

A feasibility study into the measurement of W and Z cross sections with the ATLAS detector

Eleanor Dobson

Linacre College, University of Oxford



Thesis submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy at the University of Oxford

Trinity Term, 2009



Dedicated to my family

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Abstract

In 2009 the Large Hadron Collider at CERN in Geneva, Switzerland, is expected to start colliding head on two proton beams at 7 (to be increased to 14) TeV centre of mass energy. ATLAS is a general purpose detector built to monitor the resultant activity from LHC collisions. ATLAS and the LHC will facilitate a precise measurement of W and Z boson production cross sections (σ_W and σ_Z) and their ratio $\mathcal{R}$. In first data W and Z events may be used as ‘standard candle events’ to understand detector performance, and are interesting in their own right as they are a powerful tool to test and constrain further the Standard Model. Any significant deviation from the predicted behaviour of these events could be one of the first indications of physics beyond the Standard Model, and so understanding these events is of paramount importance to new physics searches.

It is important, whenever possible, not to rely on Monte Carlo simulation when measuring the above (or indeed any) quantities. This analysis proposes methods of understanding the detector response and efficiency from data using $Z \rightarrow ll$ events, as well as techniques to fold in such quantities to measure σ_W , σ_Z (with the branching ratio for decay in the electron channel) and $\mathcal{R}$ along with their predicted uncertainties for an early data scenario (100 pb^{-1}).

Acknowledgements

I would like to thank the Science and Technology Facilities Council (STFC) as well as the Oxford Physics department for providing financial support during this degree. It has been a great pleasure to work in the Oxford Physics department and I personally thank the secretarial and IT teams, as without their continuous support I don't think I could have completed this work.

My biggest thanks go to my supervisor, Dr. Tony Weidberg, for his excellent supervision. He has always had time for my questions and even more importantly never lost his faith in me. I also extend this gratitude towards my referees: Nick Ellis, Daniel Froidevaux, Joey Huston and Maarten Boonekamp who have been of invaluable help in the last six months during what has at some points been a very stressful time. I am very grateful for the help of Jon Butterworth and the rest of the UCL group in writing my first research proposal which proved to be very helpful also in other job applications. I also want mention my appreciation towards my undergraduate tutors John March-Russell, Laura Taroni and Stephen West for inspiring my interest in physics in the first place, and for continuing to support me throughout my PhD studies.

Starting an analysis out at CERN was not without its problems and for this reason I would also like to thank the Liverpool group and in particular Mike Flowerdew for the help in getting started when I went to CERN. I would like to thank the 'ntupling team' at Oxford, whos datasets I have used for this final work. I would like to personally mention those at CERN to whom I am particularly grateful for support and help in the beginning stages of my analysis work: Alessandro Tricoli, Teresa Martin, Richard Hawkings, Nick Barlow, Thomas Kittelmann, as well as countless others whom I don't have space here to mention by name. I am extremely grateful to the time that Stephen Gibson invested in me particularly at the beginning stages of my thesis in getting me introduced to ATLAS and the FSI system.

It has been a great pleasure to complete this analysis as part of the 'R team' and I attribute this to Matthias and Troels for the interesting discussions and analysis that have taken place in the last two years. I would also like to thank the convenors of the ATLAS sub-groups in which I have participated for their guidance.

This work is dedicated those friends and members of my family who have continued to support me throughout the last four years.

Foreword

I believe it is important for a researcher to gain a wide range of skills and thus during my PhD studies have strived to obtain this. I have worked on hardware and technical software as well as physics studies, and have contributed significantly to ATLAS papers on all three of these areas. However, new recommendations of the physics department suggest that a thesis should be of a length between 100 and 150 pages. For this reason it was not practical to document in this thesis all the topics to which I have contributed in the last four years. This thesis is a summary of a self-contained analysis that I have performed during my PhD, representing about 50% of the work I have done during my PhD studies. The remaining work is briefly described in the following two paragraphs and much is documented in notes and papers, which are cited in the text.

In my first year I designed and implemented the use of optical switches in the laser frequency scanning interferometry alignment system (FSI) for the ATLAS Semiconductor Tracker (SCT). The switches are now successfully installed and double the effective laser power available to the system. This work has been presented in two international conferences and written into two papers [1][2]. I was also involved in the SCT cabling and optical fibre testing for the SCT as part of my service work.

I am the sole author of the FSI software which interpolates between FSI node positions to give a map of predicted module positions in the SCT. My work on this has been written up as an ATLAS note [3]. I have also performed similar analysis on photogrammetry survey data, identifying previously unmeasured elliptical deformations, which is now written up the work as a public note [4] cited by the SCT engineering paper [5], of which I am an author.

The LHC was not taking data at the time of writing. Although the work described above does in fact involve real data, the work presented in this thesis is Monte Carlo (MC) simulation. The purpose of the analysis is to design and develop methodology to be used once data arrives. However, certain omissions (in particular, background from dijets) have been made due to the pragmatic difficulties of including these in MC simulation. I have built the analysis tools to be as flexible as possible to account for such unknowns that will arise in real data, and given recommendations for ‘real data procedure’ where appropriate.

As is detailed in a chapter of this thesis, I have performed an extensive study of the tag and probe efficiency measurement technique in $Z \rightarrow ee$ events as a part of the trigger and electron/photon performance working groups [7][8]. My code formed the basis of the official tag and probe tools which are now integrated into the ATLAS software. I also worked within the W/Z boson + jets working group studying the impact of hadronic activity on the detector efficiencies [7], and presented this work in two international conferences [17] [18].

I was the sole author of the chapter concerning the data driven measurement of missing transverse energy (E_t) performance in $Z \rightarrow ll$ events for the E_t and jets performance group in their recent performance paper [9]. I have developed methods to exploit the geometry of a $Z \rightarrow ll$ event as well as its similarity to a $W \rightarrow l\nu$ event to measure E_t scales and resolutions to high precision and is described in this thesis. Using such techniques I have identified problems with the hadronic recoil reconstruction within ATLAS, and I have worked with the hadronic calibration group using the results as a diagnostic tool for new calibration constants. My analysis code now forms part of the official E_t performance package. I investigated the impact of detector scales and resolutions upon the detector acceptance

and am liaising with physics groups to port code to do this into the benchmark and insitu performance packages.

My analysis topic, described in this work, is a study on the measurement of $\mathcal{R}$ (ratio between W and Z cross production sections) in the ATLAS detector. Myself and two collaborators have written three notes on the analysis [19][20][21]. I have performed other preliminary analysis studies which, due to space requirements, I have not been able to include in this work although I hope to develop them further in the future. I am developing novel ways to measure differential W and Z cross sections, again exploiting the geometry of $Z \rightarrow ll$ decays. I am also developing a model independent unfolding technique to correct differential distributions to hadron level, and was responsible for the ATLAS fast simulation validation in $W \rightarrow e\nu$ events.

The ATLAS and CMS collaborations are, by particle physics standards, of unprecedented size. A lot of work in recent years, to some of which I have contributed, has gone into officially documenting the ATLAS detector and physics. The topic explored in this work is also very well understood and documented from a theoretical standpoint. For these reasons the detector and theory explanations are brief, instead giving weight to a detailed description of the methodology developed and solutions suggested for problems encountered along the way. This enables a primary aim of this thesis; to communicate such affairs to the rest of the ATLAS collaboration, several of whom are working on the same topic. It should also be pointed out at this point that, due to the large-scale nature of ATLAS, this work should be considered as the work of a large number of collaborators too numerous to mention, although specific contributions are referenced as they arise.

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1. BACKGROUND INFORMATION

1.1 Introduction

The purpose of this work is to assess the feasibility of the measurement of the W and Z production cross sections in the electron decay channel as well as their ratio $\mathcal{R}$. Given that the work is carried out using solely Monte Carlo simulation, more emphasis is given to methods of understanding the detector performance well enough to make the measurement, rather than a focus on the end result.

The first chapter gives a general overview of the theory, the ATLAS detector and the analysis. Chapter 2 describes how $Z \rightarrow ee$ events may be used to understand the detector response to objects necessary for the determination of $\mathcal{R}$. Chapter 3 looks at the determination of the acceptance and uses the responses determined in chapter 2 to study corrections that need to be made to this quantity. Chapter 4 deals with the evaluation and removal of backgrounds to both $Z \rightarrow ee$ and $W \rightarrow e\nu$ decays. Chapter 5 is a detailed study into a data-driven method of evaluating efficiencies. Finally chapter 6 brings all chapters together into an overall projection for expected uncertainties for ATLAS measurements of $\mathcal{R}$ and $\sigma(W \rightarrow e\nu)$, $\sigma(Z \rightarrow ee)$ measurements in early data at the LHC.

1.2 Standard Model (SM)

The Standard Model [22] describes the fundamental particles (fermions) and their interactions (mediated by gauge bosons). Other than gravity, it describes all the interactions of known particles. The Standard Model is a product of the strong interaction (Quantum ChromoDynamics or QCD) with the electromagnetic and weak (electroweak) interactions. The fundamental constituents of matter as described in the Standard Model are summarised in table 1.1.

