

A Measurement of the W Boson Charge Asymmetry with the ATLAS Detector

Samuel Robert Whitehead
Somerville College, Oxford



Thesis submitted in partial fulfilment
of the requirements for the degree of
Doctor of Philosophy

University of Oxford, Michaelmas Term 2011

A Measurement of the W Boson Charge Asymmetry with the ATLAS Detector

Samuel Robert Whitehead
Somerville College, Oxford

Thesis submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

October 2011

Abstract

Uncertainties on the parton distribution functions (PDFs), in particular those of the valence quarks, can be constrained at LHC energies using the charge asymmetry in the production of $W^\pm$ bosons.

This thesis presents a measurement of the electron channel, lepton charge asymmetry using 497 pb^{-1} of data recorded with the ATLAS detector in 2011. The measurement is included in PDF fits using the machinery of HERAPDF and is found to have some constraining power beyond that of existing W charge asymmetry measurements.

Dedicated to my family

Acknowledgements

My supervisor, Tony Weidberg, deserves a lot more than a mention here to thank him for all that he's done for me. Not only has he always been willing to break things down to the simplest level to help me understand, but by his regular requests to “borrow my brain”¹ amongst other things has helped me to develop my confidence as a physicist.

To all the people who passed on their knowledge of the ATLAS detector, its software framework and documentation (as hidden as it can be) throughout the course of my DPhil, thank you; without your guidance, I'd have been more lost for longer and this thing wouldn't have gotten done. Particularly I'd like to thank: Amanda Cooper-Sarkar for all of her help with PDFs; Kristin Lohwasser for passing on all of her knowledge on the asymmetry and showing me that it's possible to work all night every night; James Ferrando and Hugo Beauchemin for being the all knowing postdocs that all postdocs should try to aspire to be like; Çiğdem Işsever for being Tony's replacement while I was at CERN; Mark Sutton for all of his help getting APPLGrid up and running; Ellie Dobson for telling me not to work as hard as Kristin, and teaching me the virtues of cheese; Richard Nickerson for teaching me that a real lab must include some component held in place by black tape; Sue, Kim and Laura in the Oxford secretariat for all their help; and everyone that I've inevitably forgotten. If I came to you with a (stupid) question and you didn't just ignore me, then thank you for helping.

To everyone who I've met during my time in Oxford and at CERN, through physics, Somerville College, the Clarendon Scholarship, Aussie Rules and Rugby League - most of you won't even open the cover of this, but without you this would never have been the exciting adventure that it was, so, thank you. Of course, special mention goes to the poor fools who had to share lunch and coffee breaks with me (and in some cases an office) all year for three years, in no particular order: theBODDY, Pinder, Dan, Phil, Caterina and James.

Most importantly, I'd like to thank my family for supporting me, in all the ways that you've always supported me. Including, of course, Hana: thank you - I wouldn't want to have done it without you.

¹Though I'm fairly sure that on most occasions my brain was of no use...

Contents

Introduction	1
1 The LHC and the ATLAS detector	2
1.1 The LHC	2
1.2 The ATLAS detector	3
1.2.1 ATLAS coordinate system	4
1.2.2 Physics and detector requirements	5
1.2.3 Components of the ATLAS detector	7
1.2.4 ATLAS data acquisition	13
2 R & D for LHC upgrade: speckle pattern interferometry	16
2.1 Upgrade to the LHC	16
2.2 Laser speckle	18
2.3 Interferometry	22
2.3.1 In plane	23
2.3.2 Out of plane	25
2.3.3 Sensitivity	27
2.3.4 Noise	27
2.4 Oxford ESPI system	29
2.4.1 Hardware	29
2.4.2 Software	31
2.5 Preliminary Results	33
2.5.1 Measurement of CTE of aluminium	33
2.5.2 Out of plane calibration	35
2.5.3 Summary	35
3 W charge asymmetry theory	36
3.1 Proton structure	36
3.2 Proton-proton collisions	37
3.3 PDFs	39
3.3.1 PDF uncertainties	41
3.3.2 Phase space	43
3.3.3 Importance of PDF knowledge for discovery physics	44
3.4 Constraining PDFs with W charge asymmetry	45
3.4.1 Origin of the asymmetry	45
3.4.2 Measurement: lepton charge asymmetry	48

3.4.3	Previous measurements	50
4	W+ jets asymmetry	53
4.1	W +jets production	53
4.1.1	Simulation of W +jet production	54
4.1.2	Event selection	55
4.1.3	Phase space	55
4.2	Asymmetry	56
4.3	Investigation of inclusive variables	59
4.4	Investigation of backgrounds	60
4.4.1	As a function of jet multiplicity	61
4.4.2	As a function of invariant mass	63
4.4.3	Instrumental backgrounds	64
4.5	PDF sensitivity	65
4.6	Conclusions	68
5	$W \rightarrow e\nu$ event selection	69
5.1	Dataset and pileup	69
5.1.1	Pileup in ATLAS	70
5.2	Electron trigger and reconstruction	71
5.2.1	EM trigger	71
5.2.2	Electron reconstruction	72
5.2.3	Electron identification	73
5.2.4	Efficiency scale factors	73
5.2.5	Electron isolation	74
5.2.6	Object quality	74
5.3	$E_{\text{T}}^{\text{miss}}$ reconstruction	75
5.3.1	$E_{\text{T}}^{\text{miss}}$ cleaning	76
5.4	Backgrounds to $W \rightarrow e\nu$ production	77
5.4.1	Monte Carlo datasets	78
5.5	$W \rightarrow e\nu$ selection cuts	79
5.5.1	Event preselection	79
5.5.2	Lepton selection	81
5.5.3	Final event selection	82
6	Determination of QCD Background	87
6.1	Data driven methods	87
6.2	Template method	88
6.2.1	Choice of template variable	89
6.2.2	Background template development	90
6.2.3	Template fit	91
6.2.4	Systematic uncertainties	93
6.2.5	Template fit as applied to data	94
6.3	$E_{\text{T}}^{\text{miss}}$ vs Iso method	95
6.3.1	Initial QCD background estimate	98

6.3.2	Electroweak removal	99
6.3.3	Correlation of E_T^{miss} and $E_T^{\text{cone}}(0.3)$	101
6.3.4	Further sources of systematic uncertainty	103
6.3.5	QCD background estimate as a function of pseudorapidity	104
7	Measurement and uncertainties	106
7.1	Background subtraction	106
7.2	Correction to truth asymmetry	106
7.3	Systematic uncertainties	109
7.3.1	Trigger and identification biases	110
7.3.2	Charge misidentification	112
7.3.3	Generator choice	115
7.3.4	Backgrounds	118
7.3.5	Electron energy scale and resolution	119
7.3.6	E_T^{miss} uncertainty	120
7.3.7	Isolation uncertainty	125
7.3.8	Other negligible effects	128
7.3.9	Summary of Uncertainties	128
7.4	Final lepton asymmetry result	129
8	PDF fits with asymmetry data	134
8.1	PDF fits	134
8.1.1	χ^2 formulation	136
8.1.2	PDF uncertainties	138
8.1.3	HERA data	139
8.2	Including further data in the fit	140
8.2.1	Analytical calculation with k-factors	140
8.2.2	APPLGrid and MCFM	141
8.3	Including asymmetry data in fits	143
8.3.1	Future work	148
8.4	Conclusions	150
9	Conclusions	151
A	Template Fits	154
	Bibliography	156

List of Figures

1.1	Cut-away view of the ATLAS detector	4
1.2	Relation of θ to pseudorapidity	5
1.3	Inner Detector	9
1.4	ATLAS Calorimetry	12
1.5	LAr EM Calorimeter	13
2.1	Proposed stave concept	17
2.2	Speckle pattern geometry	20
2.3	The setup for the Oxford ESPI system	22
2.4	In plane geometry	23
2.5	Out of plane geometry	26
2.6	Lower frequencies reveal fringes in an otherwise noisy line profile	32
2.7	CTE measurement	34
2.8	Out of plane calibration	35
3.1	Experimentally probed phase space	44
3.2	Attainable x as a function of y_W	47
3.3	PDFs and W asymmetry at LHC energies	49
3.4	W rapidity and lepton pseudorapidity	50
4.1	Leading order W +jets production processes for different initial partons	54
4.2	Kinematic region covered by W +jet production	56
4.3	The kinematic range as a function of x and Q^2 for different jet multiplicities	57
4.4	Asymmetry as a function of jet multiplicity	58
4.5	Initial parton contributions to W production	59
4.6	Distribution of the total invariant mass for different jet multiplicities	60
4.7	The lepton charge asymmetry as a function of invariant mass variables	61
4.8	Number of events and asymmetries as a function of jet multiplicity	62
4.9	Number of background and signal events and asymmetries as a function of M_{reco}	64
4.10	PDF comparison	66
5.1	$W^\pm$ transverse momentum spectra	80
5.2	Observables cut on in W selection: E_T and E_T^{miss} before selection cuts	84
5.3	Observables cut on in W selection: E_T and E_T^{miss}	85
5.4	Observables cut on in W selection: $E_T^{\text{cone}}(0.3)$ and m_T	86
6.1	Charge separated E_T^{miss} template fit	92

6.2	Inclusive template fits	95
6.3	QCD background as a function of pseudorapidity	96
6.4	E_T^{miss} vs Iso	97
6.5	Correlation of E_T^{miss} and $E_T^{\text{cone}}(0.3)$	102
6.6	Shape of two discriminating variables	103
6.7	QCD background as a function of pseudorapidity	104
7.1	Example background fits	111
7.2	Identification efficiency	113
7.3	Charge misidentification rate	116
7.4	Axis definitions for fake E_T^{miss} study	121
7.5	E_T^{miss} bias extraction	122
7.6	Example fits to fake E_T^{miss} components	124
7.7	Recalculated E_T^{miss} distribution	125
7.8	Isolation efficiency	128
7.9	Measured lepton asymmetry and predictions	132
8.1	Full uncertainty bands for individual datasets: u_v	144
8.2	Full uncertainty bands for individual datasets: d_v	145
8.3	Shape comparison for individual datasets	146
8.4	Comparison including all additional datasets	148
A.1	QCD template fits in endcap region $ \eta > 1.52$	154
A.2	QCD template fits in barrel region $ \eta < 1.37$	155

List of Tables

2.1	Approximate deformation (nm) sensitivity for a ~ 1 m stave	27
3.1	Main processes included in global PDF analyses	41
4.1	Signal and background as a function of jet multiplicity	63
4.2	Signal and background as a function of M_{reco}	65
4.3	Systematic uncertainties as a function of jet multiplicity	67
4.4	Systematic uncertainties as a function of M_{reco}	67
5.1	MC Samples	79
5.2	Cut flow for 497.27 pb^{-1} of 2011 ATLAS data	83
6.1	Electron identification variables from which reverse cut combinations are formed	91
6.2	$E_{\text{T}}^{\text{miss}}$ and $E_{\text{T}}^{\text{cone}}(0.3)$ boundaries	98
6.3	Number of events observed in each region for the inclusive case	99
6.4	Iterative EW removal results	100
7.1	Observed signal and estimated backgrounds	107
7.2	Correction factors, corrected totals and asymmetry	109
7.3	Correction factors calculated using POWHEG +PYTHIA	117
7.4	Systematic uncertainties on QCD background estimate	118
7.5	Systematic uncertainty on the asymmetry due to uncertainties on electron energy scale and resolution	119
7.6	Systematic uncertainty on asymmetry as determined using recalculated $E_{\text{T}}^{\text{miss}}$	126
7.7	Systematic uncertainties on asymmetry from isolation corrections	126
7.8	Systematic uncertainty on asymmetry due to isolation efficiency difference .	129
7.9	Final asymmetry measurement with total uncertainties	133
7.10	Final asymmetry measurement correlated uncertainties	133
8.1	Output parameters for PDF fits with asymmetry data (individual)	147
8.2	Output parameters for PDF fits with asymmetry data (cumulative)	149
8.3	χ^2 for PDF fits with asymmetry data	149
8.4	χ^2 for PDF fits with asymmetry data	149

Introduction

The purpose of this thesis is to present a measurement of the electron channel lepton charge asymmetry using 497 pb^{-1} of 2011 ATLAS data and its subsequent inclusion in Parton Distribution Function (PDF) fits.

The first chapter gives an overview of the ATLAS detector, and the sub-detectors that are important to the measurement. Chapter 2 describes the development of a system to make measurements of thermo-mechanical deformations of prototype inner detector components for the future ATLAS upgrade. In chapter 3, the theoretical foundations required to undertake this measurement are summarised including a description of PDFs and the importance of the W asymmetry in constraining them. A phenomenological study of a possible future measurement of the W charge asymmetry in bins of jet multiplicity is presented in chapter 4.

Chapters 5, 6 and 7 present the $W \rightarrow e\nu$ selection criteria, QCD background determination and asymmetry measurement respectively. Chapter 7 also includes detailed discussion of all systematic uncertainties considered. Finally, in chapter 8, the measured lepton charge asymmetry is included in PDF fits using the machinery of HERAPDF. The constraints on the PDFs provided by the data beyond those of previously published asymmetry measurement are discussed.

Chapter 1

The LHC and the ATLAS detector

With its unrivalled energy and luminosity, the start-up of the Large Hadron Collider (LHC) brings the high energy physics community to the edge of the next discovery. This chapter gives a brief overview of the physics motivating the construction of the ATLAS detector at the LHC along with a description of the various aspects of the detector itself.

1.1 The LHC

The LHC at CERN¹ is a circular particle accelerator with a circumference of approximately 27 km designed to collide proton beams with centre of mass energies of up to 14 TeV [1]. The specific kinematics of pp collisions are discussed in some detail in Chapter 3. In order to circulate protons for collision at 14 TeV, superconducting dipole magnets with a strength of 8.33 T are required. The technical challenge presented by the design and production of the magnets required to bend, squeeze and focus the beam is one of the major challenges of the building of the LHC.

ATLAS (A Toroidal LHC ApparatuS [2]), CMS (Compact Muon Solenoid[3]), LHCb (Large Hadron Collider beauty[4]) and ALICE (A Large Ion Collider Experiment[5]) are the four main experiments located around the LHC ring. LHCb is dedicated to measurements involving B -mesons and the understanding of CP-violation in the early universe, and ALICE

¹CERN, the European Organisation for Nuclear Research, is located on the Franco-Swiss border near Geneva and was commissioned in 1954 to promote academic collaboration in Particle and Nuclear Physics.

is a detector set up with the primary focus on the study of the quark-gluon plasma, a phenomenon that will be studied during the LHC heavy ion runs. ATLAS and CMS however are general purpose detectors designed to study a broad range of physics, from precision measurements within the context of the Standard Model to the detection and study of any of a number of possible models that reach beyond the Standard Model of particle physics.

During the course of data taking in 2011, from which data will be used for this thesis, the LHC operated at a centre of mass energy of $\sqrt{s} = 7 \text{ TeV}$ allowing the detector to be commissioned without adding undue pressure on the magnet system before it was ready. The anticipated design luminosity of $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ was also not attained in this period, but a relatively low maximum instantaneous luminosity of $\mathcal{L} = 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ was achieved. Such a luminosity, despite being lower than the design luminosity, has resulted in a total integrated luminosity of 497 pb^{-1} recorded in the first half of 2011 and included in this thesis.

1.2 The ATLAS detector

It is important that a general purpose detector such as ATLAS be able to accurately resolve the position and energy of those particles that are the decay products of heavier unstable particles that are to be studied in more detail. It is also important to have a hermetic detector able to resolve the direction and magnitude of any missing transverse momentum produced in the interaction, so as to get a handle on the ‘invisible’ decay products such as the neutrino. It is clear then, that the design requirements are in part derived from the defined physics goals of the collaboration, both of which will be presented in the next sections. It is useful to first introduce the ATLAS coordinate system, the components of which are referred to throughout this thesis.

1.2.1 ATLAS coordinate system

The nominal interaction point defines the centre of the ATLAS coordinate system, with the anti-clockwise beam direction, as viewed from above, defining the z axis and the $x - y$ plane transverse to the beam direction. The positive x direction is defined as the vector pointing toward the centre of the LHC ring from the centre of the detector, while the positive y axis points directly up from the interaction point. In terms of a coordinate system in (R, ϕ, θ) , R is the transverse distance from the z axis, ϕ is the azimuthal angle measured from the x axis around the beam axis ($\phi \in (-\pi, \pi]$), and θ is the polar angle from the beam axis ($\theta \in [0, \pi]$). A cut-away view of the ATLAS detector is shown in figure 1.1.

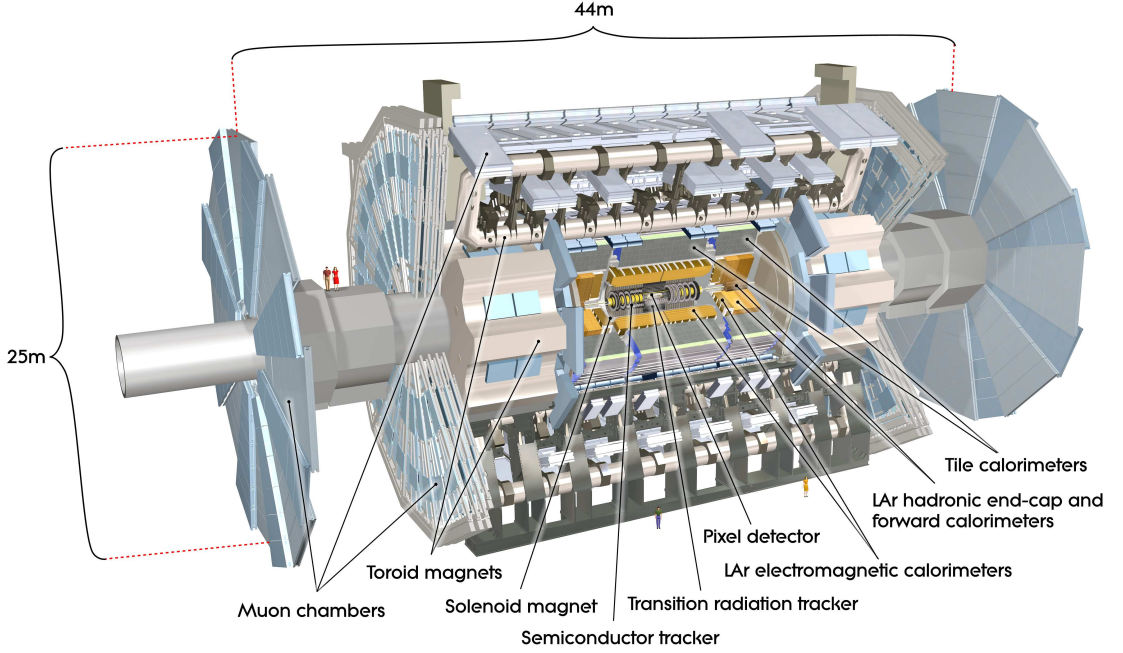


Figure 1.1: Cut-away view of the ATLAS detector

The z direction is along the beampipe from right to left, the positive x direction is on the horizontal plane coming out of the page and the positive y is up. Figure from [2].

Since the z component of momentum of an incoming parton in a pp collision is not known, the *rapidity*, y , is a particularly useful parameter. The rapidity, intervals of which are Lorentz invariant, is defined as

$$y = \frac{1}{2} \ln \frac{E + p_L}{E - p_L} \quad (1.1)$$

where p_L is the longitudinal component of momentum, and E is the energy. For a massless particle, the rapidity is equivalent to the *pseudorapidity*, η , defined as

$$\eta = -\ln \tan \frac{\theta}{2}. \quad (1.2)$$

The pseudorapidity is a good approximation to the rapidity in the ultra-relativistic limit, and is a useful parameter to describe the ‘forwardness’ of a particle as it takes as input only the θ of an object. Figure 1.2 shows various pseudorapidities along with their corresponding θ values on the zy plane. Finally, the transverse momentum, p_T , and missing transverse momentum, E_T^{miss} , are defined as vectors in the transverse ($x - y$) plane.

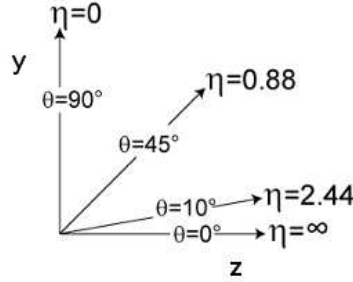


Figure 1.2: Relation of θ to pseudorapidity

1.2.2 Physics and detector requirements

Being a general purpose detector, it is difficult to cover the diversity of physics searches and measurements being undertaken with the ATLAS detector entirely. Some representative examples of the sort of physics that drives the determination of the detector requirements are presented briefly here.

Higgs The Standard Model (SM) of particle physics has so far proved to be an extremely powerful theory of the underlying processes that govern the electroweak (EW) and strong forces, however there exists still one missing piece of the puzzle. In order that SM particles have mass, there is required to exist a field with a non zero vacuum expectation value - the so called Higgs field. Via a spontaneous symmetry breaking, three components of the Higgs

field mix with the W and Z bosons giving them mass, while the one remaining degree of freedom becomes the Higgs boson. The decay channels of the SM Higgs are varied and it is important that the detector be sensitive to all channels in order to determine the Higgs boson's existence or lack thereof.

Precision SM measurements The LHC environment makes for a significant increase in statistics of heavy bosons and quarks compared to lower energy machines. Even in early data, as used in this thesis, it is possible to further constrain PDFs and SM EW parameters. The couplings of the top quark, for example, are still not known to nearly as great a precision as other SM particles. In order to make use of the high statistics ATLAS top quark samples, the ATLAS detector must have instrumentation that allows for an accurate identification and measurement of top quark properties. Measurement of the W boson charge asymmetry, as is the main subject of this thesis, is another such precision measurement that will be discussed in further chapters in much detail.

Very high p_T objects Heavy resonances such as W' and Z' could occur leading to exceptionally high p_T leptons, which require excellent charge identification and high resolution in order to reconstruct. Similarly, high- p_T jets could arise as a signature of many new physics models and calorimetry must be designed so as to measure this p_T as accurately as possible and meet the requirement that such jets do not punch through to the muon system.

Dark matter candidates Supersymmetric models predict that the supersymmetric analog to SM particles would decay conserving R-parity². If such models are realised in the LHC energy regime, then conservation of R-parity would result in the lightest supersymmetric particle being stable. Such a particle would not be detected within the detector so would lead to large missing transverse energy, and would provide an excellent dark matter candidate - something that is sorely missed from the current picture of the universe.

²Standard model particles have R-parity of 1 while their supersymmetric analogues have R-parity of -1 where R is defined as $R = (-1)^{2j+3B+L}$, with j being spin, B the baryon number and L the lepton number of the particle in question.

Though the above list is not exhaustive, and the link to the detector requirements somewhat incomplete, it is clear that in order to be a general purpose detector it is important to be capable of covering a wide range of possible measurements. This then leads to the following list of requirements [2]:

- Due to the experimental conditions at the LHC, the detectors require fast, radiation-hard electronics and sensor elements. In addition, fine detector granularity is needed to handle the particle fluxes and to reduce the influence of overlapping events.
- Large acceptance in pseudorapidity with almost full azimuthal angle coverage is required.
- Good charged-particle momentum resolution and reconstruction efficiency in the inner tracker are essential. For offline tagging of τ -leptons and B -jets, vertex detectors close to the interaction region are required to observe secondary vertices.
- Very good electromagnetic (EM) calorimetry for electron and photon identification and measurements, complemented by full-coverage hadronic calorimetry for accurate jet and $E_{\text{T}}^{\text{miss}}$ measurements, are important requirements, as these measurements form the basis of studies of many physics channels.
- Good muon identification and momentum resolution over a wide range of momenta and the ability to determine unambiguously the charge of high p_{T} muons are fundamental requirements.
- Highly efficient triggering on low p_{T} objects with sufficient background rejection, is a prerequisite to achieve an acceptable trigger rate for most physics processes of interest.

1.2.3 Components of the ATLAS detector

For a complete description of the ATLAS detector and the many components required to operate in unison in order to take data, the reader is referred to [2]. In the following sections,

three main components are discussed in some detail: the inner detector (ID), the calorimeters and the data acquisition system.

Starting from the beam pipe the ID, shown in figure 1.3, is comprised of the pixel detector, the semiconductor tracker (SCT) and the transition radiation tracker (TRT). To create a field in which charged particles will acquire some curvature in order that a momentum and charge can be extracted from their tracks, a solenoid magnet system surrounds the ID. The central solenoid creates a 2 T magnetic field within the ID, with a length of 5.3 m and a diameter of 2.5 m. The thickness of the solenoid magnet is only 45 mm in order to reduce as far as possible the amount of non-detecting material in the detector. Outside the solenoid is the calorimetry, shown in figure 1.4. First the EM calorimeter, followed by the hadronic calorimeter. Finally, the muon system consists of a very large muon spectrometer (extending to 11 m radius) along with the toroidal magnet system from which ATLAS takes its name. This toroidal magnet system delivers a field in the muon spectrometer of between 0.2 T and 3.5 T, allowing for a separate measurement of the muon momentum and charge, independent of the ID.

In the following brief description of these components, only the tracking and calorimetry are discussed in any more detail, as this thesis is focused on a measurement requiring the understanding of electrons and E_T^{miss} primarily. Following these two components a discussion of the ATLAS trigger system and data acquisition is presented.

Tracking detectors

The track density in the ID at design luminosities amounts to approximately 1000 particles emerging from the interaction point with each bunch crossing. In such an environment, where one requires high precision measurements of momentum and vertex position, the detectors are required to have excellent precision with a similarly excellent granularity. The combination of the Pixel, SCT and TRT detectors provide this.

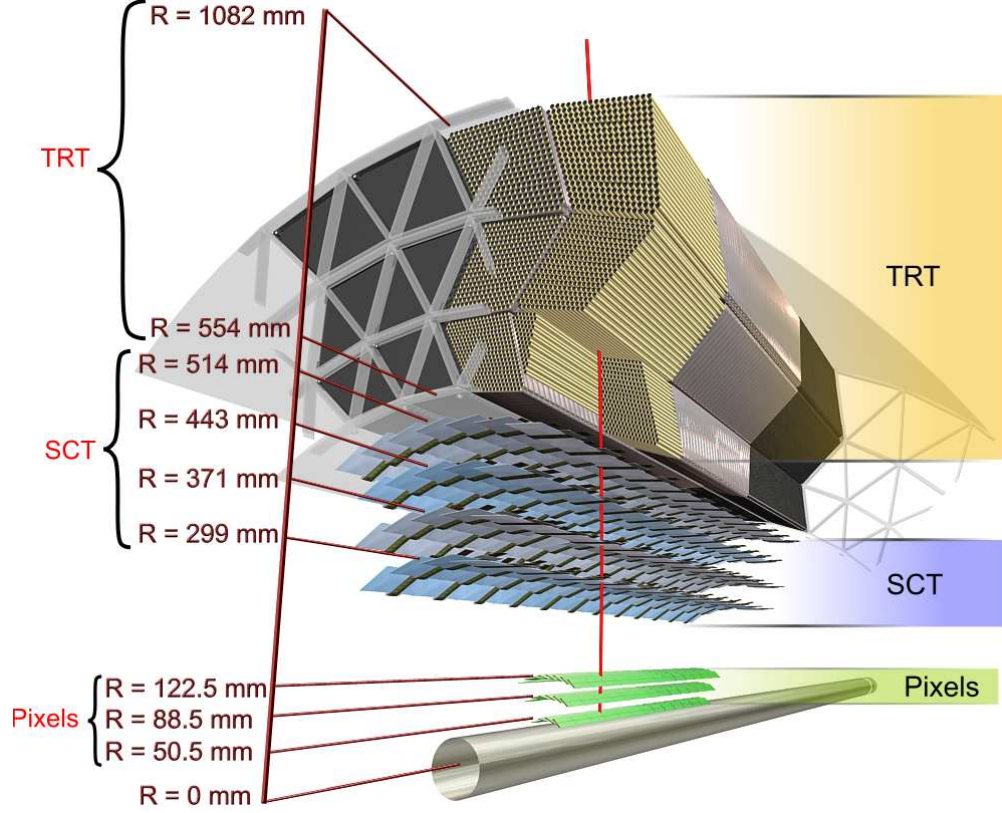


Figure 1.3: Inner Detector

Drawing showing the sensors and structural elements traversed by a charged track of 10 GeV p_T in the barrel inner detector ($\eta = 0.3$). The track traverses successively the beryllium beam-pipe, the three cylindrical silicon-pixel layers with individual sensor elements of $50 \times 400 \mu\text{m}^2$, the four cylindrical double layers (one axial and one with a stereo angle of 40 mrad) of barrel silicon-microstrip sensors (SCT) of pitch $80 \mu\text{m}$, and approximately 36 axial straws of 4 mm diameter contained in the barrel TRT modules within their support structure. Figure from [2].

Pixel Detector The pixel detector is comprised of high granularity silicon pixel sensors. These pixels are mounted on three concentric cylinders in the barrel and disks in the endcap regions. They provide an intrinsic resolution of $10 \mu\text{m}$ in $R - \phi$ and $115 \mu\text{m}$ in z or R in the barrel or endcap respectively. If only one pixel was ever hit by a track the simple result of the uniform distribution that the resolution, $\sigma = \text{pitch}/\sqrt{12}$ would hold, however there is a significant sharing of charge with neighbouring pixels which improves the resolution. This is a significant effect in the pixel detector as it has an analogue readout system whereby a binary readout with time over threshold gives analogue information on the pulse height. With this analogue information the charge centroid can be determined which improves the resolution.

Electron-hole pairs produced when a particle passes through a pixel element will drift to the electrodes. This current will cause a corresponding current to be induced in the electrodes which will be amplified and a threshold applied to produce a binary output. Each track is expected to produce 3 such hits. With its excellent resolution, the pixel detector is very important in the measurement of vertices and is consequently very important for physics involving B -mesons or τ -leptons. Such a system is however too expensive to extend further than the 12.3 cm to which the 3rd barrel section extends.

SCT detector The SCT detector consists of 4 barrel sections and 9 disks for each of the endcaps. Operating similarly to the pixel detector the SCT elements are however of coarser granularity, with the silicon strip detectors providing an intrinsic accuracy of $17\ \mu\text{m}$ in $R - \phi$ and $580\ \mu\text{m}$ in z (R) in the barrel (disks). Each layer consists of 2 strip detectors, crossed at a small stereo angle of 40 mrad to allow determination of the hit position along the strip. The SCT extends the ID to a radius of 51.4 cm, with each track passing through approximately 4 modules.

TRT detector The final element of the ID is the TRT detector, providing a different approach to tracking than the first two elements. The straw tubes of the TRT are 4 mm in diameter. In the barrel they are 144 cm in length and lie parallel to the beam while in the endcaps they are 37 cm in length and lie radially. When a charged particle passes through the gas inside the straw (a $Xe\text{-}CO_2\text{-}O_2$ mixture), it will ionise the gas mixture. Drift electrons will undergo an amplification as they move close to the central gold plated tungsten wire running down the centre of the straw due to a high voltage being applied. This gas gain increases the number of electrons by a factor of approximately 10,000, making the previously weak signal detectable. Additionally, the gas mixture will be ionised by transition radiation photons arising from the traversal by the charged particle of the polyethylene material in which the straws are embedded. Since the number of transition radiation photons is proportional to the Lorentz factor, $\gamma = \frac{E}{m}$, the lower mass electrons will lead to higher charge deposition than pions and other hadrons. This allows for a high threshold to distinguish

electrons from hadrons alongside the low threshold for track reconstruction. The TRT has no sensitivity in the longitudinal direction, z , providing an intrinsic resolution of $130\ \mu\text{m}$ in $R - \phi$ per straw, however when combined with the SCT and pixel hits, helps to provide an overall robust pattern recognition and excellent $R - \phi$ and z resolution in the ID.

Calorimetry

ATLAS calorimetry extends to a pseudorapidity of 4.9^3 with different considerations being made in different regions to account for the predominant physics channels and the radiation environment. The EM calorimeter in the central region must have excellent resolution so as to make accurate measurement of the energy of central photons and electrons, while the forward calorimetry need only be of fine enough detail to make a measurement of jet objects and $E_{\text{T}}^{\text{miss}}$. The techniques used in each region therefore vary somewhat. The calorimeters must also contain EM and hadronic showers while avoiding punch through to the muon system, making the depth of the calorimeters an important consideration.

The $E_{\text{T}}^{\text{miss}}$ is a very important quantity to understand in LHC interactions as it is an important part of many physics signatures. The missing transverse momentum is used, since to a good approximation the initial transverse momentum of the particles entering the detector is zero, while the total momentum in any given parton interaction is not known. $E_{\text{T}}^{\text{miss}}$ can arise from mismeasurement of jets, particles lost into cracks or non detecting material in the detector or from particles such as neutrinos which are not detected in the detector volume. $E_{\text{T}}^{\text{miss}}$ is calculated by performing a weighted sum of the EM and hadronic calorimeter activity in the transverse plane and determining where and by how much this total transverse energy is unbalanced.

Electromagnetic calorimeter The EM calorimeter is a lead and liquid argon (LAr) calorimeter where the absorber and sampler are arranged in an accordion shape in order to improve speed and give complete ϕ coverage without cracks. The EM calorimeter is divided

³The Forward Calorimeter extends to $|\eta| = 4.9$ however the EM and hadronic calorimetry is restricted to $|\eta| < 3.2$. The former is not used in this thesis so will not be discussed further.

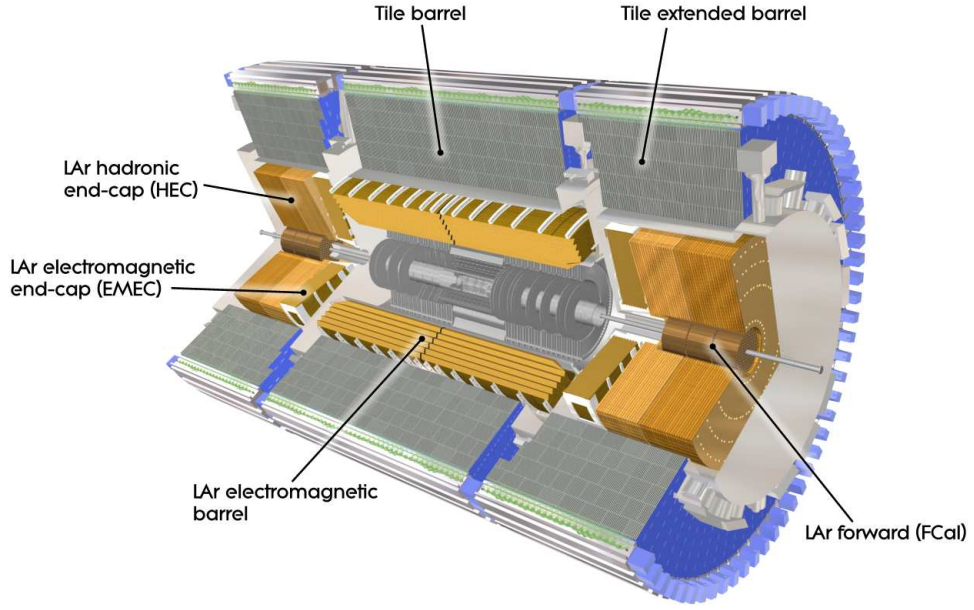


Figure 1.4: ATLAS Calorimetry

Cut-away view of the ATLAS calorimetry system, with the ID visible in grey in the centre. Figure from [2].

into a barrel ($|\eta| < 1.475$) and two endcap ($1.375 < |\eta| < 3.2$) sections. In the central region ($|\eta| < 2.5$) the calorimeter is divided into three layers, while inside $|\eta| < 1.8$ there is also a presampler of active liquid argon to correct for energy lost by electrons and photons before they reach the calorimeter. In total the depth of the EM calorimeter corresponds to approximately 24 radiation lengths as indicated in a sketch of the layout of a barrel module shown in figure 1.5. As electrons and photons enter the EM calorimeter they will initiate a cascade of particles by means of pair production and Bremsstrahlung. This shower will liberate electrons in the liquid argon sampler which are collected and detected as electronic pulses. Measuring the signal and looking at the shape in the calorimeter gives an indication of the energy and type of the particle.

Hadronic calorimetry The hadronic calorimeter system consists of a tile calorimeter and two liquid argon endcap calorimeters. The tile calorimeter has a barrel part ($|\eta| < 1.0$) and two extended barrels ($0.8 < |\eta| < 1.7$) with layers of steel as absorber and scintillating tiles as active material. The tile calorimeter extends from an inner radius of 2.28 m to an outer

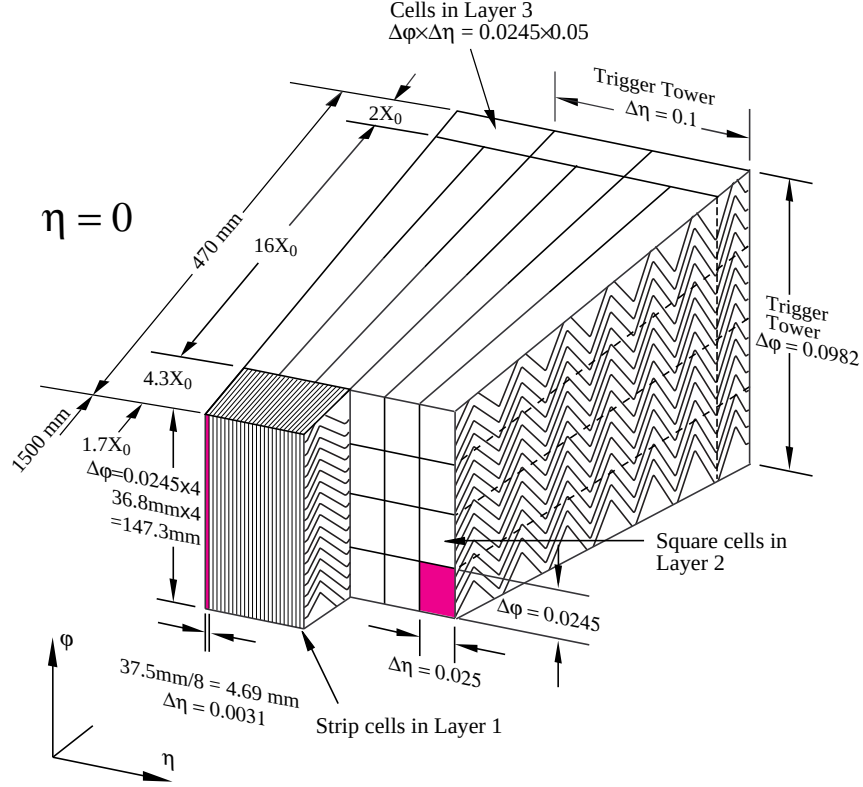


Figure 1.5: LAr EM Calorimeter

Sketch of a EM calorimeter barrel module with granularity also displayed. Figure from [2].

radius of 4.25 m. Liquid argon is used in the end cap region as active material and copper as absorber as the radiation doses are too high for scintillators. Since the hadronic calorimeters are located outside the EM calorimeters, no electrons or photons should reach them. The hadrons interact in the dense absorber, then the resulting shower is detected in the active material (scintillator or liquid argon).

1.2.4 ATLAS data acquisition

Nominal bunch crossing rate for the LHC is 40 MHz but with an average event size of approximately 1.3 MB the ATLAS trigger system must reduce this rate to approximately 200 Hz to be stored for further processing. This reduction in rate requires a very fast and efficient rejection of background online. The trigger system is split into three levels: L1, L2 and the event filter (EF).

L1 is a hardware trigger that produces a trigger decision within $2.5\,\mu\text{s}$ to reduce the total rate from 40 MHz to 75 kHz. The L2 trigger takes as input regions in phase space that have been selected by the L1 trigger to contain signals of interest. In these regions of interest L2 applies software based algorithms at full detector granularity and precision looking only at information in those regions (approximately 2% of the total event data). The L2 trigger reduces the rate to approximately 3.5 kHz in an average time of 40 ms. The final step in the chain is the EF, which reduces the rate to approximately 200 Hz using offline selections in a few seconds.

The ATLAS trigger system is designed to significantly reduce the rate of data to be stored to disk, however due to the high rate of production for certain processes in the LHC environment it is not possible to take all events passing the full trigger chain in some instances. ATLAS will therefore apply prescales, so that for a given trigger, only a fraction of events for a particularly high rate trigger will be allowed to pass that trigger; the rest of the events being lost. These prescale factors are varied within the course of a run so as to use up the entire allowable bandwidth at the EF stage.

A more detailed description of the ATLAS trigger system can be found in [2, 6, 7], while the specific example of the trigger used for the analysis presented in this thesis is held to chapter 5.

Data formats

One year of nominal ATLAS data taking at the LHC will result in approximately a petabyte of data, so it is not possible to store all data from the LHC experiments on individual computer farms to process locally. After initial processing at CERN, the data is distributed across the many computing centres that make up the LHC Computing Grid (LCG), a world-wide distributed computing network. At this point the LCG allows for users from the experiments to submit their analysis code to run at the various sites at which the data is located. After the analysis is complete, the output is stored on the Grid for the user to retrieve to further analyse locally.

To allow easier access to data and simulation, additional data formats are introduced. The Event Summary Data (ESD) format contains the detailed output of the detector reconstruction and is produced from raw data. All relevant variables needed for data analysis are stored (for particle identification, track re-fitting, jet calibration etc.) so that rapid tuning of reconstruction algorithms and calibrations can be carried out. ESDs are about 500 kB per event. The Analysis Object Data (AOD) format is a summary of the reconstructed event, and contains sufficient information for most analyses. The AOD can be produced from the ESD, significantly reducing time and computing requirements. AODs are approximately 100 kB in size per event.

In addition to the ESD and AOD formats there are derived formats which reduce the size of the dataset considerably. The most common format for day to day analysis is the D3PD⁴ (or ntuple), which stores ROOT⁵ trees containing the relevant variables for a particular analysis. This thesis uses predominantly D3PDs from the standard model group in ATLAS, slimmed to remove unnecessary variables and stored locally for quick analysis.

⁴The ATLAS collaboration has introduced various ‘Derived Physics Dataset’ (DPD) formats, where each successive version is a slimmed down version of the last. The D3PD is an object suitable for most analyses and takes the form of a ROOT file containing a ROOT TTree object.

⁵ROOT is an open source framework for data processing, born at CERN, at the heart of the research on high-energy physics[8, 9].

Chapter 2

R & D for LHC upgrade: speckle pattern interferometry

Polarised, coherent light incident on an optically rough surface appears as a speckle pattern. Electronic Speckle Pattern Interferometry (ESPI) makes use of this phenomenon to measure the deformation of surfaces below the micron scale. The ESPI system developed in Oxford will be used to test the mechanical properties of prototype support structures for the high luminosity (HL) LHC upgrade of the inner tracking detector in ATLAS. ESPI and the work carried out to develop the Oxford system will be introduced herein along with some recent results of testing the system. Many of the concepts discussed in this chapter are covered in further detail in [10, 11].

2.1 Upgrade to the LHC

Within ten years from the commencement of operation, the LHC upgrade programme will have incrementally reached a luminosity above that for which the current detector was designed. Various elements of the LHC machine will have reached their radiation limits and will need to be replaced. There is a physics argument for further increasing the luminosity of the LHC. The final physics case will be contingent on the discoveries during the first years of operation, but it is already the case that with higher luminosity there will be an improved discovery potential for rare events. However there are challenges associated with such an

upgrade. The current detectors will require upgrades to deal with the greatly increased number of tracks through the detector and energy deposits in the calorimeters.

For the ATLAS detector, the SCT and TRT will be replaced with a new inner detector system. This strip detector concept consists of integrated carbon support structures, ‘staves’, which are essentially planks consisting of two skins 1.2 m by 0.1 m separated by a low density foam, with several semiconductor detector modules mounted on both surfaces of each structure. These structures are then mounted onto a support cylinder to hold them in position. Figure 2.1 shows a schematic view of the proposed stave system. For an in depth discussion on the integrated stave concept see [12]. Such a structure has the claimed advantages of minimising radiation length, simplicity of manufacture, the ability to manufacture in parallel and the simplicity of installation and repair during installation. Exploiting the integrated stave concept allows the lowest mass system given the constraints imposed by the cooling, power and read-out requirements in the higher luminosity environment.

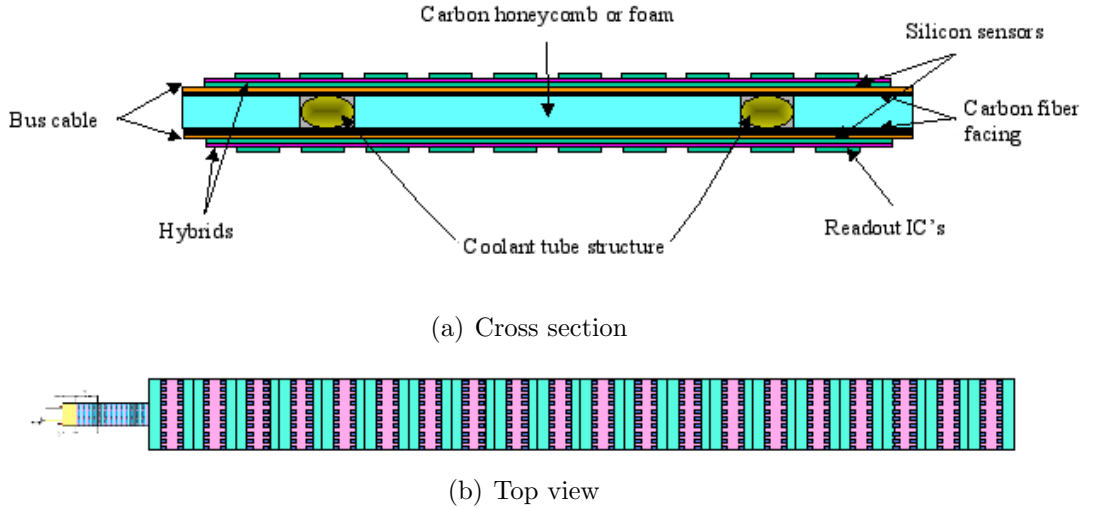


Figure 2.1: Proposed stave concept

The single sided silicon detector modules are mounted on top and bottom side of a carbon structure with integrated services and cooling. Images taken from [12].

As is the case when building any new detector system, the way that the individual parts will behave when situated inside the detector must be investigated a priori. One such way that thermo-mechanical deformations in prototype staves can be diagnosed is using ESPI to monitor the deformation of the surface while the stave undergoes cooling. The stave should

be visible in its entirety whilst cooling as it is important to know how the entire object is warping. One reason that it may warp is that the cooling pipe has a different coefficient for thermal expansion (CTE, $\alpha = \frac{1}{L} \frac{dL}{dT}$) to the carbon structure through which it runs¹. If the way that the pipe is mounted in the carbon was not correctly configured, the changes in the shape of the cooling pipe might well propagate through the carbon structure causing strains and deformations that would degrade the positioning accuracy of the mounted silicon detectors, or in extreme cases cause structural damage. ESPI is a particularly useful way of quantifying any deformations for several reasons. It is possible to view the entire stave at once and monitor how it is changing over time. The process is non-contact and is able to detect deformations on the scale of half the wavelength of light, up to a few microns.

2.2 Laser speckle

Laser speckle is an interference effect resulting from coherent laser light being incident upon an optically rough surface. Huygens principle states that each point of the surface acts as a spherical light source. As the surface is rough on the scale of the wavelength of light, there are differences in path length for the light originating at each point on the surface that result in constructive and destructive interference at some point away from the surface. This interference pattern is the speckle pattern that is observed. In order to perform the measurement of thermo-mechanical deformation described above using ESPI, it is necessary to understand fully this speckle pattern.

Beginning with the above assumption that each point on the surface acts as a source of spherical waves, it is clear that the amplitude of the scattered light at any point away from the surface is the sum of the amplitudes from each point on the surface. As the surface varies randomly on the scale of the wavelength of the illuminating light, λ , the phase differences contributing to the scattered light sum at a distant point will also be random. This leads to

¹Literature for the material that is likely to be used to encase the cooling pipes, POCOfoam [13], a thermally conductive graphite foam, suggests a CTE of $\sim 1 \text{ ppm/K}$ as compared to aluminium at $\sim 22 \text{ ppm/K}$ or stainless steel at $\sim 15 \text{ ppm/K}$.

what is often termed a ‘random walk’, with a random set of phase vectors adding to give a random resulting amplitude at a given point. Consider figure 2.2(a), in which the reflected light is considered at a distance from the object in question. The point Q when moved on a plane parallel to the reflecting object will sample a different random amplitude, and hence intensity. This random intensity variation appears as a speckle pattern.

Detailed derivations of the statistical properties of speckle are carried out in [10]. The results, which can be found summarised in [11] for example, are shown here where they are considered of use in understanding the speckle pattern for use in ESPI.

