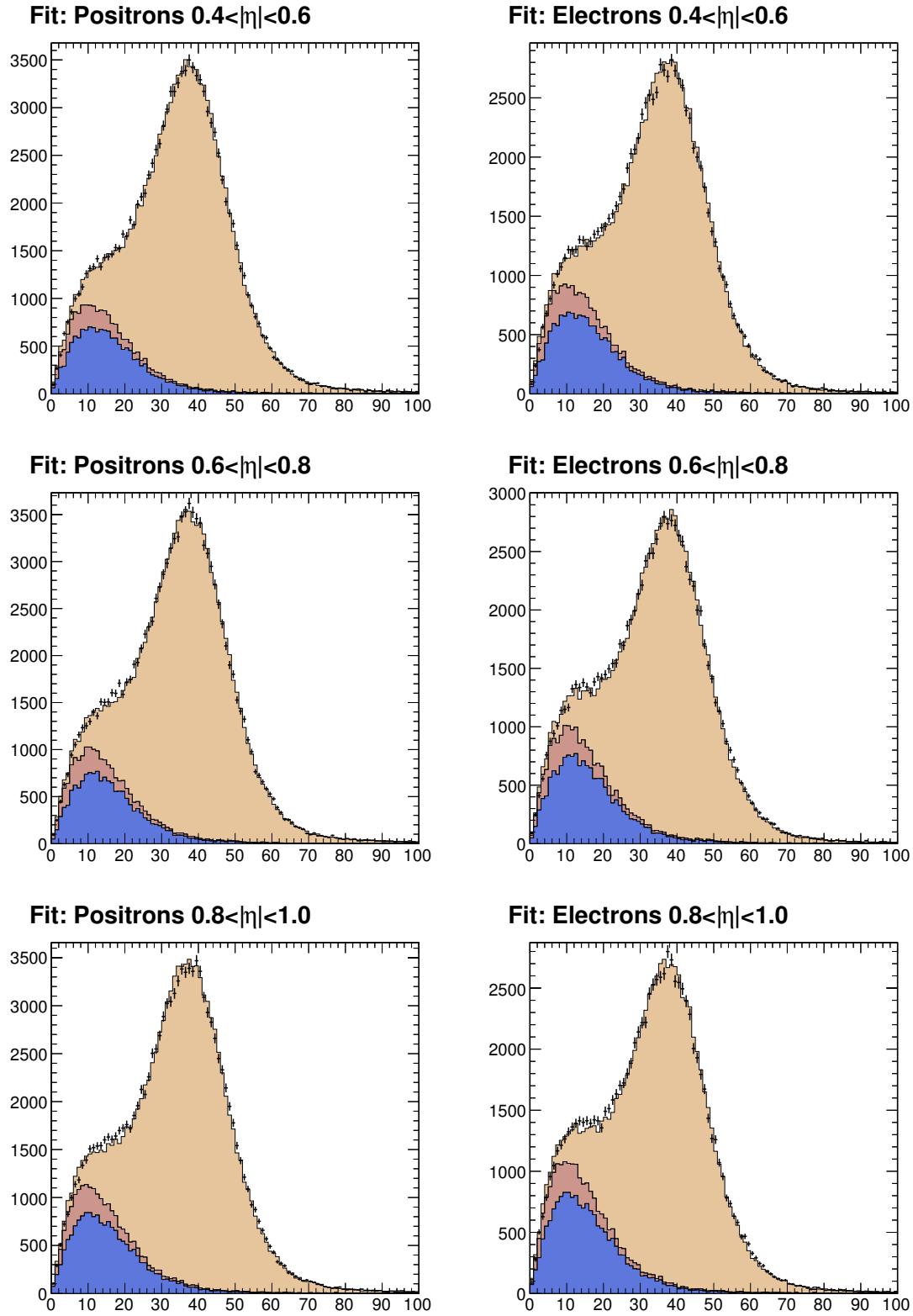


Figure B.4: The fit to E_T^{miss} for pseudorapidity bins 4,5 and 6. The x -axis is the particle flow E_T^{miss} (GeV) and the y -axis is the number of events (GeV^{-1}).