Whilst the Standard Model has been hugely successful in explaining matter and its interactions, it has certain limitations. Many approaches to extend the SM have been made to include gravity and/or additional new interactions. These are referred to as Beyond the Standard Model (BSM) theories.

Particle	Types
Quarks	u, d, s, c, b, t $\bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}, \bar{t}$
Charged leptons	$e^\pm, \mu^\pm, \tau^\pm$
Lepton neutrinos	ν_e, ν_μ, ν_τ $\bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$
Bosons	$W^\pm, Z^0, \gamma, g$
Postulated	H^0

Tab. 1.1: Particle spectrum of the Standard Model

1.3 Massive vector bosons

The massive (~ 80 and ~ 91 GeV) vector bosons, $W^\pm$ and Z^0 , are the mediators of the weak force. They were predicted by electroweak theory and, following their discovery[24]¹, were subsequently studied at a CERN-based $p\bar{p}$ collider in the 1980s.

1.3.1 W/Z physics at hadron colliders

Boson production

In a hadron collider such as the LHC, massive vector bosons are usually produced via parton-parton scattering from constituents within the incoming hadrons. The rest of the hadrons (spectator partons) will then undergo the process of fragmentation (hadronisation) which causes hadronic deposits in the detector (the underlying event). The process described above is shown in figure 1.1.

Feynman diagrams such as the ones in figure 1.2 may be used to describe the Leading Order (LO) production and decay mechanisms of W and Z bosons (in this case, the hard process) at hadron colliders. Hard gluons may be emitted in the form of Initial State Radiation (ISR), the treatment of which features in Next to Leading Order (NLO) calculations. Ideally these will be reconstructed as hadronic jets in the detector.

The likelihood of production of the bosons (or indeed, any process in the collision) is described by a production cross section σ , which is proportional to a matrix element squared

¹ although first experimental evidence of the weak neutral current was actually seen in a bubble chamber[25].

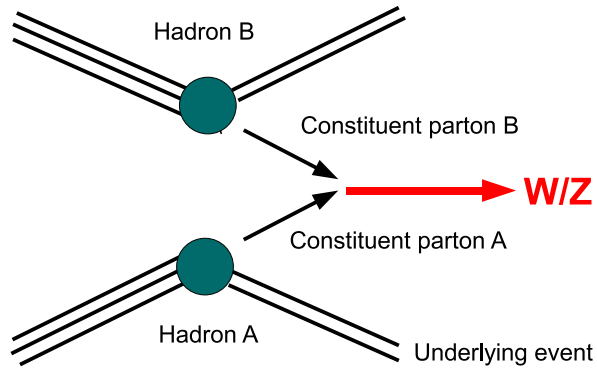


Fig. 1.1: Schematic for production of W and Z bosons (V bosons) in a hadron collider

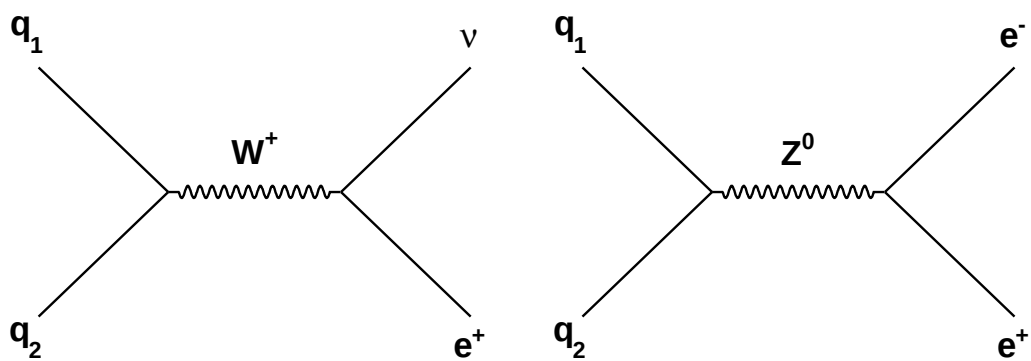


Fig. 1.2: Leading order Feynman diagrams for production (and decay) of W^+ (the equivalent W^- process is described if the e^+ is replaced by e^- and the neutrino ν by an anti-neutrino $\bar{\nu}$) and Z bosons in a hadron collider

(for example, equation A.56 in [26]). The matrix element $\mathbf{M}$ is an amplitude for the process to occur, and may be computed by summing over initial state interaction amplitudes (the square of which correspond to interaction probabilities).

The momentum distributions of the incoming partons (quarks and gluons) within the hadron affect these interaction probabilities. They are then of vital importance in calculating cross sections for such processes. These are determined by Parton Density Functions (PDFs). These are analytical fits (obtained using a combination of theory and experimental data) which describe the momentum distributions of partons inside a hadron.

The cross section of a production mechanism gauges the rate of production of the particle in question:

$$N = \sigma \mathcal{L}, \quad (1.1)$$

where N is the number of particles produced in a particular run of the detector and $\mathcal{L}$ is the integrated luminosity over the run. Figure 1.3 shows the scaling of cross sections of various processes with centre of mass energy $\sqrt{s}$. It may be seen that, at LHC energies, W and Z bosons will be produced in their millions (and this rate of production increases as the $\sqrt{s}$ increases²) even in fairly early running but their production rate will be swamped by that from QCD events (where hadrons are produced in the hard process).

Boson decay

Massive vector boson production is immediately followed by a subsequent decay into leptons or hadrons. Again, gluons may be emitted, this time in the form of Final State Radiation (FSR). In a similar manner to the production rate, the decay rate may be calculated from the matrix element, which is a sum over final state interaction probabilities rather than initial state ones. Table 1.2 summarises all allowed decay modes of the W and Z bosons, along with their branching ratios $\mathbf{Br}$, defined as follows (in the example of $W \rightarrow e\nu$ decay):

$$\mathbf{Br}(W \rightarrow e\nu) = \frac{\Gamma(W \rightarrow e\nu)}{\Gamma(W)}, \quad (1.2)$$

² It should be mentioned that, at the point of writing, the expected startup $\sqrt{s}$ in early running of the LHC has just been reduced from 10 to 7 TeV.

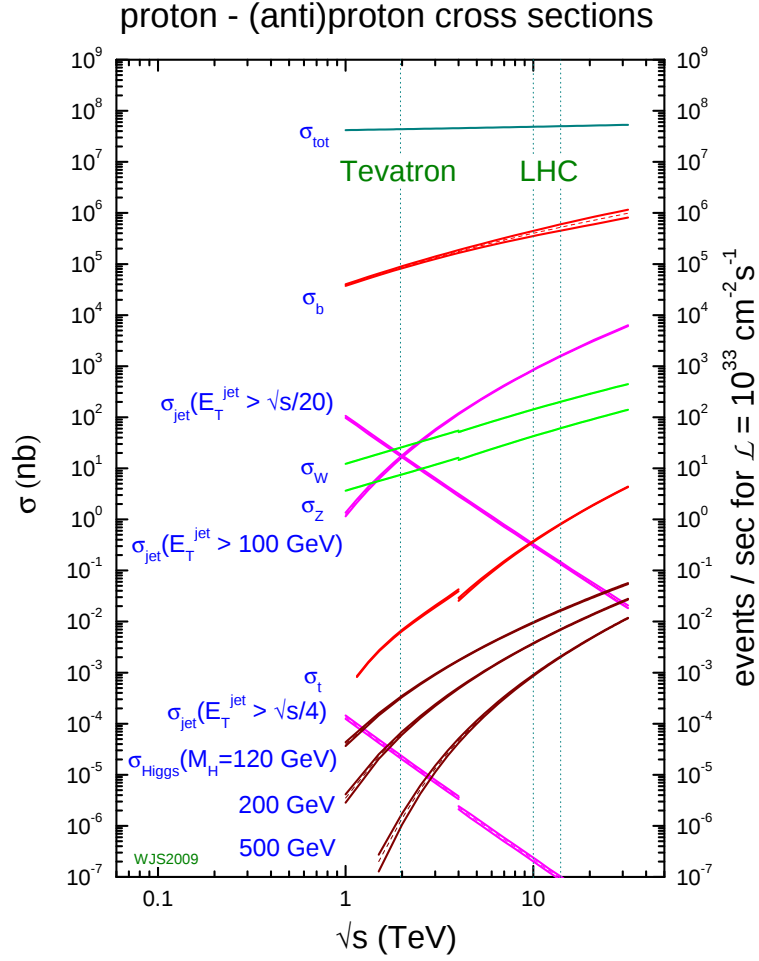


Fig. 1.3: Behaviour of cross sections of processes with $\sqrt{s}$ [27].

where $\Gamma(W \rightarrow e\nu)$ is the partial decay rate of the W decay into an electron and a neutrino, and $\Gamma(W)$ is the total decay rate of the W .