Comparing the intensity of the speckle field at two points, the reasonable assumption that the intensities at two very near points are closely related holds true. As the two points are moved apart, the intensities become different. As fluctuations do not have a fixed frequency, the speckle size can not be quantified, however it can be related to the autocorrelation function of the intensity distribution, $\mathbf{R}(\mathbf{r}_1, \mathbf{r}_2) = \langle I(\mathbf{r}_1)I(\mathbf{r}_2) \rangle$. As $\mathbf{r}_1$ and $\mathbf{r}_2$ become sufficiently separated, the intensities at the two points will no longer be related ($\mathbf{R}(\mathbf{r}_1, \mathbf{r}_2) = \langle I(\mathbf{r}_1) \rangle \langle I(\mathbf{r}_2) \rangle$). The transition to the latter form of the autocorrelation function gives an indication of the speckle size.

In [10] the autocorrelation is derived to be

$$\mathbf{R}(\Delta x, \Delta y) = \langle I \rangle^2 \left\{ 1 + \text{sinc}^2 \left(\frac{L\Delta x}{\lambda z} \right) \text{sinc}^2 \left(\frac{L\Delta y}{\lambda z} \right) \right\}, \quad (2.1)$$

for the case where the surface is uniformly illuminated over an area of $L \times L$, with z being the distance between viewing and object planes and $(\Delta x, \Delta y)$ representing the change in viewing position. The average size of a speckle can be taken to be the first zero for the sinc function:

$$(\Delta x)_{\text{speckle}} = \frac{\lambda z}{L} \quad (2.2)$$

This result can be understood from simple geometric considerations also. Consider the

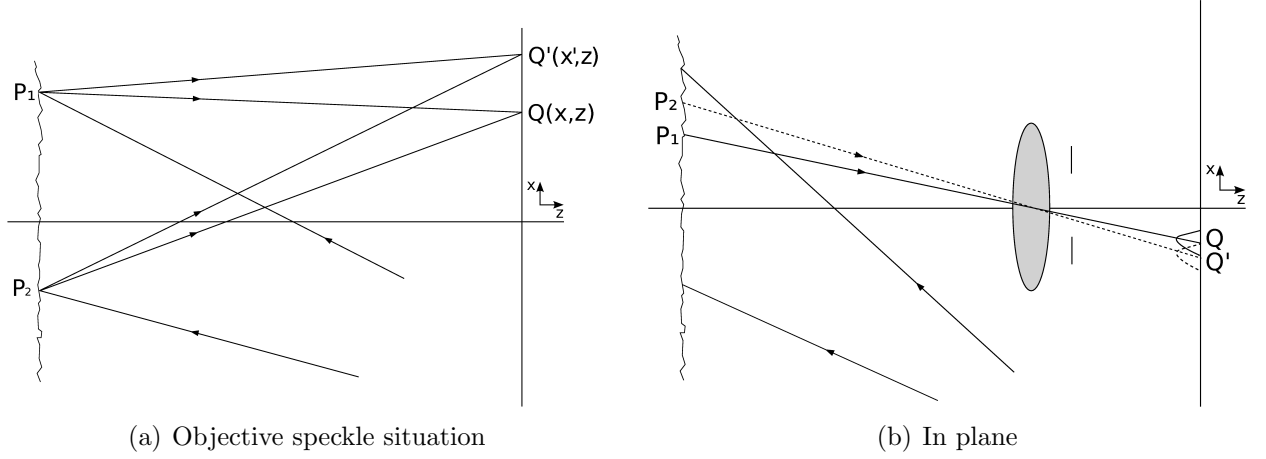


Figure 2.2: Speckle pattern geometry

A simple demonstration of the origin of an (a) objective speckle pattern and a (b) subjective speckle pattern.

situation of figure 2.2(a). P_1 and P_2 represent the bounds of illumination given to be of separation L in the previous calculation. The path difference from points P_1 and P_2 to a point Q on the viewing surface is to first order

$$(P_1Q - P_2Q) \simeq \frac{xL}{z}, \quad (2.3)$$

while the path difference from the same points on the image to a point Q' at $x' = x + \Delta x$ is

$$(P_1Q' - P_2Q') \simeq \frac{xL}{z} + \frac{\Delta xL}{z}. \quad (2.4)$$

The change in relative path to Q and Q' is then $\Delta s \simeq \frac{\Delta xL}{z}$. In the case where this change is approximately λ , the phases will be sufficiently different that the intensity at Q will no longer be related to that at Q' . In this case, the relationship of equation 2.2 is recovered:

$$\frac{\Delta xL}{z} \simeq \lambda. \quad (2.5)$$

The case where the speckle pattern is observed as an image after passing through an

aperture, is commonly referred to as a subjective speckle pattern. The pattern itself, in this case, is dependent on the properties of the imaging system. The light originating at each point on the surface that passes through a circular aperture will form a diffraction pattern in the form of an Airy disk on the image plane. Given that most of the light from a given point will be contained within the first maximum of the Airy disk, it can be said that the area of influence of that point is given by the radius to the first minimum of the Airy disk. The intensity at the point in the centre of this area of influence will however be the result of all points on the surface whose light falls within the area of influence. Due to the optical roughness of the surface, each wavefront contributing to the area of influence will undergo interference to produce some random intensity for that point. The light at two points in the image that have been scattered from many points in common on the surface will not differ dramatically, however two points on the image plane whose light comes from separate influencing areas on the object from which the light was scattered will be uncorrelated.

Consider figure 2.2(b). Light originating from point P_1 on the illuminated surface will pass through the aperture and produce an Airy disk on the image plane centred at point Q . All points near P_1 whose corresponding Airy disks are centred within the area of influence of Q will contribute to the observed intensity at Q . The first minimum of the Airy disk formed of the light from point P_2 coincides with Q so light from point P_2 makes no contribution to the complex amplitude of the light at Q . Points within an area centred on P_1 with a radius of the distance between P_1 and P_2 contribute to the intensity of light at Q .

The distance between Q and Q' is simply the position of the first minimum of the Airy disk, $\frac{1.22\lambda\nu}{a}$, where a is the diameter of the viewing lens aperture and ν is the distance from the aperture to the image plane. Consequently, the diameter of the speckle should be twice this distance, $\frac{2.44\lambda\nu}{a}$. This is confirmed to be the case by looking at the autocorrelation function, as in [10].

The origin of the term subjective speckle lies in the fact that the properties of the speckle, for example its size, depend on the viewing apparatus. This phenomenon means that, for example, two different people will likely see the same surface differently under the

same conditions, due to their eyes not being identical. In order to measure deformations of surfaces using speckle patterns, it is important to remove the dependence on the imaging system as much as possible.

2.3 Interferometry

To perform measurements of surface deformation using the properties of laser speckle, a subtraction of two subsequent images of the object is performed. In this interferogram, ‘fringe patterns’ will be visible that describe the change in the object. To achieve a subtraction that depends only on the object under illumination, two light sources are used that will interfere with each other to produce a speckle pattern. The orientation of the two laser sources depends on whether deflections in the plane of the object (in plane) or normal to the object’s surface (out of plane) are to be measured. The two different configurations used in the Oxford ESPI system are shown in figures 2.3(a) and 2.3(b) and discussed in further detail in section 2.4. For the in plane case, two sources illuminate the object directly at an angle from each side, while for out of plane measurements, a reference beam is combined with the reflected light from one source just prior to entering the imaging system.

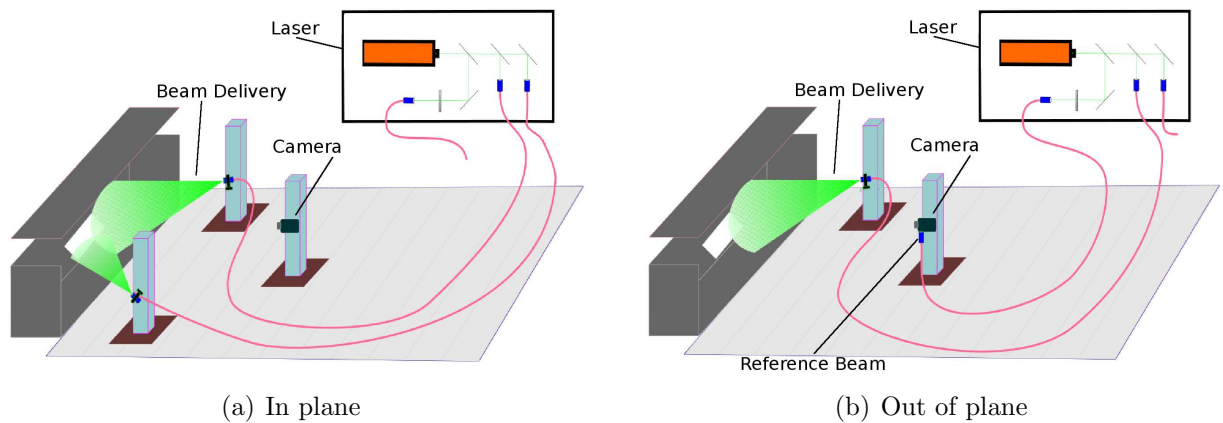


Figure 2.3: The setup for the Oxford ESPI system

To make measurements of deformation in plane mode (a), the object is illuminated with two beams of laser light. For the out of plane (b), it is necessary to directly illuminate the CCD with part of the light which requires a modified camera. Images taken from [14].

For both geometries, performing a subtraction highlights intensity correlations. That is, if a particular speckle changes between dark and bright between the two photographs, the subtraction will appear as a bright speckle. It is important to avoid loss of spatial correlation however. This will occur if the speckle pattern moves such that the set of points contributing to a particular speckle in the image changes significantly. This speckle decorrelation occurs for deformation greater than $\sim 10\mu\text{m}$. In practice, the loss of spatial correlation is not so much of an issue so long as the object is moving very slowly, as the user can simply take a new baseline photograph from which to make further subtractions from.

2.3.1 In plane

The displacement that each contour of the interferogram represents, relative to the adjacent contour can be determined by simple geometric considerations. Looking at the in plane mode, figure 2.4, the calculations are as follows.

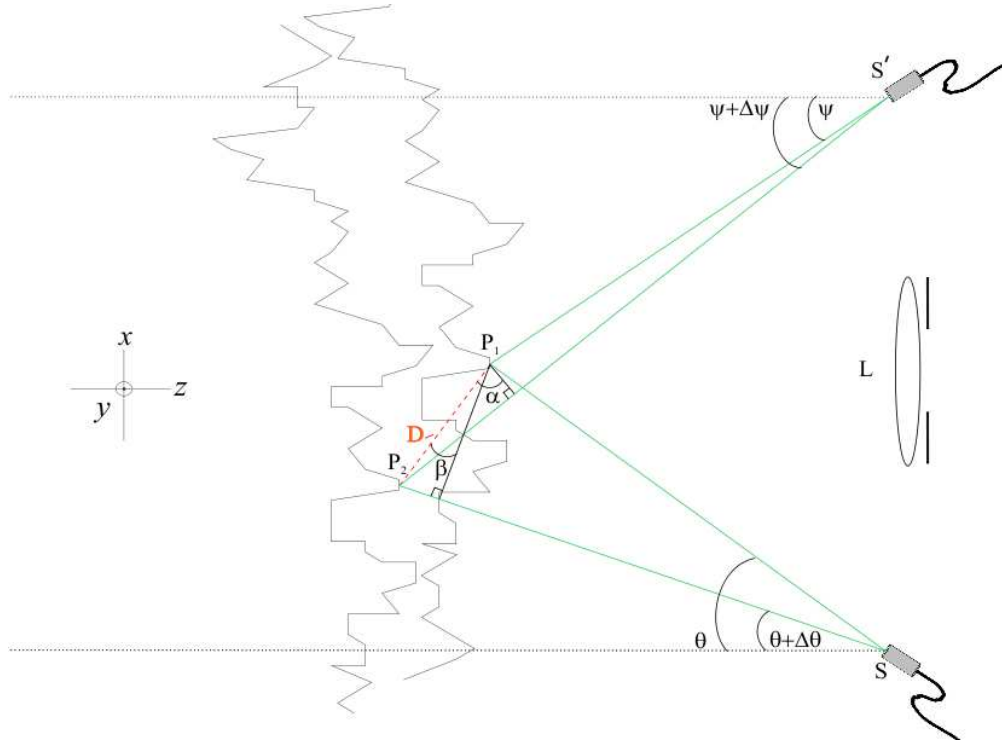


Figure 2.4: In plane geometry

Geometry for a surface that has undergone a deformation such that point P_1 moves to P_2 . This image is taken from [14].

The path difference between two wavefronts before and then after the deformation is:

$$\begin{aligned}\Delta l &= [S'P_2 - SP_2] - [S'P_1 - SP_1] \\ &= [S'P_2 - S'P_1] - [SP_2 - SP_1] \\ &= \Delta S' - \Delta S\end{aligned}$$

An auxiliary line can then be drawn to make a right angle triangle as seen in the diagram. It is possible to now define δ as the angle that the displacement vector D makes with the $x - y$ plane. For entirely in plane motion, this will be 0. Looking at figure 2.4:

$$\begin{aligned}\Delta S' &= D \sin \alpha \quad \Delta S = D \sin \beta \\ \Delta S' &= D \sin (\delta + \psi) = D [\sin \delta \cos \psi + \sin \psi \cos \delta] \\ \Delta S &= D \sin (\delta + \theta) = D [\sin \delta \cos \theta + \sin \theta \cos \delta]\end{aligned}$$

The change in path difference is:

$$\Delta l = \Delta S' - \Delta S = D [\sin \delta (\cos \psi - \cos \theta) + \cos \delta (\sin \psi - \sin \theta)]$$

In normal operation θ and ψ are of the same magnitude, so $\theta = -\psi$. Dark fringes will occur when the change of path difference between two images is an integer number of wavelengths, so that a bright speckle will remain bright, in order that in the subtraction it will appear dark. So finally it can be seen that, if the assumption is made that motion is completely in the plane of the object (i.e. $\delta = 0$), and that the illumination angle, $\theta = 60^\circ$, the relative separation between two dark fringes is:

$$\lambda = \Delta l = 2D \sin \theta$$

$$D = \frac{\lambda}{2 \sin \theta} \approx 300 \text{ nm}$$

For each further fringe in the interferogram, the object has deformed by 300 nm . In practice, it is not possible to identify the formation of a single fringe. More than one fringe is needed to determine that there are fringes present. This means that in reality the sensitivity of the system in the central region is more like 900 nm . To be able to probe such small deformations is crucial in testing the characteristics of, for example, prototype staves for the ATLAS upgrade.

2.3.2 Out of plane

A consideration of the out of plane geometry follows in a similar way to the in plane mode. In this case the object is illuminated with one wavefront and is projected onto the image plane alongside a reference beam which maintains the same phase throughout the measurement. When changes in displacement normal to the surface occur, fringes are detected due to changes in the combined phase. These phase changes originate in the displacement of the object under illumination.

Consider figure 2.5. The change in phase when the surface moves such that a point P_1 moves to P_2 depends on the change in path length, $\Delta l = (SP_2 + P_2L) - (SP_1 + P_1L)$. Using the displacement vector and given the fact that in reality $D \ll SP_1, SP_2$ so that SP_1 is essentially parallel to SP_2 , this can be reformulated to

$$SP_2 - SP_1 = \frac{\vec{D} \cdot \vec{SP_1}}{SP_1} \quad \text{and} \quad P_2L - P_1L = \frac{\vec{D} \cdot \vec{P_1L}}{P_1L}. \quad (2.6)$$

In the case where the angles θ and ψ are small, the projection of $\vec{D}$ in the direction of the viewing apparatus is approximately the z component of $\vec{D}$. In this case, to a good

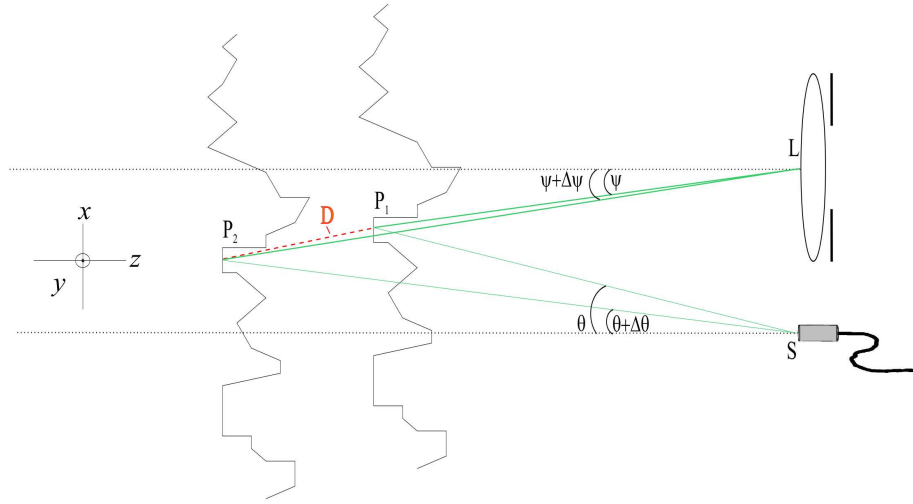


Figure 2.5: Out of plane geometry

Geometry for a surface that has undergone a deformation such that point P_1 moves to P_2 . In this figure, the displacement is greatly exaggerated. Image taken from [14].

approximation, $\Delta l = D_z(\cos \theta + \cos \psi)$. The corresponding change in phase can thus be expressed as

$$\Delta \phi = 2\pi(\cos \theta + \cos \psi)D_z/\lambda. \quad (2.7)$$

Sensitivity in this configuration is to displacement out of the plane of the object. Contours of similar brightness in the interferogram correspond to change in phase of π , corresponding to a displacement of just under half of the wavelength of the illuminating light:

$$D_z = \frac{\lambda}{2(\cos \theta + \cos \psi)}. \quad (2.8)$$

Motion in the plane of the object will not contribute to the development of fringes but will cause loss of spatial correlation.

2.3.3 Sensitivity

It is important to note that while a single fringe may represent a movement of approximately half a wavelength, in practice the system is not sensitive to such precision. A single fringe appears simply as a light or dark band across the image and it is difficult to interpret as a fringe in most instances. For clear identification of fringes, more than one must be visible.

The displacement that a single fringe indicates varies depending on the angle of illumination, as shown in sections 2.3.1 and 2.3.2. This, along with the fact that one requires upwards of three fringes to be able to accurately determine their existence, means that the sensitivity to object movement changes across the object.

	Centre of Object	Edge of Object
In plane	900	680
Out of plane	275	300

Table 2.1: Approximate deformation (nm) sensitivity for a ~ 1 m stave

A simple calculation looking at the angle of illumination and number of fringes required yields the estimate of the sensitivity for deformation of a typical stave of length 1 m given in table 2.1. While in theory the resolution of fringes is limited by the imaging technology, in practice the predominant issue is noise.

2.3.4 Noise

As can be seen in the section 2.5, the contours in ESPI interferograms are not always exceptionally sharp, and in most cases are very noisy. There are various sources of noise, some of which can be accounted for, while others are ignored where possible. The main sources of noise are listed here.

Spatial decorrelation occurs, as mentioned previously, when either of the interfering wavefronts is displaced at the CCD by a similar magnitude to the speckle size. When this happens, the contribution to a given pixel is different for successive photons, mean-

ing that the subtraction is no longer making valid comparisons. To avoid this affect the system is kept as isolated as possible to remove the possibility of excess displacement.

Poor isolation of the environment can cause such displacements. To keep environmental noise such as vibrations in the building from affecting the ESPI system, the laser table is mounted on air cushions that are pumped up prior to operation.

Laser fluctuations can result in differing intensities between successive photographs causing fluctuations in visibility of fringes. In the case where the polarisation of the laser light is varying, the resulting fringes are also affected.

Camera response fluctuations can cause subtraction of two recorded intensities to be an incorrect representation of the true intensity difference.

Camera saturation can occur whereby a particular point in the frame is particularly reflective, resulting in an excessively bright area in the image. If this area is saturated, the area will appear as black in the subtraction, which can give the illusion of fringe features.

Illuminating wavefront artefacts can appear. An example of such an artefact is the appearance of fine vertical fringes in all images taken in the out of plane mode. This has been determined to come from the beam splitting setup in the modified camera. To allow the introduction of a reference beam to the imaging system, an optical fibre feeds a small fraction of the original laser light into the side of the camera, just in front of the CCD. This is then reflected onto the CCD by use of a glass slide. The fine pattern seen is thought to be an effect related to the two sides of the glass slides both providing reflections. This disappears almost entirely in the subtraction, but is however visible still. Such artefacts need to be taken into account by the user during analysis.

Noise is particularly evident in dark areas of an interferogram due to the way subtractions are made. The absolute value of difference in a given pixel is considered so that no matter

whether the noise makes a pixel darker or brighter, the resulting subtraction will be brighter. In this way, noise erodes the darker areas of an interferogram making them appear less dark.

At particularly large displacements, fringes will be closer together. In such cases noise is considerably more problematic, as it acts to smear the dark fringes and renders them more difficult to read. When fringes are beginning to fade, the user can take a new baseline image from which to subtract further images, taking note of the number of fringes present.

Interferograms are essentially entirely composed of dark pixels due to their nature as a subtraction of very similar images. Image manipulation in the form of application of a ‘ γ factor’ is therefore necessary in order to observe displacement contours. The two endpoints (minimum and maximum pixel brightness) are fixed and a correction curve defined by the exponent γ is used to adjust the displayed brightness of each pixel. A γ correction of 0.45, for example, makes fringes visible where previously the interferogram appears entirely dark. Images presented in the next section have had such a correction applied in order that the fringes be visible.

2.4 Oxford ESPI system

The ESPI system developed in the context of this thesis was derived from a similar set up that had been used to make measurements of vibrational modes and other deformations of the ATLAS SCT barrel structure. This previous work is detailed in [14]. The system required the development of new software and various hardware additions in order to make use of the ESPI technique in research and development of the stave concept for the HL-LHC ATLAS upgrade. In this section details of the improvements and developments are discussed.

2.4.1 Hardware

The system rests on a floating optical table, supported by air springs to insulate the setup from vibrations in the laboratory propagating through to disturb the measurement. A

532 nm laser is split into three parts, two of which are of equal intensity and carry the majority of the light, with the third carrying only a small proportion to act as a reference beam for the out of plane measurements. The system initially coupled this light to fibres for transport to the illumination site at the opposite end of the optical table, however after the completion of work by the author it was decided that the increase in light yield made it worthwhile to remove the optical fibre coupling for the two main illumination beams and to enclose the entire light path up to the object [15]. This decision was made at the same time that a new, more powerful laser was introduced. The laser with which the following results have been obtained is a 532 nm continuous wave diode laser that produces an average of 445 mW with 1% long term power stability and spectral linewidth < 200 MHz. The decision to move to the free-space configuration was made, along with the decision to upgrade the laser in use, in order that the speckle pattern be bright enough that an entire stage could be imaged without shifting the camera and the beam directions to image the outside edges. The two main components of the beam are diverged using a pair of lenses, one spherical and one cylindrical, which spread the beam asymmetrically in the x and y directions to form an elliptical, Gaussian beam. The lenses are held on an adjustable mount which allows their relative positions to be changed so the spread of the beam can be adjusted. The third, weaker component of the initial beam is however still transported to a specially constructed camera via a fibre optic cable, where it illuminates the CCD.

Within the beam delivery system, there are two mechanical shutters which can be controlled from outside the lab. Switching the orientation of these shutters leads to a switch in the direction of sensitivity of the system from in plane to out of plane or vice versa. Software provisions were made to make this an automated process to allow streaming of in and out of plane images simultaneously. This was found to lead to vibrations in the system, causing a lack of stability in both streams. Further work is required to integrate this automation into the system.

The object under scrutiny is mounted in an environmental chamber with a triple glazed front window. The chamber is engineered to provide a control region where humidity can

be lowered and the air cooled so that prototype staves can be mounted within to be cooled via their internal cooling system. A cooling system was constructed to maintain a cold air temperature inside the chamber. Aside from the thermal isolation of the environmental chamber, the entire ESPI lab is thermally isolated. This is important as small changes to the optical system on the scale of the speckle size can lead to speckle decorrelation and loss of fringe patterns.

The speckle patterns are captured using a modified Hitachi KP-F100 digital video camera connected to a PC outside of the main laboratory. Also outside of the lab is an ELMB² to read in and control the various temperature and humidity sensors placed around the ESPI system for monitoring purposes.

2.4.2 Software

The purpose of this programme of research is to bring the Oxford ESPI system to a point where it can be used to make measurements of the structural deformation of inner detector components for the ATLAS upgrade effort. In order to achieve this goal, various software tools were created using National Instruments' LabView [17]. LabView is a platform and development environment for a visual programming language where code is built up by connecting different function nodes on a graphical block diagram. The resulting Virtual Instruments (VIs) then execute according to the structure of the block diagram.

Various VIs have been assembled using the IMAQ Vision toolkit for use in ESPI, with the Acquisition and Analysis VIs forming the core of the ESPI process.

Acquisition As the name suggests, this program is used primarily for acquiring images from the digital camera. The basic process involves taking a frame from the camera, waiting a user specified amount of time, then taking a second image. The two images are subtracted, and the interferogram saved. Outside of this main functionality, the user can view a continuous video of the object, which is helpful for focusing the camera. Instead of one frame at

²Embedded Local Monitor Board [16].

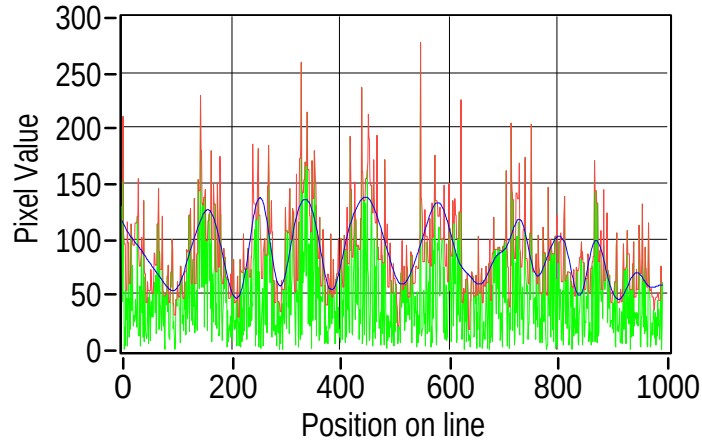


Figure 2.6: Lower frequencies reveal fringes in an otherwise noisy line profile
 The green line shows the pixel value from the unaltered image. The red is the result of the ‘close’ operation while the blue is the result of a Fourier decomposition of the line with all but the lowest 5% of frequencies removed. The resulting distribution clearly shows the location of fringes.

a time, several frames can be taken in succession and combined, effectively increasing the exposure time beyond the capabilities of the digital camera. This reduces time sensitivity, but if the timescale of the deformation is greater than approximately half a second, this can be advantageous to increase the signal to noise ratio.

Analysis This VI has various functions to help analyse the fringe patterns resulting from ESPI. The user can load a saved image, apply one of several different threshold routines to obtain a clearer view of the fringes, then apply a skeletonizing algorithm to further isolate the positions of the fringes. This algorithm determines the centre of the fringe and draws a line through it. From this it is possible to measure distances using a caliper tool. Alternatively, a profile across the fringe can be drawn and the lowest frequency Fourier components are plotted so the fringe positions can easily be seen amongst the noise as shown in figure 2.6. When decomposed into its frequency components by a Fourier transform, a fringe pattern will have a lot of higher frequency noise. By removing this higher frequency noise, and applying an inverse Fourier transform to the result, the lower frequency shows the fringes with much greater clarity.

Various other morphological transformations can be carried out using LabView’s inbuilt

tools. The red line on figure 2.6 is the result of a ‘close’ operation: a ‘dilation’, whereby the output pixel value is the maximum of all pixels in the input pixel’s neighbourhood, followed by an ‘erosion’, in which the output pixel value is the minimum of all pixels in the input pixel’s neighbourhood. This operation, one of many available, gives a line profile that shows much less fluctuation than the original making it easier to identify the fringes by line.

Aside from these two main functionalities, various other software tools were created for monitoring of temperature and humidity as well as manual manipulation and display of interferograms.

2.5 Preliminary Results

The following preliminary results were carried out after the completion of work by the author. The system was brought to a fully functioning level, however during this time, no prototype staves were available for testing. The following tests are therefore the work of R. King [15] and serve to show that the system is operational.

2.5.1 Measurement of CTE of aluminium

As an exercise in determining the system’s capabilities of carrying out in plane measurements of staff-sized objects, the CTE was measured for an aluminium test staff of approximately the same dimensions as the anticipated prototype staves.

Inside the environmental chamber, the test plank was fixed at one end and allowed to rest on a bracket at the other end. The dimensions of the test plank were $136\text{ cm} \times 15\text{ cm}$. Once sealed in the chamber, dry air was pumped into the chamber at a rate of 5 l/min to prevent condensation forming during cooling. The system was observed to be stable, with no fringes forming in the in plane mode. From an initial plank temperature of 25°C the cooling system was started with a target temperature of 10°C . In 52 minutes the temperature of the plank evened out to 13°C .

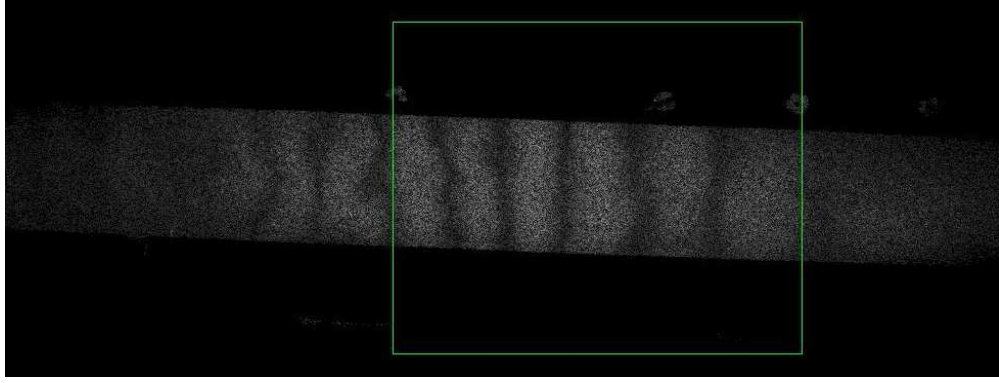


Figure 2.7: CTE measurement

A snapshot of fringe development. The green box outlines the RoI in which the fringe counting was performed.

Only a region of interest (RoI) corresponding to 45 cm on the test plank was considered as the interferograms were most easily visible in the central region of the plank. The fact that the entire region will move under the deformation is taken into consideration by counting fringes that enter and leave the RoI. Any deformation in the test object will lead to a non-zero difference between the two. Figure 2.7 shows a snapshot of the fringe development, along with the RoI used in calculating the CTE.

Results were used from period approximately 36 minutes long over which the stove cooled by 8°C . In this period the total difference in fringes, $N_{fringe}^{in} - N_{fringe}^{out} = 83$. By taking into consideration the wavelength of the light, the distance to the object under illumination and the angle of incidence, each fringe can be shown to represent a deformation of $0.9\ \mu\text{m}$. This gives a total deformation of $74.7\ \mu\text{m}$ and a CTE of $\alpha = \frac{1}{L} \frac{dL}{dT} = 20.75\ \text{ppm}/^{\circ}\text{C}$. An uncertainty arising from the high level of electronic noise on the PT100 temperature sensors of $\pm 0.5^{\circ}\text{C}$ and an estimate of that arising from the crude fringe counting process of 15% combine to give a value of $(20.75 \pm 3.3)\ \text{ppm}/^{\circ}\text{C}$. This compares favourably with the accepted value of $23.1\ \text{ppm}/^{\circ}\text{C}$.

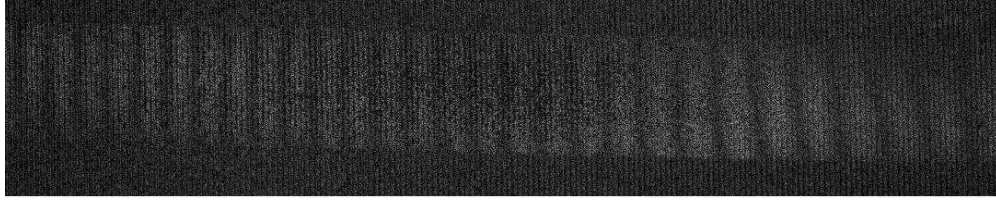


Figure 2.8: Out of plane calibration

Fringes after displacement of one end of test piece in direction normal to surface.

2.5.2 Out of plane calibration

The previous example shows that the in plane mode is working with some accuracy. To demonstrate that the out of plane mode is behaving in the expected manner the same aluminum test piece was mounted to the environmental chamber via a block with ‘leaf spring’ type hinge. This type of hinge moves more predictably over small distances than a conventional pinion hinge. The other end rested on a linear stage fixed to a bracket. By moving the stage to force the end of the plank toward or away from the camera by a few microns, vertical fringes can be seen appearing along the length of the test object. Figure 2.8 shows the fringes formed under such a deformation.

This pattern of fringes is exactly what one would expect from an out of plane rotation, with the number of fringes consistent with the distance that the far end has moved forward.

2.5.3 Summary

The two tests outlined above mimic similar tests done during the development of the system and show that the system behaves as expected. Since the completion of the set up of the system, various prototype stove objects have been imaged however further results are omitted from this thesis.

Chapter 3

W charge asymmetry theory

A measurement of the W charge asymmetry within the proton-proton collision environment of the LHC requires an understanding of the structure of the proton and of the physics processes that lead to W production. This chapter gives a brief introduction to some of the theory required to understand the motivation for and measurement of the W charge asymmetry at the LHC.

3.1 Proton structure

The Quark Parton Model (QPM) originally identified the valence quarks as the elementary constituents of the proton after deep inelastic scattering experiments in the 1960s and 1970s confirmed the composite nature of the proton [18, 19, 20]. These valence quarks (two up quarks and a down quark in the case of the proton) carry all the flavour information of the proton. When it was found that not all of the momentum of the proton could be attributed to the valence quarks, the QPM was improved to include gluons and the $q\bar{q}$ pairs known as sea quarks into which gluons can fluctuate.

The $SU(3)$ flavour group of Quantum Chromodynamics (QCD) describes the interactions of quarks and gluons, with the charge of the strong force known as colour [21, 22]. On account of the non-abelian nature of the $SU(3)$ group, the strength of the interaction between strongly interacting particles increases with distance. This leads to quarks only appearing in bound hadronic states and is known as confinement. In the case of a hadron jet, the $q\bar{q}$ pair separate

until there is enough energy to create another $q\bar{q}$ pair [23, 24, 25, 26].

When investigating proton substructure, the resolving power of the probe is expressed in terms of the energy scale Q^2 , where Q is the momentum transfer between the probe and the proton. When $Q^2 \lesssim 1 \text{ GeV}$ the proton's substructure can not be resolved. As Q^2 increases, the distance scales that the probe can 'see' decrease, and hence the QCD interaction strength decreases. This is known as asymptotic freedom, and can be thought of in a similar way to the concept of charge screening in the case of electromagnetism, except that the self coupling of the gluon provides loops that effectively 'anti-screen' the central charge.

3.2 Proton-proton collisions

Current knowledge of proton structure comes predominantly from deep inelastic scattering experiments, while most precision EW measurements have been made with e^+e^- colliders. Using protons in colliders presents an inherently more difficult environment. At high energy, the momentum transfer between the protons is high and the substructure is resolved. A hard scatter occurs when two partons, one from each of proton, interact. These can be regarded as free, point-like particles and the cross section of the two body parton-parton interaction via a resonant state X is represented as $\hat{\sigma}_{\text{parton-parton}} \rightarrow X$, where X could be a W or Z boson. This cross section can be calculated using perturbative QCD.

In a collision, incoming protons carry a momentum P_i , where $i = 1, 2$ for the two considered protons. In each proton, some momentum, p_i , is carried by the parton involved in the hard scatter and it turns out that this momentum fraction, x , is an important quantity:

$$x_i = \frac{p_i}{P_i}. \quad (3.1)$$

The other important variable is the energy scale of the process, Q^2 . In the case of a resonant scattering, the mass of the resonance, M_X , the sum of the four momenta of its decay products (particles 3 and 4 in the interaction) and the centre of mass energy of the

proton beams, $\sqrt{s} = P_1 P_2$ are directly related to the scale of the process:

$$Q^2 = (p_1^\mu + p_2^\mu)^2 = M_X^2 = (p_3^\mu + p_4^\mu)^2 = s x_1 x_2 \quad (3.2)$$

The rapidity, y , gives a measure of the boost of the produced resonance in the z direction and hence a measure on the difference between x_1 and x_2 , since the incoming partons are essentially massless and carry no transverse momentum so the longitudinal momentum of the resonance is defined by the incoming partons $p_z^X = (x_1 - x_2) \frac{\sqrt{s}}{2}$. Similarly, the energy of the resonance is defined by the incoming partons $E^X = (x_1 + x_2) \frac{\sqrt{s}}{2}$.

$$y_X = \frac{1}{2} \ln \frac{E^X + p_z^X}{E^X - p_z^X} \quad (3.3)$$

$$= \frac{1}{2} \ln \frac{(x_1 + x_2) \frac{\sqrt{s}}{2} + (x_1 - x_2) \frac{\sqrt{s}}{2}}{(x_1 + x_2) \frac{\sqrt{s}}{2} - (x_1 - x_2) \frac{\sqrt{s}}{2}} \quad (3.4)$$

$$= \frac{1}{2} \ln \frac{x_1}{x_2} \quad (3.5)$$

The rapidity and the mass of the resonance thus provide constraints such that the momentum fraction of the partons involved can be determined. The parton distribution functions (PDFs) give the probability of finding a parton inside the proton and they depend on both the scale, Q^2 , and the momentum fraction, x . These functions do not take an analytical form, and are determined via parameterised fits to data. The practicalities of making such PDF fits, along with a preliminary fitting exercise including the ATLAS W charge asymmetry as presented in this thesis, will be deferred until chapter 8. In the meantime, the general concepts of PDF fitting are presented in section 3.3 below and the scope for their improvement using the asymmetry data discussed briefly.

In proton-proton collisions, these PDFs are particularly important, as only the four momenta of the final states are known. The remaining quarks and gluons not involved in the hard scatter emerge from the collision point as colourless hadrons, detectable in the event

alongside the resonance and its decay products. This hadronic activity is referred to as the underlying event, and is an inevitable issue that must be dealt with in the proton-proton environment. Despite this unpredictability in the form of the underlying event, the cross section for the resonant process can still be calculated by separating the cross section into two parts: the part describing the hard, parton-parton interaction, $\hat{\sigma}_{p_1 p_2 \rightarrow X}(\alpha_s, Q^2)$, where α_s is the coupling strength of the strong force, and the part describing the initial makeup of the proton, the PDF, $f_p(x, Q^2)$ [27] where p can be any parton. This factorisation theorem can be represented as,

$$\sigma_{PP \rightarrow X} = \text{PDF} \otimes \text{Hard scatter} = \sum_{p_1 p_2} \int dx_1 dx_2 f_{p_1}(x_1, Q^2) f_{p_2}(x_2, Q^2) \hat{\sigma}_{p_1 p_2 \rightarrow X}(\alpha_s, Q^2) \quad (3.6)$$

The predicted cross section depends on the PDFs input into the calculation. It is therefore vital to understand and constrain uncertainties on PDFs.

3.3 PDFs

As discussed above, PDFs describe the way in which the proton's momentum is shared between its partons. These are complicated objects as the gluons, valence quarks and different flavours of sea quark all carry a different fraction of the proton's momentum. Also, the form of the PDFs with respect to the momentum fraction, x , depends strongly on the scale of the process, Q^2 . Despite the fact that the form of the PDFs can not be calculated analytically, the rate at which they evolve in Q^2 can be. This is done using perturbative QCD and the DGLAP equations, the latter of which are a set of equations that describe the evolution of PDFs as a function of $\ln Q^2$ in terms of so called splitting functions $P_{p_1 p_2}$ with p_1 and p_2 representing partons [28, 29]. These splitting functions, themselves functions of x and $\alpha_s(Q^2)$, describe the interactions between the partons. The DGLAP equations can be summarised as

$$\frac{\partial}{\partial \ln Q^2} \begin{pmatrix} q_i(x, Q^2) \\ g(x, Q^2) \end{pmatrix} = \sum_j \int_x^1 \frac{d\xi}{\xi} \begin{pmatrix} P_{q_i q_j}(\frac{x}{\xi}, \alpha_s(Q^2)) & P_{q_i g}(\frac{x}{\xi}, \alpha_s(Q^2)) \\ P_{g q_j}(\frac{x}{\xi}, \alpha_s(Q^2)) & P_{g g}(\frac{x}{\xi}, \alpha_s(Q^2)) \end{pmatrix} \begin{pmatrix} q_j(\xi, Q^2) \\ g(\xi, Q^2) \end{pmatrix}. \quad (3.7)$$

The fitting of PDFs, in general, begins with the parameterisation of the PDF for a given parton, or linear combination thereof, as a function of x at a starting scale. The starting scale Q_0^2 , normally chosen to be the lower limit for which perturbative QCD is applicable, around 1-2 GeV². The PDFs are evolved up to the Q^2 values of the data using the DGLAP equations where they are convoluted with the sub-process cross sections to form predictions of the measurable cross sections. A global χ^2 is then defined and minimised during fitting so as best to fit all available data. Using the analytic form of evolution equations to evolve the PDFs in Q^2 while fitting to data allows fits to include data from a range of experiments covering different areas of the x - Q^2 plane. Experiments that are sensitive to PDFs include ep and νp scattering, proton colliders and fixed target experiments. As the PDFs are universal, it does not matter what process is used to probe the structure. Table 3.1, taken from [30], shows the main processes included in current global PDF analyses along with the partons and x range affected.

There are several collaborations performing PDF fits, all taking a slightly different view as to what data should be included and the exact form of the parameterisation. The CTEQ [31, 32, 33] and MSTW [30] collaborations are two of the predominant ones, both determining PDFs from a wide range of data using the method outlined above. Another key player in the field is HERAPDF¹ [34], who use data from the HERA accelerator [35] only to produce their fits. Other notable collaborations who show success in predicting PDFs by fitting to data include NNPDF [36], who use a neural network approach, and ABKM [37]. All of the available PDF sets can be accessed over a x - Q^2 grid using the program LHAPDF [38].

¹Using the existing framework of HERAPDF and the HERA dataset included in the fits, the impact of including the W charge asymmetry data from ATLAS will be tested in chapter 8.

Process	Sub-process	Partons	x range
$\ell^\pm\{p, n\} \rightarrow \ell^\pm X$	$\gamma^* q \rightarrow q$	$q, \bar{q}, g$	$x \gtrsim 0.01$
$\ell^\pm n/p \rightarrow \ell^\pm X$	$\gamma^* d/u \rightarrow d/u$	d/u	$x \gtrsim 0.01$
$pp \rightarrow \mu^+ \mu^- X$	$u\bar{u}, d\bar{d} \rightarrow \gamma^*$	$\bar{q}$	$0.015 \lesssim x \lesssim 0.35$
$pn/pp \rightarrow \mu^+ \mu^- X$	$(u\bar{d})/(u\bar{u}) \rightarrow \gamma^*$	$\bar{d}/\bar{u}$	$0.015 \lesssim x \lesssim 0.35$
$\nu(\bar{\nu})N \rightarrow \mu^-(\mu^+)X$	$W^* q \rightarrow q'$	$q, \bar{q}$	$0.01 \lesssim x \lesssim 0.5$
$\nu N \rightarrow \mu^- \mu^+ X$	$W^* s \rightarrow c$	s	$0.01 \lesssim x \lesssim 0.2$
$\bar{\nu} N \rightarrow \mu^+ \mu^- X$	$W^* \bar{s} \rightarrow \bar{c}$	$\bar{s}$	$0.01 \lesssim x \lesssim 0.2$
$e^\pm p \rightarrow e^\pm X$	$\gamma^* q \rightarrow q$	$g, q, \bar{q}$	$0.0001 \lesssim x \lesssim 0.1$
$e^+ p \rightarrow \bar{\nu} X$	$W^+ \{d, s\} \rightarrow \{u, c\}$	d, s	$x \gtrsim 0.01$
$e^- p \rightarrow \nu X$	$W^- \{u, c\} \rightarrow \{d, s\}$	u, c	$x \gtrsim 0.01$
$e^\pm p \rightarrow e^\pm c\bar{c} X$	$\gamma^* c \rightarrow c, \gamma^* g \rightarrow c\bar{c}$	c, g	$0.0001 \lesssim x \lesssim 0.01$
$e^\pm p \rightarrow \text{jet} + X$	$\gamma^* g \rightarrow q\bar{q}$	g	$0.01 \lesssim x \lesssim 0.1$
$p\bar{p} \rightarrow \text{jet} + X$	$gg, qg, q\bar{q} \rightarrow 2j$	g, q	$0.01 \lesssim x \lesssim 0.5$
$p\bar{p} \rightarrow (W^\pm \rightarrow \ell^\pm \nu) X$	$ud \rightarrow W, \bar{u}\bar{d} \rightarrow W$	$u, d, \bar{u}, \bar{d}$	$x \gtrsim 0.05$
$p\bar{p} \rightarrow (Z \rightarrow \ell^+ \ell^-) X$	$uu, dd \rightarrow Z$	d	$x \gtrsim 0.05$

Table 3.1: Main processes included in global PDF analyses

The three groups correspond to fixed target, HERA and Tevatron. Each process includes an indication of the dominant partonic sub-processes, the primary partons probed and the approximate x range constrained by the data. Table extracted from [30].

3.3.1 PDF uncertainties

Understandably, PDFs are subject to various sources of uncertainty. The standard method, used by MSTW and CTEQ, for representing these uncertainties is a Hessian method.

In the Hessian method, systematic offset parameters are fitted together with the theoretical parameters. Such parameters are required so as to treat point-to-point correlated systematic errors in a correct manner by separating them from the Gaussian, uncorrelated systematic and statistical uncertainties. The theoretical prediction is fitted to the data while allowing the data points to move collectively according to their correlated systematic uncertainties. The errors on the parameters are calculated using the covariance matrix which is the inverse of a single Hessian matrix, H , expressing the variation of the global χ^2 with respect to both theoretical and systematic offset parameters, p_i ,

$$H = \begin{pmatrix} \frac{\partial^2 \chi^2}{\partial p_1 \partial p_1} & \frac{\partial^2 \chi^2}{\partial p_1 \partial p_2} & \cdots & \frac{\partial^2 \chi^2}{\partial p_1 \partial p_{n-1}} & \frac{\partial^2 \chi^2}{\partial p_1 \partial p_n} \\ \frac{\partial^2 \chi^2}{\partial p_2 \partial p_1} & \frac{\partial^2 \chi^2}{\partial p_2 \partial p_2} & \cdots & \frac{\partial^2 \chi^2}{\partial p_2 \partial p_{n-1}} & \frac{\partial^2 \chi^2}{\partial p_2 \partial p_n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \frac{\partial^2 \chi^2}{\partial p_{n-1} \partial p_1} & \frac{\partial^2 \chi^2}{\partial p_{n-1} \partial p_2} & \cdots & \frac{\partial^2 \chi^2}{\partial p_{n-1} \partial p_{n-1}} & \frac{\partial^2 \chi^2}{\partial p_{n-1} \partial p_n} \\ \frac{\partial^2 \chi^2}{\partial p_n \partial p_1} & \frac{\partial^2 \chi^2}{\partial p_n \partial p_2} & \cdots & \frac{\partial^2 \chi^2}{\partial p_n \partial p_{n-1}} & \frac{\partial^2 \chi^2}{\partial p_n \partial p_n} \end{pmatrix}. \quad (3.8)$$

For more information on the formulation of χ^2 when using the Hessian method, see section 8.1.1 and [20].

The Hessian matrices obtained are not necessarily diagonal. For ease of error propagation the matrix is therefore diagonalised and an eigenvector basis of parameters formed [20, 32, 26]. The PDFs are varied along the positive and negative axes of each of these eigenvectors, and the resulting error sets made available for calculation of the uncertainty band.