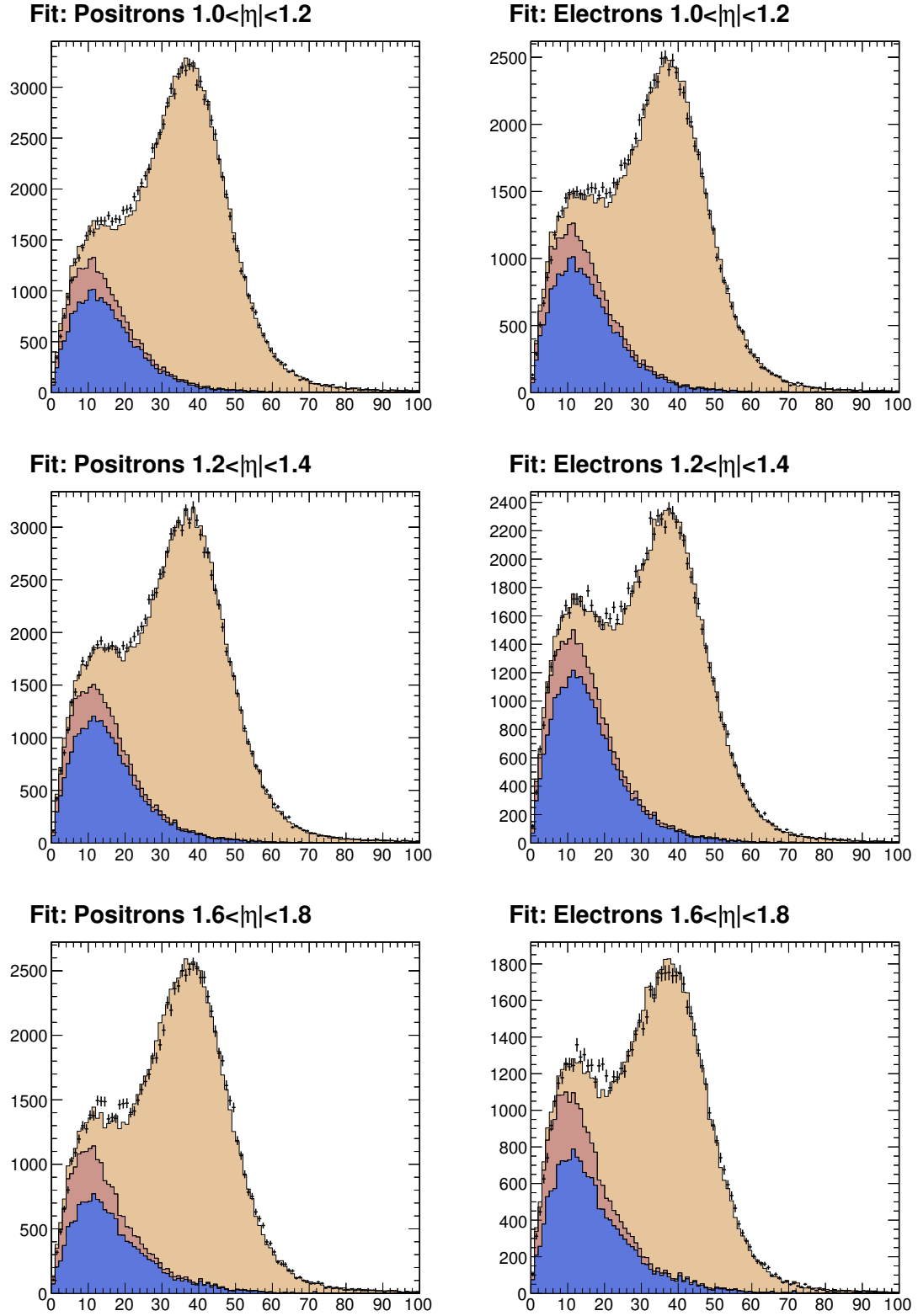


Figure B.5: The fit to E_T^{miss} for pseudorapidity bins 7,8 and 9. The x -axis is the particle flow E_T^{miss} (GeV) and the y -axis is the number of events (GeV^{-1}).