The following may be noted from the table:

- The decay into hadrons is the dominant mode for both bosons. The reason for this is a ‘colour factor’: a decay to a certain quark type is possible for each color³ (red, green or blue) of the quark. However hadron decays will be extremely difficult (if not impossible) to distinguish from QCD background at the LHC and it is not expected that these decays may be used to measure boson cross sections.
- The Z branching ratio to charged leptons is smaller than that for W due to the extra Z decay mode into two neutrinos for which the W has no equivalent.

³ an internal degree of freedom of the quark

Boson	Decay mode	Branching ratio
W	$e\nu_e$	$10.75\pm 0.13\%$
	$\mu\nu_\mu$	$10.57\pm 0.15\%$
	$\tau\nu_\tau$	$11.25\pm 0.20\%$
	hadrons	$67.60\pm 0.27\%$
Z	e^+e^-	$3.363\pm 0.004\%$
	$\mu^+\mu^-$	$3.366\pm 0.007\%$
	$\tau^+\tau^-$	$3.370\pm 0.008\%$
	invisible	$20.00\pm 0.06\%$
	hadrons	$69.91\pm 0.06\%$

Tab. 1.2: Measured branching ratios for W and Z boson decays [28]

- Due to lepton universality the couplings of W and Z to different charged lepton types are the same and the branching ratios are therefore very similar (in the massless-lepton approximation they are the same).

The Drell Yan process

The process in the so-called $Z \rightarrow ee$ dataset used in this analysis is the Drell Yan (DY) [29] process. This is a mechanism by which a lepton anti-lepton pair is created by the exchange of a virtual photon (γ^*) or a Z boson, shown in the Feynman diagram of figure 1.4.

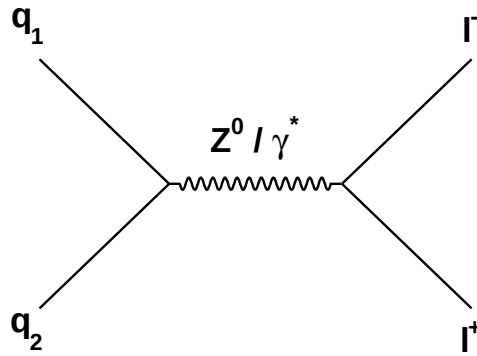


Fig. 1.4: Leading order Feynman diagrams for the DY process in a hadron collider

As has been described, the cross section is proportional to the total matrix element squared, which in this case is $|\mathbf{M}_Z + \mathbf{M}_\gamma|^2$ [46]. Thus the general form of the cross section

will be of the form:

$$\sigma \propto (\text{Photon term})^2 + 2(Z \text{ photon interference term}) + (Z \text{ term})^2. \quad (1.3)$$

The terms relevant to a Z cross section measurement are the second and third: those containing Z contribution. The pure photon term forms a continuum background, the treatment of which is discussed in later chapters.

Measurements to be made in the electroweak sector

The LHC will produce W and Z bosons (V bosons) in their millions and thus is an ideal tool for studying them in detail. Recently the ATLAS collaboration published Monte Carlo (MC) analyses concerning, amongst other studies, measurements involving these particles[10]. A summary of these measurements in addition to some others is given in table 1.3.

Measurement	Timescale	Quantities to be extracted
σ_V	Early running >10 pb ⁻¹	• Detector calibration • Test of NLO predictions • PDF constraints • Γ_W and V_{cs} extraction
$\mathcal{R} = \sigma_W/\sigma_Z$ $d\sigma_Z/d\eta_{Boson}$ $d\sigma_V/dP_{T_{Boson}}$ $d\sigma_V/d(\text{jet multiplicity})$ $dR/d(\text{jet multiplicity})$ W asymmetry	Intermediate running >500 pb ⁻¹	• PDF constraints • Test of gluon resummation techniques • Strong coupling constant α_s • SM background to many new physics searches (supersymmetry, Higgs...) • Deviation from SM prediction of this quantity could be a sign of new physics • Constraints on PDFs
Z asymmetry W mass	Subsequent running >1fb ⁻¹	• Effective weak mixing angle, $\sin^2 \theta_{eff}^{lept}$ • Indirect determination of Higgs boson mass

Tab. 1.3: Measurements to be made in the electroweak sector at the LHC with the expected integrated luminosity (that is, timescale) required for a good measurement. ‘ V ’ refers to a massive vector boson (W or Z).

A measurement of $\mathcal{R}$ as a Standard Model test

The quantity $\mathcal{R}$ (when measured in the electron decay channel) is defined as follows:

$$\mathcal{R} = \frac{\sigma_W \cdot \mathbf{Br}(W \rightarrow e\nu)}{\sigma_Z \cdot \mathbf{Br}(Z \rightarrow ee)} \quad (1.4)$$

$$= \frac{\sigma(W \rightarrow e\nu)}{\sigma(Z \rightarrow ee)}. \quad (1.5)$$

The quantities in equation 1.5 are what will be referred to as the total cross sections of process $W \rightarrow e\nu$ (or $Z \rightarrow ee$): a combination of the production cross section of the boson, σ_V , with its branching ratio $\mathbf{Br}$ in the electron channel decay.

The theoretically calculated value of this quantity $\mathcal{R}$ is around 10 at a collision energy of ~ 10 TeV. The value is determined by a range of factors: the masses of the bosons, their couplings and their possible decay mechanisms as well as the PDFs and centre of mass energy.

As a test of the Standard Model, $\mathcal{R}$ has advantages over a straightforward cross section measurement of $W \rightarrow e\nu$ and $Z \rightarrow ee$ from both an experimental and theoretical standpoint. It is sensitive to many of the quantities that a W or Z cross section measurement would be, but has the advantage of being *independent* of the luminosity present in the sample (of course, providing that the same run was used to calculate both denominator and numerator of equation 1.5!), which at 10% in early data is shown in this work to be by far and away the dominating uncertainty in W and Z cross section measurements. Certain theoretical assumptions will also cancel in the ratio, at least to some degree, in a determination of $\mathcal{R}$, such as gluon resummation (re-ordering power series to eliminate divergences which would otherwise be present in the treatment of soft gluons) techniques and PDF assumptions.

As well as being used to calibrate the detector, $\mathcal{R}$ has been used at the Tevatron to indirectly measure the following quantities [30]:

- **Total W decay width Γ_W in the SM framework:**

Using theoretically derived values of the Z and W total cross sections σ_Z and σ_W as well as the Z branching ratio to electrons, $\mathbf{Br}(Z \rightarrow ee)$, $\mathbf{Br}(W \rightarrow e\nu)$ may be extracted

and used to calculate the total width of the W , Γ_W using the relation[30]:

$$\Gamma_W = (3 + 2f_{QCD})\Gamma(W \rightarrow e\nu), \quad (1.6)$$

where f_{QCD} is a QCD color correction factor.

- **CKM matrix element V_{cs} :**

The inverse of $\mathbf{Br}(W \rightarrow e\nu)$ is related to a sum over all W flavour changing quark couplings V_{ij} (known as CKM matrix elements). This may be used to indirectly measure the least well known of these: V_{cs} , describing the $W \rightarrow cs$ coupling.

In ATLAS, it is hoped that a measurement of $\mathcal{R}$ may facilitate the following physics studies:

- **PDF studies:** A measurement of $\mathcal{R}$ may be used to constrain the heavy quark PDFs, which at LHC energies contribute to the Z ($b\bar{b}$ coupling) but not the W ($t\bar{b}$ coupling) cross section [31].
- **$\mathcal{R}$ in a differential perspective:** Many new physics signatures have a decay chain resulting in a final state configuration of 1 or 2 leptons plus jets and possibly missing transverse energy. Such decays will affect the ratio measurement especially at high jet multiplicities and thus a measurement of $\mathcal{R}$ differentially with, for example, the number of reconstructed jets may be used as a generic search for new physics [32].

1.4 The LHC and the ATLAS detector

1.4.1 The Large Hadron Collider (LHC)

Upon commencement of operation, the Large Hadron Collider [33] at CERN, represented in figure 1.5, will be the largest and most powerful particle collider in the world, increasing the centre of mass energy by an eventual factor of seven from its closest competitor. Bunches of up to 10^{11} protons will be accelerated around the 27 km LHC tunnel and collide at a rate of 40 MHz at four interaction points round the ring to provide 7 TeV (to be increased to 14 TeV) proton-proton collisions, eventually at the design luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. Activity at the collision points will be monitored by four detectors: ATLAS, CMS, LHCb and ALICE, where ATLAS and CMS have been built as general purpose detectors designed to search for new physics.