The calculation of the uncertainty in the measurement of an observable A arising from the PDF uncertainty can be calculated by looking at the error sets in conjunction with the central set [26]. In the following formulae, asymmetric upward and downward variations, ΔA_+ and ΔA_- respectively, are determined by adding in quadrature the biggest deviation in each direction coming from each of the variations along the i th eigenvector, S_i^+ and S_i^- , with respect to the central prediction, S_i^0 . In the case that there is no deviation of the observable in the upward (downward) direction from both PDFs in a given eigenvector pair, the contribution to the total deviation is set to 0.

$$\Delta A_+ = \sqrt{\sum_{i=1}^{N_{eig}} (\max(B_i^+, B_i^-, 0))^2}$$

$$\Delta A_- = \sqrt{\sum_{i=1}^{N_{eig}} (\max(-B_i^+, -B_i^-, 0))^2}$$

with $B_i^+ = A(S_i^+) - A(S_i^0)$ and $B_i^- = A(S_i^-) - A(S_i^0)$

3.3.2 Phase space

Data from HERA, fixed target experiments and to some extent the Tevatron have been fitted by the PDF collaborations who include global data. Figure 3.1 shows the kinematic plane for the LHC and existing experiments. This seems to indicate that PDFs can be reliably evolved to the energy regime of the LHC. However this can be somewhat deceptive, since not all flavours have been measured for all x ranges using the existing data. For example, the MSTW global fit includes data sensitive to the valence quark PDFs down to only $x \approx 10^{-2}$ [30]. Thus valence quarks remain to be determined for lower x values so LHC data will provide information in a kinematic regime that has never been probed before. Measurements at the LHC will provide a test of current PDF knowledge and allow improvements in uncertainty and ultimately, understanding.

As the LHC will probe lower x values than previous experiments were capable, there is the possibility that the DGLAP formalism may become invalid. The reason for this potential invalidity is that the DGLAP formalism uses the leading log formalism, whereby only terms of the same order of n in $\alpha_s^n (\ln Q^2)^n$ are included in the PDF evolution². It turns out however, that some terms including powers of $\ln(\frac{1}{x})$ become relevant at low values of x . A possible solution to this problem is the BFKL approximation [20, 40, 41]. This approach attempts to describe multiple gluon emissions in the region where the gluon density is very high, at low x . This is done by resumming the leading logs in $\ln(\frac{1}{x})$. Predictions of additional radiation

²In the next-to-leading log DGLAP evolution, terms of $\alpha_s^n (\ln Q^2)^{n-1}$ are also considered

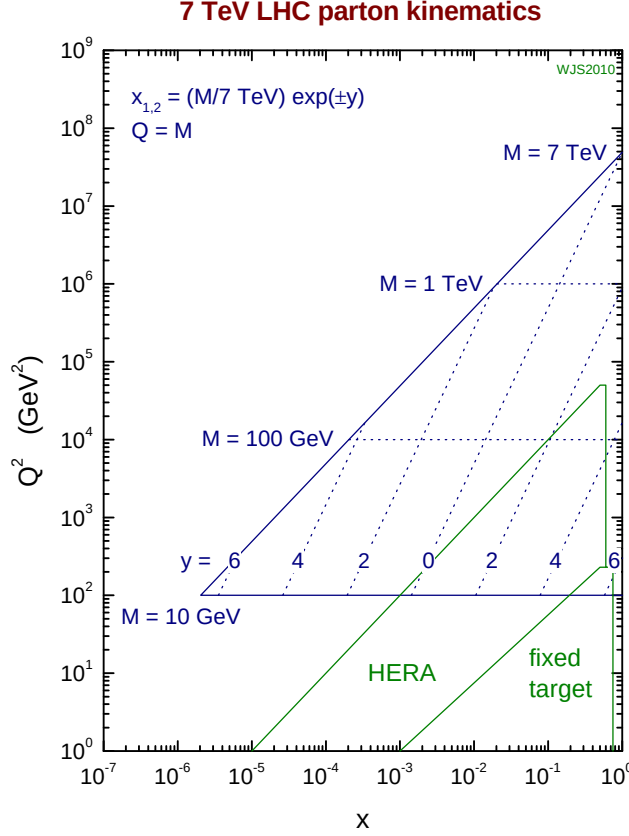


Figure 3.1: Experimentally probed phase space

The range of the momentum fraction, x , and energy scale, Q^2 , probed by the LHC operating at 7 TeV centre of mass energy, HERA and fixed target experiments is shown. The large triangle with is the LHC kinematic range. Plot by J. Stirling. [39]

from BFKL over that of the DGLAP formalism have been suggested within the HERA data [42, 43, 44, 45]. Another suggestion that a solution like the BFKL approximation is required is that MSTW has reported worsened χ^2 values from global fits including very low x data [46]. An improvement in the χ^2 to these low x data when implementing a $\ln(\frac{1}{x})$ resummation gives further evidence that such new techniques are likely necessary [47]. Such complications around the inclusion of low x data could become relevant at the LHC, where low x processes are expected.

3.3.3 Importance of PDF knowledge for discovery physics

It is clear that in a proton-proton environment it is vital to understand PDFs. All production cross sections for SM and new physics alike depend on these distributions. It is

therefore important that predictions are tested and measurements provided that will serve to accurately define and constrain PDF error bands. An underestimated PDF error could result in a missed discovery due to an overestimate of the background, or could easily result in a false claim of discovery. An example of such a false positive occurred at the Tevatron where an observation of an apparent excess in high E_T dijet production as compared to next-to-leading order (NLO) predictions suggested the possibility of composite quarks or new physics. The excess was however a relic of an underestimated PDF uncertainty. After improvement of the error determination for the PDFs and inclusion of relevant data from CDF, the discrepancy disappeared [48, 49].

3.4 Constraining PDFs with W charge asymmetry

One LHC measurement capable of providing constraints in PDF fitting is the W boson charge asymmetry [21]. The W boson is theoretically well understood, having been studied in great detail at previous e^+e^- colliders such as LEP and $p\bar{p}$ colliders such as the Tevatron. At the LHC, the W boson, which comes in both positive and negative charge, is predominantly produced via Drell-Yan annihilation processes, in which a quark and anti-quark annihilate, creating a W boson. The W boson can decay into a $q\bar{q}$ pair or a $\ell\nu_\ell$ pair, where $\ell \in \{e, \mu, \tau\}$. In this thesis, only decays to an electron or positron final state will be considered: $W^+ \rightarrow e^+\nu_e$ and $W^- \rightarrow e^-\bar{\nu}_e$.

As described in section 3.2, W production cross sections can be calculated in proton-proton collisions by factorising it into a partonic cross section and contribution from PDFs. The scale of the process, Q^2 , is set to be the mass of the resonance, $M_W^2 = (80.34 \text{ GeV})^2$.

3.4.1 Origin of the asymmetry

To first order, to produce a W^+ an up and anti-down quark are required while to produce a W^- a down and an anti-up quark are required. $W^\pm$ production is therefore most sensitive

to the $u(x)$, $\bar{d}(x)$, $d(x)$ and $\bar{u}(x)$ distributions. This is however only at leading order, and there are certainly other contributions from other quark flavours. For example, $c\bar{s} \rightarrow W^+$ is not explicitly suppressed by EW couplings in the CKM matrix so contributes (at the level of $\sim 25\%$ for central rapidities), while terms such as $u\bar{s} \rightarrow W^+$ are suppressed [50]. The charge asymmetry is then defined as a function of the rapidity of the W boson:

$$A_W = \frac{d\sigma_{W^+}/dy_{W^+} - d\sigma_{W^-}/dy_{W^-}}{d\sigma_{W^+}/dy_{W^+} + d\sigma_{W^-}/dy_{W^-}}. \quad (3.9)$$

Now looking at the leading order parton contributions to the partonic cross section, it can be seen that at central rapidity where $x_1 \approx x_2$,

$$A_W \approx \frac{u(x)\bar{d}(x) - d(x)\bar{u}(x)}{u(x)\bar{d}(x) + d(x)\bar{u}(x)} \quad (3.10)$$

$$\approx \frac{u_v(x) - d_v(x)}{u_v(x) + d_v(x) + 2S(x)}. \quad (3.11)$$

The second line follows as the up and down quark distributions can be split into contributions from valence and sea, $u(x) = u_v(x) + \bar{u}(x)$ and $d(x) = d_v(x) + \bar{d}(x)$, and the assumption that the sea is SU(2) flavour symmetric at low x , $\bar{u}(x) = \bar{d}(x) = S(x)$. Equation 3.11 clearly demonstrates that the W charge asymmetry is sensitive to valence quark distributions.

As described by equation 3.2, the product of x_1 and x_2 in Drell-Yan W production is restricted to $sx_1x_2 = Q^2$ and the ratio of $\frac{x_1}{x_2}$ is also restricted according to equation 3.5 for a particular W rapidity. Combining these two results, the minimum and maximum x values for a given collision energy can be obtained as below.

$$x_{\min} = \frac{M_W}{\sqrt{s}} e^{-y_W^{\max}} \quad (3.12)$$

$$x_{\max} = \frac{M_W}{\sqrt{s}} e^{+y_W^{\min}} \quad (3.13)$$

The x range is displayed over the acceptable rapidity range of $0 < |y_W| < 3$ in figure 3.2 for various centre of mass energies. Already at current LHC energies and intermediate W rapidities, the probed x range is dropping below that of the Tevatron.

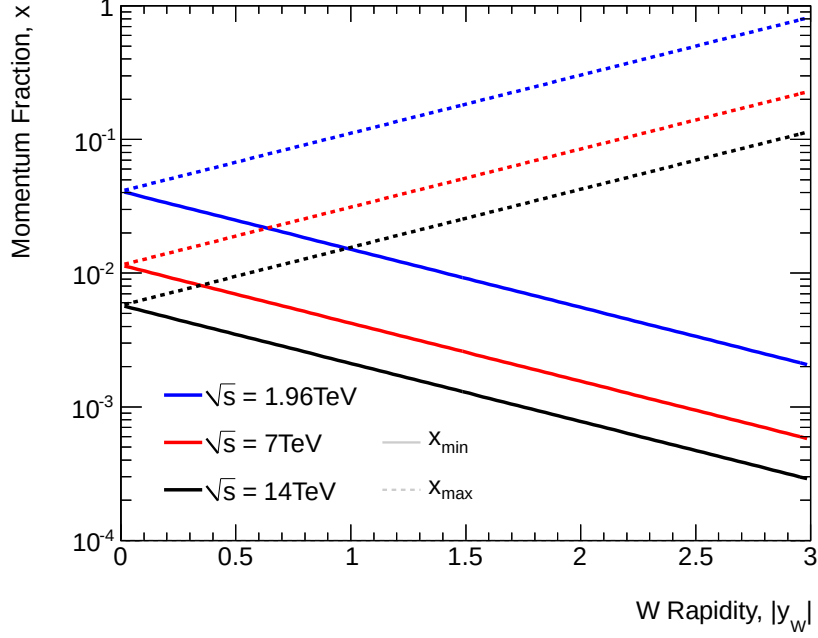


Figure 3.2: Attainable x as a function of y_W

The range of x available at a given centre of mass energy and W rapidity is shown for three different collider energies. In blue, the Tevatron at 1.96 TeV, in red the current LHC operational energy, 7 TeV, and in black the anticipated LHC energy, 14 TeV.

The W charge asymmetry at the LHC will be a measurement at the lowest x ever to probe the difference in the up and down quark distributions directly. The experiments at HERA can constrain the ratio of u and d quarks by looking at charged current events where a W is exchanged between the incoming lepton and the proton. Such measurements however are made at higher x and in general do not overlap with the kinematic regime of W production at the LHC. The input of the ATLAS W charge asymmetry is therefore a very important contribution to our understanding of the structure of the proton.

Predictions

As discussed previously, the production of W bosons at the LHC probes a new region of phase space. As such the current predictions from the PDF groups are based on as yet untested

assumptions concerning the input distributions. The measurement is especially sensitive to variations in the shapes of the valence distributions. Figure 3.3(a) shows the valence, sea and gluon distributions as predicted by MSTW08 (blue) and CT10 (red) PDF sets. One can immediately see that the shapes are somewhat different for the valence quarks. In figure 3.3(b), the resulting W charge asymmetry is shown using the two PDFs. The predictions are shown at NLO, where the leading order (LO) calculation has been corrected with predetermined ‘k-factors’ [39], as further described later in section 8.2.1. For central rapidities especially, there is a significant discrepancy.

3.4.2 Measurement: lepton charge asymmetry

Rather than directly measure the W rapidity distribution, the decay $W \rightarrow \ell\nu$ is detected and the lepton charge asymmetry measured as a function of lepton pseudorapidity. Studies to determine the feasibility of a direct W asymmetry measurement at ATLAS are presented in [51]. Ambiguities in the direction of the neutrino result in lowered efficiency for selecting the correct W rapidity. Given that the theory of W decays are well understood and calculable, the lepton pseudorapidity is an adequate quantity to feed into PDF fits, and hence is normally chosen.

A scatter plot using MC showing the W rapidity and the lepton pseudorapidity is shown in figure 3.4. There is a good correlation between the two, with the rapidity of the boson differing from that of the lepton by up to one unit in rapidity.

The lepton charge asymmetry is defined analogously to the W charge asymmetry in equation 3.9.

$$A_\ell = \frac{d\sigma_{\ell^+}/d\eta_{\ell^+} - d\sigma_{\ell^-}/d\eta_{\ell^-}}{d\sigma_{\ell^+}/d\eta_{\ell^+} + d\sigma_{\ell^-}/d\eta_{\ell^-}} \quad (3.14)$$

As the W decay is governed by V–A couplings [52], the correlation between lepton and W variables can be calculated [53, 54]. Since several W rapidities contribute to a given lepton

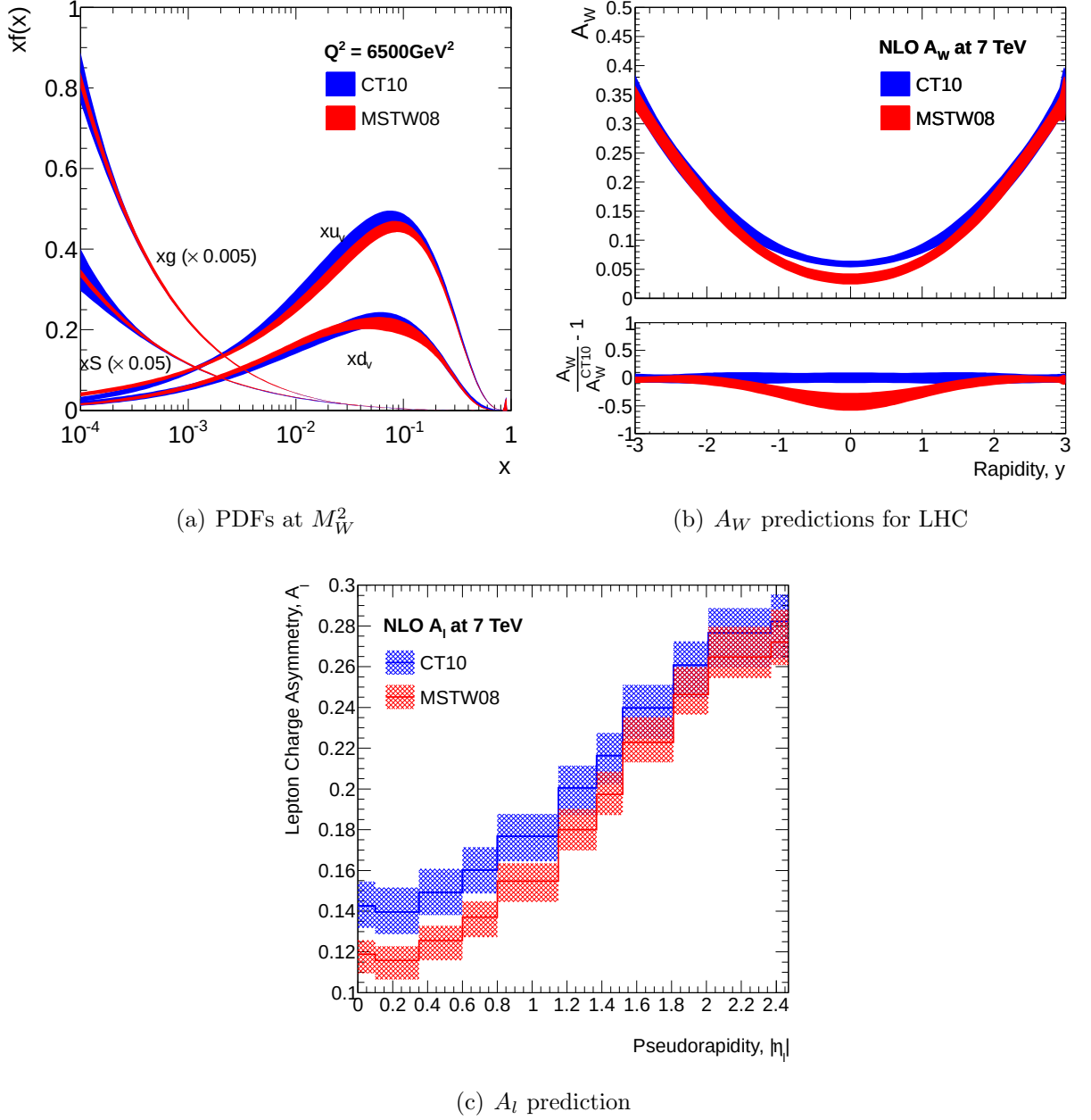
Figure 3.3: PDFs and W asymmetry at LHC energies

Figure (a) shows the u_v , d_v , $S = (\bar{u} + \bar{d})/2$ and the gluon distribution. This plot was made using LHAPDF to access PDF values. Figure (b) shows the NLO W asymmetry for 7TeV. The predictions are clearly in disagreement at central W rapidities. The lower part of the plot shows the uncertainties with respect to the CT10 prediction. Figure (c) shows the lepton charge asymmetry, discussed in section 3.4.2. The discrepancy between PDF sets is reduced in the case of the lepton asymmetry, but is still visible.

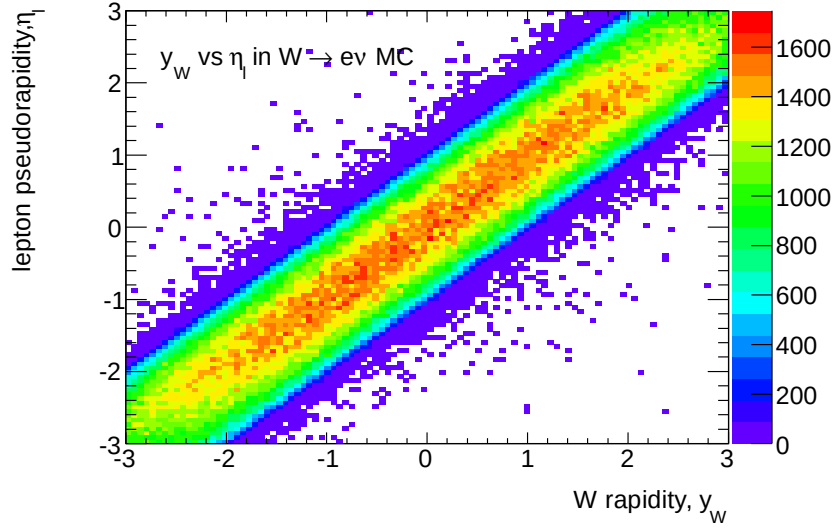


Figure 3.4: W rapidity and lepton pseudorapidity

Scatter plot showing the distribution of W rapidity to lepton η for MC truth events in a PYTHIA sample. Events pass basic lepton selection cuts of $p_T^e > 25$ GeV, $E_T^{miss} > 25$ GeV and $m_T > 40$ GeV as will be used and described in chapter 5.

pseudorapidity, as described by the angular distribution of the W decay, the asymmetry does not vary as sharply with increasing η_ℓ as it does with y_W . This can be seen in figure 3.3(c), where the lepton asymmetry as predicted using MSTW08 and CT10 PDF sets is shown along with PDF error bands. Though the difference in the predictions toward the centre of the detector seen in A_W is less clear in the A_ℓ distribution, there is clearly still a significant discrepancy that the input of early ATLAS data could begin to address.

3.4.3 Previous measurements

The experiments at the Tevatron collider have made various measurements of the W charge asymmetry. Such measurements are in fact slightly different to measurements at the LHC due to the proton-antiproton environment at the Tevatron. The W^+ is naturally boosted along the direction of the incoming proton, as to first order it requires an u quark, and the W^- along the direction of the incoming antiproton, as it requires an $\bar{d}$ quark. This results in an asymmetry that is not symmetric about central rapidities. The measurements are however comparable in that they are also sensitive to the difference in the u and d quark

distributions.

Measurements of this quantity at the Tevatron began as early as 1992 with a data sample 4.05 pb^{-1} [55]. Using this dataset, the lepton asymmetry was presented in bins up to $|y| < 1.7$ with errors up to 100 %. A measurement using 170 pb^{-1} followed that was also binned in transverse energy of the lepton, E_T^ℓ [56]. Due to the nature of the angular distribution of decay leptons, such a measurement is sampling a narrower range of y_W with a particular lepton rapidity.

In the latest measurements of the electron [57] and muon [58] asymmetries with 0.75 fb^{-1} and 0.3 fb^{-1} respectively were made by the D0 collaboration. The electron channel measurement was published in bins of lepton E_T . Current PDF predictions do not match the D0 data well, particularly in the high E_T^ℓ bin. It is beyond the scope of this thesis to speculate as to the causes of this discrepancy.

CDF have taken an approach whereby they reconstruct the y_W distribution to produce a direct W charge asymmetry [59]. This approach has been studied in the LHC environment [51], and disregarded in the proton-proton environment due to additional ambiguity in the direction of the incoming quark or anti-quark.

Since the LHC began high energy collisions in 2010, there have been some measurements of W asymmetry. The ATLAS collaboration published an asymmetry measurement in only two bins of lepton pseudorapidity, showing very early data to agree within uncertainties with all predictions [60]. Using the full 2010 dataset, the ATLAS collaboration published a measurement of the muon charge asymmetry using 31 pb^{-1} . The electron channel was not included in this paper after a misunderstood feature appeared in the data showing an unexpected charge asymmetry in the electron identification efficiencies. This effect is tested for in the 2011 dataset considered for this thesis in section 7.3.1. The CMS collaboration has published an electron and muon asymmetry using 36 pb^{-1} [61] of 2010 data. All of the LHC measurements of the asymmetry are consistent with predictions within uncertainty bands.

The dataset included in the analysis presented in this thesis is significantly larger than

those used in the above ATLAS and CMS papers. A phenomenological study of a possible future measurement of the asymmetry as a function of jet multiplicity will be presented in the next chapter before discussing the higher luminosity W asymmetry measurement itself and its implications for PDF fits.

Chapter 4

W + jets asymmetry

Extending the measurement of the W charge asymmetry to a differential measurement in jet multiplicity could be a useful extension of the measurement. Such a measurement would be sensitive to PDFs at larger Q^2 and x than the asymmetry in the inclusive case. The work in this chapter was done in collaboration with the authors of [62], and includes only generator level studies.

4.1 W + jets production

In chapter 3, the underlying origin of a charge asymmetry in W events was introduced. The production of W bosons via simple Drell-Yan $q\bar{q}$ collisions was considered without any discussion of the presence of other hard objects in the event. There are however many different mechanisms which lead to jet¹ production in association with a W boson.

Figure 4.1 shows the three different categories of event giving rise to jets in association with W bosons, split by the number of gluons amongst the initial partons. Where in exclusive W production the energy scale of the process is the mass of the resonance, $Q^2 = M_W^2$, the scale in events where jets are produced can be higher. In order to produce more jets, the centre of mass energy of the parton-parton interaction must be higher, in turn meaning that the x values probed must be larger in W +jets production. Therefore, the W +jets cross section measurement probes different x and Q^2 than exclusive production.

¹A jet can be seen as a group of collimated particles, which have been generated by the hadronisation of the parton in the scattering process. In ATLAS, jets are reconstructed by applying a jet clustering algorithm to calorimeter energy deposits.

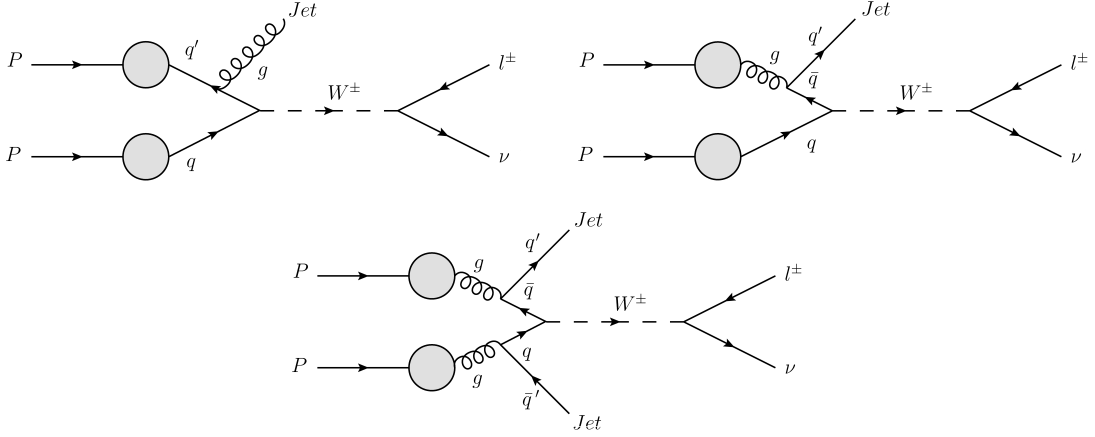


Figure 4.1: Leading order W +jets production processes for different initial partons

4.1.1 Simulation of W +jet production

The studies in this chapter are based on W +jets samples generated at a centre of mass energy of 7 TeV using the Monte Carlo (MC) generator ALPGEN 2.13 [63]. The ALPGEN generator provides a simulation of W production for jet multiplicities from 0 to 5. It generates events according to the exact matrix elements at LO in QCD and EW interactions and performs matching between the LO calculation and hadronisation to avoid double counting. Hadronisation was performed using the HERWIG [64] parton shower MC. Six separate samples of $W \rightarrow e\nu_e + n_p$ were created with n_p , the number of ‘extra partons’ in the event, lying in the range 0-5.

Background samples of $t\bar{t}$ and single-top production were made using MC@NLO 3.41 [65, 66, 67]. Double-counting of the overlap between single top- tW channel and $t\bar{t}$ production was corrected using the diagram removal scheme [68]. The events produced by MC@NLO were showered using HERWIG [64].

The ALPGEN samples were generated using the CTEQ6L1[32] PDF sets, whilst the MC@NLO samples made use of the CTEQ6.6 [31] PDF set. In both cases the underlying event was simulated using the model of JIMMY [69]. Electromagnetic final state radiation was simulated using PHOTOS [70, 71] and τ decays were performed using the TAUOLA package [70].

4.1.2 Event selection

Generated events are required to contain an electron or positron with transverse energy $E_T^e > 20$ GeV and absolute value of the pseudorapidity $|\eta^e| < 2.5$. The events must have missing transverse momentum (from escaping neutrinos), $E_T^{miss} > 25$ GeV. Jets were reconstructed using the anti- k_T algorithm [72] in the inclusive mode with $R = 0.4$, requiring $p_T^{jet} > 20$ GeV, $|\eta^{jet}| < 3.1$, and for which $\Delta R(e-jet) > 0.2$, where $\Delta R(e-jet)$ is defined as the separation in $\eta - \phi$ space of the lepton and the jet. All selections were made on the final state after hadronisation.

4.1.3 Phase space

In the ALPGEN generator, several choices of scale are available, the scale chosen for this study was $M_W^2 + \sum (p_T^{jet})^2$ where the sum runs over all parton jets². The distribution for ALPGEN events passing the selection in the kinematic plane is shown in figure 4.2; the majority of events contain no jets so lie along the $Q^2 = M_W^2$ line. A significant tail to higher values of Q^2 and x is however visible. Also shown in figure 4.2 is a duplicate of figure 3.1 showing comparison of this region to the kinematic region covered by HERA measurements of deep inelastic scattering [34] and to the region covered by resonance production at the LHC in general. The distribution of events in the given plane for W production in association with different numbers of jets is shown in figure 4.3, where the expected shift to higher Q^2 and x with increasing jet multiplicity is clearly visible.

The measurement of W +jets events at the LHC moves to higher values of x , so towards the kinematic regime in which the Tevatron measures inclusive W production. Although the majority of the W +jet events lie at approximately $Q^2 = M_W^2$, the same scale of inclusive measurements at the Tevatron, by choosing events with multiple jets this Q^2 is increased, thereby diverging from the Tevatron kinematic regime. There will still be interest in the

²The scale includes contributions from hard partons radiated in the event, whereas the jet selection in this study uses a jet algorithm after showering and hadronisation. For this reason there can be events with scale greater than the W mass that migrate into the W +0 jet event selection.

LHC measurement as: the Q^2 probed is not exactly the same, the quark combinations in pp collisions are not exactly the same as in $p\bar{p}$, and mutiple measurements provide valuable cross checks of experimental input to PDF fits.

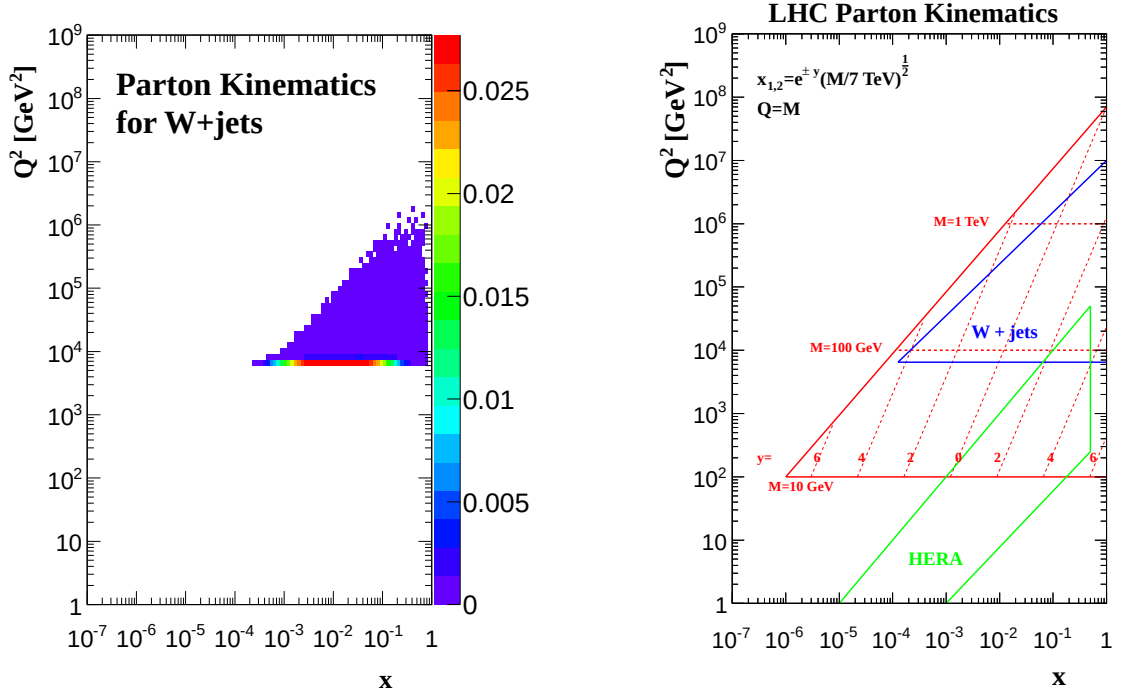


Figure 4.2: Kinematic region covered by W +jet production. Shown for the cuts outlined in section 4.1.2. The scale on the left hand figure show the fraction of events produced in that region according to the ALPGEN generator. On the right the kinematic plane is illustrated after the style of [73].

4.2 Asymmetry

In this chapter, simplified versions of the W and lepton asymmetries defined in equations 3.9 and 3.14 are defined as

$$A_W = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}} \quad (4.1)$$

$$\text{and } A_\ell = \frac{N_{\ell^+} - N_{\ell^-}}{N_{\ell^+} + N_{\ell^-}}. \quad (4.2)$$

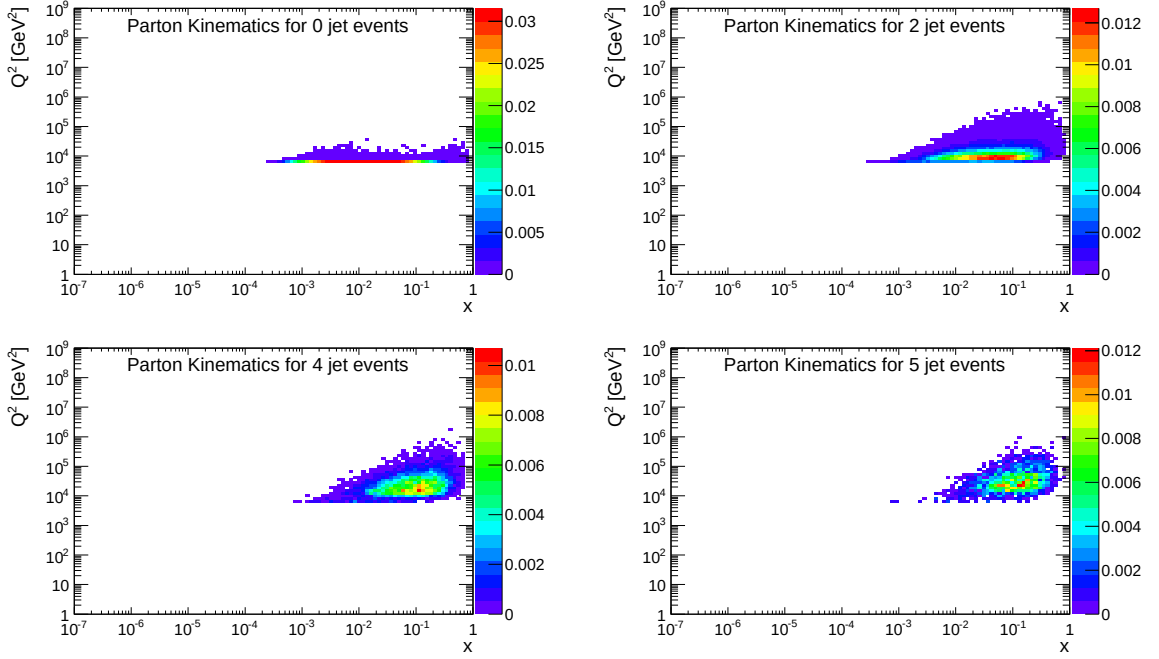


Figure 4.3: The kinematic range as a function of x and Q^2 for different jet multiplicities. Shown are jet multiplicities of 0, 2, 4 and 5. Other details as for the left hand part of figure 4.2.

A W charge asymmetry is expected for initial parton combinations of $q\bar{q}$ and qg , however an initial parton combination of gg will result in charge symmetric production. The magnitude of the observed asymmetry therefore depends on the relative contribution from each of these parton combinations. The number of $W^\pm \rightarrow e^\pm \nu$ events produced by ALPGEN as a function of the number of jets gives a charge asymmetry as shown in figure 4.4.

The asymmetry initially falls from $W+0$ jets to $W+1$ jet but then rises steadily with number of jets. This can be understood in terms of three effects:

1. the addition of contributions involving initial gluons acts to reduce the asymmetry;
2. increasing the Q^2 increases the sea and gluon contribution relative to the valence contribution, reducing the asymmetry;
3. increasing $x_{1,2}$ reduces the sea and gluon contribution relative to that of the valence quark, increasing the asymmetry.

The relative contributions from initial $q\bar{q}$, qg and gg processes to W production is shown

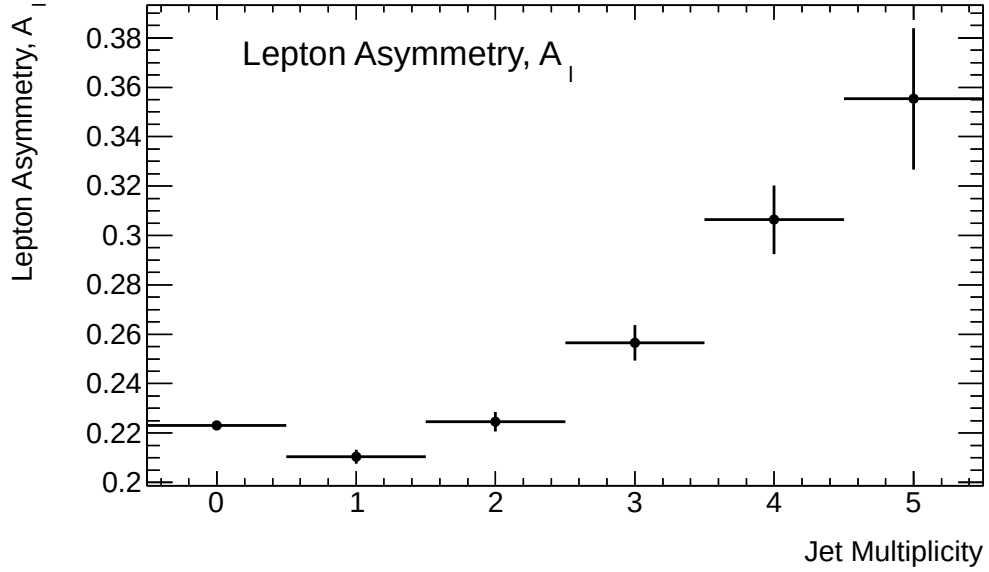
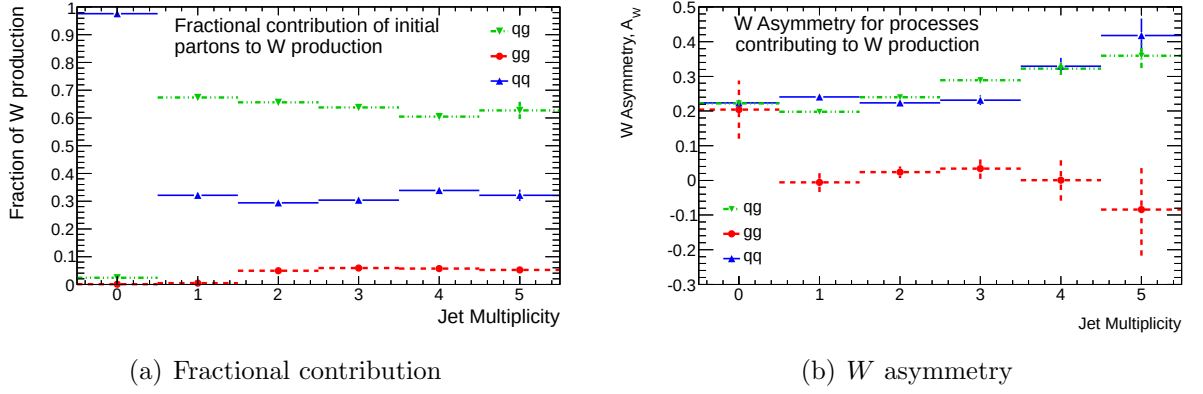


Figure 4.4: Asymmetry as a function of jet multiplicity

The lepton charge asymmetry, as defined in equation 4.2, as a function of jet multiplicity.

in figure 4.5(a). For $W+0$ jet production, $q\bar{q}$ is the dominant hard process and is responsible for almost 100 % of events. Only very few qg and gg initiated events migrate into the 0 jet bin. Starting from the $W+1$ jet bin, qg processes contribute around 65 % of the total $W+n$ jet production, while $q\bar{q}$ processes only contribute around 35 %. Hence it can be seen that the decrease in the asymmetry from $W+0$ jets to $W+1$ jet comes from effect 1. The gg processes start to play a role in the $W+2$ jet bin. For this and also the higher jet multiplicities gg contributes roughly 5 %, $q\bar{q}$ 30-35 % and qg 60-65 %. When moving from $W+2$ jets up to higher multiplicities ALPGEN indicates that effect 3 is dominant, driving the asymmetry to higher values.

Figure 4.5(b) shows the expected asymmetries for the different partonic processes. qg and $q\bar{q}$ production processes exhibit approximately the same asymmetry, driven by the valence quark differences. For gg production the asymmetry is very close to zero and shows large fluctuations due to the fact that the statistics of the MC samples used are quite small. Selecting a multiplicity of 2 or more thus increases sensitivity to the gluon distribution as the gg processes reduce the asymmetry relative to pure qg and $q\bar{q}$ processes.

Figure 4.5: Initial parton contributions to W production

The contribution of different initial parton-types to the different jet multiplicity bins is shown in (a). The asymmetry arising from different initial parton-types in different multiplicity bins is shown in (b). The high asymmetry in the $W+0$ jet bin from gg is a statistical fluctuation from the expected value of 0.

4.3 Investigation of inclusive variables

Three variables defined for arbitrary jet multiplicities are considered: the true invariant mass of the W +jet system, the visible invariant mass of the system, and the ‘reconstructed’ invariant mass of the system.

The true invariant mass of the process is defined as the magnitude of the summed four-vectors of all jets, leptons and the neutrino in the event. The distribution of this quantity is shown in figure 4.6. It is clear that as the jet multiplicity is increased, the mode of the distribution is shifted to higher values of invariant mass.

In figure 4.7(a), the W charge asymmetry is shown as a function of the true invariant mass with a clear positive gradient. The asymmetry shows a steady increase with respect to true invariant mass. Unfortunately, the true invariant mass does not represent a quantity which can be unambiguously reconstructed from measurements in a physical detector. Instead the total visible invariant mass, M_{vis} , was considered as an alternative. This is defined as the invariant mass of the vector sum of the lepton and all of the jets. As can be seen in figure 4.7(b), although not as clear as the true invariant mass case, there is a slight increase in asymmetry with M_{vis} .

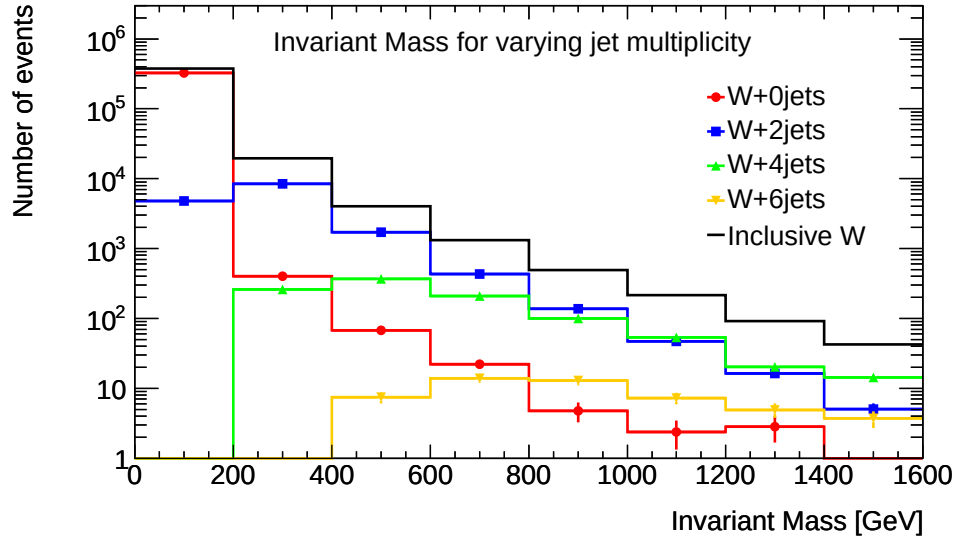


Figure 4.6: Distribution of the total invariant mass for different jet multiplicities. Shown for different jet multiplicities as a function of true invariant mass of the system as predicted by the ALPGEN generator. The number of events is normalised to 100 pb^{-1} .

It is possible to reconstruct the invariant mass of the W +jets system up to a two fold ambiguity by applying a W mass constraint to the electron and missing transverse momentum (e.g. neutrino) system [51]. This yields a quadratic equation in the longitudinal component of the missing momentum, P_Z^ν . Solving the equation gives two solutions, of which the closest to 0 is chosen. The resulting asymmetry as a function of this ‘reconstructed’ invariant mass, M_{reco} , is shown in figure 4.7(c). There is a much stronger rise in asymmetry as a function of this variable than for the visible invariant mass.

4.4 Investigation of backgrounds

A discussion of the prospects for measuring the charge asymmetry in W +jets would not be complete without a short discussion of processes that are likely to form backgrounds. In this section, only the irreducible backgrounds are discussed in detail. These are $W \rightarrow \tau \nu$, single top production (t-channel, s-channel and Wt associated production), $t\bar{t}$ production and $Wb\bar{b}$. All of these processes feature at least one lepton and genuine missing transverse momentum from a neutrino in the final state, and possibly also hadronic jets.

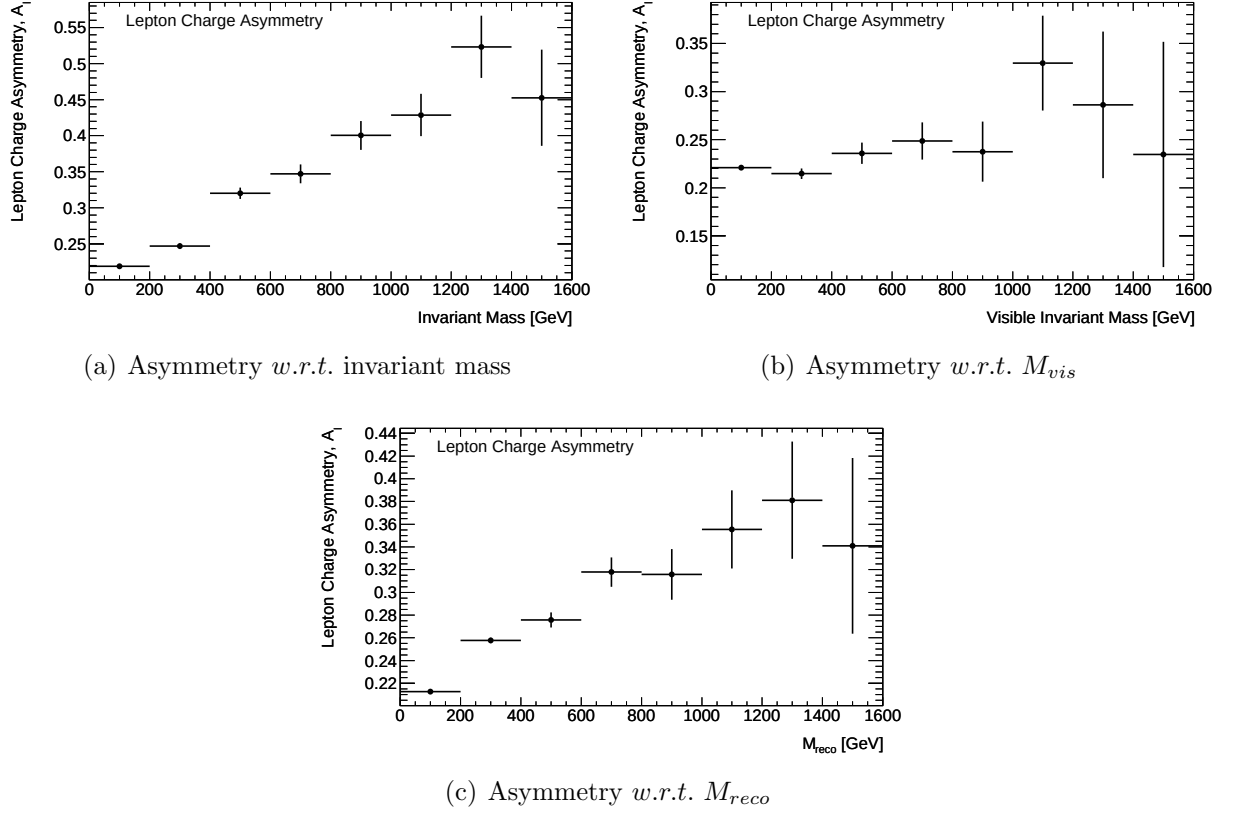


Figure 4.7: The lepton charge asymmetry as a function of invariant mass variables. The asymmetry is shown to vary significantly as a function of the true invariant mass in (a). In (b) the asymmetry as a function of M_{vis} is shown, where the neutrino is left out of the sum. Finally, (c) shows the asymmetry as a function of M_{reco} with a clear positive gradient.

4.4.1 As a function of jet multiplicity

Figure 4.8 shows the expected irreducible backgrounds and W +jets signal as a function of jet multiplicity for an integrated luminosity of 100 pb^{-1} . Events identified as e^+ events are displayed with solid lines, e^- events with a dashed line. The number of $W \rightarrow e\nu$ signal and $W \rightarrow \tau\nu$ background events decreases steadily with jet multiplicity and the ratio of $W \rightarrow e\nu$ to $W \rightarrow \tau\nu$ events stays approximately constant. As expected, the number of background events from single top production, $t\bar{t}$ and $Wb\bar{b}$ backgrounds increases with the jet multiplicity. As a consequence, the total background level rises, when measured as a percentage of the $W^\pm$ signal³, from 1-2% in the 0 jet bin to 7-10% in the 2 jet bin.