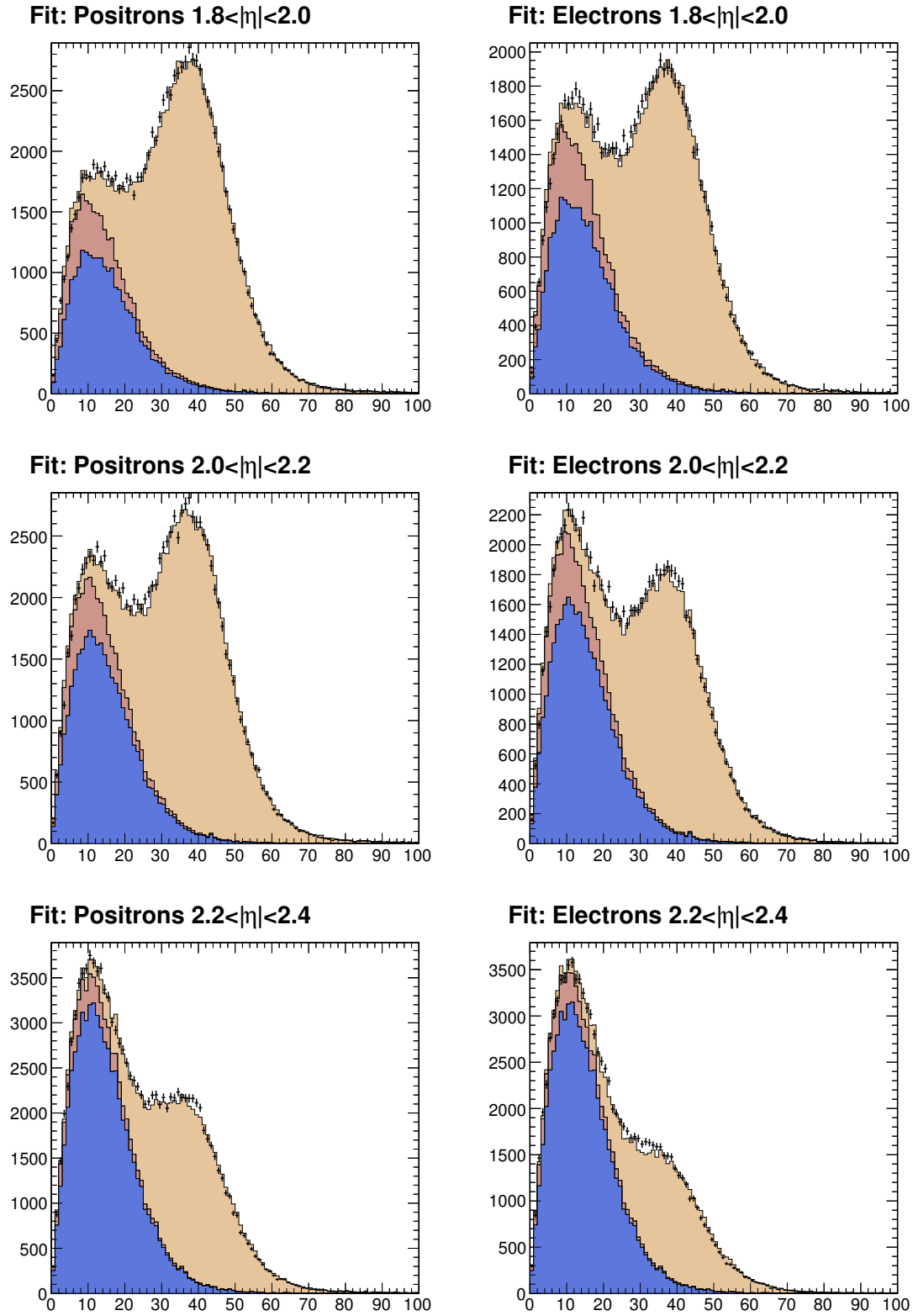


Figure B.6: The fit to E_T^{miss} for pseudorapidity bins 10 and 11. The x -axis is the particle flow E_T^{miss} (GeV) and the y -axis is the number of events (GeV⁻¹).

Appendix C

Monte Carlo Samples

Monte Carlo (MC) simulation samples have been used to develop analysis techniques and estimate some of the background contributions. The samples used in this thesis are summarised in Tables C.1 and C.2. Several different MC simulations have been used to cross-check MC predictions and help assigning experimental systematic uncertainties.

The next-to-leading order (NLO) MC simulations based on the POWHEG [81], PYTHIA [70] or MadGraph [72] event generators. The QCD multijet backgrounds are generated with the PYTHIA event generator. Taus are simulated using TAUOLA [82]. All generated events are passed through the CMS detector simulation using Geant4 [83] and then processed using a reconstruction sequence identical to that used for collision data.