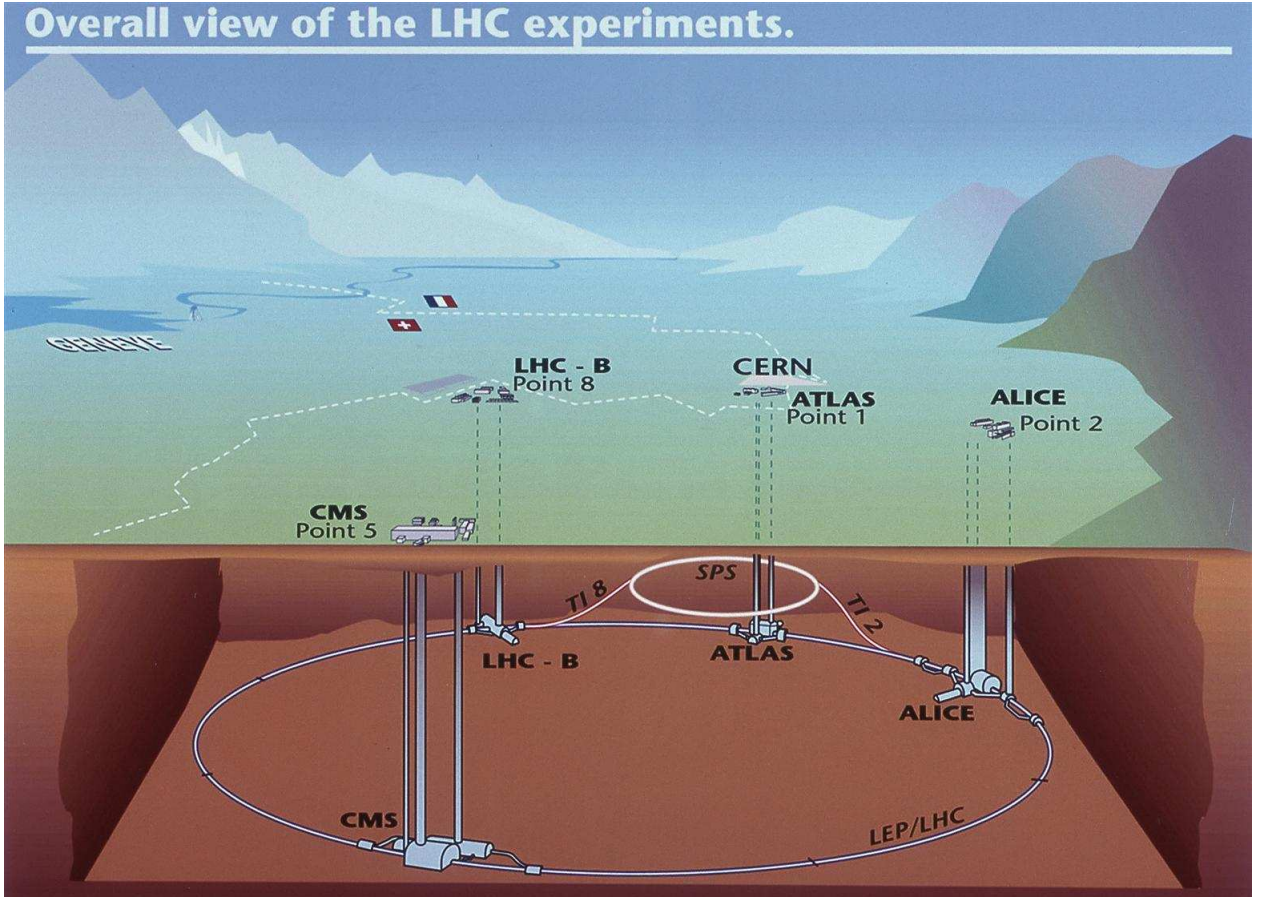


Fig. 1.5: CERN accelerator complex

1.4.2 A Toroidal Lhc Apparatus (ATLAS)

The main features of the physics programme at the ATLAS detector [34] are briefly outlined below.

- **SM physics**

ATLAS is expected to study the properties of the electroweak W and Z bosons, as well as precision measurements on the top quark. In addition, QCD events will be prevalent at the LHC and it is hoped that studies of these may increase understanding of the strong force. Such measurements will facilitate new physics searches as well as aiding theoretical predications in the Standard Model.

- **Search for the SM Higgs Boson**

The Higgs mechanism [23] provides an explanation of electroweak symmetry breaking, and in addition predicts the existence of a neutral massive particle, the Higgs boson. The search for the Higgs boson is a primary research aim of ATLAS and the LHC.

- **BSM searches**

Another major aim of ATLAS is to discover physics beyond the Standard Model. Perhaps one of the main focuses is the search for SuperSYmmetry (SUSY) [35], although ATLAS is well equipped to search for many other exotic scenarios [11].

The physics benchmark goals have been translated into design requirements of the ATLAS detector [34] which are summarised below:

- Fast, radiation-hard electronics and sensor elements.
- High detector granularity and acceptance.
- Large acceptance in pseudorapidity with almost full azimuthal coverage.
- Momentum resolution and reconstruction efficiency in the inner tracker, with the vertex detectors close to the interaction point.
- Electromagnetic (for electrons and photons) and hadronic (for jets and $\cancel{E}_t$) calorimetry.

- Good muon identification and momentum resolution over a wide momentum range.
- Efficiency of triggering on both low and high momentum objects.

The final design of ATLAS is shown schematically in figure 1.7, which shows in three dimensions all the main components of the experiment. The detector geometry consists of a central cylindrical barrel section with endcaps at both ends of the detector.

ATLAS is described by a coordinate system $[R, \phi, z]$, where the z axis points along the beam pipe, R is the transverse distance from the interaction point, and ϕ is defined such that the x axis points from the interaction point to the centre of the LHC ring. The coordinate system used to describe the motion of particles is the $[P_T, \eta, \phi]$ system. P_T is the transverse momentum of the particle, $\mathbf{P} \cdot \sin \theta$, and pseudorapidity η is used to describe the boost of particles parallel to the beam axis, defined thus:

$$\eta = -\ln[\tan^{-1}(\theta/2)], \quad (1.7)$$

where the polar angle $\theta = \tan^{-1}(y/z)$.

Another co-ordinate commonly used is the angular (ΔR) separation between two particles:

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}. \quad (1.8)$$

ATLAS, like most particle detectors, has an ‘onion type’ structure: it consists of separate elements designed to look for different types of particles, built from the centre outwards. Figure 1.6 shows, in the x-y plane, a simulated event traversing the ATLAS detector. The main detector components (inner detector, electromagnetic and hadronic calorimeters and muon chambers) have been shown.

ATLAS is clearly an enormously complex machine and to explain all of its components in more detail would be beyond the scope of this thesis, especially seeing as the design of the detector has been extensively described in dedicated documents [34]. However, those components of the detector directly relevant to this analysis are outlined in the next section.

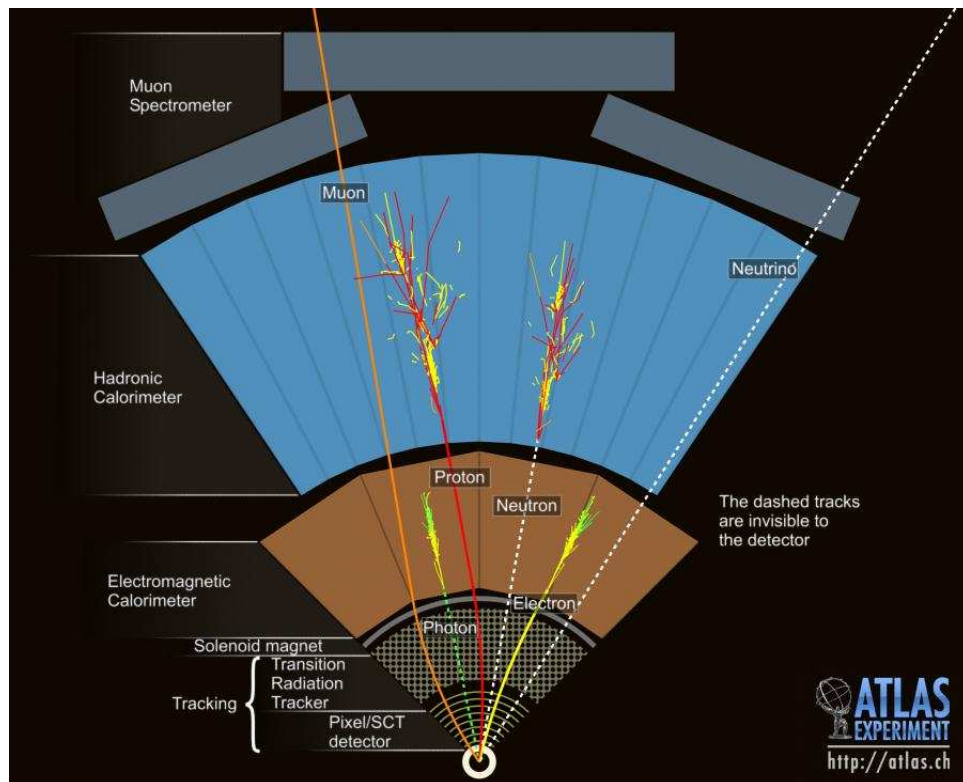


Fig. 1.6: A transverse slice of the ATLAS detector (<http://atlas.ch>)