In the lower part of the figure the asymmetry of the signal, the background and the

³ $f_{\text{Bkg}} = \frac{\text{Number of background events}}{\text{Number of signal events}}$

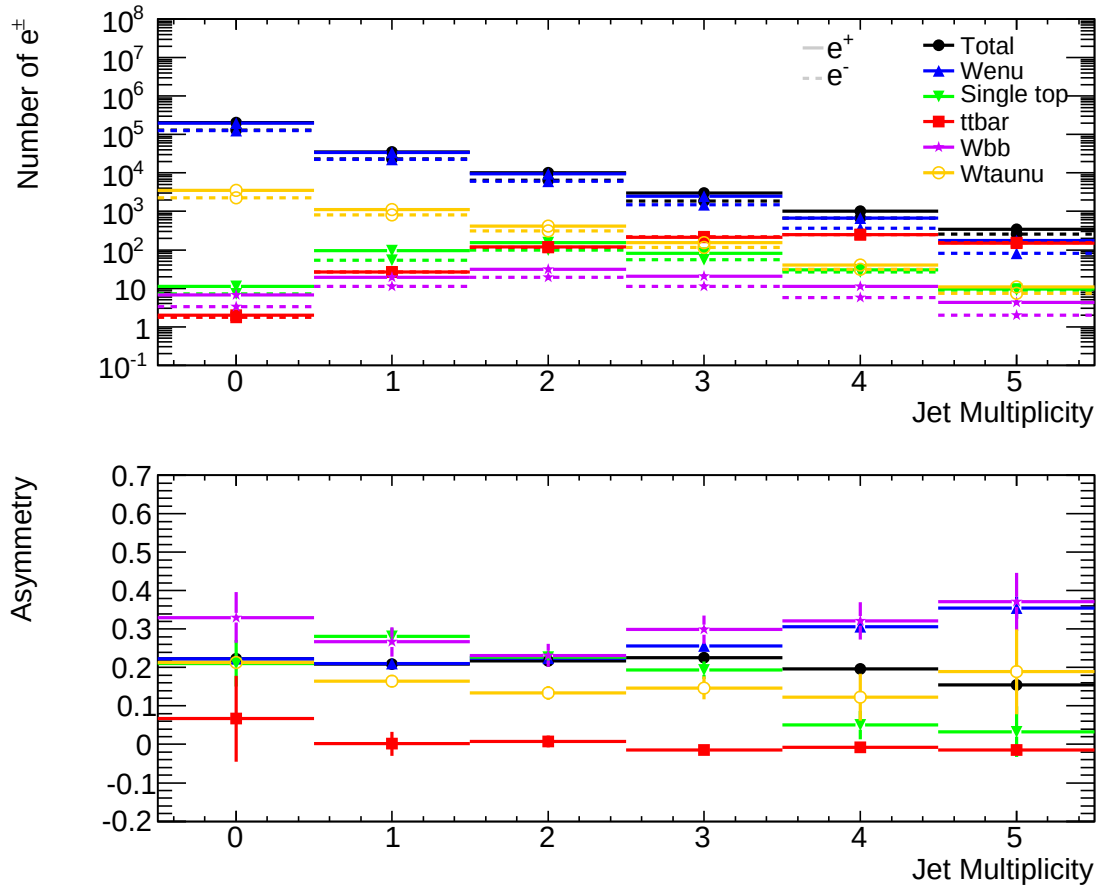


Figure 4.8: Number of events and asymmetries as a function of jet multiplicity. Shown for $W^\pm$ +jets events and irreducible backgrounds as a function of jet multiplicity. The MC yields are normalised to an integrated luminosity of 100 pb^{-1} .

Sample	Jet multiplicity					
	0 Jets		1 Jet		2 Jets	
	e^+	e^-	e^+	e^-	e^+	e^-
$W \rightarrow e\nu$	199278	126565	34269	22356	9524	6030
$W \rightarrow \tau\nu$	3533	2292	1119	803	408	312
Single t (t channel)	10	5	81	43	123	72
Single t (s channel)	0.5	0.3	4	2	8	4
Single t (Wt)	1	2	11	9	25	22
$t\bar{t}$	2	2	27	27	118	116
$Wb\bar{b}$	7	3	20	11	31	19
total background	3553 ± 42	2304 ± 34	1262 ± 23	895 ± 19	713 ± 11	546 ± 9
f_{Bkg} (%)	1.78	1.82	3.68	4.00	7.49	9.05

Table 4.1: Signal and background as a function of jet multiplicity
Number of events for $W^\pm$ +jets events and irreducible backgrounds as a function of jet multiplicity. These numbers, predicted by ALPGEN, are normalised to 100 pb^{-1} .

total selected events is shown. Except for $t\bar{t}$ production, all of the considered backgrounds exhibit an asymmetry of about the same level as the W +jets signal process. The symmetric $t\bar{t}$ background makes up only 1 % of the W +jets signal.

The numbers of selected $W^\pm$ events in the first three bins of jet multiplicity are also given in table 4.1 for the different samples. The numbers are scaled to a luminosity of 100 pb^{-1} .

4.4.2 As a function of invariant mass

When considering a measurement in bins of M_{reco} the situation is very similar. This is shown in figure 4.9, where in the upper half the number of $W^\pm$ events is shown separately for the signal and the various irreducible backgrounds for 100 pb^{-1} . Again, the W +jets and $W \rightarrow \tau\nu$ events steadily decrease, while the other backgrounds increase. All of the irreducible backgrounds exhibit an asymmetry over the whole reconstructed invariant mass range considered apart from $t\bar{t}$ as shown in the lower part of figure 4.9. Once again, it can be seen that the charge-asymmetric backgrounds exhibit a similar charge asymmetry to the W +jets signal.

The percentage of background events compared to the signal events sum up to roughly 2 % in the low reconstructed invariant mass region ($0 < M_{\text{reco}} < 200 \text{ GeV}$), while it grows up to 8 % in the third reconstructed invariant mass bin considered ($400 < M_{\text{reco}} < 600$

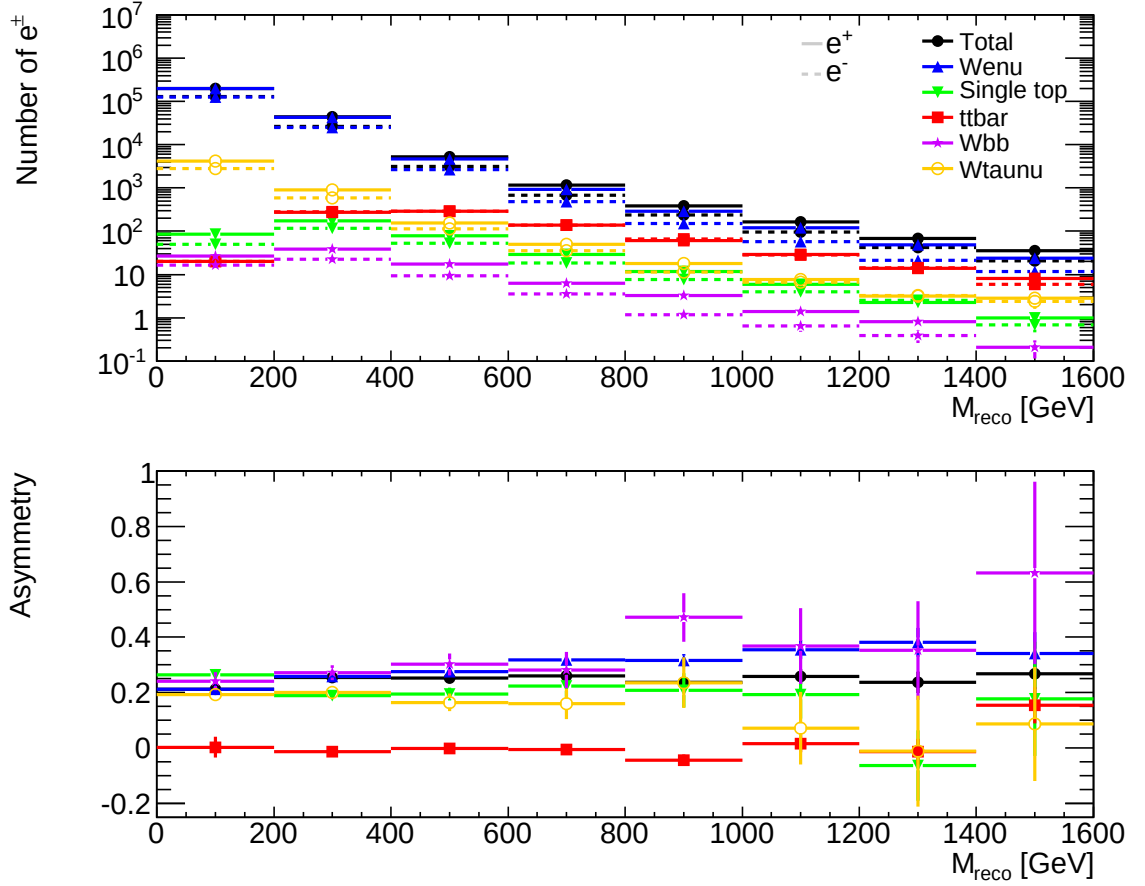


Figure 4.9: Number of background and signal events and asymmetries as a function of M_{reco} . Shown for $W^\pm$ +jets events and irreducible backgrounds as a function of M_{reco} , normalised to an integrated luminosity of 100 pb^{-1} .

GeV). Table 4.2 summarises the number of background and signal events for these bins for a luminosity of 100 pb^{-1} , with the statistical uncertainty on the total background reflecting that of the MC samples.

4.4.3 Instrumental backgrounds

The backgrounds arising from misclassification of Z +jets or QCD multijet events as $W^\pm$ events due to mismeasurements of missing transverse momentum or misidentification of leptons is potentially significant. For inclusive studies of the W asymmetry, the $Z \rightarrow ee$ contribution was found to be essentially negligible (see chapter 7). However, the QCD background is expected to play a major role. In inclusive W analyses its size is expected to

	Reconstructed invariant mass					
	$0 < M_{\text{inv}}^{\text{true}} < 200 \text{ GeV}$		$200 < M_{\text{inv}}^{\text{true}} < 400 \text{ GeV}$		$400 < M_{\text{inv}}^{\text{true}} < 600 \text{ GeV}$	
Sample	W^+	W^-	W^+	W^-	W^+	W^-
$W \rightarrow e\nu$	197162	128017	43128	25454	4747	2695
$W \rightarrow \tau\nu$	4134	2794	894	597	156	112
Single t (t channel)	73	40	18	69	52	29
Single t (s channel)	4	2	9	5	3	2
Single t (Wt)	8	7	5	44	24	22
$t\bar{t}$	20	20	275	282	292	293
$Wb\bar{b}$	27	16	39	22	18	9
total background	4266 ± 45	2879 ± 37	1380 ± 20	1019 ± 16	545 ± 8	468 ± 7
f_{Bkg} (%)	2.16	2.25	3.20	4.00	11.48	17.36

Table 4.2: Signal and background as a function of M_{reco} . Number of events for $W^\pm$ +jets events and irreducible backgrounds as function of the reconstructed invariant mass. These numbers are normalised to 100 pb^{-1} .

be around 5-10 % of the signal. In the W +jets analysis these events will mainly contribute to the 1 and 2 jets bin, thus making the QCD background one of the largest sources of uncertainties for higher jet multiplicities and invariant masses. Data driven methods to determine this QCD background are discussed for the inclusive measurement in chapter 6.

4.5 PDF sensitivity

The lepton asymmetry as a function of jet multiplicity is shown in figure 4.10 for various PDF sets. These predictions were obtained using PDF reweighting (as a function of Q^2 and x) from the nominal W +jet samples. The predictions are shown for the MSTW 2008 [30], CTEQ 6.6 [31] and NNPDF 2.0 [74] PDFs all of which were derived from NLO QCD fits. The PDF uncertainty is quite stable as a function of jet multiplicity, being around 0.008-0.013 for each of the bins. The relative PDF uncertainty is around 4-6 %. The largest differences between the NLO QCD PDF sets occur at jet multiplicities of 0 and 1, where the CTEQ 6.6 and MSTW predictions are not compatible with each other. The differences are less marked as a function of M_{reco} , but in the lowest bin MSTW 2008 and CTEQ 6.6 are once again incompatible. The NNPDF 2.0 central value agrees with CTEQ 6.6 across the full multiplicity and M_{reco} ranges.

In order to assess the prospect of a measurement of the W +jets charge asymmetry, the

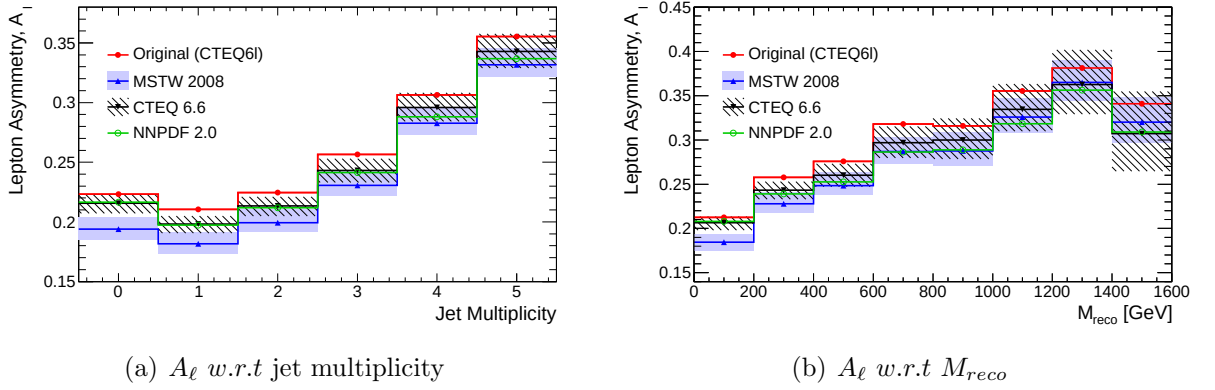


Figure 4.10: PDF comparison

Distribution for the jet multiplicity (left) and reconstructed invariant mass (right) for different PDF sets

following approach was used: firstly, the statistical uncertainty on the W asymmetry from the expected number of $W^\pm$ events for 100 pb^{-1} was calculated. Only the first three bins are shown as there are more likely to be inaccuracies in the MC as the jet multiplicity and invariant mass increase. In order to account for realistic efficiency losses due to trigger, lepton reconstruction and identification, a statistical uncertainty for the expected number of $W^\pm$ events detected with an efficiency of 70 % is also calculated.

The irreducible background in each bin is subtracted and the asymmetry calculated. To obtain an uncertainty due to this subtraction, an uncertainty on the MC prediction of 20 % is assumed as a conservative estimate. The background is varied up and down by 20 % and the asymmetry recalculated to determine the uncertainty. Acceptance corrections are not expected to be applied, since they will depend on the PDF predictions themselves. Instrumental backgrounds and systematic uncertainties on the charge determination will play a role. Since other uncertainties cannot be assessed without detector simulation, an estimate of the uncertainty on the asymmetry of 1 % is given. The uncertainty on the asymmetry due to QCD background prediction in chapter 6 is of approximately this magnitude and this is thought to be the largest contributor.

Table 4.3 gives an overview of the expected uncertainties for a measurement of the asymmetry as a function of jet multiplicity using integrated luminosity of 100 pb^{-1} . The total

	Jet Multiplicity		
	0 Jets	1 Jet	2 Jets
Asymmetry	0.22	0.21	0.22
Luminosity of 100 pb⁻¹			
σ_{stat} (acceptance)	0.002	0.004	0.008
σ_{stat} (70 % efficiency)	0.002	0.005	0.009
$\sigma_{\text{irreducible}}$ $\sigma_{\text{Background}}$ σ_{QCD}	0.00004	0.0003	0.002
$\sigma_{\text{Background}}$	0.002	0.002	0.002
σ_{total}	0.003	0.005	0.009

Table 4.3: Systematic uncertainties as a function of jet multiplicity

The total uncertainty, σ^{total} , uses the statistical error based on the efficiency corrected number of events.

	Reconstructed invariant Mass		
	$0 < M_{\text{reco}} < 200 \text{ GeV}$	$200 < M_{\text{reco}} < 400 \text{ GeV}$	$400 < M_{\text{reco}} < 600 \text{ GeV}$
Asymmetry	0.21	0.26	0.28
Luminosity of 100 pb⁻¹			
σ_{stat} (acceptance)	0.002	0.004	0.01
σ_{stat} (70 % efficiency)	0.002	0.004	0.01
$\sigma_{\text{irreducible}}$ $\sigma_{\text{Background}}$ σ_{QCD}	0.00008	0.001	0.005
$\sigma_{\text{Background}}$	0.002	0.003	0.003
σ_{total}	0.003	0.005	0.01

Table 4.4: Systematic uncertainties as a function of M_{reco}

The total uncertainty, σ^{total} , uses the statistical uncertainty based on the efficiency corrected number of events.

uncertainty quoted, σ^{total} , uses the statistical uncertainty with the efficiency-reduced number of W events. When comparing σ^{total} with the asymmetries expected in the respective bins, it becomes clear that at least a luminosity of 100 pb⁻¹ is needed in order to make a measurement with uncertainties smaller than the differences in the jet multiplicity bins. The other instrumental systematic uncertainties in this case should not exceed 2-3 % in the 1 and 2 jet bin. As is shown however in section 4.5, the PDF uncertainty in each bin is approximately of the same size.

When looking at the reconstructed invariant mass, the situation becomes even more favourable as is shown in table 4.4. After collecting 100 pb⁻¹, the expected uncertainty is smaller than the differences between the bins of reconstructed invariant mass, even allowing for a $\sim 5\%$ additional uncertainty in the various bins.

4.6 Conclusions

The studies in this chapter have shown that the electron charge asymmetry in events with W bosons produced in association with jets is more sensitive to the PDFs at higher x than the asymmetry in inclusive W production. Measuring the asymmetry in exclusive jet bins or inclusively as a function of the invariant mass of the W +jets system further refines this sensitivity to different regions of the kinematic plane. The irreducible backgrounds have a largely negligible influence on the measured asymmetry at lower jet multiplicities with the most significant background ($W \rightarrow \tau\nu$) exhibiting a similar charge asymmetry to the signal. A measurement with some ability to constrain the uncertainties on PDFs should be possible with an integrated luminosity of $\mathcal{O}(100) \text{ pb}^{-1}$. This is achievable with the current dataset, however a measurement is beyond the scope of this thesis. With attention increasingly falling on the use of the lepton charge asymmetry as a means of constraining backgrounds to new physics [75], performance of these measurements is of particular interest.

Though measurement of the W +jets asymmetry in data will be omitted from this thesis and left as potential future work, it is clear that there is significant promise in pursuing a measurement of the W charge asymmetry as a function of jet multiplicity. The asymmetry has been shown to also increase with the true invariant mass, however this variable is sensitive to detector effects and is easily lost. It is however possible that a reconstructed invariant mass could be constructed, against which to measure the asymmetry and to further constrain PDFs. The rest of this thesis will be focused on the measurement of the inclusive (in jet multiplicity) lepton charge asymmetry using ATLAS data and subsequent inclusion in PDF fits.

Chapter 5

$W \rightarrow e\nu$ event selection

The branching ratio of W bosons to an electron and neutrino is 10.75 % [53]. Such processes are easier to distinguish amongst the jet dominated backgrounds of the proton-proton environment than, for example, W bosons decaying hadronically. However, cuts must be considered carefully so as to remove as much background as possible while still collecting a significant fraction of the available signal. This chapter will outline important details relevant in the selection of $W \rightarrow e\nu$ events along with a detailed list of selection cuts and description of the dataset used in this thesis.

5.1 Dataset and pileup

In this thesis, 497.27 pb⁻¹ of 7 TeV ATLAS data from 2011 is included. Significant progress was made in 2010 to collect a total of approximately 35 pb⁻¹ data available for such an analysis, and in fact many of the techniques applied in this thesis were thoroughly tested on the 2010 dataset. However, due to differences in LHC operating conditions between 2010 and 2011, including a different bunch train structure, bunch spacing and consequently pileup contribution, these two datasets are quite different and it has been decided to present this analysis of the W charge asymmetry with only 2011 data. It should be noted that many calibration constants used were derived with the 2010 dataset included [76].

5.1.1 Pileup in ATLAS

The only significant contribution from pileup in 2010 data was *in time* pileup. In time pileup is additional vertices in a given event caused by more than one collision occurring in a given bunch crossing.

The data collected in 2011 however, had a much greater contribution from *out of time* pileup than that collected in 2010. Such pileup occurs when running with so called bunch trains, with smaller bunch spacing. In 2011 the LHC ran with a bunch train structure and only 50 ns between bunches. This means that as the next bunch crossing is underway, particles and signals from the previous bunch crossing have not yet left parts of the detector. This is an issue for the calorimetry which has a much slower response than the tracking detectors. Such residual events can lead to misreconstructed physics objects where calorimeter or muon system signals are important. The main handle in the case of pileup including an out of time contribution is the average number of interactions per bunch crossing, or $\langle\mu\rangle$, averaged over bunch crossings and luminosity blocks¹. The activity in the detector left over from the previous bunch crossing depends the number of collisions in the previous bunch crossing, so this variable is a good handle with which to rescale MC.

$$\langle\mu\rangle_{exp} = \frac{L\sigma_{inel}\Delta t}{x_r}, \quad (5.1)$$

where L is the instantaneous luminosity² (nominally $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ but $\sim 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ in early 2011), Δt is the bunch spacing (nominally 25 ns, 50 ns in early 2011), σ_{inel} is the inelastic cross section ($\sim 70 \text{ mb}$ at 14 TeV or $\sim 60 \text{ mb}$ at 7 TeV) and x_r is the fraction of possible bunch crossings around the LHC that actually have collisions (nominally 0.8, at 0.43 in 2011). With these figures, currently $\langle\mu\rangle = 7$ while at nominal running conditions

¹ATLAS data taking is divided into runs and luminosity blocks. A luminosity block corresponds to the data accumulated in a small period of time (2-3 minutes) and a run is a collection of luminosity blocks. Dividing the data into smaller portions allows exclusion of single problematic data taking periods more easily.

²The luminosity in early running is calibrated using Van der Meer scans to determine the cross sectional area of colliding beams. Information from forward detectors, such as the LUCID Cerenkov counters in the forward region and minimum bias scintillators, is used to determine total interaction rates.

$\langle\mu\rangle = 22$ is expected. This $\langle\mu\rangle$ can be modelled in simulation, despite imperfections in this modelling due to the irregularities of the $\langle\mu\rangle$ behaviour over time in real data. MC is reweighted according to $\langle\mu\rangle$ for 2011 data.

5.2 Electron trigger and reconstruction

In order to select W boson candidates, it is important to understand the trigger chain and electron reconstruction algorithms that results in the selection of events containing high p_T electrons.

5.2.1 EM trigger

The specifics of the EM trigger in ATLAS follow the same general pattern as described in section 1.2.4. At L1, a sliding window looking at the energy sum of 4 trigger towers, each of which spans 0.1×0.1 in η - ϕ space, is used to find a local E_T maximum. The most energetic pair of two adjacent towers in such a trigger cluster are then added to determine the E_T of the EM shower. As the 2×2 trigger window slides, one can also look at the EM isolation ring of 12 towers surrounding the central window, or the corresponding hadronic towers behind the EM cluster and isolation ring. Triggers including cuts on isolation are however not validated for use within the timescale of this thesis. In the simplest case, if the E_T of the EM shower at a given local E_T maximum exceeds the L1 trigger threshold then it is passed to L2.

The regions of the detector where the L1 trigger threshold was exceeded are passed to the L2 trigger for further decisions. Such a region includes the isolation ring so totals 0.4×0.4 in η - ϕ space. The L2 decision is made with full granularity of the various detectors. First, an L2 trigger cluster of size 0.075×0.175 in η - ϕ is formed around the cell with the highest E_T in the region of interest. Including information from the ID, various cuts can now be made on variables related to energy, track shapes and shower shapes so as to distinguish between

photons and electrons and also to reject jet backgrounds.

Finally, at the EF stage, a full reconstruction is run taking into account the entire event and improved alignment and calibration constants. This is very similar to the offline reconstruction algorithm however cuts applied at trigger level are configured such that there is a high efficiency with respect to the offline selection. The trigger chain used in this analysis corresponds to the trigger with the lowest E_T and electron identification requirements of available unprescaled trigger, the `EF_e20_medium` trigger chain. This trigger has some shower shape and track requirements placed on the electron candidate with an E_T of 18 GeV required at L1 and 20 GeV at L2 and EF level.

5.2.2 Electron reconstruction

ATLAS electron reconstruction is seeded by an EM cluster that has been identified by a sliding window algorithm. The window is larger for electrons than it is for photons due to the increased likelihood of interaction with material upstream and also as there is track bending from the magnetic field. The exact dimensions of the sliding window change as a function of position in the detector. Track matching is performed on reconstructed clusters to identify electron candidates. A track is considered to match a cluster if the separation between cluster and extrapolated track η and ϕ is less than 0.05 and 0.1 respectively. Since all such objects with associated tracks are considered electron candidates, converted photons can also, at this level, be reconstructed as electrons. These ‘container level’ electrons show very high efficiency for high E_T electrons but are also contaminated with high levels of backgrounds.

The sum of all layers of the EM calorimeter gives the cluster energy. Energy scale corrections are applied, as measured by the ATLAS subgroup concerned with electron and photon performance in early data using well constrained $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ decays amongst other things [76].

It is also important to accurately model the material budget using in situ data measure-

ments since the presence of more or less material than is estimated leads to greater losses in energy and more converted photons in the electron container. Such a misunderstanding would have impacts on energy measurement and particle identification. This has been done by using collision data to, study the track reconstruction efficiency [77, 78, 79, 80], the photon conversion rate [81], the energy flow in the EM calorimeter [82], EM shower shape variables and the E/p ratio [76].

Since the MC does not reproduce the energy resolution seen in data, energies of electrons in MC are smeared in such a way that the width of the Z peak matches that of data.

5.2.3 Electron identification

Despite high efficiency for reconstructing high E_T electrons, a large number of fakes are expected at the LHC. Such fakes come from the dominant jet background, and a set of cuts based on calorimeter and tracking information have been defined for use in analyses to identify good isolated electron candidates, like those produced in Z and W decays. These particle identification cuts are split into three levels: loose, medium and tight. Exact details of cuts applied can be found in [6, 76], however a brief outline to the cuts follows.

Loose electrons are defined based on geometric acceptance, shower shape in the second sampling of the calorimeter and hadronic leakage variables.

Medium electrons are further defined based on shower shape in the first layer of the calorimeter. Track quality and track-cluster matching requirements are also added.

Tight electrons must pass cuts on E/p , further track matching cuts, inner Pixel layer hit requirements and TRT particle identification requirements.

5.2.4 Efficiency scale factors

The electron and photon performance subgroup have measured the efficiency of triggering, reconstructing and identifying high E_T electrons [76]. The efficiency in MC was found to

be slightly different to that of data. Therefore MC events are weighted by a scale factor in order to correct the efficiency in MC to be the same as that in data. These scale factors are provided for charge inclusive efficiencies. In section 7.3.1, an analysis is carried out to determine if any charge asymmetric effects have been missed by this treatment.

5.2.5 Electron isolation

Real electrons originating in W boson decays are expected to have high transverse energy and to be isolated. Conversely, non-isolated electron candidates such as QCD jets are accompanied by further particles, which deposit additional energy close to the candidate. Calorimeter isolation variables are calculated by looking at the energy deposited in a cone of radius R_0 around the electron candidate with the central cells of the electron cluster removed. R is a distance measurement in η - ϕ space ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$). An isolated candidate will have less energy deposited in this cone so will have a lower value for the isolation variable.

In this analysis a cut on the calorimeter isolation determined with a cone of $\Delta R = 0.3$ is used, $E_T^{cone}(0.3)$. There are two corrections applied to the isolation: a correction to remove electron energy leakage effects; and a correction that is parameterised as a function of number of primary vertices to take pileup into account [83]. Both of these effects have the effect of lowering the isolation in the case of true isolated electrons, resulting in the possibility that isolation energy can become negative. This can be seen in figures 5.4(a) and 5.4(b) where the isolation dips as low as -5 GeV.

5.2.6 Object quality

Throughout data taking, some channels in the calorimeter become problematic and are unable to be correctly read out. An electron candidate that is reconstructed on the edge of such a region must not be considered. Only 2-3 % of channels in the calorimetry are affected, and a robust method of determining the systematic uncertainty on the final measurement resulting in this treatment is given in a software tool provided by the electron and photon

performance subgroup. The resulting uncertainty on the final measurement is detailed in section 7.3.1.

As the MC is processed before the entire dataset is accumulated, channels can be lost during data taking that are not taken into consideration in the MC. A tool is therefore used to check a fraction of the MC events corresponding to the fraction of data with new missing channels. This tool further rejects electrons that would have been rejected in data taken after MC processing.

On top of occasional dead channels in the calorimeter, dealt with as above, a detector level flag stored on an event by event basis is filled to point to dramatic problems related to various sub-detectors. In particular, events with noise bursts and data integrity errors in the LAr calorimeter can be identified and rejected with such a flag. The amount of data rejected by this cut is very small, as can be seen in the cut flow shown in table 5.2.

5.3 E_T^{miss} reconstruction

The leptonic decay of a W boson produces a neutrino, which does not leave any signature in the detector. Its presence must therefore be inferred from large E_T^{miss} in an event. Fake missing transverse energy can arise from gaps in detector coverage, dead regions, noise or fluctuations in jet energy scale.

For the analysis presented in this thesis, the E_T^{miss} definition used is the ATLAS **LocHadTopo** E_T^{miss} . Three dimensional topological cells are clustered to establish basic calorimeter signals at which point analysis of the cluster shape allows classification for calibration and corrections so as to retrieve the correct energy scale. The missing transverse momentum is determined by summing the contributions of all calorimeter energy deposits and determining the direction and magnitude of the imbalance. A more complicated definition, **RefFinal** combines physics objects such as electrons, photons, muons, τ -leptons, high and low p_T jets and any remaining calorimeter activity [84]. As this latter definition contains many components, its validation lags that of the simpler approach and there are still some features that

are not fully understood within the timeframe of this thesis. For this reason, LocHadTopo will be used.

5.3.1 E_T^{miss} cleaning

E_T^{miss} quality cuts are determined so as to remove events with jets originating in localised high energy calorimeter deposits that do not come from the proton-proton collision under consideration. Primarily, this is to remove events coming from beam gas and halo, but could also include, for example, high energy discharges in the hadronic endcap calorimeter, high p_T cosmic muons undergoing a hard Bremsstrahlung, or coherent noise from the electromagnetic calorimeter. All such events happen at a very low rate, however their presence could impact the measurement of E_T^{miss} by altering the shape of the high E_T^{miss} tail. This cleaning procedure is a subset³ of those performed on jets.

Early in 2011, contact with 6 front-end boards in the LAr calorimeter was lost. This means that there is a small acceptance loss which was not able to be corrected until the next scheduled shutdown of the detector, after the completion of this thesis⁴. No trigger information or energy measurements can be made within this region. The object quality cuts described above take care of this for electron candidates, however to reduce the effect on E_T^{miss} a further cut must be made.

An event is vetoed if any calorimeter jet above a certain p_T threshold falls within the vicinity of the gap in acceptance: $-0.1 < \eta < 1.5$ and $-0.5 < \phi < -0.9$. The jet p_T should be above 30 GeV in MC, and above $(30 * \frac{1 - \text{BCH_CORR_JET}}{1 - \text{BCH_CORR_CELL}})$ GeV in data, where BCH_CORR_CELL and BCH_CORR_JET are the fractions of the jet energy coming from, respectively: the cell level correction using neighbouring cells assuming the same energy density; and the jet level correction using jet shape from MC. By using the MC jet shape, this should correct for jets in which part of the energy deposit has been lost into the acceptance gap. A variation of 20 % on the threshold of 30 GeV is considered as a systematic on this basic cut.

³This analysis uses the so called *loose jet cleaning* and a veto of events containing *ugly* jets.

⁴This has since been fixed and data taken in the latter half of 2011 is not affected.

5.4 Backgrounds to $W \rightarrow e\nu$ production

In selecting $W \rightarrow e\nu$ events with high E_T , isolated electrons and large E_T^{miss} , there are some other processes that can mimic the signal.

$W \rightarrow \tau\nu$

The τ -lepton can decay into an electron and a second neutrino producing an event with high E_T^{miss} and an isolated electron. This is an irreducible background that must be estimated using MC simulation.

QCD dijets

As jets can be misidentified as electrons, and dijet events can generate fake E_T^{miss} , QCD events represent a significant background. MC lacks the necessary statistics and accuracy to determine this background without a data driven background determination. Such methods will be discussed in chapter 6.

$Z \rightarrow ee$

Events in which one prong of the Z decay falls outside detector acceptance or fails to be reconstructed can appear to be $W \rightarrow e\nu$ events.

$Z \rightarrow \tau\tau$

As either τ -lepton can decay into an electron and neutrinos, there is the potential for both E_T^{miss} and an isolated electron in this channel.

$t\bar{t}$

As the top quark decays, a real W boson is produced which can in turn decay in a way that mimics the signature of a $W \rightarrow e\nu$ event.

Di-Boson

Though a very small background, events in which W or Z bosons are produced in pairs involve real W bosons so are a background to this channel.

5.4.1 Monte Carlo datasets

All the above described backgrounds apart from QCD are well understood theoretically. This means that to estimate the contamination of the signal, the simulated ATLAS MC samples are normalised to the integrated luminosity of the data and background yields extracted.

Signal MC is generated using MC@NLO [66] and showered with HERWIG [64]. Further cross checks are made in section 7.3.3 using samples generated with POWHEG [85, 86, 87, 88] and showered using PYTHIA [89]. For both POWHEG and MC@NLO samples, the CTEQ 6.6 NLO PDF is used as input. DiBoson and $t\bar{t}$ are also generated with MC@NLO and showered with HERWIG. The LO generator PYTHIA is used to model all other backgrounds and to provide another alternative signal MC for further cross checks. PYTHIA uses the MRST LO* PDF⁵.

All generators are interfaced to PHOTOS [70, 71] to simulate final state QED radiation and TAUOLA [70] was used to simulate τ -lepton decay. GEANT4 [91] is used to model the ATLAS detector. All samples are so called MC10b, indicating that they are simulated with an Poisson distributed $\langle\mu\rangle$ about an average of 8, and bunch spacing of 50 ns. MC10b also incorporates information regarding alignment, material distribution and the underlying event obtained using 2010 data. Table 5.1 documents the samples used and their effective integrated luminosity.

W boson p_T reweighting

Analyses of the p_T spectra of $W^\pm$ bosons within ATLAS have shown the NLO generators to insufficiently model p_T^W [93]. In this thesis, as in [92], since the transverse momentum spectrum as described by the LO PYTHIA generator is in good agreement with data⁶, the NLO generators have an additional weight applied in order to reweight the generator level transverse momentum to that of PYTHIA. Figure 5.1 shows the p_T^W distributions at generator

⁵This is an attempt by the PDF community to provide a PDF that performs well with a LO generator such as PYTHIA without the inherent x -dependent problems that are presented by both LO and NLO PDFs. For details see [90].

⁶PYTHIA was tuned to Tevatron data.

Sample		Dataset	Generator	Effective Lumi (fb^{-1})
$W^+ \rightarrow e^+\nu$		106081	MC@NLO	0.55
$W^- \rightarrow e^-\nu$		106082	MC@NLO	0.59
$W^+ \rightarrow e^+\nu$		108297	POWHEG +PYTHIA	0.16
$W^- \rightarrow e^-\nu$		108300	POWHEG +PYTHIA	0.23
$W \rightarrow e\nu$		106043	PYTHIA	0.67
$W \rightarrow \tau\nu$		107054	PYTHIA	0.22
$Z \rightarrow ee$		106046	PYTHIA	5.03
$Z \rightarrow \tau\tau$		106052	PYTHIA	2.02
$t\bar{t}$		105200	MC@NLO	0.19
Di-Boson	WW	105985	HERWIG	16.98
	ZZ	105986	HERWIG	22.36
	WZ	105987	HERWIG	256.7

Table 5.1: MC Samples

Signal and Backgrounds to $W \rightarrow e\nu$, MC datasets used to estimate them, and the effective luminosity of each sample. All MC used was processed to D3PD level by the ATLAS Standard Model W/Z group. The effective luminosity of a sample is the number of events divided by the cross section and filter efficiency of the sample. Cross sections used for normalisation are the NNLO cross sections as used in [92].

level and the corresponding weights required.

5.5 $W \rightarrow e\nu$ selection cuts

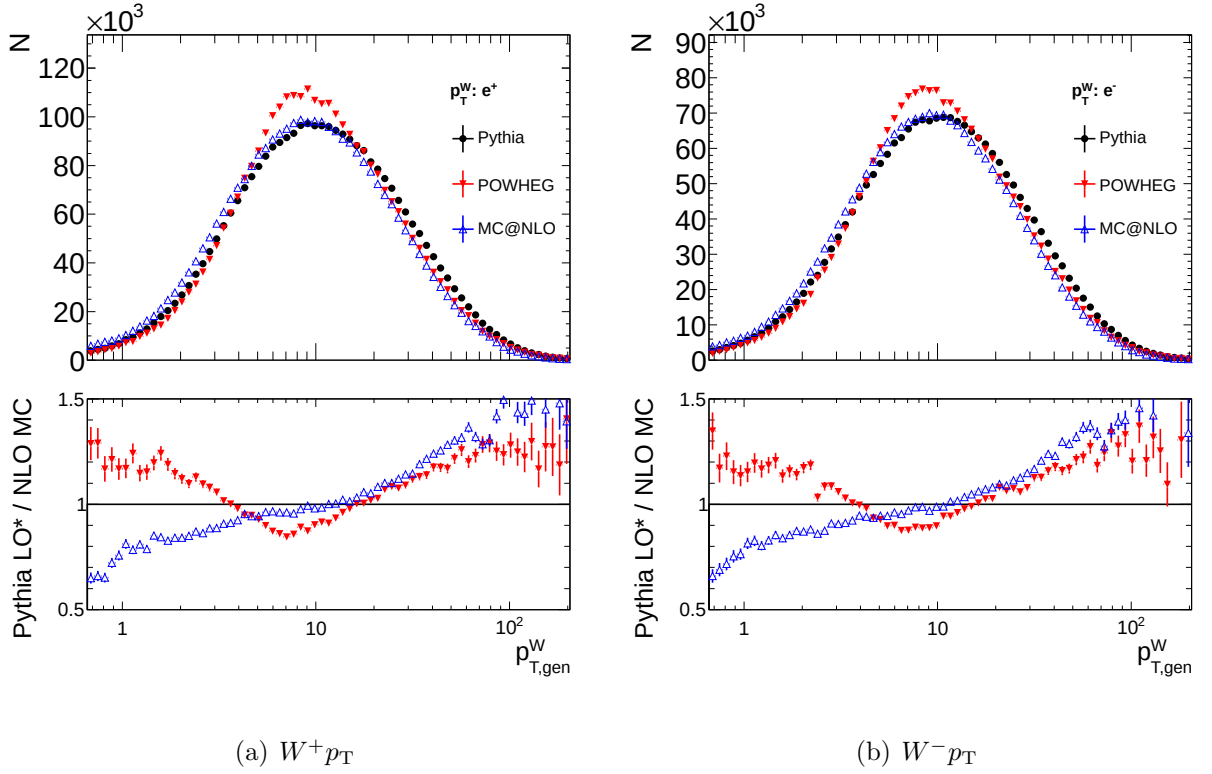
The following documents all cuts made to select $W \rightarrow e\nu$ candidates in data. They are split into three categories; event preselection, with cuts to select good proton-proton collisions; lepton selection, to select good electron candidates; and final event selection, with event level cuts based on the $W \rightarrow e\nu$ event topology.

5.5.1 Event preselection

There are three main cuts used in this analysis to remove non-collision background. They are as follows:

Good run list

The good run list (GRL) list determines which runs and luminosity blocks correspond

Figure 5.1: $W^\pm$ transverse momentum spectra

Generator level p_T spectra for PYTHIA, MC@NLO and POWHEG +PYTHIA and the corresponding weights required to correct the NLO generator distributions to that of PYTHIA.

to times when the ATLAS detector and machine were operating with basic beam, detector and data quality requirements satisfied. The GRL used in this analysis is the so called, `pro08-03_WZjets_allchannels` for 2011 data. For obvious reasons, this selection criteria is not applied to MC. The amount of data rejected by this selection is in fact quite small, however cuts made here do not reject any true W events.

Trigger

In 2011 data an event filter trigger with medium identification requirements on an electron of at least 20 GeV in p_T , `EF_e20_medium`, was the lowest unprescaled trigger. Using the above GRL and this trigger, the total integrated luminosity used in this thesis is 497.27 pb^{-1} .

Primary vertex requirement

As a final requirement to reject non-collision background, the event is required to have

at least one reconstructed primary vertex that has at least 3 tracks associated to it. This removes potential beam-beam background and cosmic events.

5.5.2 Lepton selection

Electron candidates are required to pass a number of cuts before they are considered to be part of a $W \rightarrow e\nu$ event. Initially, there must be at least one electron in the event that passes the following preselection cuts:

$E_T > 15 \text{ GeV}$

The transverse energy is measured using the energy deposited in the cluster and the pseudorapidity as measured by either the track, in the case where there are more than 3 silicon hits in the inner detector, or the calorimeter otherwise.

$|\eta_{\text{cluster}}| < 2.47$

The pseudorapidity of the electromagnetic cluster must be within the EM calorimetry and must also not lie within the ‘crack region’ between the barrel and endcap calorimeters, i.e. $1.37 < |\eta_{\text{cluster}}| < 1.52$.

Hard electron

A reconstructed electron can be seeded by a high energy EM calorimeter deposit, in which case it is classified as a ‘hard’ electron, or it can be seeded by a track, in which case it is classified as a ‘soft’. The electron must have been reconstructed as either a ‘hard’ electron or satisfied both ‘hard’ and ‘soft’ electron requirements.

Object quality cuts

During data taking, some channels have become problematic in that they can not be properly read out, as described in section 5.2.6.

Medium identification criteria

As described in section 5.2.3, medium identification cuts include both track and calorimeter based requirements.

If there is at least one electron passing the above preselection cuts, the following cuts are applied to the highest E_T electron passing tight identification requirements in the event. That is, it must pass the following:

Tight identification criteria

Tight identification cuts introduce further requirements as described in section 5.2.3.

$E_T > 25 \text{ GeV}$

Transverse energy, measured in the same way as the preselection cut, must be high in order to reject electrons coming from secondary decays or other non W backgrounds.

$E_T^{\text{cone}}(0.3) < 4 \text{ GeV}$

The calorimeter based isolation in a cone of $\Delta R < 0.3$ must be small to reject the normally non-isolated QCD background.

5.5.3 Final event selection

Finally, the event must pass the following cuts:

E_T^{miss} cleaning

Cuts applied to ensure good quality E_T^{miss} as described in section 5.3.1.

$Z \rightarrow ee$ veto

In order to reject events in which there are two high energy electrons, there must not be more than one preselected electron passing medium identification requirements in the event.

$E_T^{\text{miss}} > 25 \text{ GeV}$

A true $W \rightarrow e\nu$ event will have high missing transverse momentum due to the neutrino present.

$m_T > 40 \text{ GeV}$

The transverse mass is reconstructed from the missing transverse momentum and the

electron in the event. Requiring this to be greater than 40 GeV significantly reduces QCD and other backgrounds in which the E_T^{miss} and electron are not from the decay of a W boson.

LArError

As described in section 5.2.6, there is required to be no dramatic problems in the LAr calorimeter.

Figure 5.2 show the distribution of two key variables before any lepton selection is applied (after event preselection only). The QCD background in these plots is purely illustrative and derived from QCD background MC. Figures 5.3 and 5.4 show the distribution of some key variables after full $W \rightarrow e\nu$ selection. MC distributions of various potential backgrounds, discussed in more detail in section 5.4 are shown in the plots alongside signal MC and data. All MC is normalised by effective luminosity to the integrated luminosity of the data taken. Table 5.2 shows the number of events selected after each cut.

Cut	Events passing
Event preselection	28471536
Hard Electron	28405365
η cuts	27365186
$E_T > 15\text{GeV}$	25094341
Object Quality cuts	24916669
Medium Identification	21633080
Tight Identification	5617251
$E_T^{\text{cone}}(0.3) < 4\text{ GeV}$	3938465
$E_T > 25\text{ GeV}$	2621952
$Z \rightarrow ee$ veto	2470769
E_T^{miss} cleaning	2461171
$E_T^{\text{miss}} > 25\text{ GeV}$	1507206
$m_T > 40\text{ GeV}$	1466340
LArError	1466238

Table 5.2: Cut flow for 497.27 pb^{-1} of 2011 ATLAS data

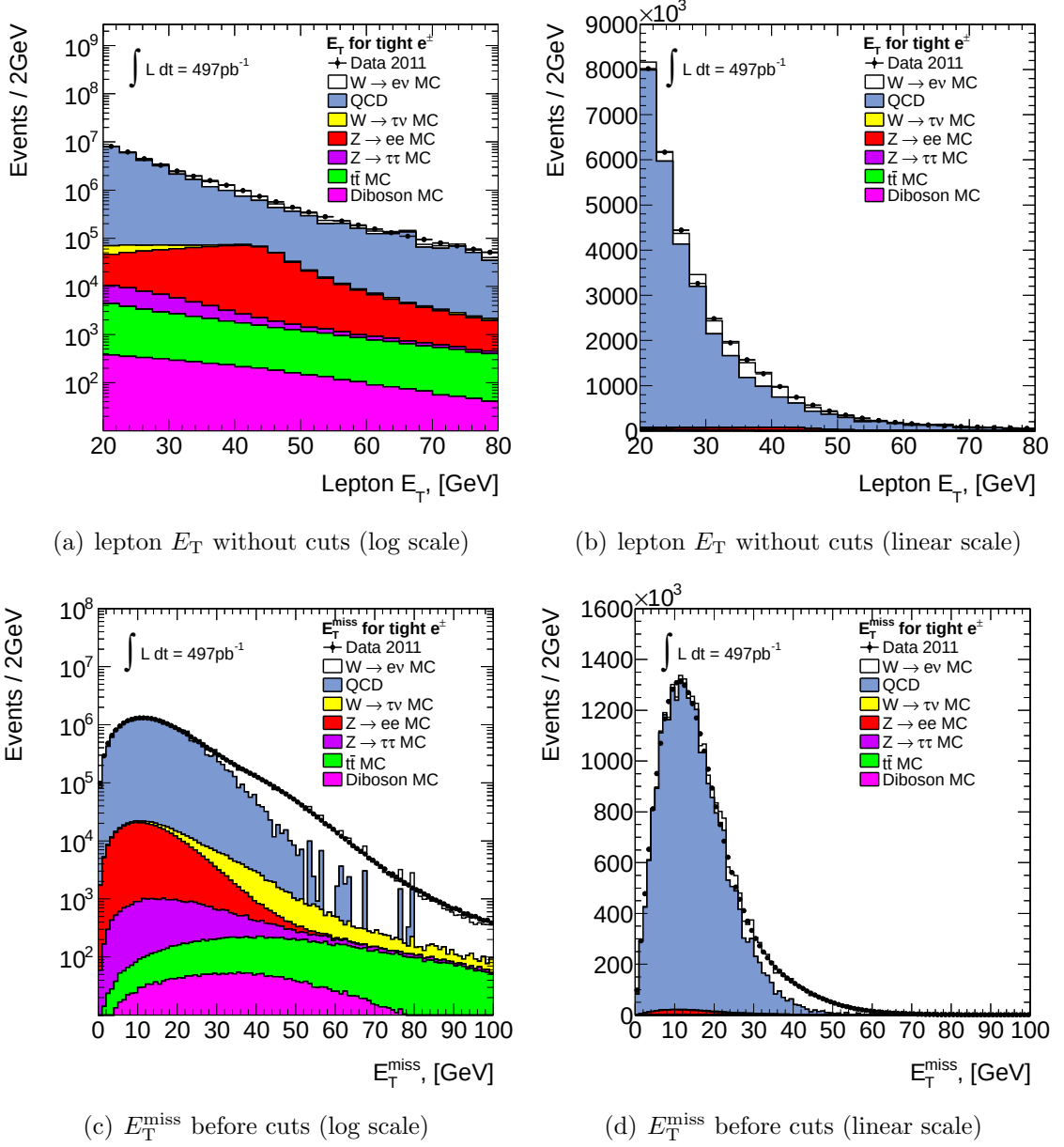


Figure 5.2: Observables cut on in W selection: E_T and E_T^{miss} before selection cuts $W \rightarrow e\nu$, $t\bar{t}$ and Diboson use MC@NLO, while all other MC derived backgrounds are from PYTHIA. QCD background is here also MC derived. The normalisation of the QCD MC is set to scale the total number MC events to that of data, and should be taken only as an indication of the approximate QCD background shape.