C.1 36 pb⁻¹

Sample	Dataset
$W^+ \rightarrow e^+ \nu$	WPlusToENu_CT10_TuneZ2_7TeV-powheg-pythia
$W^- \rightarrow e^- \nu$	WPlusToENu_CT10_TuneZ2_7TeV-powheg-pythia
$W \rightarrow \tau \nu$	WToTauNu_TuneZ2_7TeV-pythia6-tauola
DY $M_{e^+e^-} > 20$ GeV	DYToEE_M-20_CT10_TuneZ2_7TeV-powheg-pythia
DY $M_{\tau^+\tau^-} > 20$ GeV	DYToTauTau_M-20_CT10_TuneZ2_7TeV-tauola
$t\bar{t}$ + jets	TT_TuneZ2_7TeV-pythia6-tauola
QCD EM-enr $20 < \hat{p}t < 30$ GeV	QCD_Pt-20to30_EMEnriched_TuneZ2_7TeV-pythia6
QCD EM-enr $30 < \hat{p}t < 80$ GeV	QCD_Pt-30to80_EMEnriched_TuneZ2_7TeV-pythia6
QCD EM-enr $80 < \hat{p}t < 170$ GeV	QCD_Pt-80to170_EMEnriched_TuneZ2_7TeV-pythia6
QCD $(b, c \rightarrow e)$ $20 < \hat{p}t < 30$ GeV	QCD_Pt-20to30_BCtoE_TuneZ2_7TeV-pythia6
QCD $(b, c \rightarrow e)$ $30 < \hat{p}t < 80$ GeV	QCD_Pt-30to80_BCtoE_TuneZ2_7TeV-pythia6
QCD $(b, c \rightarrow e)$ $80 < \hat{p}t < 170$ GeV	QCD_Pt-80to170_BCtoE_TuneZ2_7TeV-pythia6
γ + jets $30 < \hat{p}t < 50$ GeV	G_Pt-30to50_TuneZ2_7TeV-pythia6
γ + jets $50 < \hat{p}t < 80$ GeV	G_Pt-50to80_TuneZ2_7TeV-pythia6

Table C.1: The Monte Carlo (MC) samples used in the 36 pb⁻¹ measurement. The QCD EM-enr are samples of QCD that have been enriched with EM events. The Drell-Yan (DY) samples include $Z \rightarrow \ell\ell$ and $\gamma \rightarrow \ell\ell$. All the samples are from the *Fall10* MC production.

C.2 840 pb⁻¹

Sample	Dataset
<i>PYTHIA</i>	
$W \rightarrow e\nu$	WToENu_TuneZ2_7TeV_pythia6
$W \rightarrow \tau\nu$	WToTauNu_TuneZ2_7TeV_pythia6_tauola
$t\bar{t} + \text{jets}$	TT_TuneZ2_7TeV_pythia6_tauola
QCD EM-enr $20 < \hat{p}t < 30$ GeV	QCD_Pt-20to30_EMEnriched_TuneZ2_7TeV_pythia6
QCD EM-enr $30 < \hat{p}t < 80$ GeV	QCD_Pt-30to80_EMEnriched_TuneZ2_7TeV_pythia6
QCD EM-enr $80 < \hat{p}t < 170$ GeV	QCD_Pt-80to170_EMEnriched_TuneZ2_7TeV_pythia6
QCD ($b, c \rightarrow e$) $20 < \hat{p}t < 30$ GeV	QCD_Pt-20to30_BCtoE_TuneZ2_7TeV_pythia6
QCD ($b, c \rightarrow e$) $30 < \hat{p}t < 80$ GeV	QCD_Pt-30to80_BCtoE_TuneZ2_7TeV_pythia6
QCD ($b, c \rightarrow e$) $80 < \hat{p}t < 170$ GeV	QCD_Pt-80to170_BCtoE_TuneZ2_7TeV_pythia6
$\gamma + \text{jets}$ $50 < \hat{p}t < 80$ GeV	G_Pt-50to80_TuneZ2_7TeV_pythia6
<i>MadGraph</i>	
$W \rightarrow \ell\nu$	WJetsToLNu_TuneZ2_7TeV_madgraph_tauola
$DY \rightarrow \ell^+\ell^-$	DYJetsToLL_TuneZ2_M_50_7TeV_madgraph_tauola
$t\bar{t} + \text{jets}$	TTJets_TuneZ2_7TeV_madgraph_tauola

Table C.2: Monte Carlo samples used in the 840 pb⁻¹ measurement. All samples are from the *Summer11* MC production.

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