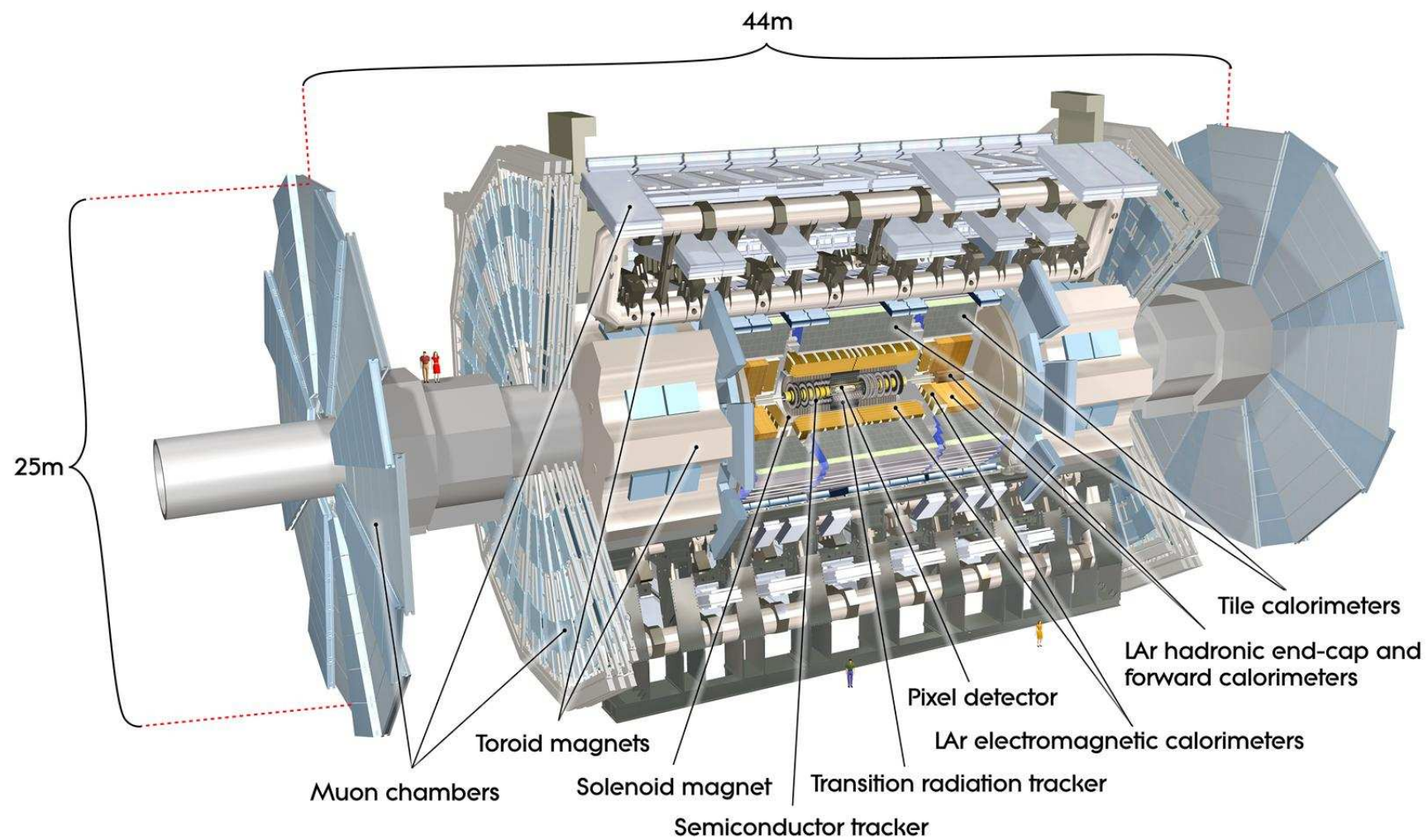


Fig. 1.7: The ATLAS detector (<http://atlas.ch>)

1.4.3 W and Z bosons in the ATLAS detector

This analysis investigates the feasibility of an ATLAS measurement of cross sections for $W \rightarrow e\nu$ and $Z \rightarrow ee$ as well as their ratio in early data (100 pb^{-1}). A cross section has already been described from a theoretical point of view, but the equation from an experimental perspective is as follows:

$$\sigma(\text{process}) = \frac{N}{\mathcal{L}} \quad (1.9)$$

$$= \frac{N_{\text{observed}} - N_{\text{background}}}{A \cdot \epsilon_R \cdot \epsilon_T \cdot \mathcal{L}}. \quad (1.10)$$

Equation 1.10 summarises the steps required to correct the number of events *seen* in the detector, N_{obs} , to the number of events N *produced* in the detector (which is needed to compare the result with theory). In short, one must correct for the background $N_{\text{background}}$ from other channels after event selection, the detector acceptance (A), the trigger and reconstruction efficiencies (ϵ_T and ϵ_R), and the luminosity $\mathcal{L}$ (not needed in the determination of the ratio $\mathcal{R}$). With the exception of luminosity which is measured by dedicated detectors in the forward regions[53][54], the determination of and subsequent correction for these quantities is the focus of this analysis.

As has been described in the preceding section, decay components in this channel include electrons (decay products), hadronic deposits (underlying event and hard gluon emission) and missing energy (the neutrino in W decay will not, to a good approximation, interact with the detector). The inner detector and the calorimeters are the major components of the detector required to reconstruct these events, and so the relevant details of these elements are outlined below.

Electron tracking and the Inner Detector (ID)

The ID is responsible for reconstructing the tracks and vertices of charged leptons and charged hadrons. The whole inner detector sits inside a 2 Tesla solenoidal magnetic field which bends the paths of the charged particles with a radius of curvature dependent on their

momenta. Thus by studying the properties of the track, the particle charge and momentum may be measured. In the case of electrons, these quantities are needed for the purposes of identification and momentum determination.

The ID is constructed from many separate elements which will record a ‘hit’ (which is time stamped and also provides a spatial measurement due to the element position) if a charged particle passes through them. The strategy of tracking adopted by ATLAS is to join up these hits to reconstruct the passage of the particle through the detector. The ID consists of three different components and thus three tracking technologies, described below.

The Pixel Detector

As the name suggests, the pixel detector elements are high granularity (size $50 \times 400 \mu\text{m}$) silicon pixels mounted onto three concentric cylinders and 5 disks in each of the two high pseudorapidity ‘endcap’ regions. If a particle passes through a pixel element it will provide an electric signal (from the electron-hole pair created by the particle) which is then amplified and compared to a set threshold to give a binary output. The pixel detector is responsible for measuring impact parameters and is thus crucial in b and τ physics at ATLAS.

The Semi-Conductor Tracker (SCT)

The principle of operation of the SCT is very similar to the Pixel detector, but the elements are of coarser granularity: silicon strips mounted onto modules which are glued onto 4 cylindrical concentric barrels and 9 disks mounted onto each of 2 endcaps. Silicon microstrips in the SCT are glued into back-to-back pairs with a stereo angle of 40 mrad between them which facilitates a spatial measurement of the particle in the z direction.

The Transition Radiation Tracker (TRT)

The TRT consists of drift tubes of diameter 4 mm and length 144 cm lying parallel to the beam axis in the barrel region, and radially in the end caps. Passing charged particles will ionise the gas inside the tubes causing an electrical signal along an anode wire situated in the middle of the tube. The signal, if above a low threshold, is then read out. High energy photons produced by transition radiation [36] of the charged particle will pass a high threshold. Transition radiation is more likely in electrons than in pions and this will be

exploited by the TRT in identification of these particles.

Electron energy, missing energy and the calorimeters

The purpose of the calorimeters is to measure the energy of electrons, photons and jets. A sub-objective is to study the properties of the energy deposits of said particles to aid their identification. The other purpose of the calorimeters is a measurement of missing transverse energy ($\cancel{E}_t$): the missing energy measured by summing up all energy deposits in the transverse plane defined by the x and y axes.

If the calorimeters were perfectly hermetic and the input centre of mass energy known precisely, a measurement of missing energy would be possible. Unavoidably however, there are gaps in the detector to allow for electrical, optical and cryogenic services which contributes to missing energy (not to mention the energy lost down the beam pipe). In addition, the centre of mass collision energy depends on the input energy of the parton which, being determined by the PDFs, cannot be evaluated on an event by event basis. However, a good assumption is that the input *transverse* momenta of the incoming particles is zero, and thus transverse missing momenta (which is, to a good approximation, equal to transverse missing energy $\cancel{E}_t$) may be reconstructed by a weighted sum of the calorimeter (and muon chamber) deposits in the transverse plane (see chapter 2, which also discusses the performance of the calorimeters).

Due to the different properties of electronic and hadronic objects, the calorimeter is divided into electromagnetic (EM) and hadronic (Had) sections. These again have a central barrel ($0 < |\eta| < 1.5$) and forward region (separated into end cap and forward calorimeters).

The calorimeters must avoid particles punching their way through them and thus are made of dense material. Both calorimeters are of a sampling design; particles interact with layers of dense absorber material causing a particle ‘shower’, which is then detected and read out by layers of sampler material interspersed with the absorber plates. The precise mechanisms of detection for electromagnetic and hadronic calorimeters differ slightly as detailed below.