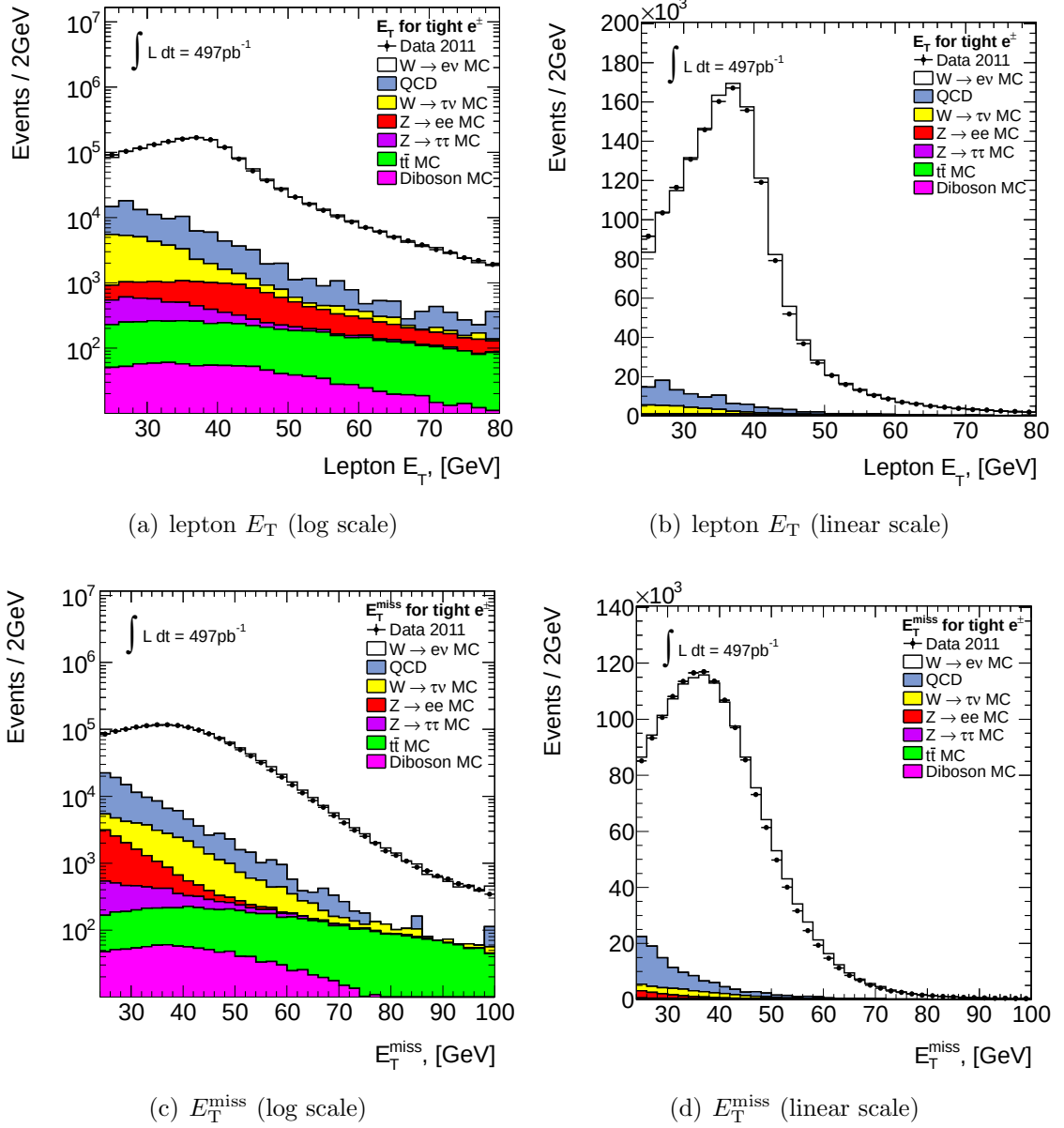


Figure 5.3: Observables cut on in W selection: E_T and E_T^{miss} . $W \rightarrow e\nu$, $t\bar{t}$ and Diboson use MC@NLO, while all other MC derived backgrounds are from PYTHIA. QCD is derived using a reverse cut selection as described in chapter 6.

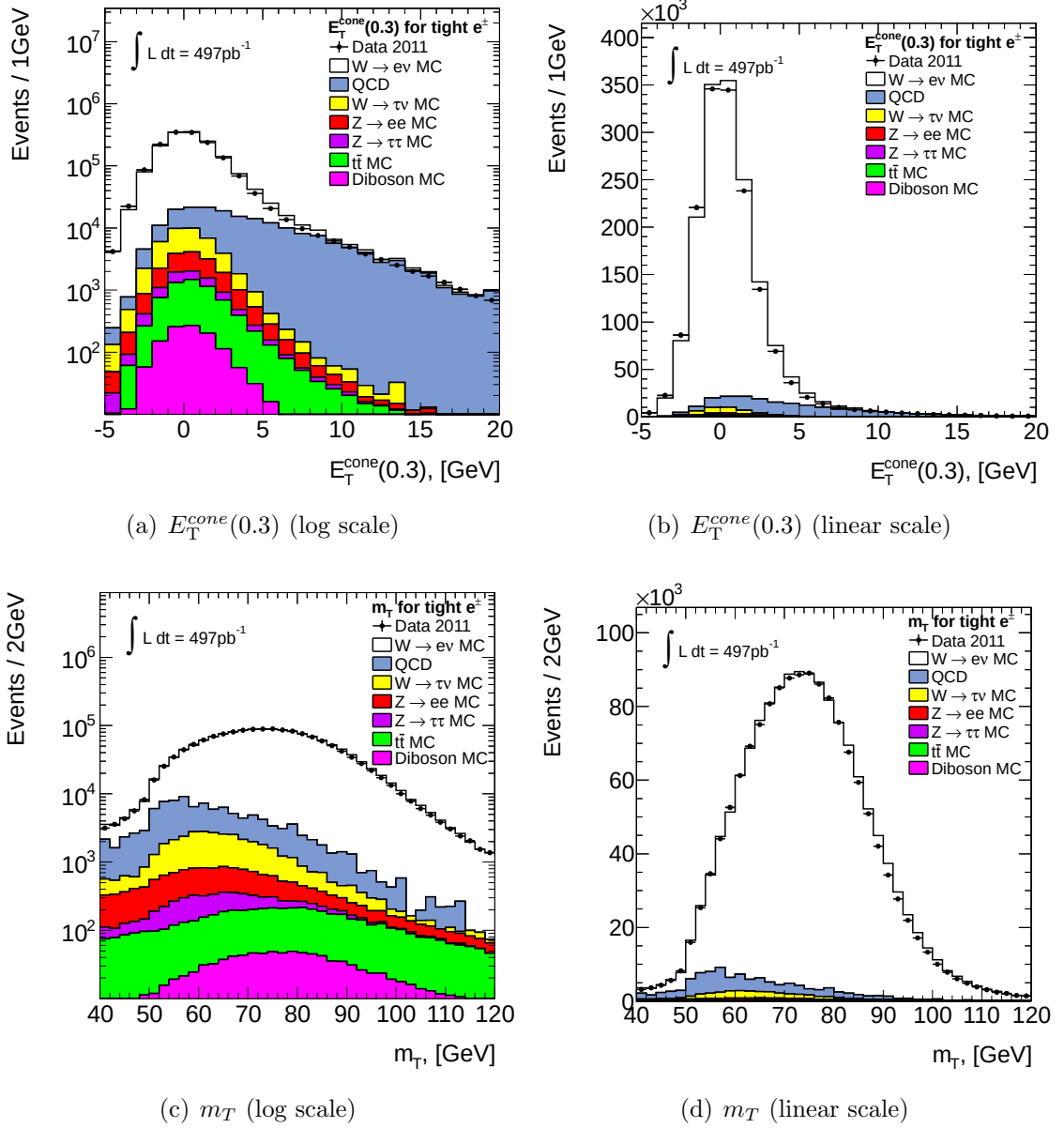


Figure 5.4: Observables cut on in W selection: $E_T^{\text{cone}}(0.3)$ and m_T . $W \rightarrow e\nu$, $t\bar{t}$ and Diboson use MC@NLO, while all other MC derived backgrounds are from PYTHIA. QCD is derived using a reverse cut selection as described in chapter 6.

Chapter 6

Determination of QCD Background

A subset of the reconstructed electron candidates passing standard identification cuts will in fact be QCD jets of partonic origin (*fake electrons*). QCD jets are produced in LHC conditions at a very high rate, so although the probability of misidentifying such a jet as an electron is small, these jets are a major background to analyses involving identification of $W \rightarrow e\nu$ events.

6.1 Data driven methods

A method that takes only data into consideration when determining the QCD background is desirable as MC simulation of QCD jets is not sufficiently advanced to model fake electrons correctly. There are three main arguments for a data driven method:

- The full detail of the substructure of a jet along with the way in which partons shower, hadronise then fragment into jets is difficult to fully capture in simulation.
- Even if this modelling was entirely accurate, the theoretical uncertainty on multijet production and the underlying event are large so the rate of fake electrons could still only be predicted to low accuracy.
- Finally, should simulation perfectly predict the rate of fake electrons in the detector, MC could still not be relied upon as the computational resources necessary to account for the statistics present in the data would be so large as to make such an endeavour impossible (since the fake probability is so low, and the jet rate so high).

In this section two approaches to the determination of the QCD background to $W \rightarrow e\nu$ events are discussed. The first is the ‘template method’, in which a QCD background and signal template are simultaneously fit with respect to a discriminating variable to data in order to determine the contribution of each. The QCD background distribution is taken from a sideband region - one in which electron candidates are almost certainly misreconstructed QCD jets. Secondly, a simple method that uses the separation of fake and real electrons in the $E_T^{\text{miss}} - E_T^{\text{cone}}(0.3)$ plane to determine the QCD background in the signal region, the ‘ E_T^{miss} vs Iso’ method. Both methods will be applied to the final data set to extract a value for the QCD background.

6.2 Template method

The template method takes the distribution of an observable, the *template variable*, which shows good differentiation between signal and QCD background and simultaneously fits a template for QCD background and signal¹ to it. The result of the fit is an estimate of the relative normalisations of the two templates. Using this, and any subsequent cut on the template variable, one can determine the QCD background expected in the signal region. In this thesis, the signal template used is derived from MC samples of the $W \rightarrow e\nu$ signal, along with all other background sources listed in section 5.4. The background template is derived from data by applying all cuts on the candidate events but reversing two or three of the cuts made on electron identification variables.

In summary, the method is as follows. Further details follow the summary:

- Choose a variable which shows good distinction between true electrons and fake electrons. This variable is called the ‘template variable’
- Create a distribution in this variable that is free of fake electrons. In this thesis this ‘signal template’ will be from MC.

¹The *signal template* is strictly not only signal but includes all MC derived background sources.

- Create a distribution in the template variable that is composed entirely of QCD background events, the ‘background template’. The details of this step for this thesis are as follows:
 - Require that 2 or 3 of the cuts that make up the medium and tight electron identification selection are *failed*, while all other electron identification cuts are passed.
 - Since each of these cuts is very efficient in selecting true electrons, any event that passes these ‘reversed cut’ criteria, are likely to be fake electrons.
 - Test the output distributions to ensure that the shape is as expected for QCD background, and that true electrons have indeed been rejected.
- Take the signal and background templates and simultaneously fit them to data that has undergone normal selection cuts to determine what fraction of signal and background is required.
- The fitted background template is the estimate of the QCD background.

6.2.1 Choice of template variable

The E_T^{miss} variable shows good separation between QCD background and signal. Due to the real neutrino in $W \rightarrow e\nu$ events, there is naturally a high E_T^{miss} , while any E_T^{miss} in QCD background events is due to mismeasurements of jets, so is typically low. For this reason, E_T^{miss} is chosen as the primary template variable. In addition, it is useful to determine the QCD background using a different template so as to provide a check. A second template variable is therefore chosen to be the isolation variable used in the selection of $W \rightarrow e\nu$ events, $E_T^{\text{cone}}(0.3)$. Electrons from W decays are expected to be very clean and consequently isolated in the detector, whereas QCD background events, being mostly misreconstructed jets, are often less isolated.

6.2.2 Background template development

A background template should model the shape of QCD background events that pass all cuts, while containing as few signal events as possible. The strategy taken in this thesis for choosing which electron identification cuts to reverse was to compare the shape of the resulting distribution to that produced by the full $W \rightarrow e\nu$ selection on dijet MC. While there are insufficient statistics and understanding to use this MC to produce the QCD background template, it provides a good benchmark against which to test for significant deviations from a particular reversed cut combination.

To identify a good set of cuts to reverse, sets of two or three electron identification cuts introduced at medium or tight level were reversed. In order to reverse medium cuts, a trigger is required that has had a lower level of electron identification criteria applied. For this reason, the `EF_e20_loose` trigger is used, in which only a loose electron identification selection is applied. This trigger is heavily prescaled in 2011 data, resulting in an accumulated dataset corresponding to only 8.2 pb^{-1} from which to obtain QCD background templates. All selection cuts were made except those on $E_T^{\text{cone}}(0.3)$ and E_T^{miss} and the distributions of the two chosen template variables then compared to the same distribution in QCD multijet MC using a Kolmogorov-Smirnov (K-S) test.

The K-S test can be used to determine the probability that, within statistical uncertainty, two distributions are derived from the same probability density function; that is, that their shapes are consistent. To perform the test, a ROOT function is employed that returns a probability between 0 and 1. A value of 1 indicates that the two distributions are certainly derived from the same probability density function (i.e. that their cumulative distributions are identical), while a value of 0 indicates that they are very much different. The procedure involves building a cumulative distribution for each sample and comparing these. The use of the cumulative distribution makes the method more robust against lower statistics datasets and results in much better performance than a χ^2 test in such cases. Ideally the K-S test should be performed with unbinned samples, however a ROOT function is provided to deal with histogrammed data.

As a starting point, all reversed cut combinations yielding a K-S result of greater than 50 % for both E_T^{miss} and $E_T^{\text{cone}}(0.3)$, as well as a $W \rightarrow e\nu$ rejection of greater than 98 % are used. The latter of these requirements was tested by looking at the number of $W \rightarrow e\nu$ MC events that passed the reversed cut selections as compared to tight selection. This yields a list of 17 cut combinations. The 8 electron identification cut variables from which these 17 combinations are formed are listed in table 6.1. The distributions are then added together so as to yield high enough statistics that a template fit can be performed in bins of pseudorapidity.

Identification variable	Description
ConversionMatch	Cut eliminating electrons matched to a photon, introduced at tight level
ClusterStripsDEmaxs1	Cut on the difference between the first and second energy maximum in strips, introduced at medium level
TrackBlayer	Cut requiring a hit on the inner Pixel layer, introduced at tight level to reject photon conversions
TrackMatchPhi	Cut on the ϕ difference between cluster and extrapolated track in the 2nd sampling, introduced at tight level
TrackMatchEoverP	Cut on the energy-momentum matching, E/p , introduced at tight level
TrackTRTRatio	Cut on the ratio of high threshold TRT hits to all TRT hits, introduced at tight level to reject hadrons
TrackA0Tight	Cut on the distance of closest approach, introduced at tight level
TrackMatchEtaTight	Cut on the η difference between the cluster and the extrapolated track in the 1st sampling, introduced at tight level

Table 6.1: Electron identification variables from which reverse cut combinations are formed. More details on these cuts, amongst others used in electron identification in ATLAS can be found in [6, 76].

6.2.3 Template fit

The QCD background and signal templates are simultaneously fitted to the data through a standard likelihood fit using Poisson statistics. This is performed using the ROOT TFractionFitter class [94]. The errors computed by the TFractionFitter class have undergone some criticism for the simplistic Poissonian approach, specifically in the choice to work with the

fraction rather than number of events in each template [95]. The returned fractions are correct with uncertainties somewhat inflated, however not to a point that any correction is required. Another interesting feature of the class used, is that the input templates are allowed to vary, bin by bin, within their statistical uncertainty. This means that the result of the fit is somewhat different to the addition of the scaled template histograms. With correct treatment, this is not a problem for extracting the QCD background estimate in the signal region.

The template fit is performed in both E_T^{miss} and $E_T^{\text{cone}}(0.3)$. Due to the perceived greater uncertainty in the determination of isolation², the estimate from the E_T^{miss} template is taken as the central value with the difference between this and that estimated from the $E_T^{\text{cone}}(0.3)$ template fit being used as a systematic uncertainty. Template fits are carried out in bins of absolute pseudorapidity ($|\eta|$) corresponding to those used in the asymmetry measurement.

The QCD background is assumed to be charge symmetric, so to aid in statistical precision, the template fits are only carried out in bins of pseudorapidity for combined charge. A check is performed on the inclusive sample to look for charge asymmetry, as shown in figure 6.1. In the inclusive case, the predicted QCD background for e^+ is (35350 ± 1854) while for e^- the value is (37879 ± 2069) . The two values are entirely consistent within statistical uncertainties.

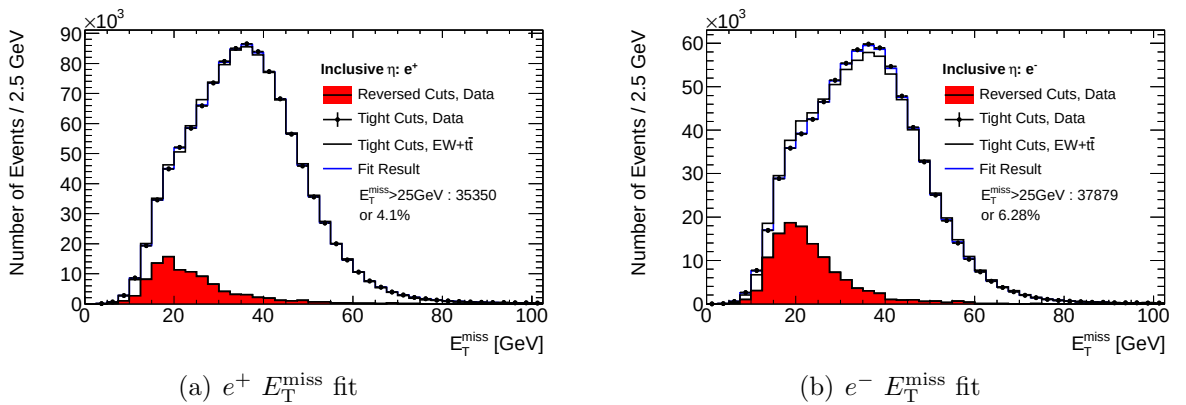


Figure 6.1: Charge separated E_T^{miss} template fit
The fit to the E_T^{miss} for both electrons and positrons. The QCD background estimates are consistent.

²The isolation has been studied in less detail than the E_T^{miss} in early data. There are also, as described in section 5.2.5, corrections applied to account for known problems in the reconstruction of isolation.

6.2.4 Systematic uncertainties

The statistical uncertainty is derived from: that of the reverse cut template; the fraction returned in the fit and its uncertainty; and the integral of the data over the fit range that is used to normalise the QCD background histogram. The systematic uncertainties are not measured in bins of pseudorapidity due to lack of statistics in the QCD background template, but rather the fractional uncertainties determined in the inclusive case and used for each bin. The following sources of systematic uncertainty are considered:

- As mentioned above, the difference in the QCD background estimate as determined by use of E_T^{miss} and $E_T^{\text{cone}}(0.3)$ as the template variable is considered a systematic uncertainty. This is an extreme limit on the uncertainty coming from the choice of template variable and yields an uncertainty of 9.8 %.
- The bin widths of the QCD background and MC templates, as well as the data histogram are halved then doubled. The larger of the deviations is taken to be the uncertainty due to the binning: 1.4 %.
- The fit range is nominally set to cover both the signal and background dominated regions while not extending too far into the tails of the distribution. This range is varied such that each edge is varied up or down by 10 % with either one or both edges being varied. The average deviation of 8 QCD background estimates is then used to determine the uncertainty arising from fit range. The uncertainty is then 0.1 %.
- An uncertainty due to the choice of the QCD background template is determined by using two different reverse cut templates: one in which the reversed cut E_T^{miss} template must yield a K-S result greater than 90 % instead of 50 %, with no requirement on the isolation template³; and a template using a reversed isolation selection as used in [60]. The average deviation from the nominal QCD background estimate of the two alternate templates leads to a systematic uncertainty of 20.7 %

³This yields 23 combinations formed of the 7 cuts in table 6.1 with one additional cut: `ClusterStripsWtot`, a cut on the shower width in the 1st sampling introduced at medium level

- A conservative uncertainty due to the shape of the signal template is given to be the difference between the estimates obtained using PYTHIA and MC@NLO MC to model the signal. The MC@NLO generator, as the name suggests, correctly models NLO effects, and in capturing these additional effects tends to alter the shape of lepton E_T and E_T^{miss} distributions slightly. In addition to this, the MC@NLO generator uses HERWIG for showering and hadronisation, which uses a different model to the PYTHIA approach. The difference between the two is a conservative estimate as All other EW backgrounds remain the same since the $W \rightarrow e\nu$ component is the largest contributor. This uncertainty is determined to be 18.8 %.

The three main systematic uncertainties come from the choice of template variable, and the choice of the two templates. These uncertainties are quite large, and an average could be considered, however they are a conservative estimate of the effects and for the purposes of this thesis are propagated onto the measurement as they are.

6.2.5 Template fit as applied to data

Figure 6.2 shows the template fit in E_T^{miss} inclusively in pseudorapidity and charge. The result of the fit, using the systematic uncertainties above is

$$N_{QCD} = 72327.0 \times (1 \pm 3.85\% (stat) \pm 20.7\% (sys, a) \pm 18.8\% (sys, b) \\ \pm 9.8\% (sys, c) \pm 1.4\% (sys, d) \pm 0.1\% (sys, e))$$

where systematics $a-e$ are from variations of the QCD background template, signal template, template variable, the bin width and the fit range respectively. This corresponds to a QCD background of $(4.93 \pm 1.47)\%$ in the signal region of $E_T^{\text{miss}} > 25 \text{ GeV}$.

Figure 6.3 displays the QCD background estimate with statistical uncertainty as a function of lepton pseudorapidity. The systematic uncertainties calculated in the inclusive case are used for all bins. The individual template fits for each bin are shown in appendix A.

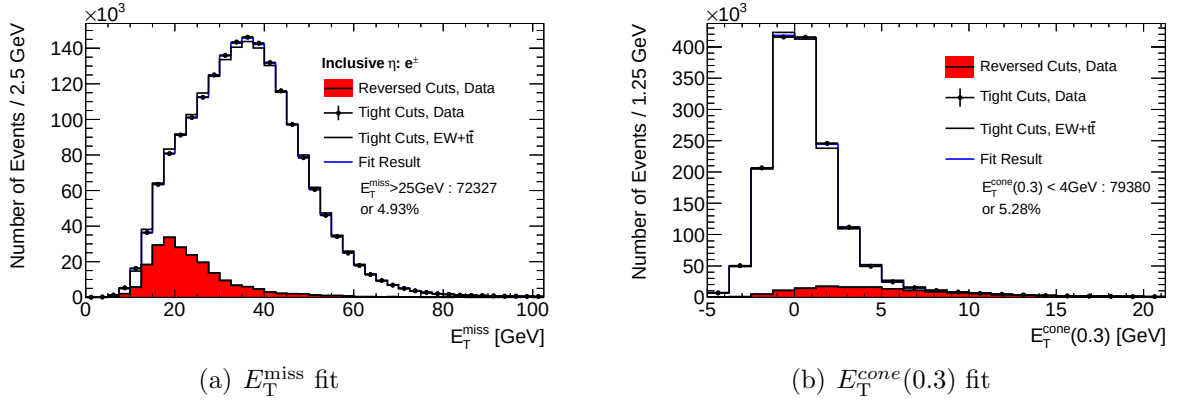


Figure 6.2: Inclusive template fits

The fit to the E_T^{miss} and $E_T^{\text{cone}}(0.3)$ using a cut reversed QCD background template and MC EW template. The red histogram is the scaled QCD background template, the white the scaled EW template. The black points are the data with all selection cuts except for that on E_T^{miss} and the blue line is the result of the fit. The result is slightly different from the combination of the two scaled histograms as it allows the histograms to vary within their statistical uncertainties.

6.3 E_T^{miss} vs Iso method

The ‘ E_T^{miss} vs Iso’ method, an example of a ‘Tiles’ or ‘ABCD’ method, has been used at CDF in the past [96, 56] to get a data driven estimate of the number of electrons arising from misreconstructed QCD jet events in the region corresponding to signal $W \rightarrow e\nu$ events. The method relies on the assumption that E_T^{miss} and $E_T^{\text{cone}}(0.3)$ are not correlated for electron candidates arising from QCD jet events, and that the signal contribution in low E_T^{miss} and high $E_T^{\text{cone}}(0.3)$ regions of phase space is small.

As can be seen in figure 5.3 of the previous chapter, the $E_T^{\text{cone}}(0.3)$ and E_T^{miss} distributions for electron candidates from QCD events are significantly different in shape to those of electrons originating from $W \rightarrow e\nu$ events. By separating the two dimensional E_T^{miss} - $E_T^{\text{cone}}(0.3)$ space into four regions of low and high E_T^{miss} and $E_T^{\text{cone}}(0.3)$, three kinematic regions enriched in electrons originating in QCD events and one corresponding to the signal region are obtained.

To implement the method to determine the QCD background, a two dimensional plot of E_T^{miss} - $E_T^{\text{cone}}(0.3)$ is produced for all electron candidates that pass standard electron selection

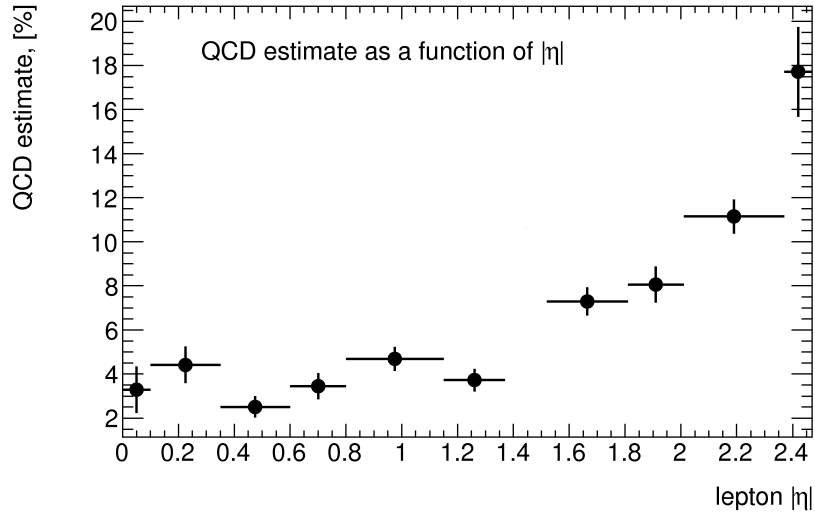


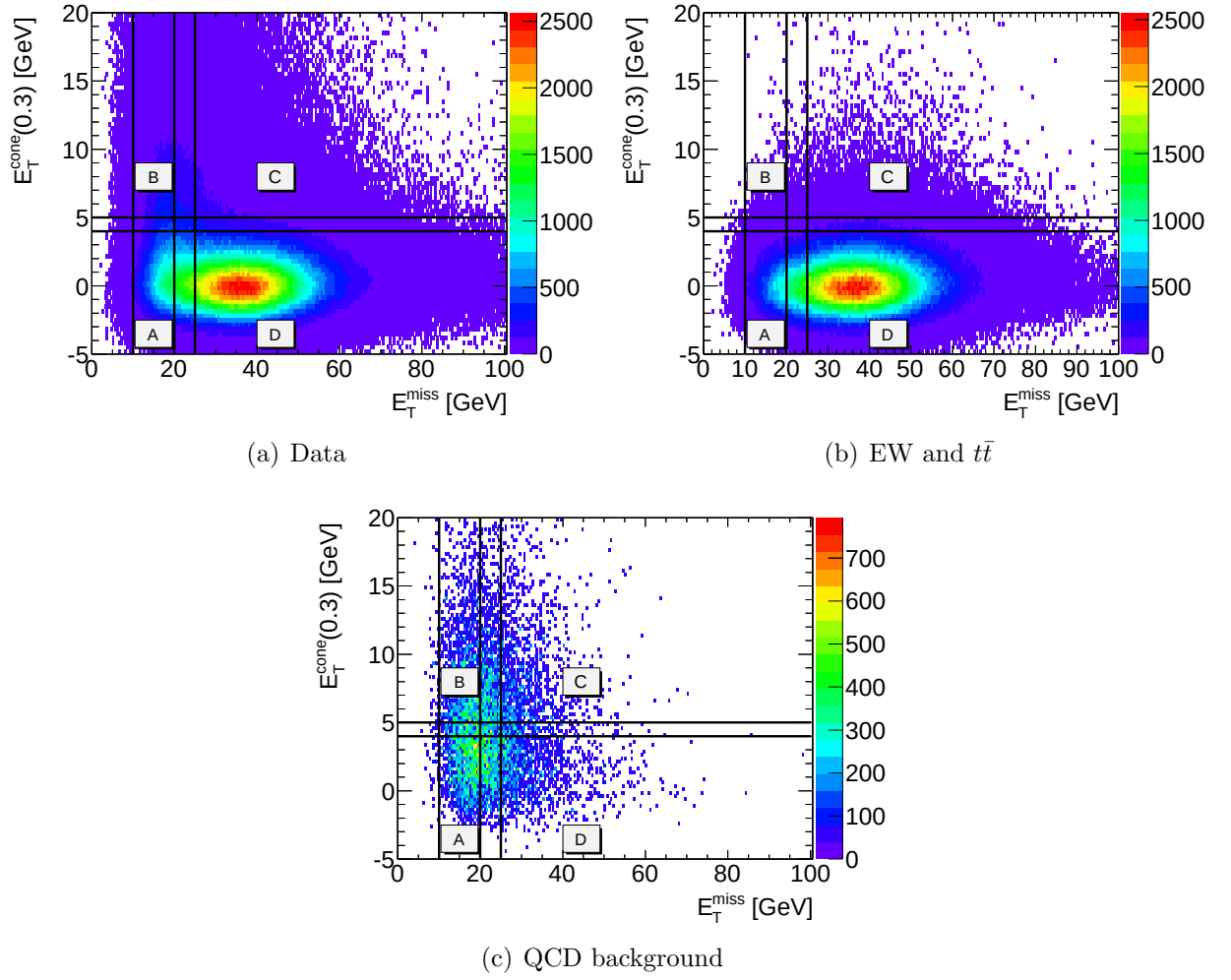
Figure 6.3: QCD background as a function of pseudorapidity
 The QCD background as determined by the template fit in E_T^{miss} . Only the statistical uncertainty is shown.

cuts, described in chapter 5, except for $E_T^{\text{cone}}(0.3)$ and E_T^{miss} cuts. An example of such a plot for each of QCD background, $W \rightarrow e\nu$ with non-QCD backgrounds and Data is shown in figure 6.4. The plot is separated into four regions, denoted A , B , C and D . Regions A , B and C are QCD background rich and their boundaries are chosen so as to avoid signal contamination and variable correlation. Region D contains isolated electron candidates that occur in events with a high E_T^{miss} , which are mainly W events, and is thus the signal region.

Given the assumption that E_T^{miss} and $E_T^{\text{cone}}(0.3)$ are not correlated for the QCD background, the ratio of the number of electron candidates in A to that in B should be the same as D to C for QCD background events. In order to determine the QCD background in the signal region the number of events in the QCD background dominated region can be extrapolated using the following relation:

$$\frac{N_{A,QCD}}{N_{B,QCD}} = \frac{N_{D,QCD}}{N_{C,QCD}},$$

where N_i represents the number of electron candidates in region i . Assuming that regions A ,

Figure 6.4: E_T^{miss} vs Iso

$E_T^{\text{miss}}-E_T^{\text{cone}}(0.3)$ plane for electron candidates passing all standard electron cuts except for E_T^{miss} and $E_T^{\text{cone}}(0.3)$ cuts. QCD background events taken from a reversed cut sample are shown in figure (c), $W \rightarrow e\nu$ and other backgrounds taken from MC in (b) and data in (a).

B and C are QCD background enriched⁴,

$$\frac{N_A}{N_B} \times N_C = N_{QCD} , \quad (6.1)$$

where here, and throughout this section the number of QCD background events is referring

⁴This assumption, and these equations neglect non-QCD backgrounds present in regions A , B , C and D . Such backgrounds are considered in section 6.3.2.

to the number in the signal region, D, unless otherwise stated ie,

$$N_{QCD} \equiv N_{D,QCD}.$$

This can also be represented as a QCD background fraction in the signal region considering the number of events that are not QCD background, N_{EW} ,

$$R_{QCD} = \frac{N_{QCD}}{N_{QCD} + N_{EW}} = \frac{N_A N_C}{N_B N_D}. \quad (6.2)$$

6.3.1 Initial QCD background estimate

The boundaries of the four regions are shown in table 6.2. These regions must be adjusted when using different isolation variables. A consistent way of determining the best position of the boundaries is not presented here, however they must be chosen so as to minimise signal contamination in the QCD background regions while also minimising the effect of correlation between E_T^{miss} and isolation. Also taken into consideration are statistics: it is desirable to have a similar number of events in all of the QCD background enriched regions.

Region	E_T^{miss} boundaries	$E_T^{\text{cone}}(0.3)$ boundaries
A	10 - 20	-5.0 - 4.0
B	10 - 20	> 5.0
C	> 25	-5.0 - 4.0
D	> 25	> 5.0

Table 6.2: E_T^{miss} and $E_T^{\text{cone}}(0.3)$ boundaries

Table 6.3 shows the number of events present in each region for the inclusive case, along with a total EW contribution in each region⁵.

In the first case, the QCD background estimate is determined by applying equation 6.1 to arrive at $N_{QCD} = 224950 \pm 1275$. This represents a QCD background fraction of just over 15 %, which seems rather too high if the results of the template method are to be believed.

⁵The EW contribution here, and in the rest of this chapter, actually includes $t\bar{t}$, so is rather a ‘non-QCD’ contribution.

Sample	N_A	N_B	N_C	N_D
Data	196589	69310	79309	1461156
Total EW	113887	1847	25404	1387102

Table 6.3: Number of events observed in each region for the inclusive case

Of course, looking at the numbers in table 6.3, there is quite clearly some contamination in the QCD background enriched regions by signal and other backgrounds. The following section looks to remove this contamination.

6.3.2 Electroweak removal

QCD background rich regions in the $E_T^{\text{miss}}-E_T^{\text{cone}}(0.3)$ plane will contain some genuine electrons arising from EW processes. A simple iterative procedure is used to remove these events using MC samples of signal and background processes. The first step is to create a combined EW sample which contains the $W \rightarrow e\nu$ and all other MC derived background samples. This will provide the MC template upon which the iterative removal will be based.

The number in each region for data ($N_{A,\text{data}}, N_{B,\text{data}}, N_{C,\text{data}}, N_{D,\text{data}}$), and for the non-QCD samples ($N_{A,\text{EW}}, N_{B,\text{EW}}, N_{C,\text{EW}}, N_{D,\text{EW}}$), is measured. For each of the QCD background rich regions, from which the QCD background estimate is calculated, a new ‘EW removed’ number is calculated, which is defined as

$$N'_{i,\text{data}} = N_{i,\text{data}} - \frac{N_{D,\text{data}}}{N_{D,\text{EW}}} N_{i,\text{EW}} \quad \forall i \in \{A, B, C\}. \quad (6.3)$$

Using these new estimates for the number of QCD background events in each of A , B and C , the initial estimate of the QCD background in the signal region, D , will be,

$$R'_{QCD} = \frac{N'_{A,\text{data}} N'_{C,\text{data}}}{N'_{B,\text{data}} N_{D,\text{data}}}. \quad (6.4)$$

This estimate of the QCD background fraction in region D can now be used to further improve the weighted MC removal used in Equation 6.3. For further iterations, the following

equation is used to calculate the ‘EW removed’ numbers:

$$N'_{i,\text{data}} = N_{i,\text{data}} - (1 - R'_{QCD}) \frac{N_{D,\text{data}}}{N_{D,EW}} N_{i,EW} \quad \forall i \in \{A, B, C\}. \quad (6.5)$$

This process is continued until less than 0.01 % change is seen between iterations. The results of this iterative procedure are shown in table 6.4 where the resulting QCD background fraction is $(4.47 \pm 0.45) \%$. This is consistent with the prediction of the template method.

	N_{QCD} (R_{QCD})
Before Iterative EW removal	224949.9 (15.45 %) $\times$ (1 $\pm$ 0.57 % (stat))
After Iterative EW removal	65325.6 (4.47 %) $\times$ (1 $\pm$ 0.10 % (stat))

Table 6.4: Iterative EW removal results

The estimated QCD background is shown and in parentheses the fractional QCD background as defined in equation 6.2.

Systematic uncertainty of electroweak removal

Since the EW subtraction method investigated here only uses the ratio of MC predictions, the overall normalization used for these MC samples has no impact on the correction. The biggest source of systematic uncertainties therefore comes from the MC modelling of the shape of the E_T^{miss} and $E_T^{\text{cone}}(0.3)$ distributions for these events. To estimate the systematic uncertainty on QCD background prediction due to such an effect, the robustness of the prediction against biases in distributions indirectly affecting the computed correction is tested. To this end, the distributions of the combined EW samples have been altered in two different ways: using truth E_T^{miss} instead of reconstructed E_T^{miss} ; using ALPGEN + JIMMY samples instead of PYTHIA.

A major source of distortion of the E_T^{miss} distribution comes from detector resolution effects. By comparing the prediction with and without accounting for such effects an extreme upper limit on the systematic uncertainty of the EW removal process arising from MC modelling of the E_T^{miss} shape. Using truth E_T^{miss} rather than the reconstructed E_T^{miss} in the inclusive case, a value of $R_{QCD} = 6.73 \%$ is obtained. Given that using reconstructed E_T^{miss}

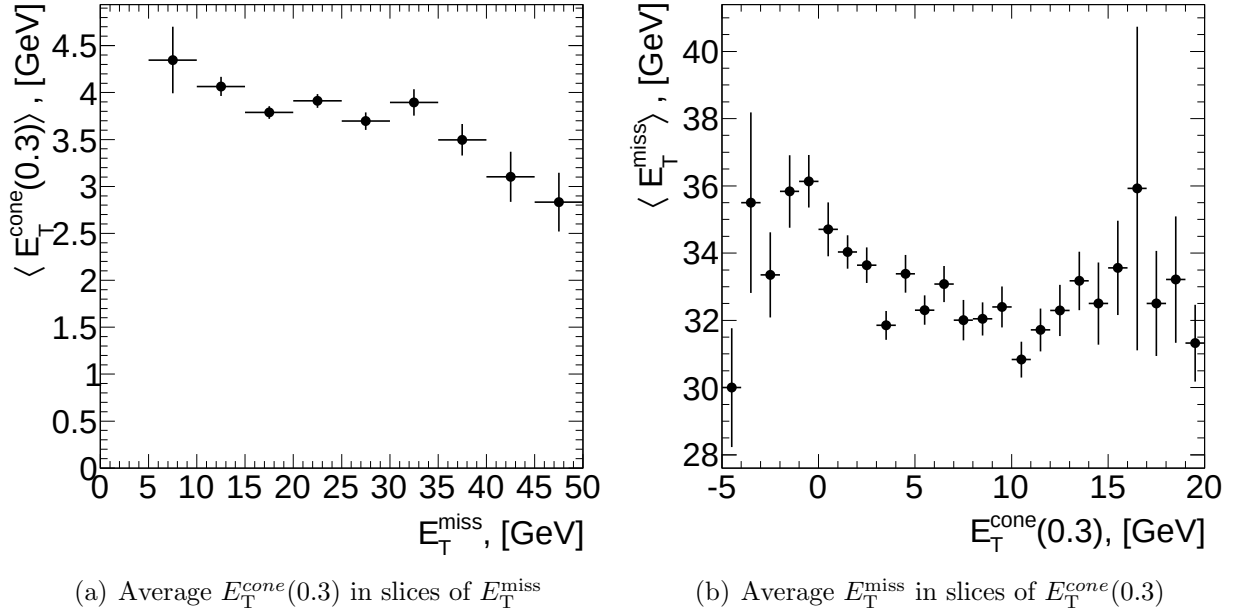
gives $R_{QCD} = 4.47\%$, this represents a 50.5% uncertainty on the EW removal method. This is an extreme estimate, as the true understanding of the detector effects on the E_T^{miss} is of course far better. In future work an approach similar to that used to estimate the uncertainty on the asymmetry due to mismeasurements of E_T^{miss} as shown in section 7.3.6. Such an approach would certainly reduce this source of uncertainty to less than 10%.

ALPGEN and PYTHIA have different methods for modelling non-perturbative QCD effects such as hadronisation and the underlying event. Using the E_T^{miss} distribution of ALPGEN +JIMMY EW samples instead of that from PYTHIA will give an indication of the systematic uncertainty arising from the different approaches. Here ALPGEN +JIMMY $W \rightarrow e\nu$, $W \rightarrow \tau\nu$, $Z \rightarrow ee$ and $Z \rightarrow \tau\tau$ is used, with $t\bar{t}$ remaining the same as before. Using ALPGEN results in a QCD background estimate of 4.56%, the relative difference from that found using PYTHIA is therefore 2%. Summing the estimated contribution from detector resolution effects and that of non-perturbative QCD modelling effects results in a systematic uncertainty of 50.5% on the QCD background estimate arising from the EW removal method. This is an upper limit on the uncertainty.

6.3.3 Correlation of E_T^{miss} and $E_T^{\text{cone}}(0.3)$

The method as described relies on the assumption that for QCD background events, the E_T^{miss} and $E_T^{\text{cone}}(0.3)$ variables are not correlated. This can be tested using the cut reversed selection as described in section 6.2.2. Figure 6.5 shows profile plots for the QCD background sample. In bins of one of the variables, the average of the other is plotted. Looking at these profile plots gives the impression that there is a possible correlation between the two variables.

A further check for correlation is carried out by comparing the shapes of the distribution of E_T^{miss} ($E_T^{\text{cone}}(0.3)$) in slices of $E_T^{\text{cone}}(0.3)$ (E_T^{miss}). This is shown in figure 6.6 and there is no obvious difference. To quantify this, a K-S test was carried out between each of the possible combinations to check for any clear discrepancy in shape difference. As expected from a visual inspection, the worst agreement comes from the slice with the lowest statistics: $-5 < E_T^{\text{cone}}(0.3) < 0$ in the case of the E_T^{miss} distributions; and $0 < E_T^{\text{miss}} < 10$ in the case of

Figure 6.5: Correlation of E_T^{miss} and $E_T^{\text{cone}}(0.3)$

Profile plots demonstrating the dependence on the average value of $E_T^{\text{cone}}(0.3)$ (6.6(a)) on E_T^{miss} and the E_T^{miss} (6.6(b)) on $E_T^{\text{cone}}(0.3)$.

the $E_T^{\text{cone}}(0.3)$ distributions. The K-S test result never drops below 10 % for any combination and there is no systematic shift in disagreement as distance between the slices increases, as would be expected in the case of correlation.

To additionally quantify the correlation, the Pearson's correlation coefficient was calculated for the distribution of QCD background events. Pearson's correlation coefficient gives a handle on the amount of linear correlation between two variables and is formed by dividing the covariance of two variables by the product of their standard deviations. A coefficient of -1 indicates a decreasing linear correlation and $+1$ an increasing linear correlation. Although two variables with no correlation will have a Pearson's coefficient of 0, a coefficient of 0 only indicates a lack of linear correlation. The coefficient is equal to -0.112 , which represents a small linear anti-correlation. This is in agreement with the profile plot shown in 6.6(a).

There is clearly some correlation, so for the purposes of this thesis the template method approach will be used and the ' E_T^{miss} vs Iso' method used a cross check only. With this in

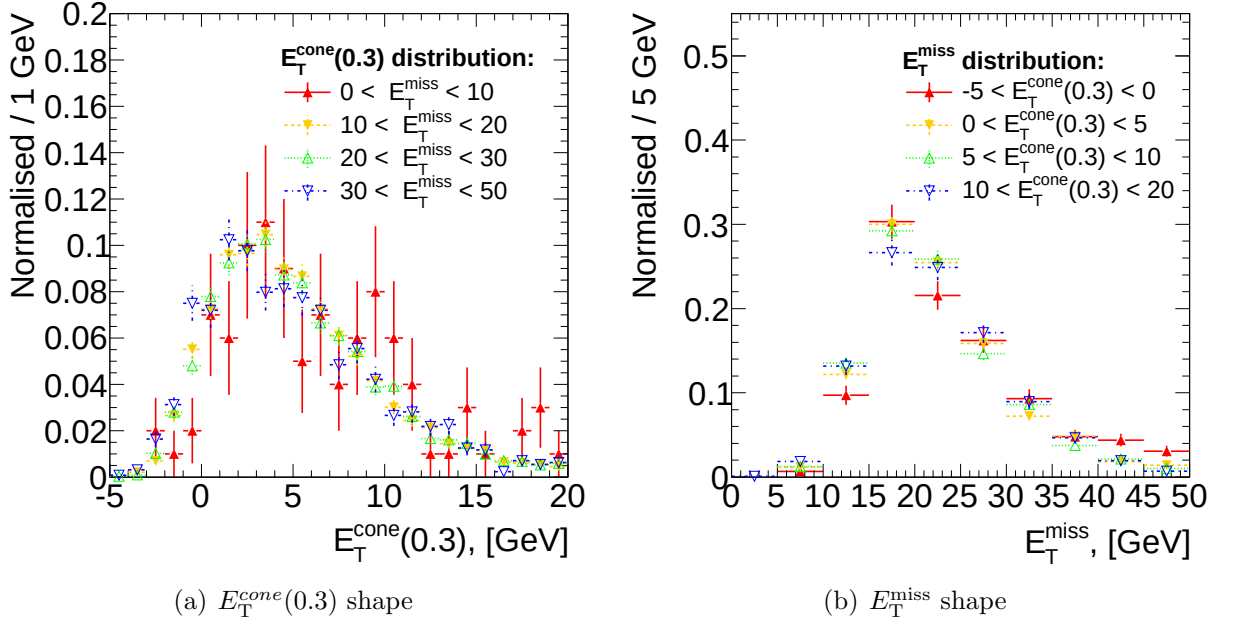


Figure 6.6: Shape of two discriminating variables
Each of E_T^{miss} and $E_T^{\text{cone}}(0.3)$ is plotted in bins of the other to determine any correlation.

mind, a systematic uncertainty on the QCD background estimate from this method of 10 % is applied as an estimate of the effect of correlation of E_T^{miss} and $E_T^{\text{cone}}(0.3)$. If the method were to be used in the future, it would be possible to try to correct for this correlation by using the reversed cut QCD background sample.

6.3.4 Further sources of systematic uncertainty

To additionally assess the systematic uncertainty of the method, the region boundaries of the QCD background enriched regions are shifted by 10 % in each direction to assess the robustness of the method. Both EW removal and any potential correlation will cause deviations from the nominal prediction. The average deviation from the nominal prediction over all variations is 5.8 % in the inclusive case. This will be used as a systematic uncertainty.

Given the above sources of systematic uncertainty, the QCD background estimate in the inclusive case is

$$N_{QCD} = 6646516.1 \times (1 \pm 0.10\% (stat) \pm 5.8\% (sys, a) \pm 50.5\% (sys, b) \pm 10\% (sys, c))$$

where systematics a - c are from the variations of the region boundaries, EW removal and correlation. This corresponds to a QCD background fraction of $(4.47 \pm 2.30)\%$. This is in agreement with the estimate from the template method for the inclusive case.

6.3.5 QCD background estimate as a function of pseudorapidity

Having estimated the systematic uncertainties from the inclusive sample, a separate two dimensional histogram can be built for each bin of lepton pseudorapidity. This method has the advantage that it has the full statistics of the final dataset, as a looser trigger requirement is not required as in the case of the template method. The QCD background estimate as predicted by this method is shown, with statistical uncertainty only in figure 6.7.

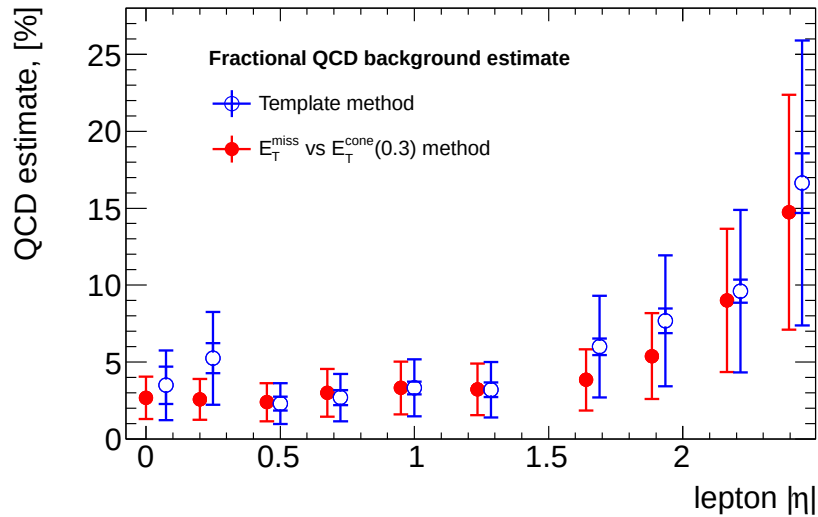


Figure 6.7: QCD background as a function of pseudorapidity

The QCD background as determined by the Template method and ‘ E_T^{miss} vs Iso’ method. The statistical uncertainty is represented by the first error bar, too small to be visible in the ‘ E_T^{miss} vs Iso’ case. The systematics as discussed in the text are then added in quadrature and the total uncertainty represented by the outer error tick.