The ElectroMagnetic (EM) calorimeters

In the lead absorber, particles cause a particle cascade (the shape of which, in conjunction with tracking information, may be used for electron and photon identification) via the processes of pair production (a photon produces an electron - positron pair: $\gamma \rightarrow e^+e^-$) and Bremsstrahlung (an electron in the electric field of a nucleus radiates a photon: $e \rightarrow e\gamma$). The resultant particle shower liberates electrons in liquid argon sampler material interspersed with the absorbers. These electrons are collected using an applied electric field and are subsequently detected as electronic pulses.

The Hadronic Calorimeters

The hadronic calorimeters are situated outside of the EM calorimeters and so no photons or electrons should, in principle, be incident on them. The particle cascade is produced by hadron-nuclear interactions in the dense iron absorber material, and detected by the sampler, which is a plastic scintillator (except in the forward regions which are more susceptible to radiation damage).

Non-local detector components

Clearly, there are many elements of ATLAS common to more than one sub-detector which are necessary in the detection and reconstruction of $W \rightarrow e\nu$ and $Z \rightarrow ee$ events, to mention a few; trigger, luminosity monitoring and reconstruction algorithms. A full description of these is far beyond the scope of the thesis but details have been extensively documented[34][6]. However, those elements particularly key to the analysis, the electron trigger and reconstruction systems, are expanded below.

Electron reconstruction in ATLAS

Electron detection, calibration and reconstruction in ATLAS are described in detail in [14] and just the main elements of the reconstruction procedure are summarised here.

As has been detailed, an electron passing through the ATLAS detector will create electronic pulses in some cells of the electromagnetic calorimeter. A sliding window

cluster (a window of fixed size which is positioned so as to maximise the amount of energy within it) is used to group these cells together, forming the base of an electron (inner detector track) or photon (no track). Depending on the analysis requirements, different tightness of electron identification criteria (known as IsEM) will be used. Efficiency of the selection will increase with looser criteria but so will background contamination.

Three main sets of cuts have been defined to facilitate flexibility of analysis: loose, medium and tight, although all levels of cuts follow the same basic strategy of identifying electrons by cutting on cluster shape, hadronic leakage and in some cases matching to an inner detector track. The sets of cuts are described below, although it must be noted that these are the cuts used in a specific Athena release version and are subject to change.

Electron identification cuts

Loose

- $\eta(\text{electron}) < 2.7$
- Ratio of transverse energy (E_T) in the first sampling of the hadronic calorimeter to that of the electromagnetic cluster (hadronic leakage)
- Shower shape and lateral width

Medium (includes loose cuts)

- Properties of the second largest energy deposit
- Total shower width and energy outside of deposit core
- Number of pixel+SCT hits and transverse impact parameter

Tight (includes medium cuts)

- Ratio of transverse energy in a cone around the deposit to the total cluster E_T
- Number of hits in the vertexing layer, TRT and track-cluster matching in energy-momentum, η and ϕ

For a W/Z physics analysis, it is advisable to use either medium (low luminosity/early data scenario) or tight (high luminosity/later data scenario) electron identification criteria, as these will provide a suitably sized signal size whilst rejecting enough jet background for the analysis. Unless stated otherwise, this study uses medium identification cuts. For a fully usable $Z \rightarrow ee$ event, both electrons must be reconstructed.

The ATLAS electron trigger system

The ATLAS trigger system, shown in figure 1.8, is described in [16], and the electron trigger system in more detail in [8]. The LHC bunch crossing rate will be 40 MHz, and the requirement of the ATLAS trigger is to reduce this incoming interaction rate to ~ 200 Hz to be written to mass storage. Hence, it needs to select around five events for every million bunch crossings and thus provide a very efficient rejection of the high background rate online.

The ATLAS trigger consists of a hardware based first level trigger (L1) and a software based high level trigger (HLT), which is further divided into the second level trigger (L2) and the event filter(EF). For a trigger chain to pass the event, all levels of the trigger must pass.

Level 1 (L1) electron trigger

The L1 trigger is a hardware trigger designed to reduce the bunch crossing rate of 40 MHz to 75 kHz. The information for the electron L1 trigger comes from trigger ‘towers’, $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ segments in the electromagnetic and hadronic calorimeters, as shown in figure 1.9. The L1 electron menu of cuts is as follows:

- The central cluster is a local maximum and passes the quoted threshold in energy (18 GeV in this study)
- 12 surrounding electromagnetic towers fall below a specified energy threshold, the threshold value depending on the trigger menu being used. The cut is designed with the purpose of requiring objects to be isolated.

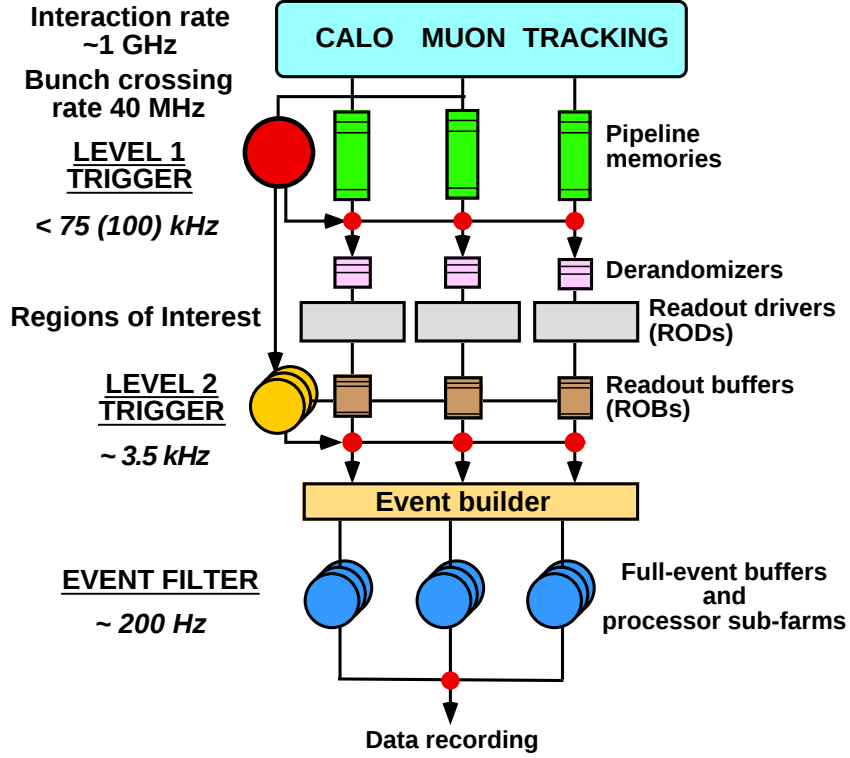


Fig. 1.8: Overview of the ATLAS trigger system

- 16 hadronic towers behind and 12 hadronic towers surrounding the cluster fall below a specified hadronic isolation energy threshold.

RoIs (Regions of Interest) are regions in $\eta\phi$ space pertaining to those areas of the detector passing these criteria. The information contained in a RoI is the only information passed to the L2 trigger system (apart from the $\cancel{E}_t$ trigger which works using global variables), with the interests of keeping the amount of data to be unpacked and analysed to a minimum and so reduce processing time.

Level 2 (L2) electron trigger

The software-based L2 trigger gives a trigger decision within ~ 10 ms, and reduces the output rate to ~ 2 kHz. Its seed is the reconstructed, full granularity L1 object with associated $\eta\phi$ position (apart from the $\cancel{E}_t$ trigger). The L2 electron trigger imposes additional cuts on shower shape and also uses inner detector information to search for tracks which match to the calorimeter cluster. Similarly to L1, only passed L2 RoIs are passed onto the EF level.

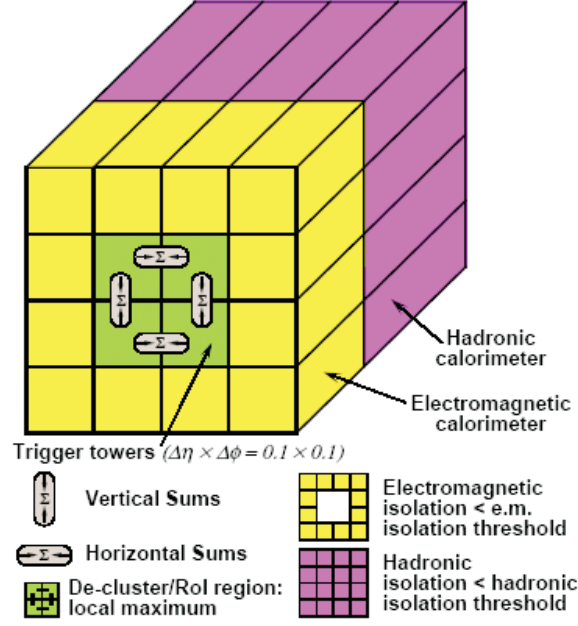


Fig. 1.9: L1 trigger towers

Event Filter (EF) electron trigger

The EF works in a very similar way to L2 in imposing both calorimeter and tracking cuts, but uses more sophisticated algorithms and thus has a longer processing time of ~ 1 s, reducing the output rate to 200Hz. At this level the offline reconstruction algorithms are used, although working in a seeded approach using the L2 RoIs (with the exception of the $\cancel{E}_t$ trigger) as opposed to reconstructing the entire event. Upon the trigger accept the EF output is appended to the event, and the event is written to mass storage.