Within statistical and systematic uncertainty, the template method agrees fully with this method. Because of the uncertainty surrounding the possible correlation between E_T^{miss} and $E_T^{\text{cone}}(0.3)$ in QCD background, in this thesis only the results of the template method will be used. In future it would be useful to develop further the estimate of the systematic uncertainty on the ‘ E_T^{miss} vs Iso’ method, as it has the clear advantage of the full statistics

of the dataset.

Chapter 7

Measurement and uncertainties

Having selected $W \rightarrow e\nu$ events and determined backgrounds, the asymmetry is calculated in this chapter. Correction to truth level is carried out and systematic uncertainties considered.

7.1 Background subtraction

With the exception of QCD background, all backgrounds are estimated using MC normalised to the total integrated luminosity of the data. For both positively and negatively charged leptons, the background subtracted number of events in each bin of absolute pseudorapidity¹ is calculated. The final estimate of each of the backgrounds listed in section 5.4 is displayed for positively and negatively charged lepton candidates in table 7.1.

7.2 Correction to truth asymmetry

The lepton charge asymmetry is defined as

$$A_\ell = \frac{d\sigma_{W\ell^+}/d\eta_{\ell^+} - d\sigma_{W\ell^-}/d\eta_{\ell^-}}{d\sigma_{W\ell^+}/d\eta_{\ell^+} + d\sigma_{W\ell^-}/d\eta_{\ell^-}}. \quad (7.1)$$

The cross section with fiducial cuts applied is used so as to avoid PDF dependent acceptance corrections that would be required to extrapolate to the full phase space.

¹The measurement is carried out in terms of $|\eta|$. This approach assumes there are no differences in each end of the detector in terms of acceptance and efficiency as confirmed by alignment measurements in early ATLAS data.

Observed signal and estimated backgrounds: positive charge										
			N_{obs}	QCD	$W \rightarrow \tau\nu$	$Z \rightarrow ee$	$Z \rightarrow \tau\tau$	$t\bar{t}$	Di-Boson	$N_{\text{obs}} - N_{\text{bkg}}$
0.0	$< \eta < 0.1$		34477	1063.7	574.6	135.0	51.5	157.8	26.1	32468.3
0.1	$< \eta < 0.35$		101893	4737.0	1716.8	428.9	173.8	465.0	80.4	94291.1
0.35	$< \eta < 0.6$		104772	2099.3	1531.4	433.6	181.3	446.0	80.6	99999.9
0.6	$< \eta < 0.8$		83406	1943.3	1249.2	375.1	127.1	309.2	62.9	79339.2
0.8	$< \eta < 1.15$		137219	3904.5	2351.1	662.1	196.9	462.5	99.1	129542.7
1.15	$< \eta < 1.37$		79018	2137.5	1292.1	422.1	129.0	220.0	54.8	74762.5
1.52	$< \eta < 1.81$		96092	4742.9	1479.4	700.7	129.9	181.1	62.0	88795.9
1.81	$< \eta < 2.01$		67172	4228.2	944.6	425.6	90.6	96.7	35.1	61351.3
2.01	$< \eta < 2.37$		130146	10141.5	2171.4	822.1	171.3	111.6	60.1	116668.0
2.37	$< \eta < 2.47$		23641	3204.7	346.2	156.3	28.0	14.0	10.4	19881.4

Observed signal and estimated backgrounds: negative charge										
			N_{obs}	QCD	$W \rightarrow \tau\nu$	$Z \rightarrow ee$	$Z \rightarrow \tau\tau$	$t\bar{t}$	Di-Boson	$N_{\text{obs}} - N_{\text{bkg}}$
0.0	$< \eta < 0.1$		26610	1063.7	403.2	127.6	51.5	155.6	26.6	24781.8
0.1	$< \eta < 0.35$		78836	4737.0	1498.3	410.1	154.4	472.1	78.0	71486.1
0.35	$< \eta < 0.6$		78699	2099.3	1440.8	417.8	135.9	439.3	75.7	74090.2
0.6	$< \eta < 0.8$		61621	1943.3	1194.9	352.2	118.2	334.2	64.2	57614.2
0.8	$< \eta < 1.15$		98317	3904.5	1723.8	648.9	186.2	471.2	97.6	91284.8
1.15	$< \eta < 1.37$		54776	2137.5	885.5	383.8	113.0	221.2	51.4	50983.6
1.52	$< \eta < 1.81$		62355	4742.9	963.3	619.6	124.4	182.6	53.6	55668.6
1.81	$< \eta < 2.01$		43090	4228.2	592.2	398.0	81.6	94.9	35.8	37659.2
2.01	$< \eta < 2.37$		81126	10141.5	1090.8	776.9	145.3	123.6	51.5	68796.2
2.37	$< \eta < 2.47$		14888	3204.7	203.1	145.1	30.9	15.0	7.9	11281.2

Table 7.1: Observed signal and estimated backgrounds

The number of observed electron candidates, N_{obs} , and all contributing backgrounds are summarised in bins of lepton pseudorapidity for the full dataset of 497.27 pb^{-1} . The background subtracted signal, $N_{\text{obs}} - N_{\text{bkg}}$, is also shown.

The fiducial cross section is defined as

$$\sigma_{W\ell^\pm}^{fid} = \frac{N_{obs}^\pm - N_{bkg}^\pm}{C_{W\ell^\pm} \mathcal{L}_{int}} . \quad (7.2)$$

Since the integrated luminosity, $\mathcal{L}_{int}$, is the same for both electrons and positrons, this cancels in the asymmetry. The asymmetry is therefore built using the corrected, background subtracted number of events for each charge. The correction factors are,

$$C_{W\ell^\pm} = \frac{N_{MC,rec}^\pm \times SF}{N_{MC,gen}^\pm} , \quad (7.3)$$

where $N_{MC,rec}^\pm$ is the number of reconstructed electrons passing all cuts in signal MC and $N_{MC,gen}^\pm$ is the number of generator level electrons passing fiducial cuts. The scale factors, SF , mentioned in section 5.2.4, take care of differences between data and MC for electron reconstruction efficiency, electron identification efficiency and trigger efficiency. These scale factors are not charge separated, so any charge asymmetric effects must be accounted for as discussed further in section 7.3.1. Also, there are no further charge selections when calculating the correction factors, so $N_{MC,rec}^\pm$ contains a small component of events in which the lepton charge is misidentified. It is therefore of interest as to whether the MC models this charge misidentification in a way consistent with that seen in data. This will be investigated in section 7.3.2.

The fiducial cross section can be calculated at different levels with respect to the corrections for QED final state radiation (FSR). In this thesis, *dressed leptons* are used, where the 4-vector of the bare lepton and all QED FSR photons within $\Delta R < 0.1$ are resummed. This corrects for only the mostly collinear part but not the wide angle part of the QED FSR.

Table 7.2 shows the nominal correction factors are calculated using MC@NLO MC and the corresponding corrected signal numbers. The uncertainty shown on the correction factors is the statistical uncertainty only².

²This takes correctly into account the binomial errors, arising from the fact that the probability that a bin contains a reconstructed electron is dependent on whether there is a truth electron in that bin.

		$C_{W\ell^+}$	$C_{W\ell^-}$	N_{corr}^+	N_{corr}^-	$A_\ell \pm (stat)$
0.0	$< \eta < 0.1$	0.591 ± 0.004	0.597 ± 0.005	54981.7	41512.7	0.14 ± 0.007
0.1	$< \eta < 0.35$	0.705 ± 0.003	0.707 ± 0.003	133777.4	101104.1	0.139 ± 0.004
0.35	$< \eta < 0.6$	0.7 ± 0.003	0.706 ± 0.003	142864.8	104992.3	0.153 ± 0.004
0.6	$< \eta < 0.8$	0.697 ± 0.003	0.697 ± 0.003	113764.0	82601.1	0.159 ± 0.004
0.8	$< \eta < 1.15$	0.654 ± 0.002	0.666 ± 0.003	198019.6	137038.9	0.182 ± 0.003
1.15	$< \eta < 1.37$	0.589 ± 0.003	0.606 ± 0.004	126859.3	84144.6	0.202 ± 0.005
1.37	$< \eta < 1.52$	0.046 ± 0.001	0.047 ± 0.002	79116.4	53742.4	0.191 ± 0.026
1.52	$< \eta < 1.81$	0.54 ± 0.003	0.548 ± 0.003	164505.8	101604.6	0.236 ± 0.004
1.81	$< \eta < 2.01$	0.544 ± 0.003	0.574 ± 0.004	112693.5	65622.0	0.264 ± 0.005
2.01	$< \eta < 2.37$	0.572 ± 0.002	0.603 ± 0.003	204086.5	114081.6	0.283 ± 0.004
2.37	$< \eta < 2.47$	0.375 ± 0.004	0.409 ± 0.005	52996.2	27563.8	0.316 ± 0.009

Table 7.2: Correction factors, corrected totals and asymmetry

7.3 Systematic uncertainties

The nature of the asymmetry measurement is such that any variations in efficiencies or corrections that are charge symmetric should cancel in the asymmetry. This means that many of the systematic uncertainties that are considered important in, for example, a charge separated cross section measurement, are less important for the asymmetry.

One important aspect that must be tested is whether the MC models the charge misidentification rate correctly, since the correction factors inherently account for this factor and are derived entirely from MC. This is tested below by considering the double ratio, $\frac{\epsilon(e^+/e^-)_{data}}{\epsilon(e^+/e^-)_{MC}}$. Any deviation from unity implies that there is some mismodelling of charge dependent effects in the MC, and a systematic uncertainty on the asymmetry must be assigned. In a similar way, since charge inclusive scale factors are used to account for differences between MC and data reconstruction, identification and trigger efficiencies, it should be checked that there are no further charge asymmetric effects within this.

For other systematic variations, dealt with in the following sections, the general approach taken in this thesis to determining the systematic uncertainty is similar to that taken in [92]. Variations are made in MC and new correction factors, $C'_{W\ell^\pm}$, calculated. These correction factors are then used with the nominal background subtracted yields and deviations from the nominal asymmetry are considered as a systematic uncertainty. For variations where

there is a corresponding up and down shift, the average deviation of the asymmetry is taken as the systematic uncertainty. It should be noted that all of the systematic uncertainties below are treated as fully correlated between W^+ and W^- so variations are applied to both correction factors simultaneously so as to properly account for this.

7.3.1 Trigger and identification biases

In this thesis, combined charge scale factors are used to adjust the reconstruction, trigger and identification efficiencies seen in MC so that they better match that of data. One minor systematic uncertainty on the asymmetry measurement comes from the systematic uncertainty on these scale factors. Details of the analysis performed to measure the efficiencies and provide these uncertainties can be found in [76]. As this uncertainty is the same for both charges, the effect is very small on the asymmetry, below the per-mille level.

There is no evidence that trigger or reconstruction efficiencies are charge asymmetric. On the other hand, there is the possibility that identification efficiencies are somewhat so. This should not be the case for an ideal detector, however early efficiency measurements using ATLAS data could still be biased by incomplete understanding of material effects and inner detector alignment. For this reason, a check of the charge separated identification efficiencies is carried out using a $Z \rightarrow ee$ ‘tag and probe’ method.

The tag and probe method uses $Z \rightarrow ee$ events to measure single electron efficiencies. To do this, one electron in the event must pass particularly stringent cuts to ensure that it is a true electron. Typically it must be matched to a trigger object as well as having all electron selection criteria applied. This then becomes the *tag* electron. Other electrons in the event, the *probe* electrons, are subject to more basic selection criteria. The efficiency of a cut is then measured by determining whether a probe electron passes or fails that cut. The number of probes passing the cut divided by the total number of probes gives the efficiency.

Event preselection cuts are made and all electrons considered must have passed cuts on pseudorapidity, object quality and have $E_T > 25 \text{ GeV}$ as described in section 5.5.2.

Following this, the tag must be matched to a trigger object in that event and it must pass tight identification criteria. A probe electron is then selected that passes basic track requirements: the number of silicon hits must be greater than seven with at least one such hit being in the Pixel detector. Track requirements are applied to the probe in order to compare to the results of [76] from which the scale factors used in this thesis are taken. Any difference between MC and data in the efficiency of reconstructing electrons with these track requirements is taken care of by the reconstruction efficiency scale factors and is not expected to be charge asymmetric. The only further requirement on a probe electron is that the invariant mass of the tag and probe pair is within the loose Z mass window of 66-116 GeV.

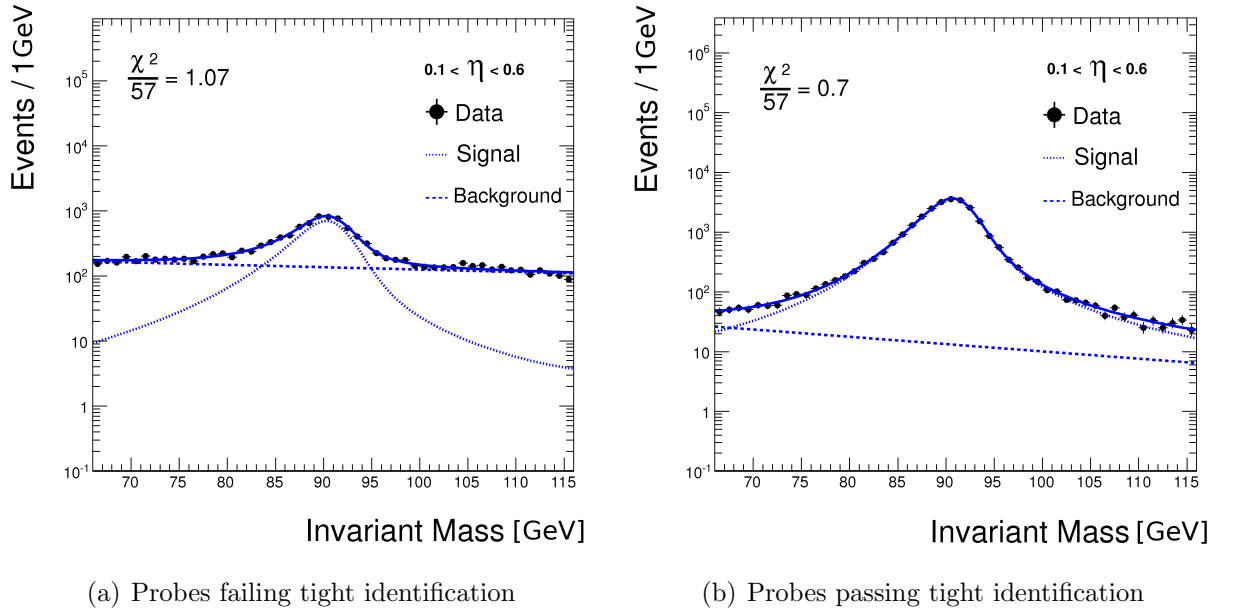


Figure 7.1: Example background fits

Fits for probes failing and passing the tight requirement. The two dashed lines are the signal and background shapes: a Breit Wigner convolved with a Crystal Ball³ function for the signal and a falling exponential for the background.

To remove background, a fit is performed using a Breit Wigner convolved with a Crystal Ball³ function for signal and a simple falling exponential for background, an example of which is shown in figure 7.1. The mass and width of the Breit Wigner are fixed at the

³The Crystal Ball function, named after the Crystal Ball Collaboration, is a probability density function consisting of a Gaussian core portion and a power-law low-end tail, below a certain threshold.

nominal values while all other parameters are free to vary within a reasonable range. The fit is carried out both for probes that do not, and those that do pass tight identification criteria. Background fits are carried out for inclusive charge based on the assumption that the background should be charge symmetric. Half of this charge symmetric background is then subtracted for each probe charge before calculating the efficiency.

After performing this background subtraction, the efficiency of selecting a tight electron is taken as the number of probes passing tight identification criteria divided by the number of probes in total. This is done for reconstructed positrons and electrons in the bins of pseudorapidity used in the asymmetry measurement and yields the results presented in figure 7.2(a). There are some differences between data and MC, but these are expected and accounted for in the analysis by the application of the charge inclusive scale factors. The most significant difference between data and MC efficiencies is in the bins nearest the acceptance gap in the calorimetry. This is due to mismodelling of the material in this region of the detector, specifically that of the cables required to readout and power the inner detector.

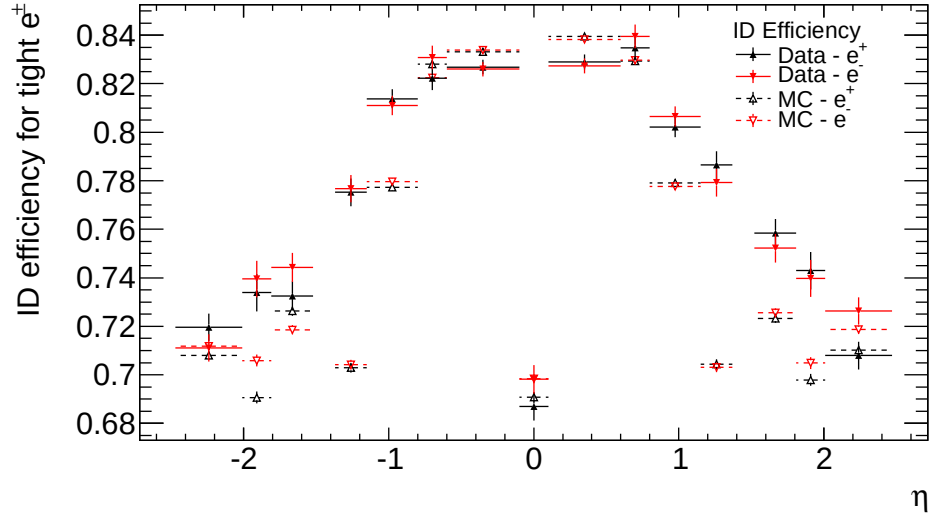
There is no clear reason to suspect any charge asymmetric effects hidden within these scale factors, as is further shown in figure 7.2(b), showing the ratio of efficiencies for positive and negative probes in both data and MC.

7.3.2 Charge misidentification

Electrons can have their charge misidentified in the ATLAS detector due to the possibility that showering electrons can have a secondary track matched to the calorimeter cluster⁴. In the case that material effects and alignment were perfectly modelled in the MC, the charge misidentification rate should show good agreement between data and MC. The correction factors take into account any misidentification of charge so long as it is correctly modelled in the MC.

To test for differences between data and MC, a slightly modified version of the tag and

⁴In the case of very high transverse momentum, the charge can be misidentified due to the finite measurement precision, however this effect is negligible for electrons considered in this analysis.



(a) Tight identification efficiency

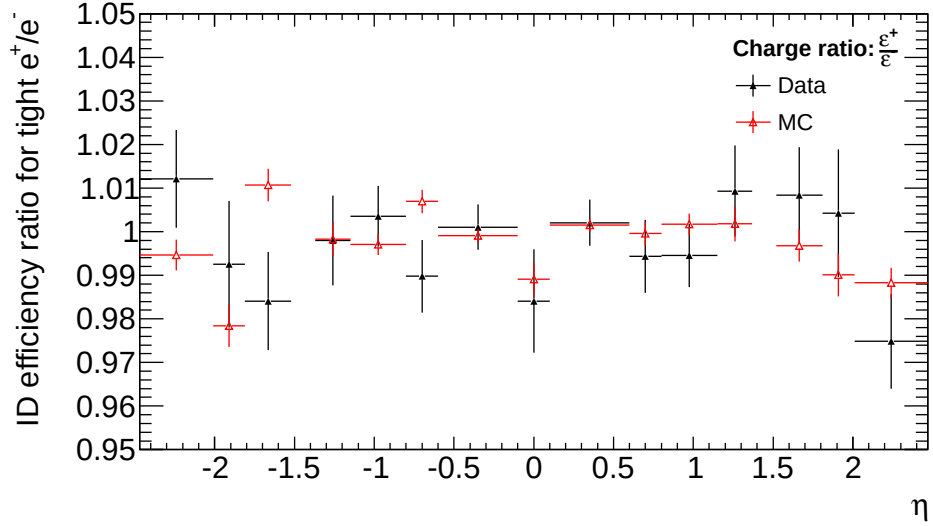
(b) Ratio of efficiencies for $e^\pm$; $\frac{\epsilon_{ID}^+}{\epsilon_{ID}^-}$

Figure 7.2: Identification efficiency

Efficiency for positively and negatively charged probes for both data and MC in 7.2(a) and the ratio of positive charge to negative charge in 7.2(b). In both plots only statistical uncertainties are shown.

probe methodology described above is adopted. Only events in which there are two electrons passing all lepton preselection described in 5.5.2, tight identification criteria and $E_T > 25$ are considered. From this preselection, a tag is considered to be a central electron candidate with $|\eta| < 0.8$. This is to reduce the chance that the tag has its charge misidentified. Probes are then selected so that the invariant mass of the tag and probe is within a tight window of

80-100 GeV. With this selection, background is negligible and its removal is not considered. A probe is considered to be misidentified in the case that the tag and probe are of the same charge, and correctly identified otherwise. If both electrons in the event can be considered as tags, then a weight of 0.5 is applied to each probe so as to avoid double counting of events. The raw misidentification rate, before considering the possibility that the tag could be misidentified, can then be calculated as

$$\epsilon_{chg}^{\mp} = \frac{N(tag\pm, probe\pm)}{N(tag\pm, probe\pm) + N(tag\pm, probe\mp)} . \quad (7.4)$$

The charge misidentification rate for *positrons* then assumes that an *electron tag* was correctly identified so that if an *electron probe* is found (i.e. a same sign event), then that probe is considered to be an incorrectly identified positron.

This method is carried out for both $Z \rightarrow ee$ MC and data and it is found that the MC agrees well with the data. The raw charge misidentification is shown in figure 7.3(a).

The correction can be made for the possibility that the tag electron has been misidentified [97].

$$\epsilon_{raw} = (1 - \epsilon_{actual}^{tag})\epsilon_{actual}^{probe} + (1 - \epsilon_{actual}^{probe})\epsilon_{actual}^{tag} \quad (7.5)$$

The tag and probe are equally likely to be misidentified for probes in the central region, so the average misidentification rate in all the central bins can be written as follows. Since the tag could be in a different central bin than the probe, all central bins are combined to get an average charge misidentification rate for all the tags.

$$\langle \epsilon_{raw}^{central} \rangle = 2(1 - \langle \epsilon_{actual}^{central} \rangle) \langle \epsilon_{actual}^{central} \rangle \quad (7.6)$$

This gives a quadratic equation in $\langle \epsilon_{actual} \rangle$. For small charge misidentification rates, one solution will be close to 0 and the other close to 1. The solution close to 0 can safely be

taken as correct in the current case of charge misidentification in ATLAS.

To evaluate the actual misidentification rate in each bin, the tag is considered to have this average misidentification rate. The misidentification rate in each bin, i , can then be extracted from

$$\epsilon_{raw}^{bin,i} = (1 - \langle \epsilon_{actual}^{central} \rangle) \epsilon_{actual}^{forwardbin,i} + (1 - \epsilon_{actual}^{forwardbin,i}) \langle \epsilon_{actual}^{central} \rangle \quad (7.7)$$

From equations 7.7 and 7.6 the actual misidentification rates can be determined. The charge averaged misidentification rate is shown in figure 7.3(b), with the ratio of positron to electron misidentification rates shown in figure 7.3(c). Even without considering systematic uncertainties on the charge misidentification rate determination, the MC and data agree excellently. This is important since even in the case where the charge misidentification rate of electrons and positrons is the same, charge misidentification acts to dilute the asymmetry since W^+ events migrate to W^- and vice versa. It has been checked here that the MC models the charge misidentification rate sufficiently well that the deviation in the asymmetry using that derived with MC rather than data is an entirely negligible effect.

This agreement suggests that the correction factors used to correct to truth level will adequately model the charge misidentification rate. Since there are no physical reasons to expect that the charge misidentification rate for positrons should be different to that of electrons, this result will be taken to confirm this and no further uncertainty on the asymmetry result will be applied.

7.3.3 Generator choice

The nominal correction factors used in this thesis are determined using the MC@NLO generator where showering and underlying event modelling is performed by HERWIG. MC@NLO is a better choice than, for example, PYTHIA which is only a LO generator. Due to the NLO nature of the generator, higher order effects such as polarisation are modelled more

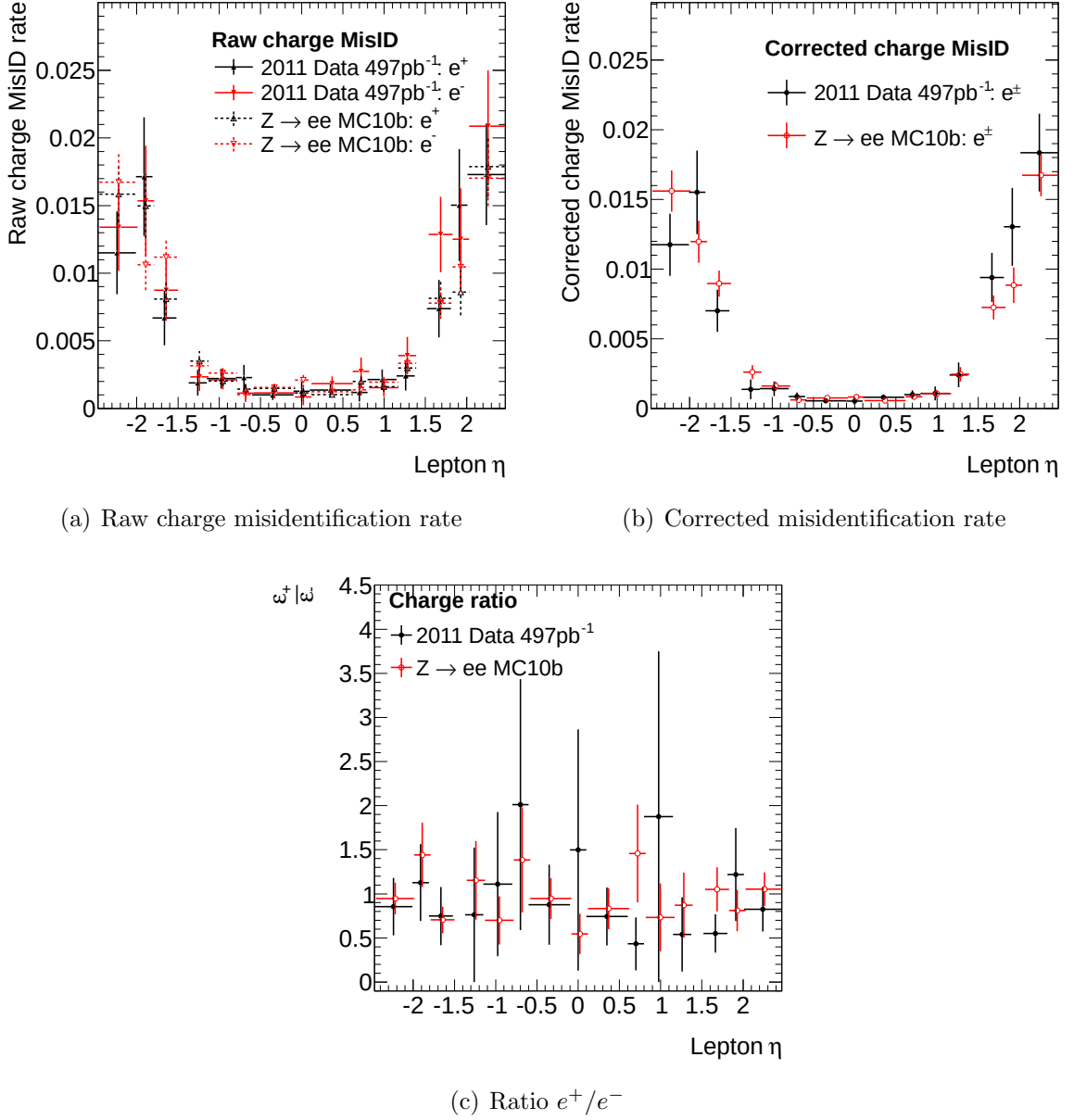


Figure 7.3: Charge misidentification rate

Raw charge misidentification rate (a) for e^+ (black) and e^- (red) in data (filled triangles) and $Z \rightarrow ee$ MC (open triangles). (b) shows the charge averaged charge misidentification rate for data (black) and MC (red). The ratio of charge misidentification rates for positrons and electrons is shown in (c).

correctly. Such effects should be important in the asymmetry measurement. To estimate the uncertainty arising due to generator choice and the way that particle showering and underlying event is modelled, the asymmetry is also calculated using correction factors determined using the POWHEG generator with showering and underlying event modelled instead with PYTHIA. The effect of generator choice and modelling of shower effects and underlying event

		$\mathbf{C_{w\ell+}}$	$\mathbf{C_{w\ell-}}$	$\mathbf{A_\ell \pm (stat)}$	$\delta(\mathbf{A_\ell})$
0.0	$< \eta < 0.1$	0.588	0.586	0.132 ± 0.015	0.007
0.1	$< \eta < 0.35$	0.71	0.707	0.135 ± 0.009	0.004
0.35	$< \eta < 0.6$	0.702	0.708	0.153 ± 0.009	0.0004
0.6	$< \eta < 0.8$	0.689	0.697	0.164 ± 0.01	0.006
0.8	$< \eta < 1.15$	0.654	0.664	0.181 ± 0.008	0.001
1.15	$< \eta < 1.37$	0.588	0.601	0.2 ± 0.01	0.003
1.52	$< \eta < 1.81$	0.547	0.549	0.231 ± 0.009	0.006
1.81	$< \eta < 2.01$	0.545	0.569	0.259 ± 0.011	0.005
2.01	$< \eta < 2.37$	0.568	0.599	0.283 ± 0.008	0.0004
2.37	$< \eta < 2.47$	0.388	0.397	0.287 ± 0.018	0.029

Table 7.3: Correction factors calculated using POWHEG +PYTHIA

The variation in the asymmetry from using correction factors derived from MC@NLO is significant in the outermost bin, however is quite small elsewhere.

are combined here to give one conservative estimate of their combined effect.

The uncertainty determined with correction factors derived from POWHEG instead of MC@NLO is, inclusive in pseudorapidity, a sub-percent effect. When binned in pseudorapidity however there is a large contribution from the final bin, where the asymmetry as calculated using POWHEG correction factors is almost 10% higher than that calculated with the nominal MC@NLO factors. The correction factors determined as a result of using POWHEG are displayed in table 7.3 along with the resulting asymmetry and deviation from the nominal.

This uncertainty is the largest uncertainty on the measurement. Its size is due largely to the lack of statistics in the POWHEG sample used. This estimate of the uncertainty due to generator choice is most certainly an overestimate. The variations in the POWHEG sample are largely statistical fluctuations and in future, alternate methods through which to obtain an uncertainty on the MC generator and parton shower models must be found, or dedicated samples with high statistics generated.

	QCD Template ($\times 10^{-4}$)	Signal Template ($\times 10^{-4}$)	Template Variable ($\times 10^{-4}$)	Fit Bin Width ($\times 10^{-4}$)	Fit Range ($\times 10^{-4}$)	Stat ($\times 10^{-4}$)
0.0 $< \eta < 0.1$	10.3	9.4	4.9	0.7	0.05	17.5
0.1 $< \eta < 0.35$	16.3	14.8	7.7	1.1	0.1	14.1
0.35 $< \eta < 0.6$	7.4	6.7	3.5	0.5	0.04	7.2
0.6 $< \eta < 0.8$	9.3	8.5	4.4	0.6	0.05	8.2
0.8 $< \eta < 1.15$	12.6	11.5	6.0	0.9	0.1	7.7
1.15 $< \eta < 1.37$	13.2	12.0	6.3	0.9	0.1	9.4
1.52 $< \eta < 1.81$	31.1	28.2	14.7	2.1	0.2	13.8
1.81 $< \eta < 2.01$	41.8	37.9	19.8	2.8	0.2	21.2
2.01 $< \eta < 2.37$	57.6	52.3	27.3	3.9	0.3	21.7
2.37 $< \eta < 2.47$	114.7	104.2	54.2	7.7	0.6	64.8

Table 7.4: Systematic uncertainties on QCD background estimate

7.3.4 Backgrounds

For QCD background, the systematic uncertainty on the background estimate is described in chapter 6. There is an uncertainty on the QCD background estimate due to: the choice of QCD background template; the shape of the signal template; the choice of template variable; the bin width used in the fit; and for the range over which the fit was made. The relative uncertainties on the QCD background estimate for each of these sources are determined to be 20.7%, 18.8%, 9.8%, 1.4% and 0.1% respectively. As these errors are simply scale factors, they could be summed in quadrature before applying to the asymmetry, however here variations are considered separately and propagated to the asymmetry to determine their effect. The resulting uncertainties on the asymmetry from each of the systematic uncertainties considered for the QCD background are tabulated in table 7.4. Also shown is the variation in the asymmetry caused by the statistical uncertainty on the QCD background estimate. Since the QCD background was determined using a charge inclusive sample, the statistical uncertainty is the same for both charges. Variations are done in the same way as the systematic uncertainties.

The uncertainties on the QCD background, when added in quadrature, present the second largest uncertainty on the asymmetry measurement after the generator uncertainty in section 7.3.3. In future measurements, this could also be reduced by obtaining higher statis-

	$e^\pm$ Energy Scale ($\times 10^{-4}$)	$e^\pm$ Energy Resolution ($\times 10^{-4}$)
0.0 $< \eta < 0.1$	4.2	6.3
0.1 $< \eta < 0.35$	2.5	2.2
0.35 $< \eta < 0.6$	3.5	2.0
0.6 $< \eta < 0.8$	1.9	0.6
0.8 $< \eta < 1.15$	1.1	1.5
1.15 $< \eta < 1.37$	2.5	0.8
1.52 $< \eta < 1.81$	3.9	1.1
1.81 $< \eta < 2.01$	5.3	2.2
2.01 $< \eta < 2.37$	2.1	2.1
2.37 $< \eta < 2.47$	0.8	1.3

Table 7.5: Systematic uncertainty on the asymmetry due to uncertainties on electron energy scale and resolution

tic QCD background samples from dedicated triggers with lower prescales and by further refining the cuts to reverse.

The dominant source of uncertainty on the EW and $t\bar{t}$ backgrounds is the uncertainty on the cross section used to normalise the MC distributions. This is 5 % and 6 % for W and Z processes respectively, then 7 % for $t\bar{t}$ and di-boson sources [92]. On top of this, there is the fact that these backgrounds are normalised to the total collected luminosity of the data. The luminosity has an uncertainty of 3.7 % that leads to further normalisation uncertainty on the background. Due to the charge symmetry of this uncertainty, the total uncertainty on these backgrounds is negligible in the final asymmetry measurement.

7.3.5 Electron energy scale and resolution

The electron scale and resolution are varied within their given uncertainties and new correction factors determined. The default energy scale corrections that are applied in data are applied in MC and varied by their uncertainty. Similarly, the energy smearing introduced in MC to improve MC agreement with data is varied within its stated uncertainty. The resulting variations in correction factors are propagated to the asymmetry and a systematic uncertainty displayed in table 7.5.

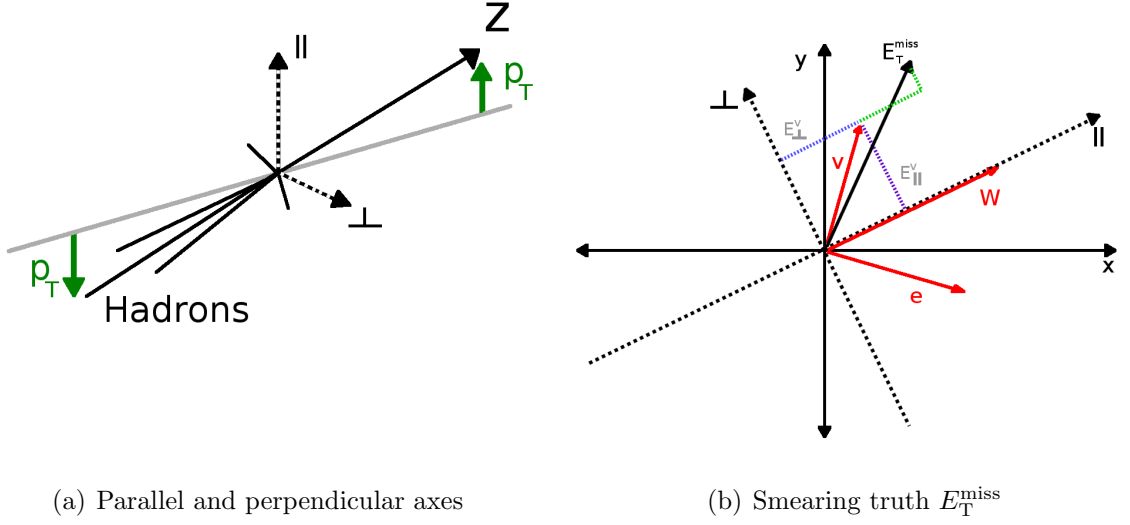
7.3.6 E_T^{miss} uncertainty

The E_T^{miss} resolution is expected to be the same for W^+ and W^- events so the measurement uncertainty largely cancels in the asymmetry. There are however slight differences in the E_T^{miss} in W^+ and W^- events so the effect of its possible mismeasurement on the asymmetry should be studied. A study is performed to get a data driven uncertainty on the E_T^{miss} by looking at so called ‘fake E_T^{miss} ’ in $Z \rightarrow ee$ events, following the methodology of [98, 99].

E_T^{miss} can be classified as real or fake, depending on whether it originates from a neutrino or not. In both $Z \rightarrow ee$ and $W \rightarrow e\nu$ events, any fake E_T^{miss} measured should be directly related to the hadrons recoiling off the boson in the event. Since the hadron production in both is assumed to be the same, the fake E_T^{miss} can be determined using $Z \rightarrow ee$ events where there are no neutrinos present, and consequently no real E_T^{miss} . Measurements of this fake E_T^{miss} can then be used to determine functions with which to smear truth E_T^{miss} (the neutrino p_T) to arrive at an approximation of the reconstructed E_T^{miss} in W events. The uncertainty on the smearing functions can be used to determine an uncertainty in the E_T^{miss} and hence the asymmetry.

$Z \rightarrow ee$ events are chosen using events in which there is at least one electron passing all preselection and tight identification criteria, and then a further electron candidate passing at least medium identification criteria. Such a choice is made over events with two electron candidates passing tight identification criteria, so as to increase statistics. The background contamination with this selection remains minimal so that for this study, no background subtraction is applied. In each event, the transverse component of the Z direction is reconstructed from the two electrons in the event. The E_T^{miss} in the event is then projected onto axes parallel, $E_{T,\parallel}^{\text{miss}}$, and perpendicular, $E_{T,\perp}^{\text{miss}}$, to the boson p_T , as shown in figure 7.4(a).

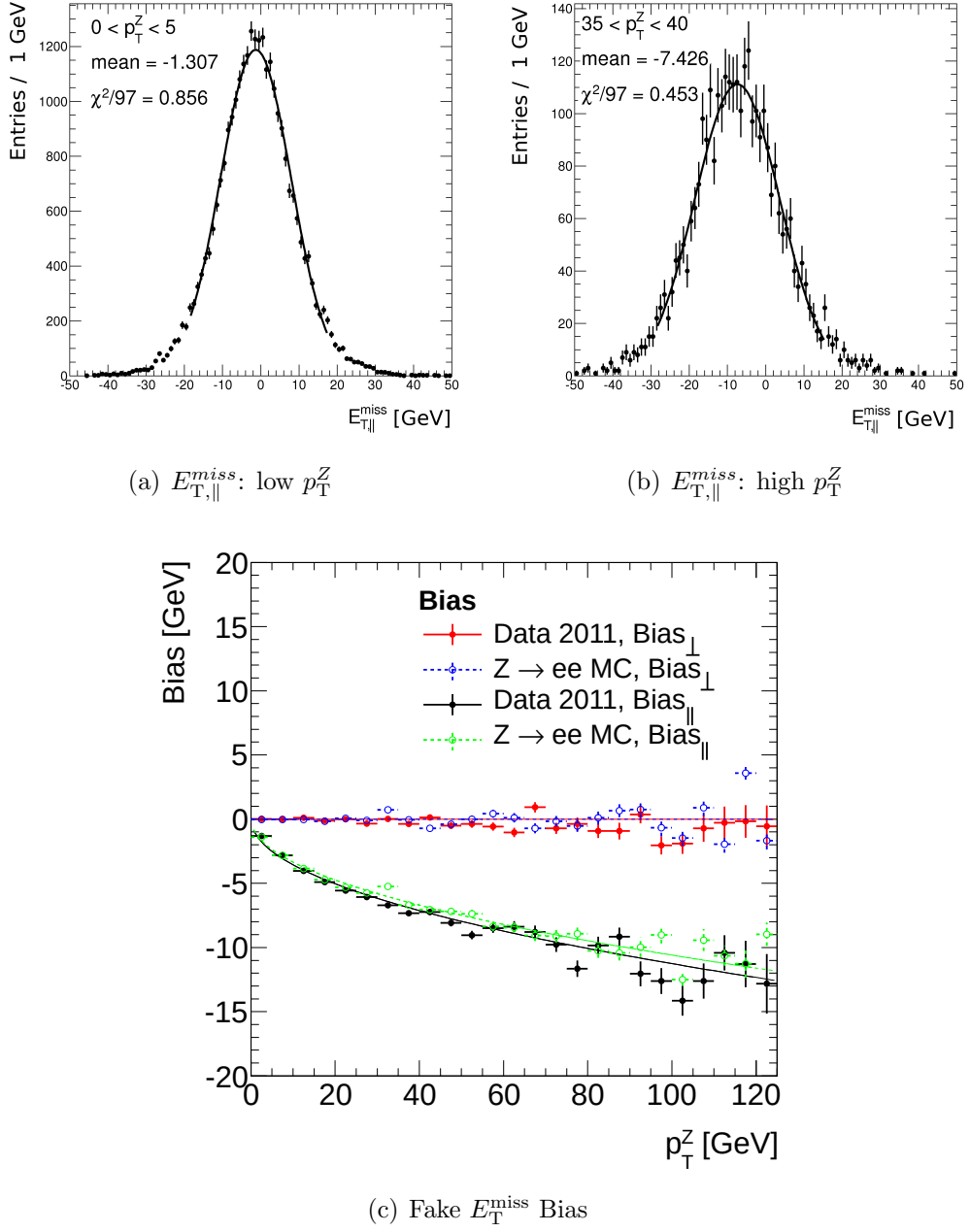
The fake E_T^{miss} is divided into two contributions, the first being from some systematic bias in the measurement, due to, for example, an incorrect energy scale. The p_T of hadrons should cancel in the perpendicular direction, so a bias is only expected in the $E_{T,\parallel}^{\text{miss}}$ distribution. This bias is measured in bins of p_T^Z , by extracting the mean of a Gaussian fitted to the $E_{T,\parallel}^{\text{miss}}$

Figure 7.4: Axis definitions for fake E_T^{miss} study

In (a) the parallel ($\parallel$) and perpendicular ($\perp$) axes are shown with respect to p_T^Z . The E_T^{miss} in Z events is projected onto these axes. The method for smearing the neutrino p_T in W events is represented in (b). The p_T of the neutrino is projected onto axes parallel ($\parallel$) and perpendicular ($\perp$) to the p_T^W and then smeared by two Gaussian functions (green dotted lines) in order to arrive at a recalculated E_T^{miss} . Figures as in [99].

distribution in each bin. Examples of such fits are shown in figures 7.5(a) and 7.5(b). The fits result in the bias distribution shown in figure 7.5(c).

The second contribution to the fake E_T^{miss} comes from effects which introduce a smearing term, primarily from the energy resolution of the detector but also, for example, hadrons lost outside of acceptance or faked by instrumental noise. To measure this term, each event has the bias in the $E_{T,\parallel}^{\text{miss}}$ direction corrected, according to the average bias measured in the previous iteration for the p_T^Z in the event. The parallel and perpendicular components of the E_T^{miss} are then plotted in bins of the scalar sum of hadronic transverse energy in the event, the $\sum E_T^{\text{had}}$. The electron E_T is removed from the total $\sum E_T$ as effects associated with electron energy resolution and scale uncertainty are negligible compared to fake E_T^{miss} arising from hadronic mismeasurements. The resolution of the fake E_T^{miss} is binned in $\sum E_T^{\text{had}}$ as it is expected that as activity in the event increases, for which $\sum E_T^{\text{had}}$ is a good indicator, more fake E_T^{miss} is generated, going as the square root of the $\sum E_T^{\text{had}}$ for fake E_T^{miss} originating in

Figure 7.5: E_T^{miss} bias extraction

In (a) and (b) the component of the E_T^{miss} parallel to p_T^Z is fit with a Gaussian in bins of p_T^Z to extract the bias. In (c) the bias is shown with blue markers representing the perpendicular component and black the parallel component. MC is shown with dashed lines and open markers.

hadronic recoil.

The resolution, taken from a Gaussian fit in each bin, ($\sigma_{\perp}$ and $\sigma_{\parallel}$), is then plotted for $E_{T,\perp}^{miss}$ and $E_{T,\parallel}^{miss}$ as a function of $\sum E_T^{had}$. Examples of the fit in bins of $\sum E_T^{had}$ are shown in figures 7.6(a) and 7.6(b).

The resulting fake E_T^{miss} resolution distribution is shown in figure 7.6(c). A square root function is fitted to the distributions giving good agreement, where the first bin is excluded from the fit due to low statistics and a poor fit to the components of the E_T^{miss} .

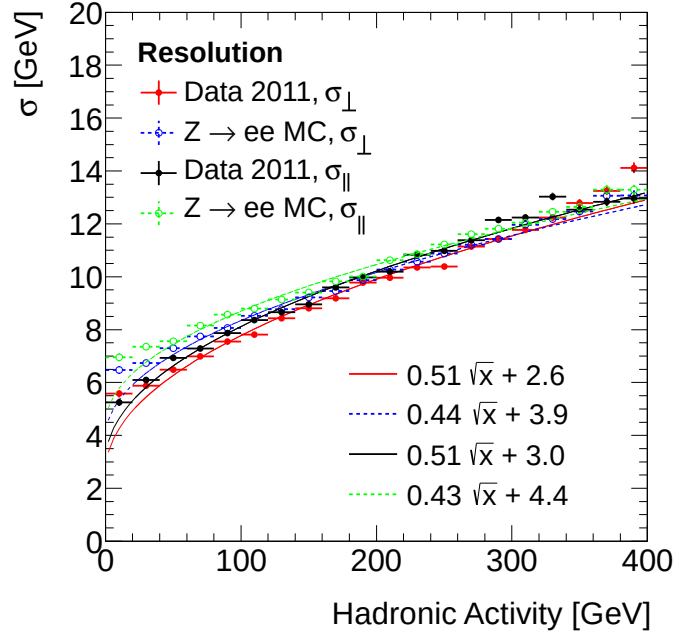
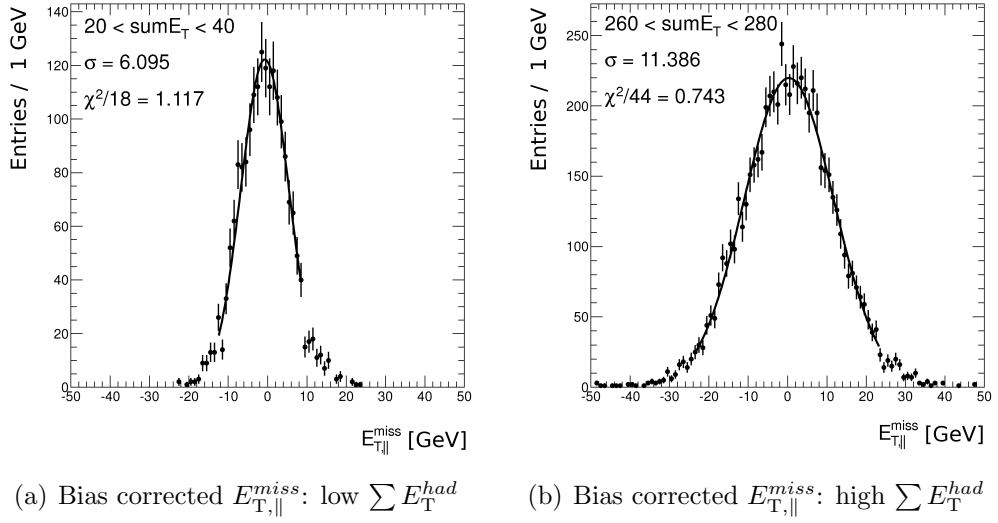
To use the components of the fake E_T^{miss} measured in $Z \rightarrow ee$ events above in W events, a correction is applied to the true E_T^{miss} originating from neutrinos. In a given MC event, the E_T^{miss} is measured at truth level (the neutrino p_T). The p_T of the W boson is reconstructed and the true E_T^{miss} projected onto the parallel and perpendicular axes as is done in Z events. The two components are then corrected as

$$E_{x,\parallel}^{\text{miss}} = p_{\parallel}^{\nu} + \text{gaus}(\text{Bias}(p_T^W), \sigma_{\parallel}(\sum E_T^{\text{had}}))$$

$$E_{x,\perp}^{\text{miss}} = p_{\perp}^{\nu} + \text{gaus}(0, \sigma_{\perp}(\sum E_T^{\text{had}}))$$

where $\text{gaus}(x, y)$ represents a Gaussian centred at x with standard deviation y . This smearing process is shown pictorially in figure 7.4(b). After correcting the perpendicular and parallel components, the ‘reconstructed’ E_T^{miss} can be used as a replacement for the normal reconstructed E_T^{miss} . The difference in shape between **LocHadTopo** and this reconstructed E_T^{miss} is shown in figure 7.7. The recalculated E_T^{miss} is somewhat high in the peak of the distribution and a little low in the higher E_T^{miss} region, however is in good agreement.