1.5 Simulation details and event selection

1.5.1 Event simulation

At the time of writing the LHC is not yet running, and thus this analysis is performed using simulated Monte Carlo (MC) data. The data format used were ROOT [37] ntuples, produced from official ATLAS simulated datasets. Reconstruction was run in the ATLAS software framework, Athena, release 14 (apart from some older plots made for qualitative purposes which state the release used to make them). Release 14 samples are generated with a centre of mass energy⁴ of 10 TeV, whereas results stated at release 13 or earlier are generated at 14 TeV. Detector simulation was performed using GEANT version 4 [38].

PYTHIA[39] version 6.323-6.411 was the default general-purpose MC generator used for the signal samples. Some plots involving additional jets in the signal event are made using ALPGEN[40] (interfaced with HERWIG/JIMMY[43][44] for hadronisation and underlying event modelling) generated samples. The radiation of photons from charged leptons was treated using the PHOTOS QED radiation package[41]. LHAPDF, the Les Houches accord PDF interface library[42], was used throughout to provide the PDF (set CTEQ6L) values. Generator-level filter cuts were applied on the samples to remove events unlikely to pass event selection. The percentage of events remaining after the filter cuts is referred to as the filter efficiency ϵ_F .

Reconstruction was run on the generated events with the purpose of trying to model as realistically as possible the ATLAS detector. In particular, detector imperfections such as misalignment and distorted magnetic field configurations were included in the simulation. Uncertainties on the performance of the objects used in the simulated samples were taken from the expected ATLAS performance after 100 pb⁻¹ [6]: an uncertainty on the electron energy scale (resolution) of 1 (20)% was implemented, and the jet energy scale was assumed to be 5% in the central region ($\eta < 3.2$). For $\cancel{E}_t$ an additional 10% uncertainty (on top of the uncertainties for leptons and jets) was assumed.

Table 1.4 lists all datasets used in the cross section analysis with relevant physics details.

⁴ at the time of writing it has just been announced that the startup energy of the LHC is likely to be 7 TeV, but this was announced after the 10 TeV analysis detailed in this thesis was completed.

Unless stated otherwise, the analysis was performed on 100 pb^{-1} of each dataset (the number of events used may be found by multiplying the quoted cross section by 100 and dividing by the filter efficiency).

Event type	Generator	Generator cuts	ϵ_F %	σ_{LO} (pb)
$Z \rightarrow ee$	PYTHIA	$M_{ee} > 60 \text{ GeV}$ + $\geq 1 \text{ e}$ with $\eta < 2.8$	96	1143.96
$W \rightarrow e\nu$	PYTHIA	$\geq 1 \text{ e}$ with $\eta < 2.8$	88	11764.6
$W \rightarrow \tau\nu$	PYTHIA	$\geq 1 \text{ e}$ with $\eta < 2.8$	87	4184
$Z \rightarrow \tau\tau$	PYTHIA	$M_{ee} > 60 \text{ GeV}$	1	1128.37
$t\bar{t}$	MC@NLO		0.55	373.59
QCD	PYTHIA	$\eta(\text{jet}) < 2.7$ + $P_T > 17 \text{ GeV}$ + jet size cuts	0.07	1.461×10^9

Tab. 1.4: Details of physics MC datasets used in the cross section calculations. Details of the MC@NLO generator are given in [45].

1.5.2 Event selection

The default selection for $W \rightarrow e\nu$ and $Z \rightarrow ee$ analyses are described below. The reader should assume this selection is used unless stated otherwise. A brief motivation for each cut is given but more detail on the rejection power of each cut is given in chapter 4. The exact cut optimisation is an extensive study that has been performed by the relevant working groups within ATLAS [10].

$W \rightarrow e\nu$ event selection

The selection for $W \rightarrow e\nu$ events is as follows:

- Event triggers through single electron trigger chain e22i (one isolated electron with $P_T > 22 \text{ GeV}$).
- Exactly 1 reconstructed electron with $|\eta| < 2.4$ (the inner detector region, needed for electrons to be reconstructed with high efficiency) and transverse momenta $P_T > 25 \text{ GeV}$ (to remove QCD background with jets faking low energy electrons). Electrons falling into the region $1.37 < |\eta| < 1.52$ are not included as this is a less efficient region of the detector (a gap in the calorimeters allows cabling services in and out of the detector).

- Reconstructed electron passing medium electron selection (IsEM) cuts as described earlier.
- Transverse missing energy ($\cancel{E}_t$) > 25 GeV. Removes backgrounds from channels with no or small true $\cancel{E}_t$ (such as $Z \rightarrow ee$).

It is worth noting that some $W \rightarrow e\nu$ analyses include some cut on hadronic activity. This analysis does not use this cut as it is an early data global cross section measurement, and the cut is more suited to precision analysis with more data (for example, the determination of the W mass [12]).

$Z \rightarrow ee$ event selection

The selection for $Z \rightarrow ee$ events is as follows:

- Event triggers through single electron trigger chain e22i.
- Exactly 2 reconstructed electrons both with $|\eta| < 2.4$, crack removal of $1.37 < |\eta| < 1.52$, and $P_T > 25$ GeV.
- Reconstructed electrons passing medium electron selection (IsEM) cuts.
- Reconstructed invariant Z mass (M_{ee}) between 80 and 100 GeV. Removes a large amount of backgrounds which do not have a peak in this region.

Jet selection

On the (rare) occasion in this analysis where jets (a spray of hadrons) were used, the selection used is as follows:

- Jets defined using a cone algorithm [13] which, at the time of the analysis being performed⁵ was the ATLAS default jet algorithm. This defines a jet as an angular cone of a certain size (0.4 in this analysis) around some direction defined to maximise the hadronic activity deposit within it. The seed upon which the jet algorithm builds is a calorimeter cluster above a certain energy threshold.

⁵ although this has now changed to an infra-red safe algorithm where the emission of soft collinear gluons does not affect the final jet topology.

-
- Jets are required to have $P_T > 20$ GeV and $|\eta| < 5.0$.
 - Before the jet container is used, overlap removal is performed. A jet is made by running a jet algorithm on stable visible particles and thus all electrons are also initially reconstructed as jets. Those ‘jets’ which lie within a certain distance ($\Delta R=0.4$) of a reconstructed electron are removed from the jet container.

2. DETECTOR RESPONSE

2.1 Introduction to detector response

Detector response refers to the detector performance in reconstructing objects such as electrons and $\cancel{E}_t$. In other words, it is a description of how precisely the particle properties are measured. As will be explained in chapter 3, it is important to *measure* and understand the detector response in order to calculate corrections to the acceptance, which is computed from the rejection power of the kinematic cuts used in the event selection. It is the objective of this chapter to discuss methods of determining resolution functions from data alone.

Detector response is represented in this analysis by what will be called a resolution function. The resolution function should form a roughly Gaussian distribution. The mean of the Gaussian distribution may be thought of as the detector *scale*, and the 1σ width of the distribution as the detector *resolution* on x .

Using a MC sample, this may be thought of, for variable x , as the distribution of $x(\text{reconstructed}) - x(\text{truth})$ on an event by event basis, where ‘reconstructed’ refers to the quantity (for example, electron P_T) output of the reconstruction software, and truth is the input electron truth P_T run through the reconstruction. This MC estimate of the detector response will be from now on referred to as the **R-T(x)** distribution.

Table 2.1 summarises the resolution functions that may be required¹ for this analysis (taking into consideration the geometrical cuts used in the event selection). A summary of the methods to determine these functions from data is also given, and these are explained in more detail subsequently.

The table states that an electron η resolution function is not required for the analysis. The reason is that, due to the high granularity of the ATLAS tracker and calorimeters, the angular resolution for an electron is very small when compared to the momentum resolution, as may be seen in figure 2.1.

As has been mentioned, the motivation for measuring resolution functions is so that acceptance smearing on the kinematic cut variables may be performed. As no cuts on $\phi(\cancel{E}_t)$ or

¹ Jets would be included in the case of a W/Z +jets cross section analysis but for an inclusive study this is not necessary.

$\phi(\text{electron})$ are used in the analysis, azimuthal resolution functions are not considered².