To estimate the uncertainty on the asymmetry using this technique, the bias and resolution are varied within their statistical error band. By ensuring that the two separate resolution functions are varied in the same direction together, there are 8 possible error combinations. The asymmetry is determined using each of these variations and the maximum deviation from the asymmetry determined using the central values of the bias and resolution functions. This deviation is taken as the uncertainty on the asymmetry due to E_T^{miss} measurement. The resulting uncertainty, shown in table 7.6, is low but represents a good first estimate of the uncertainty on the asymmetry coming from mismeasurement of E_T^{miss} .

(c) Fake E_T^{miss} ResolutionFigure 7.6: Example fits to fake E_T^{miss} components

The bias in $E_{T,\parallel}^{miss}$ is corrected for and fits made to each component of E_T^{miss} in bins of the hadronic activity in the event, $\sum E_T^{had}$, examples of which are shown in (a) and (b). In (c) the resolution as a function of $\sum E_T^{had}$ is shown, with blue markers representing the perpendicular component with respect to p_T^Z and black markers the parallel component. MC is shown with dashed lines and open markers. The fitted $a\sqrt{\sum E_T^{had}} + b$ function is also shown on the legend. The χ^2 for these fits, which exclude the first bin due to poor statistics, is acceptable, with $\chi^2/18$ ranging from 2 to 5 for the four fits.

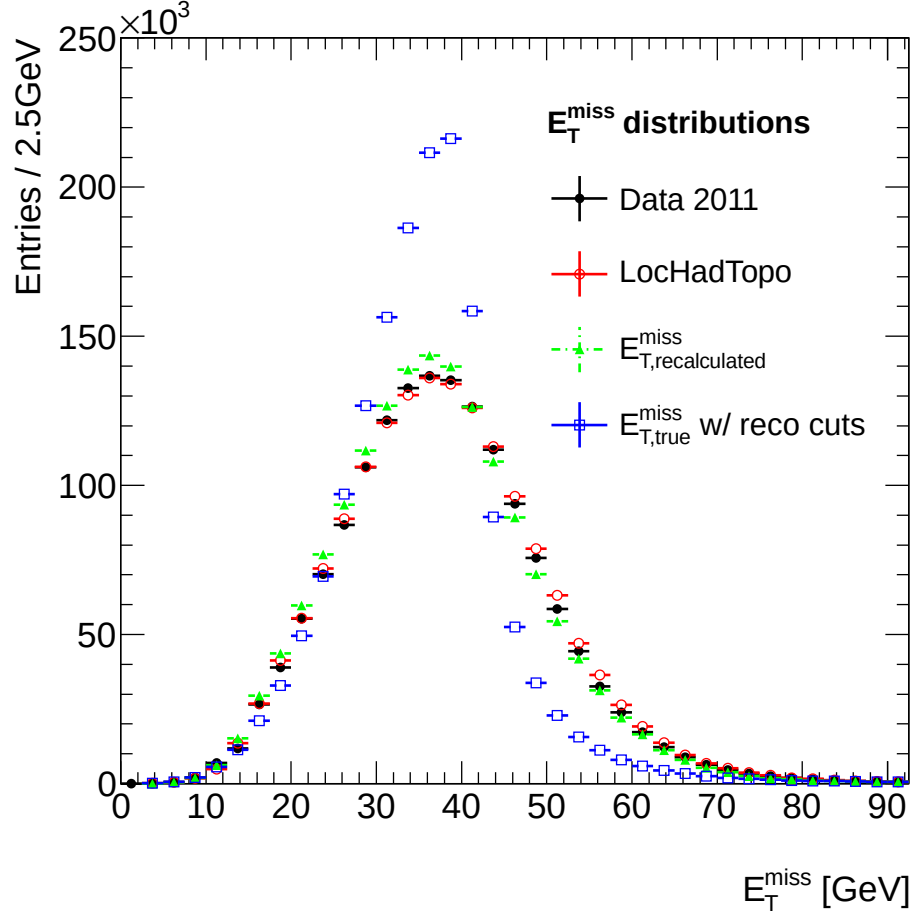


Figure 7.7: Recalculated E_T^{miss} distribution

The E_T^{miss} is recalculated using bias and resolution functions determined from data (green points), and compared to the distribution obtained by using the true E_T^{miss} from the neutrino in the event (blue open squares), the E_T^{miss} as calculated using the LocHadTopo definition (red open circles) and data (black closed circles).

7.3.7 Isolation uncertainty

This analysis uses a cut on the calorimeter isolation to reject background. This isolation, as described in section 5.2.5, has a correction applied for electron energy leakage and one to account in some part for the effect of pileup. Each of these corrections has an associated uncertainty. The isolation is varied independently for each component and the difference propagated to the correction factors and then the asymmetry. This is confirmed to be a basically charge symmetric effect with a total systematic uncertainty on the measurement from isolation corrections being less than 5×10^{-4} (half a percent) in most bins, as shown in table 7.7

	Uncertainty due to E_T^{miss} ($\times 10^{-4}$)
0.0 $< \eta < 0.1$	3.7
0.1 $< \eta < 0.35$	2.6
0.35 $< \eta < 0.6$	2.9
0.6 $< \eta < 0.8$	2.0
0.8 $< \eta < 1.15$	1.9
1.15 $< \eta < 1.37$	1.7
1.52 $< \eta < 1.81$	1.5
1.81 $< \eta < 2.01$	1.1
2.01 $< \eta < 2.37$	2.4
2.37 $< \eta < 2.47$	1.5

Table 7.6: Systematic uncertainty on asymmetry as determined using recalculated E_T^{miss}

	Energy leakage ($\times 10^{-4}$)	Pileup ($\times 10^{-4}$)
0.0 $< \eta < 0.1$	4.0	7.1
0.1 $< \eta < 0.35$	1.2	1.5
0.35 $< \eta < 0.6$	1.4	2.6
0.6 $< \eta < 0.8$	2.0	3.0
0.8 $< \eta < 1.15$	0.9	2.5
1.15 $< \eta < 1.37$	3.1	4.3
1.52 $< \eta < 1.81$	3.3	11.5
1.81 $< \eta < 2.01$	2.8	1.9
2.01 $< \eta < 2.37$	1.5	3.2
2.37 $< \eta < 2.47$	2.8	2.7

Table 7.7: Systematic uncertainties on asymmetry from isolation corrections

There is a further possible source of systematic uncertainty originating in the isolation cut used in this analysis. There are scale factors used to correct reconstruction, trigger and identification efficiencies in MC so that they more accurately represent those found in data. This is not the case for isolation. To see if there is any bias introduced, the isolation efficiency is determined using a tag and probe analysis similar to that explained in section 7.3.1, scale factors applied to MC and the effect on the correction factors and ultimately the asymmetry studied.

The tag for this study must pass all the same selection criteria as in section 7.3.1, but must also be isolated⁵. The probe must pass all the same cuts apart from isolation. The isolation efficiency is then determined by comparing the number of probes passing the isolation requirement, to the total number of probes. The isolation efficiency is determined with respect to reconstruction, trigger and identification efficiencies, so scale factors to adjust the MC efficiencies for these three effects are applied.

The efficiencies for electrons and positrons are shown in figure 7.8(a). MC does appear to require a correction in order that the efficiency of the isolated lepton selection cut be correctly modelled. The scale factors required for both positrons and electrons are shown in figure 7.8(b). There are no significant differences between positive and negative charge in these scale factors, indicating that the use of a combined charge scale factor for isolation efficiency would suffice. Since it is available, the charge separated correction factors are applied to determine the effect on the asymmetry of using such corrections.

Applying these scale factors, recalculating the corrections and determining the deviation in asymmetry yields only a very small change of less than 0.3 % in all bins, as shown in table 7.8. This deviation is simply taken as a further systematic uncertainty on the measurement.

⁵An isolated electron is one that has passed the main isolation cut used in this analysis; i.e. $E_T^{cone}(0.3) < 4 \text{ GeV}$.

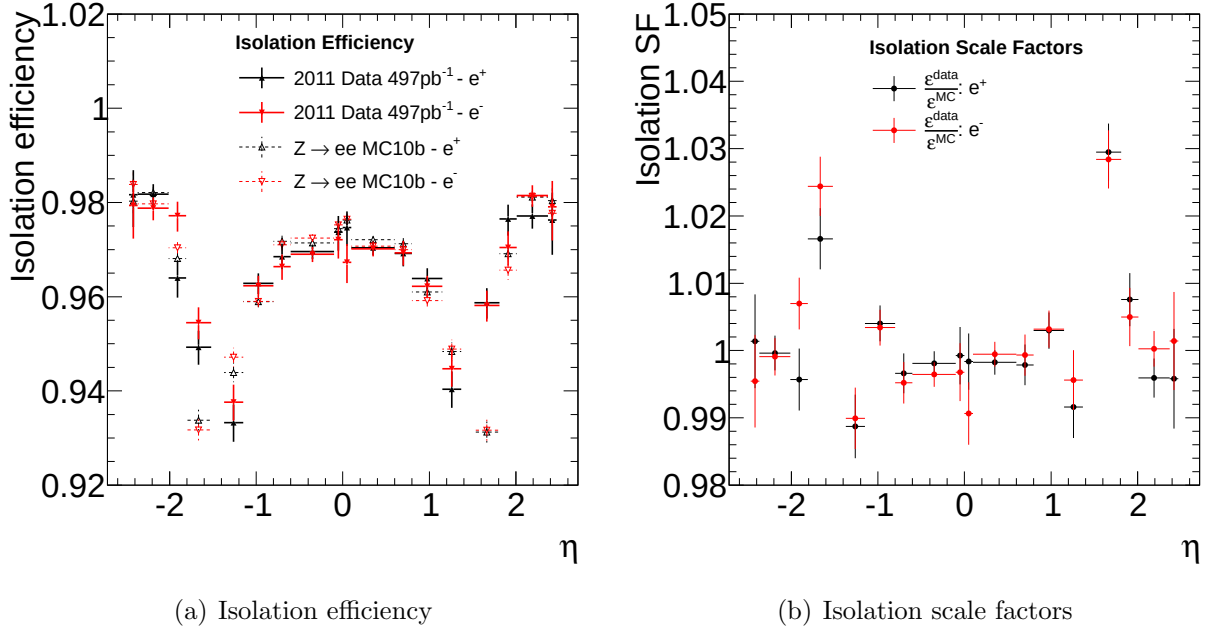


Figure 7.8: Isolation efficiency

The efficiency of the isolation cut as determined using $Z \rightarrow ee$ tag and probe is shown in (a) for data and MC for both charges of lepton. The scale factors required to correct the efficiency of the isolation cut in MC to that of data are shown in (b).

7.3.8 Other negligible effects

Effects on the asymmetry from electron object quality cuts, E_T^{miss} cleaning and the veto of jets falling near the gap in acceptance in the EM calorimeter were studied. All were entirely negligible effects on the asymmetry.

7.3.9 Summary of Uncertainties

The various uncertainties discussed in this chapter are in some cases upper limits on the effect of each on the final asymmetry. It is clear that the measurement is now dominated by systematic uncertainty rather than statistical, so to improve the power of the measurement requires further refinement of the systematic uncertainty determination.

The statistical components of the correction factors, the EW backgrounds and the data yields are included in the statistical uncertainty below. Further to this, the statistical uncertainty coming from the QCD background, and the uncertainty on the isolation corrections

			Isolation Scale Factor uncertainty ($\times 10^{-4}$)
0.0	$< \eta < 0.1$		3.5
0.1	$< \eta < 0.35$		0.3
0.35	$< \eta < 0.6$		0.8
0.6	$< \eta < 0.8$		3.9
0.8	$< \eta < 1.15$		2.6
1.15	$< \eta < 1.37$		5.6
1.52	$< \eta < 1.81$		5.2
1.81	$< \eta < 2.01$		4.5
2.01	$< \eta < 2.37$		5.4
2.37	$< \eta < 2.47$		0.04

Table 7.8: Systematic uncertainty on asymmetry due to isolation efficiency difference

are not correlated between the bins, as separate fits were carried out for each bin to determine them. The systematic uncertainty on the QCD background was determined using a sample inclusive in lepton pseudorapidity and the same fractional uncertainty applied to all bins, meaning this source of uncertainty is considered fully correlated. All of the other uncertainties presented are assumed to be fully correlated bin to bin.

7.4 Final lepton asymmetry result

The lepton asymmetry is plotted alongside predictions for three of the main PDF collaborations in figure 7.9(a). Further information on the tool used to generate these predictions, APPLGrid, will be presented in the next chapter. Similarly, a discussion of the impact on PDFs that this data can have is held to the next chapter. It is clear however that there is some discrimination between the predictions of different PDF sets in the central regions. These data, probing lower x and higher Q^2 values for the valence PDFs than ever before, agree better with the prediction of the CT10 PDF set than the MSTW 2008 set. The agreement of the predictions can be quantified using a χ^2 formula, defined as

$$\chi^2 = \sum_i \sum_j \left[A_{\ell,i}^{pred} - A_{\ell,i}^{meas} \right] V_{ij}^{-1} \left[A_{\ell,j}^{pred} - A_{\ell,j}^{meas} \right] , \quad (7.8)$$

where for a given bin, i , $A_{\ell,i}^{pred}$ is the predicted asymmetry, $A_{\ell,i}^{meas}$ is the measured asymmetry and V_{ij}^{-1} is the inverse of the covariance matrix. The covariance matrix can be defined as

$$V_{ij} = \delta_{ij}\sigma_i^2 + \sum_{\lambda} \Delta_{i\lambda}^{sys} \Delta_{j\lambda}^{sys} , \quad (7.9)$$

where σ_i represents the uncorrelated uncertainties, and $\Delta_{i\lambda}^{sys}$ the correlated systematic uncertainty due to source λ in bin i [20]. This does not take into account the uncertainty on the PDF prediction. The reduced χ^2 between the 10 data points and the CT10, HERAPDF 1.5 and MSTW 2008 predictions are, $\frac{\chi^2}{ndf} = \frac{8.3}{10}$, $\frac{16.4}{10}$ and $\frac{133.8}{10}$ respectively. This indicates that the central predictions of the CT10 and HERAPDF 1.5 PDF sets are in agreement with the measurement. The disagreement within experimental uncertainties of the central prediction of the MSTW 2008 PDF set is an indication that if these data were to be included in the fit, they would likely cause an upward shift in the central prediction.

Figure 7.9(b) shows the NLO and NNLO (next-to-next-to-leading order) predictions for the same three main PDF collaborations as calculated using DYNLO [100]. There is no significant difference between NLO and NNLO predictions, and the predictions agree well with those obtained using APPLGrid and MCFM. Final asymmetries along with uncertainties are displayed in table 7.9. The uncorrelated systematic uncertainties are shown added in quadrature, as they are used for PDF fitting. They include the uncertainty on the asymmetry due to the statistical uncertainty on the QCD background and the two isolation correction uncertainties.

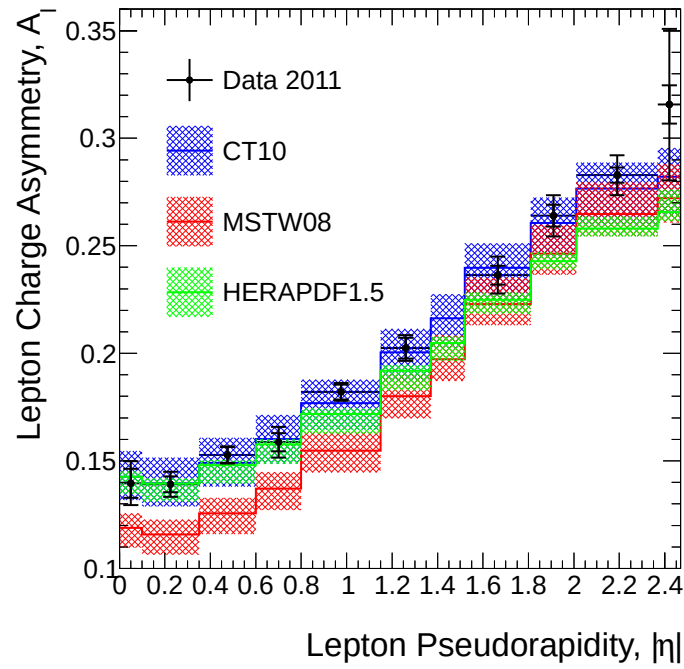
In table 7.10, each of the correlated systematic uncertainties is shown. The 13 correlated systematic uncertainty sources, labelled σ_{1-13} in the table correspond to the uncertainty on the asymmetry due to that of:

- the reconstruction efficiency scale factor, σ_1 ;
- the tight identification efficiency scale factor, σ_2 ;

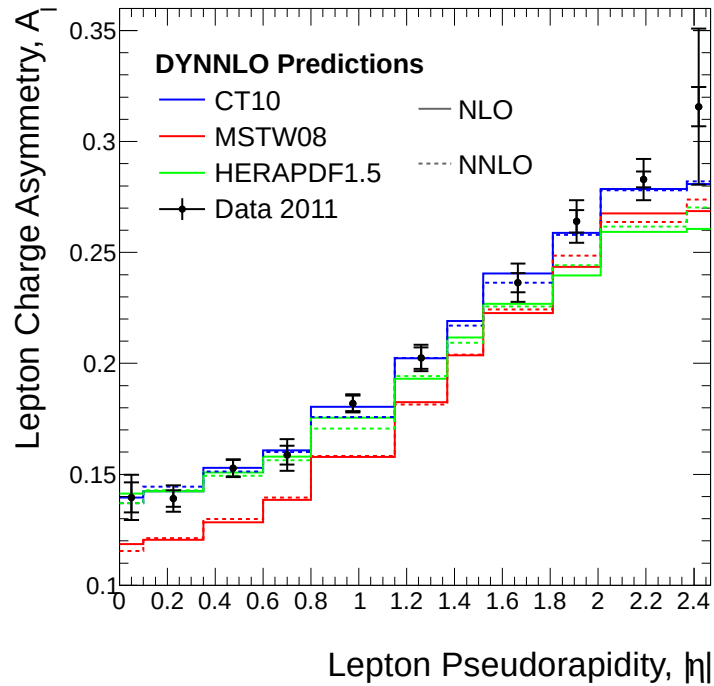
- the trigger efficiency scale factor, σ_3 ;
- the choice of generator/showering MC, σ_4 ;
- determination of QCD background, namely
 - the QCD background template choice, σ_5 ,
 - the signal template choice, σ_6 ,
 - the choice of template variable, σ_7 ,
 - the bin width used in the likelihood fit, σ_8 ,
 - the range over which the template fit was carried out, σ_9 ;
- the electron energy scale, σ_{10} ;
- the electron energy resolution, σ_{11} ;
- the measurement of E_T^{miss} , σ_{12} ;
- not using isolation efficiency scale factors, σ_{13} .

Though the measurement is now dominated by systematic uncertainties, there is still scope for improvement. In future the systematic uncertainty on the generator and showering MC choice can be reduced significantly by producing dedicated high statistics samples with which to study these effects. With the possibility that ATLAS could have up to 5 fb^{-1} of data collected by the end of 2011, there will be an order of magnitude more $Z \rightarrow ee$ events with which to more accurately measure any charge dependence in electron efficiencies. QCD background uncertainties can be reduced by increasing the statistics of the QCD background template and consequently the sample with which to make systematic variations.

Given that the current measurement is showing some discrimination between PDF sets, any future measurements where the systematic uncertainty is further reduced will provide vital information to constrain PDF uncertainties. The next chapter looks in some detail at the constraining power that this measurement can have in PDF fits.



(a) MCFM + APPLGrid predictions



(b) DYNNLO predictions

Figure 7.9: Measured lepton asymmetry and predictions

Comparison with three leading PDF predictions at NLO, made using MCFM and APPLGrid in (a) and DYNNLO in (b). The full uncertainty band is shown in (a), calculated as described in section 3.3.1, while (b) also shows the NNLO predictions. The first tick mark on the error bar represents the statistical component of the uncertainty and the outer tick mark represents the total uncertainty.

		A_ℓ	Stat	Uncor	Corr	Total
0.0	$< \eta < 0.1$	0.1396	0.0067	0.0019	0.0074	0.0102
0.1	$< \eta < 0.35$	0.1391	0.0037	0.0014	0.0043	0.0059
0.35	$< \eta < 0.6$	0.1528	0.0037	0.0008	0.0013	0.004
0.6	$< \eta < 0.8$	0.1587	0.0042	0.0009	0.0057	0.0072
0.8	$< \eta < 1.15$	0.182	0.0034	0.0008	0.0022	0.0041
1.15	$< \eta < 1.37$	0.2024	0.0048	0.0011	0.0033	0.006
1.52	$< \eta < 1.81$	0.2364	0.0044	0.0018	0.0072	0.0086
1.81	$< \eta < 2.01$	0.264	0.005	0.0021	0.0079	0.0096
2.01	$< \eta < 2.37$	0.2829	0.0036	0.0022	0.0083	0.0093
2.37	$< \eta < 2.47$	0.3157	0.0089	0.0065	0.0335	0.0352

Table 7.9: Final asymmetry measurement with total uncertainties

The pseudorapidity range, measured lepton asymmetry and absolute statistical, uncorrelated systematic and correlated systematic uncertainties are shown. Correlated uncertainties are considered 100 % correlated bin-to-bin.

	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	σ_7	σ_8	σ_9	σ_{10}	σ_{11}	σ_{12}	σ_{13}
0.0 $< \eta < 0.1$	7e-09	0.0001	4e-08	0.0072	0.001	0.0009	0.0005	7e-05	5e-06	0.0004	0.0006	0.0004	0.0004
0.1 $< \eta < 0.35$	2e-08	0.0001	7e-08	0.0036	0.0016	0.0015	0.0008	0.0001	8e-06	0.0003	0.0002	0.0003	3e-05
0.35 $< \eta < 0.6$	2e-08	0.0002	4e-07	0.0004	0.0007	0.0007	0.0004	5e-05	4e-06	0.0003	0.0002	0.0003	8e-05
0.6 $< \eta < 0.8$	2e-07	0.0002	3e-07	0.0055	0.0009	0.0008	0.0004	6e-05	5e-06	0.0002	6e-05	0.0002	0.0004
0.8 $< \eta < 1.15$	4e-08	0.0002	9e-07	0.0011	0.0013	0.0011	0.0006	9e-05	6e-06	0.0001	0.0001	0.0002	0.0003
1.15 $< \eta < 1.37$	2e-08	0.0001	1e-07	0.0027	0.0013	0.0012	0.0006	9e-05	6e-06	0.0002	8e-05	0.0002	0.0006
1.52 $< \eta < 1.81$	1e-08	0.0002	2e-06	0.0056	0.0031	0.0028	0.0015	0.0002	2e-05	0.0004	0.0001	0.0002	0.0005
1.81 $< \eta < 2.01$	3e-08	9e-05	2e-06	0.0051	0.0042	0.0038	0.002	0.0003	2e-05	0.0005	0.0002	0.0001	0.0005
2.01 $< \eta < 2.37$	1e-05	0.0002	2e-07	4e-05	0.0058	0.0052	0.0027	0.0004	3e-05	0.0002	0.0002	0.0002	0.0005
2.37 $< \eta < 2.47$	5e-06	6e-05	4e-06	0.0291	0.0115	0.0104	0.0054	0.0008	6e-05	8e-05	0.0001	0.0001	4e-06

Table 7.10: Final asymmetry measurement correlated uncertainties

The 13 correlated systematic uncertainties are shown where the uncertainties to which each column refers described in the text. These absolute uncertainties are considered fully correlated bin-to-bin.

Chapter 8

PDF fits with asymmetry data

In this chapter the formalism and machinery required to make PDF fits to W asymmetry data is introduced. The lepton charge asymmetry presented in the previous chapter is included in these fits to determine its impact.

8.1 PDF fits

As described in section 3.3, PDFs describe the way the proton's momentum is divided up amongst its constituents. The general procedure used to make fits to data and to estimate the PDF uncertainty will not be repeated in this chapter but rather the specific details of the implementation used; that of HERAPDF. The available HERAPDF fits are determined using the combined HERA dataset, and are performed in collaboration between members of the ZEUS and H1 experiments [34]. The specific code used to make PDF fits in this chapter is that of the ZEUS Collaboration, ZEUSfitter [101].

The PDFs are given a parameterisation at the starting scale of $Q_0^2 = 1.9 \text{ GeV}^2$ of the general form

$$xf(x) = Ax^B(1-x)^C(1 + \epsilon\sqrt{x} + Dx + Ex^2) \quad (8.1)$$

where the PDFs that are parameterised are the gluon, xg , the valence quarks, xd_v and xu_v , and the up type and down type anti-quark distributions, $x\bar{U}$ and $x\bar{D}$.

This general parameterisation is applied in the HERA case by initially setting ϵ , E and D to be zero and then introducing them to determine which is the best fit. Leaving E_{uv} free in the fit is found to give the best χ^2 and is retained in the central parameterisation. The resulting central parameterisation is as follows.

$$xg(x) = A_g x^{B_g} (1-x)^{C_g} - A'_g x^{B'_g} (1-x)^{C'_g} , \quad (8.2)$$

$$xu_v(x) = A_{uv} x^{B_{uv}} (1-x)^{C_{uv}} (1 + E_{uv} x^2) , \quad (8.3)$$

$$xd_v(x) = A_{dv} x^{B_{dv}} (1-x)^{C_{dv}} , \quad (8.4)$$

$$x\bar{U}(x) = A_{\bar{U}} x^{B_{\bar{U}}} (1-x)^{C_{\bar{U}}} , \quad (8.5)$$

$$\text{and } x\bar{D}(x) = A_{\bar{D}} x^{B_{\bar{D}}} (1-x)^{C_{\bar{D}}} . \quad (8.6)$$

In addition to the standard parameterisation of HERAPDF 1.0 [34], three more parameters are left free. Firstly there is an allowance that $B_{uv} \neq B_{dv}$, allowing the low x valence quarks to have different powers. This could be important when fitting the up and down valence quark PDFs using the asymmetry data. Secondly there are two further parameters¹ associated with an extended gluon parameterisation allowing the gluon PDF to become negative at low x and Q^2 . It has been seen that by evolving PDFs to lower than $Q^2 \approx 1 \text{ GeV}^2$, the gluon can become valence like and negative at low x . This is a possible sign that the DGLAP formalism breaks down in this energy regime [20]. However so long as the physical observables themselves, the construction of which involves the gluon PDF, do not become unphysical, this is not necessarily an issue.

There are further constraints applied to these parameterisations. The normalisation terms of the gluon and valence quarks are constrained by the quark number and momentum sum rules. An assumption is made that in the low x region the shape of the sea distribution for up and down type quarks is the same, requiring that there be a single B parameter for the sea component, $B_{\bar{U}} = B_{\bar{D}}$. The normalisations for the up and down type sea PDFs are

¹The parameter C'_g is fixed at the value of 25, high enough to avoid contributions from this term at high- x .

also tied together such that $A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$, where f_s is the fraction of strangeness in the down type sea ($f_s = 0.31$ for the central PDF settings [102]). There is no explicit inclusion of the charm or bottom fractions in the sea PDFs since the starting scale is chosen below the charm quark mass. The heavy quark treatment is the same as that of HERAPDF 1.0 [34]. These requirements mean that as $x \rightarrow 0$, the sea component of the up and down quark become identical. In total there are 13 parameters free in the fit.

As described in chapter 3, these parameterised PDFs are evolved in Q^2 using the DGLAP equations and used to calculate a prediction against which data points can be compared. A global χ^2 is built taking into account all of the uncertainties of the various datapoints considered. The χ^2 is then minimised by variation of the input PDF parameters,

8.1.1 χ^2 formulation

The code used to carry out PDF fits in this thesis, that of the ZEUS experiment, is one of two main codes used to fit and cross check the combined HERA dataset. A discussion on the formulation of χ^2 used in PDF fitting, and specifically ZEUSfitter follows, as described in section 6.7 of [20].

An incorrect way of treating the correlated systematic uncertainties would be to sum them in quadrature with the uncorrelated uncertainties. In doing this, the assumption would be that these errors are all Gaussian distributed, which the correlated systematic uncertainties are often not:

$$\chi^2 = \sum_i \frac{[F_i^{\text{NLO QCD}}(p) - F_i(\text{meas})]^2}{\sigma_i^2 + \Delta_i^2}, \quad (8.7)$$

where Δ_i is the quadratic sum of all the correlated systematic uncertainties, σ_i is the quadratic sum of the statistical and uncorrelated uncertainties, $F_i(\text{meas})$ is the measured value and $F_i^{\text{NLO QCD}}(p)$ is the theoretical prediction given parameters p for datapoint i .

To correctly include correlated uncertainties the covariance matrix should be used as in

equations 7.8 and 7.9. An equivalent result can be obtained by including the correlated uncertainties in the theoretical prediction,

$$F_i(p, s) = F_i^{\text{NLO QCD}}(p) + \sum_{\lambda} s_{\lambda} \Delta_{i\lambda}^{\text{sys}}, \quad (8.8)$$

such that each correlated systematic uncertainty, $\Delta_{i\lambda}^{\text{sys}}$, from source λ has its own weight, s_{λ} . The s parameters have zero mean and unit variance by construction. The χ^2 is then

$$\chi^2 = \sum_i \frac{[F_i(p, s) - F_i(\text{meas})]^2}{\sigma_i^2} + \sum_{\lambda} s_{\lambda}^2 \quad (8.9)$$

Either the systematic uncertainty parameters can be set to zero for the central fit then varied to obtain the uncertainty, or they can be fitted along with the PDF parameters. The first is known as an ‘Offset method’ is not used here while the latter is known as a ‘Hessian method’ and is used in ZEUSfitter. The fit picks out the best settings for correlated systematic shifts of the data points so that the most consistent fit to all datasets is achieved.

The formulation of the Hessian method using equation 8.9 becomes difficult with a large number of correlated uncertainties. The following formulation of the χ^2 introduced in [32] allows the contribution to the χ^2 from correlated and uncorrelated uncertainties to be evaluated separately:

$$\chi^2 = \sum_i \frac{[F_i^{\text{NLO QCD}}(p) - F_i(\text{meas})]^2}{\sigma_i^2} - BA^{-1}B, \quad (8.10)$$

where

$$B_{\lambda} = \sum_i \Delta_{i\lambda}^{\text{sys}} \frac{[F_i^{\text{NLO QCD}}(p) - F_i(\text{meas})]}{\sigma_i^2}, \quad (8.11)$$

and

$$A_{\lambda\nu} = \delta_{\lambda\nu} + \sum_i \Delta_{i\lambda}^{\text{sys}} \Delta_{i\nu}^{\text{sys}} / \sigma_i^2. \quad (8.12)$$

The optimal shifts of the systematic uncertainties can be extracted using A and B by

$s = A^{-1}B$. Minimising the χ^2 in 8.10 with respect to the PDF parameters, p , is equivalent to allowing both the PDF parameters, p , and the systematic uncertainty shift parameters, s , to be free when fitting the χ^2 in 8.9.

8.1.2 PDF uncertainties

The CTEQ² and MSTW collaborations issue a number of PDF eigenvector sets that encompass all of their uncertainties. For the published HERAPDF fits this treatment is somewhat different. There are as many pairs of eigenvector PDF sets as there are free parameters in the fit. These encode the experimental uncertainty and the error band is extracted in the same way as it is for the other PDF collaborations, as described in section 3.3.1. Further to this there are PDF sets representing the model uncertainties and the parameterisation uncertainty obtained by varying the input assumptions. Model uncertainties are treated one by one and all positive (negative) differences added in quadrature to obtain the positive (negative) model error, while for parameterisation uncertainties the maximal positive (negative) deviation is taken as the positive (negative) uncertainty.

The model uncertainties considered here are as follows:

- The strange quark fraction, f_s , which represents the fraction of the down type sea attributed to the strange quark, is varied from its central value of 0.31 down to 0.23 and up to 0.38.
- The mass of the charm quark, m_c is varied from its central value of 1.4 GeV down³ to 1.35 GeV and up to 1.65 GeV.
- The mass of the bottom quark, m_b is varied from its central value of 4.75 GeV down to 4.3 GeV and up to 5.0 GeV.
- The minimum Q^2 requirement applied to the HERA data so as to remain in the

²The CTEQ collaboration produces the new CT10 PDF sets as well as the older CTEQ sets.

³Since the starting scale, Q_0 , is required to have a value lower than m_c in the code it is set to $Q_0^2 = 1.8 \text{ GeV}^2$ for this variation.

kinematic region where it is suitable to apply perturbative QCD is varied from 3.5 GeV down to 2.5 GeV and up to 5.0 GeV

The parameterisation uncertainties considered in this work are then as follows. Other parameterisation variations were considered but found to have no significant effect.

- The starting scale $Q_0^2 = 1.9 \text{ GeV}^2$ is varied down⁴ to 1.5 GeV^2 and up⁵ to 2.5 GeV^2 .
- A variation of the parameterisation allowing $D_{u_v} \neq 0$.
- A variation of the parameterisation allowing $D_g \neq 0$.

8.1.3 HERA data

The HERA dataset used in this thesis corresponds to that used to produce the publicly available PDF set, HERAPDF 1.5, and is an extension to that presented in [34]. It includes various QCD analyses of the inclusive $e^\pm p$ scattering cross sections at HERA including of preliminary datasets⁶ as described in [103]. These cross sections can be written as a function of the proton structure functions, $F_i(x, Q^2) \forall i \in \{1, 2, 3\}$, which are themselves combinations of the PDFs. The exact form of the cross section with respect to the structure functions depends on the charge of the lepton probe and whether the charged or neutral current cross section is being measured. The different forms can be found in, for example, [20, 53] however in general the cross section goes as

$$\frac{d^2\sigma}{dx dQ^2} \propto \frac{1}{Q^4} (f(y)F_1(x, Q^2) + g(y)F_2(x, Q^2) + h(y)F_3(x, Q^2)) \quad , \quad (8.13)$$

where rather simplistically $f(y)$, $g(y)$ and $h(y)$ are functions that depend on the kinematics of the scattering.

⁴Since the starting scale and the strange quark fraction are not independent, the values of $f_s = 0.29$ and $f_s = 0.34$ for the downward and upward Q_0^2 variations respectively.

⁵Furthermore, in order that the requirement $Q_0 < m_c$ the charm mass used in the upward variation of the starting scale is $m_c = 1.6 \text{ GeV}$.

⁶The author has privileged access to these data as a member of the ZEUS collaboration

HERAPDF is notable amongst the common PDF sets for its focus on data from only one accelerator. This can be in some cases an advantage, as, for example: poorly understood corrections required to deal with nuclear or deuterium in the case of fixed target experiments are not required; there are no neutrino data heavy target corrections required; and no isospin assumptions. There are also no problems with datasets that seem to be inconsistent, since both H1 and ZEUS agree and the combination takes into account shared uncertainties correctly.

The ZEUSfitter code has been made available by its author in order to include the asymmetry measurement of this thesis [104, 105]. Studies have been ongoing for sometime on the effect of including other collider data, from the Tevatron and more recently the LHC, to the HERAPDF fits [105]. So as to not over estimate the effect that the inclusion of the measurement presented in this thesis would have on PDFs, other measurements of W asymmetry at collider experiments will also be included in fits. This includes the Tevatron asymmetries [58, 57, 59], and the recently published ATLAS muon asymmetry and CMS lepton asymmetry results [106, 61]. The very recent ATLAS inclusive W and Z data are not included in these fits as studies are still ongoing [92].

8.2 Including further data in the fit

There are two main methods currently in use to obtain NLO predictions for W and Z against which to compare the data. The first is the standard method, and involves an analytical calculation with a correction from LO to NLO, and the second uses a tool by the name of APPLGrid. Both are discussed below.

8.2.1 Analytical calculation with k-factors

The current standard within the PDF fitting community for determining theoretical predictions is to make an analytic calculation. An LO calculation can be performed quickly at

each iteration of the fit but an NLO calculation is much more time consuming. Furthermore, to make predictions at NLO for final state observables where detector acceptances or jet algorithms are required, NLO QCD Monte Carlo programs are required. To attempt to do a full NLO calculation at each iteration would be impractical, so in order to obtain an NLO prediction, the LO calculation is corrected to NLO by using k-factors. These are calculated with the starting PDF, and binned in the same way as the measurement, so that for each bin, a LO calculation can be made and a k-factor applied to obtain a NLO prediction. If the PDFs obtained after the fit are significantly different to the input PDFs, the k-factors are recalculated and the process repeated.

The use of k-factors is significantly faster than calculating the NLO prediction at each iteration where this would even be possible. However the fact that the k-factors also need to be refined, and the fits repeated, means that the process is inexact and can still suffer from speed issues.

8.2.2 APPLGrid and MCFM

A new method to determine the NLO prediction without the need for k-factors uses the APPLGrid tool [107]. APPLGrid makes use of the fact that an NLO QCD calculation involves a MC integration over a large number of events. A look-up table, across a grid in x and Q^2 , of cross section weights is generated in an MC run. These weights can then be used in combination with any PDF to determine the NLO prediction.

The details of the APPLGrid implementation can be found in [107], qualitatively however, the main steps are as follows:

- A grid is defined in terms of some variable transformation that gives good coverage of the x and Q^2 range with uniform spacing of grid points.
- The PDF is represented by its values at a grid point and is obtained elsewhere by interpolation.

- Each event in an NLO MC has an associated x and Q^2 value and a weight. Where normally the result for a particular subprocess would be the sum of the product of the weight, PDF and some coupling term, instead a weight grid is updated for each event.
- The resulting weight grid can then be combined with an arbitrary PDF and α_s subsequent to the MC run.
- To extract the final NLO prediction for a given PDF and α_s , a sum over the contributing sub processes, and in the case of pp collisions, the two contributing partons, is carried out.

In principle, any transparent NLO MC program where the event weights are accessible could be used to generate APPLGrid weight grids. For W and Z boson processes, MCFM version 5.2 has been used thus far [108]. MCFM allows the user to set various parameters such as the masses and widths of the vector bosons, the EM coupling constant $\alpha(M_Z)$, and value of the weak mixing angle $\sin^2 \theta_W$. Ongoing studies of the ATLAS inclusive $W^\pm$ and Z/γ^* cross sections suggest that the value of the weak mixing angle could be important. Its effect largely cancels in the asymmetry however so the default parameter definitions of MCFM are used, whereby $\alpha(M_Z)$ and $\sin^2 \theta_W$ are set to their derived values:

$$\frac{1}{\alpha} = \frac{\sqrt{2}G_F M_W^2}{\pi} \left(1 - \frac{M_W^2}{M_Z^2}\right); \quad \sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}; \quad (8.14)$$

where G_F is the fermi coupling constant. Cuts can be applied to the leptons in the event corresponding to the fiducial cuts of the measurement; namely $p_T^\ell > 25$ GeV, $p_T^\nu > 25$ GeV and $m_T(\ell, \nu) > 40$ GeV for the measurement presented in this thesis. Furthermore the prediction and APPLGrid weight grid are binned in absolute pseudorapidity, with the same bin definition as the measurement.

Figure 7.9(a) uses grids produced for $W^\pm$ to calculate the asymmetry for each of three major PDF sets including their error sets. Where normally such a plot might require hundreds of CPU hours to either produce separate predictions for each PDF error set, or to

loop over MC events and reweight each event to the prediction of another PDF set, the convolution of the PDF with the weight grid for this figure took no more than a minute. This same convolution is repeated at each iteration of the PDF fitting, so that a prediction can be extracted for each data point.

The APPLGrid approach has been tested against the analytical calculation and the resulting parameters are in good agreement. Apart from the more exact treatment of NLO predictions, APPLGrid has the benefit that it is easier to follow the cuts of the measurement. An example that will be implemented in the near future and can not be calculated in the fitting loop, is the W +jet charge asymmetry, where the asymmetry is binned in terms of jet multiplicity or some measure of invariant mass, as studied at generator level in chapter 4. Here a jet algorithm is required, so the use of MCFM or another NLO generator in conjunction with APPLGrid will be required if fits are to be made.

8.3 Including asymmetry data in fits

In this section PDF fits to the HERA data and various W asymmetry measurements available in the public domain along with the result of this thesis are carried out. The data included are: the CDF direct W asymmetry measurement [59]; the ATLAS muon asymmetry using 2010 data [106]; the CMS electron and muon channel asymmetries [61]; and the electron channel asymmetry using 2011 ATLAS data presented in this thesis. All systematics will be considered fully uncorrelated for all datasets apart from HERA, where the error treatment of HERAPDF 1.5 is adopted, and the 2011 ATLAS electron asymmetry where the 13 sources of correlated uncertainty are separated from the uncorrelated uncertainties and treated as in equation 8.10.

The D0 electron asymmetry measurement⁷ was also considered [57]. It was found when making fits including both the CDF and D0 data that the χ^2 achieved was poor. When

⁷The inclusive p_T measurement with $p_T^\ell > 25$ GeV is used, as is recommended for PDF fitting by the D0 collaboration. Of the available measurements from the D0 collaboration, only the electron asymmetry was tested despite the fact that a muon asymmetry exists [58]. The former includes 0.75 fb^{-1} of data while the latter includes only 0.3 fb^{-1} .

the D0 data was removed however the fit was much better. Consequently, plots and results shown below are done with the CDF direct W asymmetry as the only Tevatron input. It should also be noted that the D0 data show some tension with current global PDF fits. In particular, the CT10 PDF set has a variant, CT10W, which gives extra weight to the D0 lepton asymmetry data but the χ^2 achieved is still unsatisfactory [33].

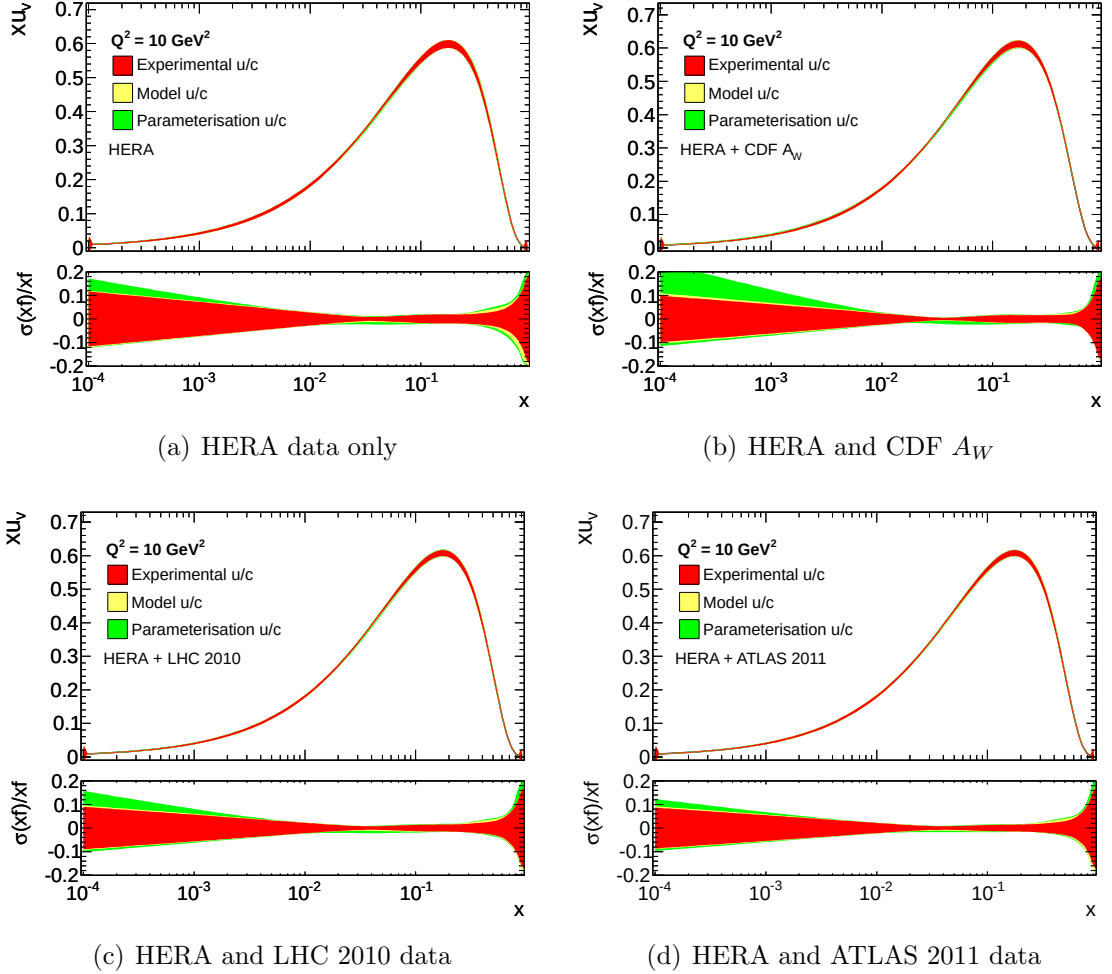


Figure 8.1: Full uncertainty bands for individual datasets: u_v . Shown at a scale of $Q^2 = 10 \text{ GeV}^2$, the up valence quark PDF with experimental (red), model (yellow) and parameterisation (green) uncertainties for: (a) HERA data only; (b) with CDF asymmetry; (c) with LHC 2010 asymmetries; and (d), with the measurement presented in this thesis.

The additional datasets will be considered in three distinct groups: ‘CDF A_W ’, ‘LHC 2010’, for the published CMS and ATLAS asymmetries; and ‘ATLAS 2011’ for the data presented in this thesis. Figures 8.1 and 8.2 show the up and down valence quark PDF distributions along with their fractional uncertainty bands for each of these datasets indi-

vidually.

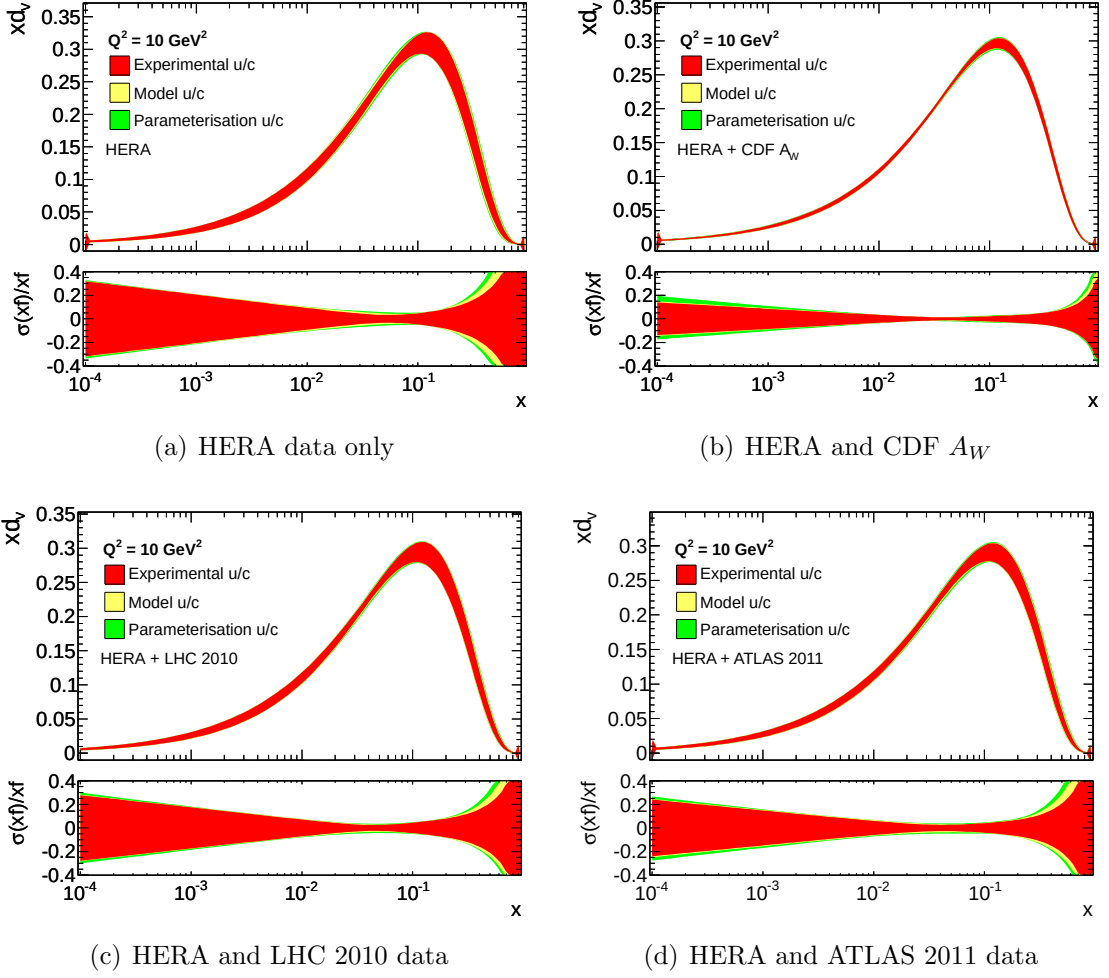


Figure 8.2: Full uncertainty bands for individual datasets: d_v . Shown at a scale of $Q^2 = 10 \text{ GeV}^2$, the down valence quark PDF with experimental (red), model (yellow) and parameterisation (green) uncertainties for: (a) HERA data only; (b) with CDF asymmetry; (c) with LHC 2010 asymmetries; and (d), with the measurement presented in this thesis.

For all the added datasets, the experimental uncertainty is reduced, with the CDF data having the largest effect. The total error is also decreased for all cases except that of the CDF data, where the parameterisation variation in which $D_{uv} \neq 0$ results in an acceptable χ^2 but shows a significant fractional deviation from the central fit at low x .

It is also interesting to consider the change in shape of the valence distributions with new data. Figure 8.3 shows the central values of each of the individual data combinations compared for both up and down valence distributions. All of the additional datasets are

pulling the shape in the same direction. For x values greater than approximately 0.02, the u_v is shifted slightly higher with respect to the HERA only fit. The d_v is shifted slightly lower in the intermediate x region $0.01 \lesssim 0.3$ and considerably higher for greater x values. In both cases, the central value when including the additional asymmetry data lies close to the edge of the total error of the fit with only HERA data.

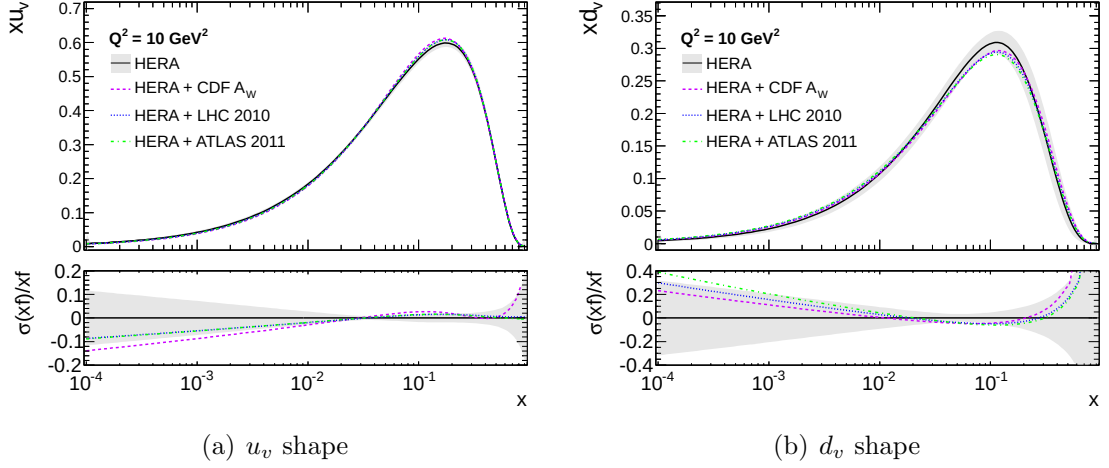


Figure 8.3: Shape comparison for individual datasets
Shown at a scale of $Q^2 = 10 \text{ GeV}^2$, the up (a) and down (b) valence quark PDF with full error band for HERA data (black line with grey band) and central value for: HERA data with CDF asymmetry only (violet dashed line); HERA data with LHC 2010 asymmetries (blue dotted line); and HERA data with the measurement presented in this thesis (green dot-dashed line).

Clearly all of the datasets discussed have differences in the way they affect the fit, where in some cases parameterisation and model uncertainties appear to be reduced while in others the main effect appears to be in the experimental uncertainties. All of the data have some effect on the shape of the valence distributions. Not shown here are the gluon and sea quark distributions, in which, as expected, there is very limited effect from these asymmetry data. The output parameters at the starting scale and their experimental uncertainty for each of the central fits with HERA and one other dataset (CDF, LHC 2010, and ATLAS 2011) are shown in table 8.1.

Figure 8.4 shows the effect of adding the asymmetry data cumulatively to the HERA data. First the CDF, then 2010 LHC and finally the 2011 ATLAS asymmetries are added to

Parameter	Fit 1	Fit 2	Fit 3	Fit 4
B_{u_v}	0.718 $\pm$ 0.024	0.751 $\pm$ 0.021	0.738 $\pm$ 0.019	0.738 $\pm$ 0.018
C_{u_v}	4.445 $\pm$ 0.119	4.289 $\pm$ 0.125	4.445 $\pm$ 0.115	4.448 $\pm$ 0.113
E_{u_v}	7.778 $\pm$ 1.303	5.74 $\pm$ 1.049	7.297 $\pm$ 1.126	7.237 $\pm$ 1.067
B_{d_v}	0.765 $\pm$ 0.067	0.706 $\pm$ 0.029	0.699 $\pm$ 0.057	0.685 $\pm$ 0.050
C_{d_v}	4.779 $\pm$ 0.516	4.143 $\pm$ 0.169	4.271 $\pm$ 0.348	4.245 $\pm$ 0.370
B'_g	-0.287 $\pm$ 0.076	-0.287 $\pm$ 0.109	-0.293 $\pm$ 0.112	-0.294 $\pm$ 0.112
A'_g	1.362 $\pm$ 0.373	1.516 $\pm$ 0.437	1.351 $\pm$ 0.395	1.359 $\pm$ 0.400
$A_{\bar{D}}$	0.578 $\pm$ 0.027	0.587 $\pm$ 0.024	0.59 $\pm$ 0.026	0.589 $\pm$ 0.026
$B_{\bar{D}}$	-0.159 $\pm$ 0.006	-0.157 $\pm$ 0.006	-0.157 $\pm$ 0.006	-0.157 $\pm$ 0.006
$C_{\bar{U}}$	3.736 $\pm$ 0.546	4.059 $\pm$ 0.508	4.025 $\pm$ 0.475	4.021 $\pm$ 0.466
$C_{\bar{D}}$	2.889 $\pm$ 0.986	3.071 $\pm$ 0.469	3.054 $\pm$ 0.889	2.921 $\pm$ 0.807
B_g	-0.227 $\pm$ 0.096	-0.237 $\pm$ 0.125	-0.237 $\pm$ 0.132	-0.238 $\pm$ 0.132
C_g	7.48 $\pm$ 1.025	7.762 $\pm$ 1.097	7.342 $\pm$ 1.19	7.394 $\pm$ 1.202

Table 8.1: Output parameters for PDF fits with asymmetry data (individual)
Fits 1-4 are: HERA data only; HERA data with CDF asymmetry; HERA data with LHC 2010 asymmetries; and HERA data with the data presented in this thesis.

the existing HERA data. The resulting experimental error band is displayed for each. Also in figure 8.4 (c) and (d) are the same plots but excluding the CDF asymmetry. Here the effect of the new ATLAS asymmetry can be seen more clearly.

At the starting scale, the parameter values of the combined central fits are displayed in table 8.2. The four fits, are the HERA only fit, the HERA with: the CDF asymmetry, the CDF and LHC 2010 asymmetries and finally, all the considered datasets. The resulting χ^2 for each dataset is shown in table 8.4. It is seen that by introducing the Tevatron data into the HERA only fit the χ^2 on the HERA data is increased by approximately 6 units. Such shifts are allowed for by using a χ^2 tolerance in PDF fitting groups that routinely include data from different sources [32, 30].

The overall uncertainties are reduced compared to the original HERA only fit, and the valence shapes changed somewhat. The impact of the LHC data beyond that of the Tevatron data is limited, however still visible.

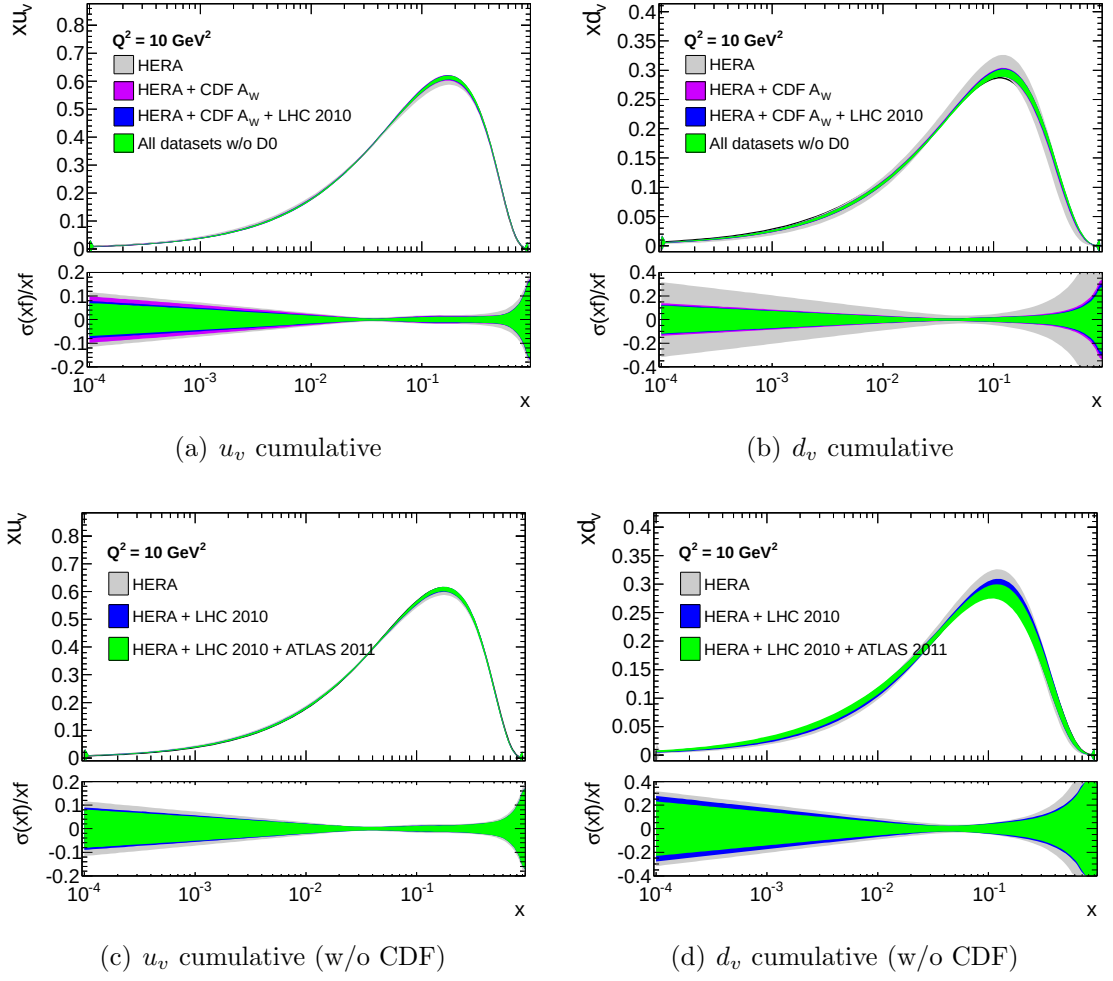


Figure 8.4: Comparison including all additional datasets

Shown at a scale of $Q^2 = 10 \text{ GeV}^2$, the up (left) and down (right) valence quark PDF with experimental error band for HERA data (grey) and similarly for, in the first row: HERA data with CDF asymmetry included (violet); HERA data with CDF and LHC 2010 asymmetries (blue); and with the measurement presented in this thesis also included (green). In the second row, the CDF asymmetry is omitted.

8.3.1 Future work

Clearly there is information on the valence quark distributions in the W asymmetry, as shown in the various fits including asymmetry data. Further information, not included here, could be obtained by including the W charge asymmetry as measured in the more forward regions using the LHCb experiment. Efforts toward including other EW measurements from colliders, such as differential W and Z cross section measurements, have already begun within the ATLAS collaboration.

Parameter	Fit 1	Fit 2	Fit 3	Fit 4
B_{u_v}	0.718 $\pm$ 0.024	0.751 $\pm$ 0.021	0.752 $\pm$ 0.017	0.751 $\pm$ 0.015
C_{u_v}	4.445 $\pm$ 0.119	4.289 $\pm$ 0.125	4.298 $\pm$ 0.123	4.320 $\pm$ 0.118
E_{u_v}	7.778 $\pm$ 1.303	5.74 $\pm$ 1.049	5.849 $\pm$ 0.989	6.091 $\pm$ 0.932
B_{d_v}	0.765 $\pm$ 0.067	0.706 $\pm$ 0.029	0.704 $\pm$ 0.027	0.699 $\pm$ 0.025
C_{d_v}	4.779 $\pm$ 0.516	4.143 $\pm$ 0.169	4.093 $\pm$ 0.154	4.032 $\pm$ 0.139
B'_g	-0.287 $\pm$ 0.076	-0.287 $\pm$ 0.109	-0.286 $\pm$ 0.111	-0.285 $\pm$ 0.112
A'_g	1.362 $\pm$ 0.373	1.516 $\pm$ 0.437	1.508 $\pm$ 0.431	1.48 $\pm$ 0.414
$A_{\bar{D}}$	0.578 $\pm$ 0.027	0.587 $\pm$ 0.024	0.589 $\pm$ 0.023	0.592 $\pm$ 0.023
$B_{\bar{D}}$	-0.159 $\pm$ 0.006	-0.157 $\pm$ 0.006	-0.157 $\pm$ 0.006	-0.157 $\pm$ 0.005
$C_{\bar{U}}$	3.736 $\pm$ 0.546	4.059 $\pm$ 0.508	4.069 $\pm$ 0.421	4.076 $\pm$ 0.382
$C_{\bar{D}}$	2.889 $\pm$ 0.986	3.071 $\pm$ 0.469	3.211 $\pm$ 0.481	3.383 $\pm$ 0.509
B_g	-0.227 $\pm$ 0.096	-0.237 $\pm$ 0.125	-0.236 $\pm$ 0.128	-0.235 $\pm$ 0.129
C_g	7.480 $\pm$ 1.025	7.762 $\pm$ 1.097	7.689 $\pm$ 1.094	7.567 $\pm$ 1.072

Table 8.2: Output parameters for PDF fits with asymmetry data (cumulative)
Fits 1-4 are: HERA data only; HERA data with CDF asymmetry; HERA data with CDF and LHC 2010 asymmetries; and all considered datasets.

Dataset	Fit 1	Fit 2	Fit 3	Fit 4
HERA Data	731.9/674	737.8/674	738/674	738.4/674
CDF A_W	-	19.1/13	19.0/13	19.6/13
LHC 2010	-	-	22.8/23	22.3/23
ATLAS 2011	-	-	-	9/11

Table 8.3: χ^2 for PDF fits with asymmetry data
Fits 1-4 are: HERA data only; HERA data with CDF asymmetry; HERA data with CDF and LHC 2010 asymmetries; and all considered datasets. The χ^2 is represented as A/B in which A is the total χ^2 for the dataset where the uncorrelated and correlated parts of the χ^2 in equation 8.10 are combined, and B is the number of data points. The fit has 13 free parameters.

Dataset	Fit 1	Fit 2	Fit 3	Fit 4
HERA Data	(729.9 + 2.0)/674	(734.9 + 2.9)/674	(735.0 + 3.0)/674	(735.4+3.0)/674
CDF A_W	-	19.1/13	19.0/13	19.6/13
LHC 2010	-	-	22.8/23	22.3/23
ATLAS 2011	-	-	-	(8.4 + 0.6)/11

Table 8.4: χ^2 for PDF fits with asymmetry data
Fits 1-4 are: HERA data only; HERA data with CDF asymmetry; HERA data with CDF and LHC 2010 asymmetries; and all considered datasets. The χ^2 is represented as (A+B)/C, where A is the part of the χ^2 coming from uncorrelated uncertainties (the first half of equation 8.9); B is the contribution from shifts relative to theory (the second half of equation 8.9, $\sum s_\lambda^2$); and C is the number of data points. The fit has 13 free parameters.

In addition to precision W and Z measurements, exercises to include ATLAS jet measurements in these fits have also begun [109] and show some impact on the gluon PDF.

Further to a simple W asymmetry measurement, a measurement of the W +jet asymmetry, as discussed at a phenomenological level in chapter 4, binned in jet multiplicity or an invariant mass variable could be pursued. Using APPLGrid and a NLO MC generator such as MCFM to include such data in PDF fits is now feasible.

8.4 Conclusions

Including the asymmetry measurement presented in this thesis alongside previous measurements of the W asymmetry in collider experiments and the latest HERA data has reduced the uncertainty on the valence PDFs. Given the x range probed in W production at ATLAS, the asymmetry measurement gives information on the valence quark distributions at lower x than has ever been measured before. The excellent agreement and minimal error reduction shown in performing fits to these data is evidence that the tools used at higher x are satisfactory in this new kinematic regime. The DGLAP evolution equations seem to work excellently, indicating that if the BFKL approximation is required, then its effect is likely only small for the probed x values. Further to the evidence provided by the fits in this chapter, agreement has been shown to very high rapidities in [110], in which predictions agree excellently with a combined asymmetry measurement using ATLAS, CMS and LHCb data from 2010.

The promise of using APPLGrid to fit data defined by more complicated observables is interesting. The use of APPLGrid to provide NLO predictions within the PDF fitting machinery has been shown to work and will no doubt be useful in future.

Chapter 9

Conclusions

With steady improvements in instantaneous luminosity over the course of running in 2010 and 2011, the LHC has delivered 497.27 pb^{-1} of triggered data to ATLAS in early 2011 that has been included in this thesis. The LHC will continue to improve operating conditions and within 10 years of running the ATLAS subdetectors will require upgrades due to the increased pressure that the planned LHC luminosity upgrade will bring. Chapter 2 focused on the development of a system to test prototype ATLAS upgrade inner detector elements for thermo-mechanical deformations. This system is now in a working state undertaking tests on prototype stave elements.

The measurement of the electron channel, lepton charge asymmetry documented in this thesis is systematics dominated, as was already the case for similar measurements using 2010 data. The systematic uncertainty due to generator choice and showering MC is the largest contribution. In future this can be constrained by the generation of high statistics dedicated samples in order to test for differences between NLO MC generators and the parton shower and hadronisation MC to which they are interfaced.

Other systematics will almost certainly be reduced with an increased data sample. The systematic uncertainty on the QCD background estimate is the second largest contributor to the total uncertainty. With the experience gained from early data measurements such as that documented in this thesis, specialist triggers are being designed so as to record

large unbiased samples from which to select QCD background by reversing selected electron identification cuts. With an increased QCD sample size, the systematic uncertainties on this measurement would be reduced significantly.

With the 5 pb^{-1} that is likely from 2011 running alone, there will be a sample with ten times the statistics of $Z \rightarrow ee$ events on which a tag and probe analysis can be carried out to more accurately determine any charge asymmetric effects in electron identification. This $Z \rightarrow ee$ sample can also be used to further reduce the already small uncertainty on the electron energy scale and resolution in ATLAS.

A further improvement to the measurement could be obtained by including the lepton charge asymmetry as measured in the muon channel. This would double the statistics of the $W \rightarrow \ell\nu$ sample. After correctly taking into account correlations between the two channels, this addition will allow for a reduction of the overall uncertainties.

The measurement gives information on the valence quark PDFs in a kinematic region that has not been explored before. The result shows discrimination between the predictions of leading PDF groups at central rapidity, where the prediction of CT10 is preferred over MSTW 2008. When included in PDF fits using the tools of HERAPDF, these data show some constraining power above that shown when including other measurements of the asymmetry; the improvements are most marked in the low x region where information on the valence quark had not previously existed.

Another important conclusion to take from this PDF fitting exercise is that in fact these data agree very well with current predictions. This agreement extends to very high rapidity at LHC energies as shown in [110] in which a combined asymmetry using ATLAS, CMS and LHCb data agrees excellently with predictions. Such an agreement serves as an indication that the DGLAP evolution equations work well down to the x probed at the LHC, and that the BFKL approach is not required, or presents only a small effect.

The use of APPLGrid to separate the PDF from NLO MC weights allows for a more precise prediction in which the NLO prediction can be calculated at each iteration of the

PDF fit. This approach means that in future fits can be made to more complicated final state observables. One such measurement is the W charge asymmetry as a function of jet multiplicity or invariant mass as described in detail at generator level in chapter 4. Such measurements are capable of further refining the x and Q^2 probed in W production at the LHC and providing improved constraints on PDFs.

Appendix A

Template Fits

Below are the individual template fits using E_T^{miss} for each of the lepton pseudorapidity bins used in the analysis.

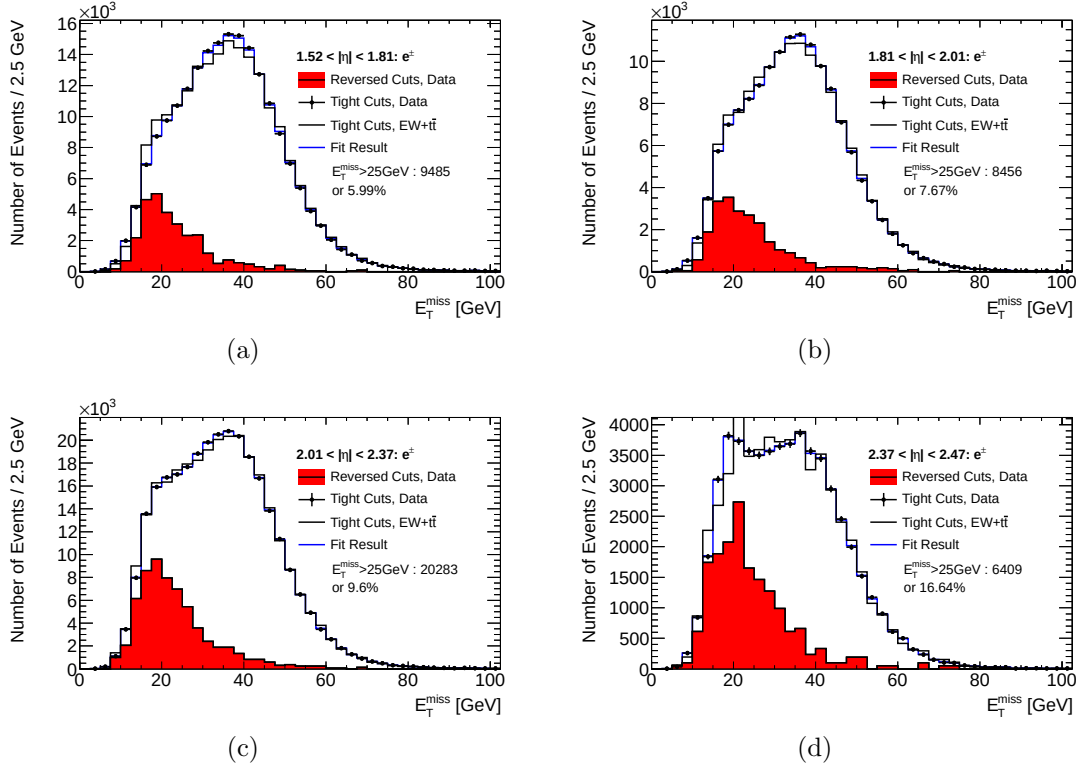
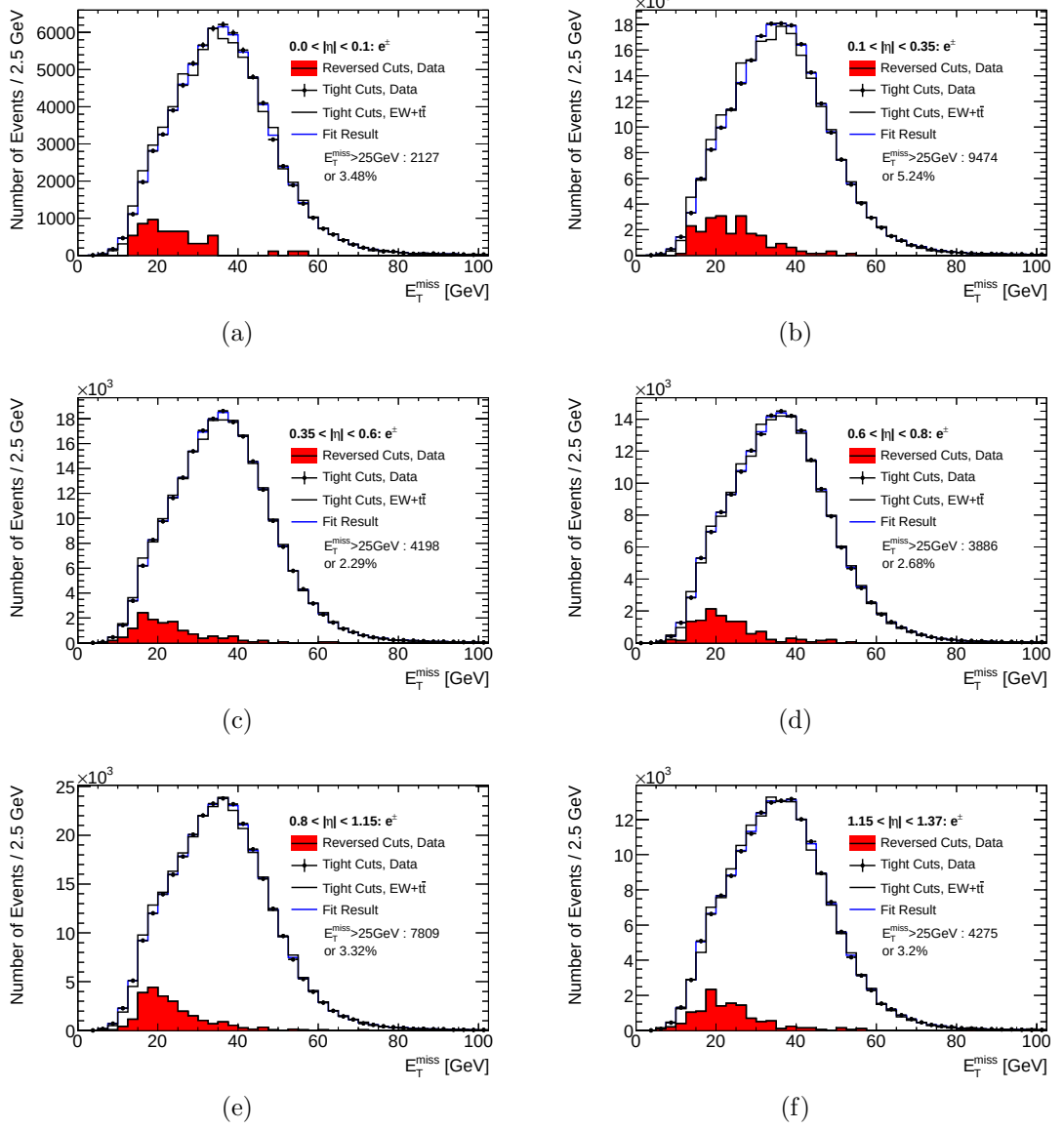


Figure A.1: QCD template fits in endcap region $|\eta| > 1.52$

Figure A.2: QCD template fits in barrel region $|\eta| < 1.37$

Bibliography

- [1] L. Evans and P. Bryant. LHC machine. *Journal of Instrumentation*, 3:S08001, 2008.
- [2] The ATLAS Collaboration. The ATLAS experiment at the CERN large hadron collider. *Journal of Instrumentation*, 2008.
- [3] S. Chatrchyan, K.A. Bloom, B. Bockelman, D. Claes, A. Dominguez, M. Eads, M. Furukawa, J. Keller, T. Kelly, C. Lundstedt, et al. The CMS experiment at the CERN LHC. *Kenneth Bloom Publications*, page 282, 2008.
- [4] The LHCb Collaboration, A. Augusto et al. The LHCb experiment at the LHC. *Journal of Instrumentation*, 2008.
- [5] E. Vercellin et al. The ALICE experiment at the LHC. *Nuclear Physics A*, 805(1-4):511c–518c, 2008.
- [6] The ATLAS Collaboration. Expected performance of the ATLAS experiment: detector, trigger and physics. *arXiv*, 901:2008–20.
- [7] ATLAS: Detector and physics performance technical design report. Volume 1. CERN-LHCC-99-14.
- [8] R. Brun and F. Rademakers. ROOT—An object oriented data analysis framework. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 389(1-2):81–86, 1997.
- [9] Rene Brun et al. Root website, 1995-2011. <http://root.cern.ch>.
- [10] J.W. Goodman and ed J.C. Dainty. Laser speckle and related phenomena. *Berlin and New York, Springer-Verlag (Topics in Applied Physics. Volume 9), 1975. 298 p*, 9, 1975.
- [11] R. Jones and C. Wykes. Holographic and speckle interferometry. 1989.
- [12] M. Cepeda, S. Dardin, M.G.D. Gilchriese, C. Haber, W.K. Miller, W.O. Miller, and R. Post. Mechanical and Cooling Design Studies for an Integrated Stave Concept for Silicon Strip Detectors for the Super LHC. (<http://cdsweb.cern.ch/record/1109141/>), Jun 2008.
- [13] Poco Graphite, Inc. POCO Foam. <http://www.poco.com>, June 2009.

- [14] D. Buira-Clark. *Speckle Interferometry and a Study of Γ_W for the ATLAS Experiment*. PhD thesis, Magdalen College, University of Oxford, 2006.
- [15] R. King. Private Communication.
- [16] ATLAS DCS. Embedded Local Monitor Board. <http://elmb.web.cern.ch>, Sep 2011.
- [17] NI LabVIEW. <http://www.ni.com/labview/>, 8 June 2009.
- [18] Elliot D. Bloom et al. High-Energy Inelastic ep Scattering at 6-Degrees and 10-Degrees. *Phys. Rev. Lett.*, 23:930–934, 1969.
- [19] M. Breidenbach et al. Observed Behaviour of Highly Inelastic electron-Proton Scattering. *Phys. Rev. Lett.*, 23:935–939, 1969.
- [20] R. Devenish and A. Cooper-Sarkar. *Deep inelastic scattering*. Oxford University Press, 2004.
- [21] R.K. Ellis, W.J. Stirling, and B.R. Webber. *QCD and collider physics*. Cambridge Univ Pr, 2003.
- [22] R. Brock et al. Handbook of perturbative QCD: Version 1.0. *Rev. Mod. Phys.*, 67:157–248, 1995.
- [23] J.D. Bjorken. Asymptotic sum rules at infinite momentum. *Phys. Rev.*, 179:1547–1553, 1969.
- [24] Richard P. Feynman. Very high-energy collisions of hadrons. *Phys. Rev. Lett.*, 23:1415–1417, 1969.
- [25] J.D. Bjorken and E.A. Paschos. Inelastic electron proton and gamma proton scattering, and the structure of the nucleon. *Phys. Rev.*, 185:1975–1982, 1969.
- [26] J.M. Campbell, J.W. Huston, and W.J. Stirling. Hard interactions of quarks and gluons: a primer for LHC physics. *Reports on Progress in Physics*, 70:89, 2007.
- [27] S.D. Drell and Tung-Mow Yan. Partons and their applications at high energies. *Ann. Phys.*, 66:578, 1971.
- [28] Yuri L. Dokshitzer. Calculation of the structure functions for deep inelastic scattering and e^+e^- annihilation by perturbation theory in quantum chromo-dynamics. (in russian). *Sov. Phys. JETP.*, 46:641–653, 1977.
- [29] G. Altarelli and G. Parisi. Asymptotic freedom in parton language. *Nucl. Phys.*, B126:298, 1977.
- [30] A.D. Martin, W.J. Stirling, R.S. Thorne and G. Watt. Parton distributions for the LHC. *Eur. Phys. J.*, C63:198–285, 2009.
- [31] P.M. Nadolsky et al. Implications of CTEQ global analysis for collider observables. *Phys. Rev.*, D78:013004, 2008.

- [32] J. Pumplin et al. New generation of parton distributions with uncertainties from global QCD analysis. *JHEP*, 07:012, 2002.
- [33] H.L. Lai, M. Guzzi, J. Huston, Z. Li, P.M. Nadolsky, J. Pumplin, and C.P. Yuan. New parton distributions for collider physics. *Physical Review D*, 82(7):074024, 2010.
- [34] The H1 and ZEUS Collaborations. Combined Measurement and QCD Analysis of the Inclusive ep Scattering Cross Sections at HERA. 2009.
- [35] HERA - A Proposal for a Large Electron Proton Colliding Beam Facility at DESY. DESY-HERA-81-10.
- [36] Richard D. Ball et al. A determination of parton distributions with faithful uncertainty estimation. *Nucl. Phys.*, B809:1–63, 2009.
- [37] S. Alekhin et al. 3-, 4-, and 5-flavor next-to-next-to-leading order parton distribution functions from deep-inelastic-scattering data and at hadron colliders. *Phys. Rev. D*, 81:014032, 2010.
- [38] M.R. Whalley and D. Bourilkov. The Les Houches Accord PDFs (LHAPDF) and LHAGLUE. *Arxiv preprint hep-ph/0508110*, 2005.
- [39] W.J. Stirling. Private Communication.
- [40] E.A. Kuraev, L.N. Lipatov, and V.S. Fadin. Pomeranchuk singularity in nonabelian gauge theories. *Sov. Phys.-JETP (Engl. Transl.);(United States)*, 45(2), 1977.
- [41] Y.Y. Balitskii and L.N. Lipatov. Pomeranchuk singularity in quantum chromodynamics. *Sov. J. Nucl. Phys.(Engl. Transl.);(United States)*, 28(6), 1978.
- [42] F.D. Aaron, A. Aktas, C. Alexa, V. Andreev, B. Antunovic, S. Aplin, A. Asmone, A. Astvatsatourov, S. Backovic, A. Baghdasaryan, et al. Three- and four-jet production at low x at HERA. *The European Physical Journal C-Particles and Fields*, 54(3):389–409, 2008.
- [43] A. Aktas et al. Measurement of dijet production at low Q^2 at HERA. *Arxiv preprint hep-ex/0401010v1*, 2004.
- [44] S. Chekanov, M. Derrick, S. Magill, B. Musgrave, D. Nicholass, J. Repond, R. Yoshida, M.C.K. Mattingly, M. Jechow, N. Pavel, et al. Forward-jet production in deep inelastic ep scattering at HERA. *Eur. Phys. C.*, 52(3):515–530, 2007.
- [45] S. Chekanov, M. Derrick, S. Magill, B. Musgrave, D. Nicholass, J. Repond, R. Yoshida, M.C.K. Mattingly, M. Jechow, N. Pavel, et al. Dijet production in diffractive deep inelastic scattering at HERA. *Eur. Phys. C.*, 52(4):813–832, 2007.
- [46] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne. Uncertainties of predictions from parton distributions II: theoretical errors. *The European Physical Journal C-Particles and Fields*, 35(3):325–348, 2004.

- [47] C.D. White and R.S. Thorne. A Global Fit to Scattering Data with NLL BFKL Resummations. *Phys.Rev.*, D75:034005, 2007.
- [48] CDF Collaboration, F. Abe et al. Inclusive jet cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8\text{ tev}$. *Phys. Rev. Lett.*, 77(3):438–443, Jul 1996.
- [49] R. Plunkett. High ET jets at CDF. *Nucl. Phys.Proc. Suppl.*, 54A:81–85, 1997.
- [50] M. Kobayashi and T. Maskawa. CP-violation in the renormalizable theory of weak interaction. *Progress of Theoretical Physics*, 49(2):652–657, 1973.
- [51] K. Lohwasser, J. Ferrando, and Ç. Issever. On direct measurement of the W production charge asymmetry at the LHC. *Journal of High Energy Physics*, 2010(9):1–19, 2010.
- [52] D.H. Perkins. *Introduction to high energy physics*. Cambridge Univ Pr, 2000.
- [53] Nakamura, K. et al (Particle Data Group). Review of particle physics. *J. Phys. G: Nucl. Part. Phys.*, 37:075021, 2010.
- [54] F. Halzen and A.D. Martin. *Quarks and leptons*. John Wiley and sons, 1984.
- [55] CDF Collaboration, F. Abe et al. Lepton asymmetry in W-boson decays from $p\bar{p}$ collisions at $\sqrt{s} = 1.8\text{TeV}$. *Phys. Rev. Lett.*, 68(10):1458–1462, Mar 1992.
- [56] CDF Collaboration, D. Acosta et al. Measurement of the forward-backward charge asymmetry from $W \rightarrow e\nu$ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96\text{TeV}$. *Phys. Rev. D*, 71(5):051104, Mar 2005.
- [57] D0 Collaboration, V.M. Abazov et al. Measurement of the Electron Charge Asymmetry in $p\bar{p} \rightarrow W + X \rightarrow e\nu + X$ Events at $\sqrt{s} = 1.96\text{ TeV}$. *Phys. Rev. Lett.*, 101(21):211801, Nov 2008.
- [58] D0 Collaboration, V.M. Abazov et al. Measurement of the muon charge asymmetry from W boson decays. *Phys. Rev. D*, 77(1):011106, Jan 2008.
- [59] CDF Collaboration, T. Aaltonen et al. Direct Measurement of the W Production Charge Asymmetry in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96\text{ TeV}$. *Phys. Rev. Lett.*, 102(18):181801, May 2009.
- [60] The ATLAS Collaboration. Measurement of the $W \rightarrow \ell\nu$ and $Z/\gamma^* \rightarrow \ell\ell$ production cross sections in proton-proton collisions at $\sqrt{s} = 7\text{TeV}$ with the ATLAS detector. *Journal of High Energy Physics*, 2010:1–65, 2010. 10.1007/JHEP12(2010)060.
- [61] CMS Collaboration. Measurement of the Lepton Charge Asymmetry in Inclusive W Production in pp Collisions at sqrt (s)= 7 TeV. 2011.
- [62] R. Buckingham, A. Cooper-Sarkar, J. Ferrando, C. Issever, K. Lohwasser, and S. Whitehead. Using the charge asymmetry in W+jet production as a new probe of parton distribution functions in different kinematic regions at the LHC. Technical Report ATL-COM-PHYS-2010-893, CERN, 2010.

- [63] M.L. Mangano, M. Moretti, F. Piccinini, R. Pittau, and A.D. Polosa. ALPGEN, a generator for hard multiparton processes in hadronic collisions. *JHEP*, 07:001, 2003.
- [64] G. Corcella et al. HERWIG 6.5: an event generator for Hadron Emission Reactions With Interfering Gluons (including supersymmetric processes). *JHEP*, 01:010, 2001.
- [65] S. Frixione and B.R. Webber. Matching NLO QCD computations and parton shower simulations. *JHEP*, 06:029, 2002.
- [66] S. Frixione, P. Nason, and B.R. Webber. Matching NLO QCD and parton showers in heavy flavour production. *JHEP*, 08:007, 2003.
- [67] S. Frixione, E. Laenen, P. Motylinski, and B.R. Webber. Single-top production in MC@NLO. *JHEP*, 03:092, 2006.
- [68] S. Frixione, E. Laenen, P. Motylinski, B.R. Webber, and C.D. White. Single-top hadroproduction in association with a W boson. *JHEP*, 07:029, 2008.
- [69] J.M. Butterworth, Jeffrey R. Forshaw, and M.H. Seymour. Multiparton interactions in photoproduction at HERA. *Z. Phys.*, C72:637–646, 1996.
- [70] P. Golonka et al. The tauola-photos-F environment for the TAUOLA and PHOTOS packages, release II. *Comput. Phys. Commun.*, 174:818–835, 2006.
- [71] P. Golonka and Z. Was. PHOTOS Monte Carlo: a precision tool for QED corrections in Z and W decays. *The European Physical Journal C-Particles and Fields*, 45(1):97–107, 2006.
- [72] Matteo Cacciari, Gavin P. Salam, and Gregory Soyez. The anti- k_t jet clustering algorithm. *JHEP*, 04:063, 2008.
- [73] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne. Parton distributions and the LHC: W and Z production. *Eur. Phys. J.*, C14:133–145, 2000.
- [74] Richard D. Ball et al. A first unbiased global NLO determination of parton distributions and their uncertainties. *Nucl. Phys.*, B838:136–206, 2010.
- [75] C.H. Kom and W.J. Stirling. Charge asymmetry in W+jets production at the LHC. 2010.
- [76] The ATLAS Collaboration. Electron performance measurements with the ATLAS detector using the 2010 LHC proton-proton collision data. *Eur. Phys. J. C*, 2011.
- [77] The ATLAS Collaboration. Charged-particle multiplicities in pp interactions at $\sqrt{s} = 900$ GeV measured with the ATLAS detector at the LHC. *Phys. Lett. B*, 688, 2010.
- [78] The ATLAS Collaboration. Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC. *New J. Phys.*, 13, 2011.
- [79] The ATLAS Collaboration. Study of the Material Budget in the ATLAS Inner Detector with K_S^0 decays in collision data at $\sqrt{s} = 900$ GeV. *ATLAS-CONF-2010-019*.

- [80] The ATLAS Collaboration. Mapping the material in the ATLAS Inner Detector using secondary hadronic interactions in 7 TeV collisions. *ATLAS-CONF-2010-058*.
- [81] The ATLAS Collaboration. Photon conversion at $\sqrt{s} = 900$ GeV measured with the ATLAS detector. *ATLAS-CONF-2010-007*.
- [82] The ATLAS Collaboration. Probing the material in front of the ATLAS electromagnetic calorimeter with energy flow from $\sqrt{s} = 7$ TeV minimum bias events. *ATLAS-CONF-2010-037*.
- [83] M. Hance. *Measurement of Inclusive Isolated Prompt Photon Production in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector*. PhD thesis, University of Pennsylvania, 2011.
- [84] The ATLAS Collaboration. Performance of Missing Transverse Momentum Reconstruction in Proton-Proton Collisions at $\sqrt{s} = 7$ TeV with ATLAS. Technical Report arXiv:1108.5602, CERN-PH-EP-2011-114, CERN, Geneva, Sep 2011.
- [85] S. Frixione, P. Nason, and G. Ridolfi. A Positive-Weight Next-to-Leading-Order Monte Carlo for Heavy Flavour Hadroproduction. *JHEP*, 09:126, 2007.
- [86] S. Frixione, P. Nason, and C. Oleari. Matching NLO QCD computations with Parton Shower simulations: the POWHEG method. *JHEP*, 11:070, 2007.
- [87] Alioli, S. and Nason, P. and Oleari, C. and Re, E. A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX. *Journal of High Energy Physics*, 2010(6):1–58, 2010.
- [88] Alioli, S. and Nason, P. and Oleari, C. and Re, E. NLO vector-boson production matched with shower in POWHEG. *Journal of High Energy Physics*, 2008:060, 2008.
- [89] Torbjorn Sjostrand, Stephen Mrenna, and Peter Skands. PYTHIA 6.4 Physics and Manual. *JHEP*, 05:026, 2006.
- [90] A. Sherstnev and R.S. Thorne. Parton distributions for LO generators. *The European Physical Journal C-Particles and Fields*, 55(4):553–575, 2008.
- [91] S. Agostinelli, J. Allison, K. Amako, J. Apostolakis, H. Araujo, P. Arce, M. Asai, D. Axen, S. Banerjee, G. Barrand, et al. GEANT4 - A simulation toolkit. *Nuclear Instruments and Methods in Physics Research-Section A Only*, 506(3):250–303, 2003.
- [92] The ATLAS Collaboration. A measurement of the inclusive $W^\pm$ and Z/γ^* cross sections in the e and μ decay channels in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Phys. Rev. D*, 2011.
- [93] The ATLAS Collaboration. Measurement of the Transverse Momentum Distribution of W Bosons in pp Collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector. Technical Report arXiv:1108.6308, CERN-PH-EP-2011-134, CERN, Geneva, Sep 2011.

- [94] R. Barlow and C. Beeston. Fitting using finite Monte Carlo samples. *Comp. Phys. Comm.*, 77:219–228, 1993.
- [95] A. Nappi. A pitfall in the use of extended likelihood for fitting fractions of pure samples in a mixed sample. *Computer Physics Communications*, 180(2):269–275, 2009.
- [96] CDF Collaboration, F. Abe et al. Measurement of W-boson production in 1.8-TeV $p\bar{p}$ collisions. *Phys. Rev. Lett.*, 62(9):1005–1008, Feb 1989.
- [97] K. Lohwasser. *The W Charge Asymmetry: Measurement of the Proton Structure with the ATLAS Detector*. PhD thesis, University of Oxford, 2009.
- [98] E. Dobson. *A feasibility study into the measurement of W and Z cross sections with the ATLAS detector*. PhD thesis, University of Oxford, 2009.
- [99] J. Buchanan. A measurement of the ratio of the $W+1$ jet and $Z+1$ jet cross sections using the ATLAS detector at the LHC. Thesis in preparation, University of Oxford, 2011.
- [100] S. Catani, L. Cieri, G. Ferrera, D. de Florian, and M. Grazzini. Vector Boson Production at Hadron Colliders: A Fully Exclusive QCD Calculation at NNLO. *Physical Review Letters*, 103(8):82001, 2009.
- [101] A. Cooper-Sarkar. ZEUSfitter update. Presented at Towards PDFs using precise ATLAS W/Z cross section measurements meeting, Dubna: <https://indico.cern.ch/contributionDisplay.py?sessionId=3&contribId=6&confId=97834>, September 2010.
- [102] A. Kayis-Topaksu et al. Leading order analysis of neutrino induced dimuon events in the CHORUS experiment. *Nucl.Phys.*, B798:1–16, 2008.
- [103] H1 and ZEUS Collaborations (Voica Radescu for the collaboration). Combination and QCD analysis of the HERA inclusive cross sections. *PoS ICHEP2010*, 168, 2010.
- [104] A. Cooper-Sarkar. HERAPDF combined fits with low energy data, and with charm data. Presented at the PDF4LHC meeting, CERN: <https://indico.cern.ch/conferenceDisplay.py?confId=98883>, July 2010.
- [105] A. Cooper-Sarkar. News for HERAPDF. Presented at the PDF4LHC meeting, CERN: <http://indico.cern.ch/conferenceDisplay.py?confId=127425>, March 2011.
- [106] The ATLAS Collaboration. Measurement of the Muon Charge Asymmetry from W Bosons Produced in pp Collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Physics Letters B*, 701(1):31 – 49, 2011.
- [107] T. Carli, D. Clements, A. Cooper-Sarkar, C. Gwenlan, G.P. Salam, F. Siegert, P. Starovoitov, and M. Sutton. A posteriori inclusion of parton density functions in NLO QCD final-state calculations at hadron colliders: The APPLGRID Project. *The European Physical Journal C-Particles and Fields*, 66(3):503–524, 2010.

- [108] J. Campbell, R.K. Ellis, and D. Rainwater. Next-to-leading order QCD predictions for $W + 2$ jet and $Z + 2$ jet production at the CERN LHC. *Physical Review D*, 68(9):094021, 2003.
- [109] C. Doglioni. *Measurement of the inclusive jet cross section with the ATLAS detector at the Large Hadron Collider*. PhD thesis, University of Oxford, 2011.
- [110] A Belloni and K Lohwasser. An extrapolation to a larger fiducial volume of the measurement of the $W \rightarrow \ell \nu$ charge asymmetry in proton-proton collisions at $\sqrt{s}=7\text{TeV}$ with the ATLAS detector. Technical Report ATLAS-CONF-2011-129, CERN, Geneva, Jul 2011.