Analysis	Object	Parameter	Method of determination
$Z \rightarrow ee$	Electron	P_T	Z mass peak
$W \rightarrow e\nu$	Electron	P_T	Z mass peak
$Z \rightarrow ee$	Electron	η	Not necessary
$W \rightarrow e\nu$	Electron	η	Not necessary
$W \rightarrow e\nu$	$\cancel{E}_t$	P_T	- Neutrino-fication (replacing an electron in a $Z \rightarrow ee$ event with a neutrino) - Axis resolution from Z events

Tab. 2.1: Resolution functions and data driven methods of determination

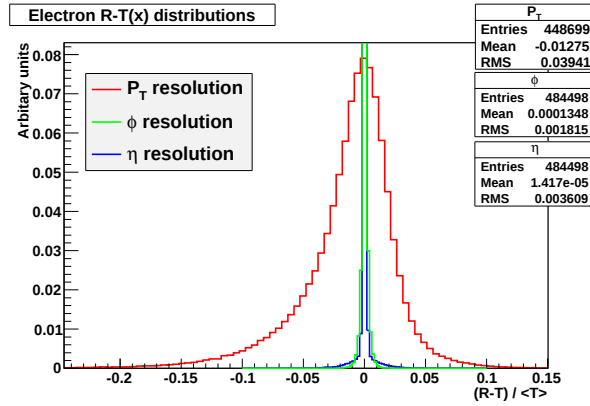


Fig. 2.1: Electron fractional $\mathbf{R-T}(\mathbf{x})$ for P_T , η and ϕ (as a fraction of the mean value of the truth quantity). The angular resolution contribution can be seen to be negligible in comparison to the transverse momenta resolution.

2.2 Electron response

The $\mathbf{R-T}(P_T)$ distributions for electrons are shown in figure 2.2(a). To make such distributions it is necessary to implement truth-reconstruction matching which is done by searching for a reconstructed electron lying within $\Delta R=0.2$ to the truth electron. The distribution is clearly non-Gaussian; it has a large asymmetric lower side tail due to Bremsstrahlung radiation in the ID (the electromagnetic force that the electron feels from the nuclei of the tracker material prompts it to emit photons and thus lose energy).

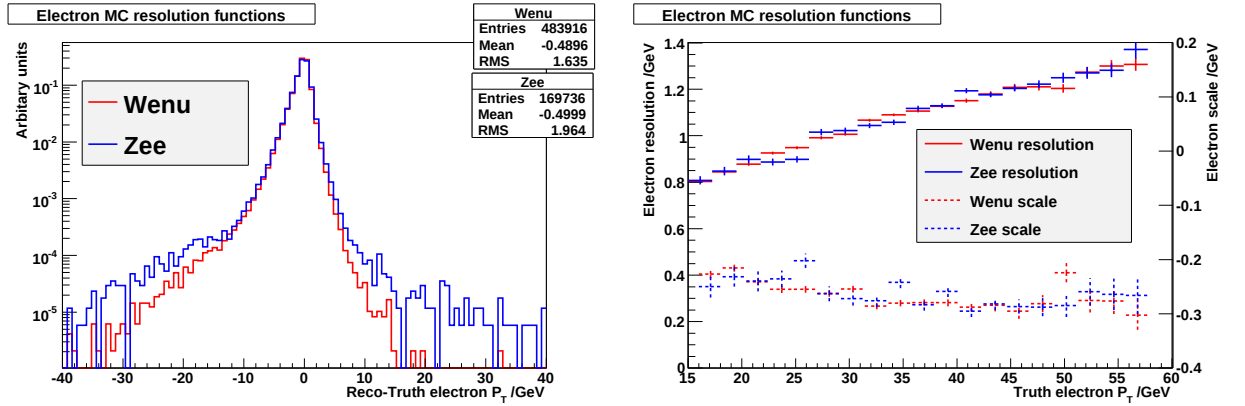
The figure also shows that the absolute P_T resolution is a little better in $W \rightarrow e\nu$ than in

² It is true that electron ϕ is used in constructing the Z mass in $Z \rightarrow ee$ analysis, which is a variable which is cut upon. However, given the electron ϕ resolution is very good (as shown in figure 2.1), this is considered a second order effect.

$Z \rightarrow ee$. This is because electrons coming from a $W \rightarrow e\nu$ decay tend to have *slightly* lower P_T than those from $Z \rightarrow ee$ due to the lower mass of the W boson than the Z , and lower P_T objects have better absolute resolution in ATLAS (see next paragraph). The higher P_T electrons from $Z \rightarrow ee$ will also tend to emit harder Bremsstrahlung radiation than those from $W \rightarrow e\nu$ causing the low side tail in the histogram produced from Z events (the small excess of events on the high side is thought to be due to the higher P_T electrons in Z decays having worse resolution).

It is necessary to study the resolution of the object with respect to its driving variable, which in the case of the electron is the size of the P_T itself. Figure 2.2(b) shows how the mean and σ (taken from $\mathbf{R-T(x)}$) of the electron P_T resolution behaves with P_T . The (absolute) resolution worsens steadily with P_T (although the fractional resolution actually improves due to stochastic effects) and a (slight) negative scale due to electron Bremsstrahlung increases with P_T as the electrons are able to emit more energetic photons in a higher P_T region.

The electron resolution function will, in practice, be determined by studying M_{ee} , whose



(a) Electron MC global resolution function in $Z \rightarrow ee$ and $W \rightarrow e\nu$ (b) Electron P_T resolution and scale as a function of electron P_T

Fig. 2.2: Electron $\mathbf{R-T}(P_T)$ distributions

mean value and width are sensitive to the electron scale and resolution respectively. The conclusion of an ATLAS study on this topic [14] was that the expected systematic uncertainty on the electron response (at the Z boson energy scale) using this method is 0.2% and 0.7% on the scale and resolution respectively.

2.3 $\cancel{E}_t$ response

2.3.1 $\cancel{E}_t$ in ATLAS

Computation

$\cancel{E}_t$ in ATLAS is, essentially, computed from the deposits in the calorimeters and muon chambers. The $\cancel{E}_t$ algorithms as well as the expected performance are described in [9]. The main $\cancel{E}_t$ reconstruction algorithm (RefFinal) is as follows:

Cell Based Method

- A sum is made over energy deposit in calorimeter cells surviving noise cuts (in this case energy deposit $> 2\sigma_{noise}$). Cells are initially calibrated using weights depending on their energy density³ to give a first approximation of the $\cancel{E}_t$ in the event.
- Corrections are made for reconstructed muons (using the measurement from the muon spectrometer) and energy lost in the cryostat (determined from MC and test beam studies).
- Cells are calibrated to the reconstructed object (electrons, taus, jets, muons) that they are assigned to (a global calibration is made for cells outside objects).

Performance

$\cancel{E}_t$ performance in this analysis is evaluated in terms of scale and resolution where those quantities are defined by:

$$\text{Scale} = \overline{\cancel{E}_t^{\text{true}} - \cancel{E}_t^{\text{reco}}}, \quad (2.1)$$

$$\text{Resolution} = \sigma \left((\cancel{E}_t \cdot \mathbf{A})^{\text{reco}} - (\cancel{E}_t \cdot \mathbf{A})^{\text{true}} \right) \quad (2.2)$$

where $\cancel{E}_t \cdot \mathbf{A}$ denotes the $\cancel{E}_t$ resolved along a chosen axis $\mathbf{A}$, and σ refers to the width of the distribution in parenthesis. $\cancel{E}_t^{\text{true}}$ is the input truth $\cancel{E}_t$ (a sum of the transverse momenta of the non interacting particles) and $\cancel{E}_t^{\text{reco}}$ is the reconstructed $\cancel{E}_t$ in the event.

³ Electromagnetic deposits in the hadronic calorimeter (subject to both electromagnetic and hadronic showering) will have a higher energy density than hadronic deposits.

The $\cancel{E}_t$ resolution in both $Z \rightarrow ee$ and $W \rightarrow e\nu$ events is largely driven by the hadronic calorimeter resolution (the resolution contribution from the electrons is small compared with that from the hadronic deposits as shown later in the chapter). Test beam studies [34](calorimetry chapter) and simulation suggest that this will scale with the transverse hadronic energy deposit, E_T , in the calorimeters:

$$\frac{\sigma(\cancel{E}_t)}{E_T} = \frac{a}{\sqrt{E_T}} + b + \frac{c}{E_T}, \quad (2.3)$$

where the three terms in the equation are explained as follows:

- **a term:** Stochastic term. Originates from the statistical nature of the calorimeters (fluctuations in the sampling fraction) and so follows a Poissonian distribution. Dominates in the middle energy region.
- **b term:** Constant term. Reflects the effect of the calorimeter non-compensation and the detector non-uniformities involved in the energy measurement. Dominates at high energy.
- **c term:** Noise term. Due to the contribution of noise to the energy measurement. Dominates at very low energies.

$\cancel{E}_t$ in both $Z \rightarrow ee$ and $W \rightarrow e\nu$ events is in the region where the stochastic term dominates (apart from the very low $\cancel{E}_t$ region where the noise term is the dominant effect), and so the behaviour of $\cancel{E}_t$ with E_T is expected to follow the form

$$\sigma(\cancel{E}_t) = a\sqrt{E_T} + c. \quad (2.4)$$

As has been described, $W \rightarrow e\nu$ analysis includes a cut on $\cancel{E}_t$ and, for this reason, $\cancel{E}_t$ performance in $W \rightarrow e\nu$ events must be measured and understood. In this analysis, $Z \rightarrow ee$ events are used to investigate techniques of estimating $\cancel{E}_t$ performance in $W \rightarrow e\nu$. In an ideal detector no missing transverse energy would be seen in this channel and thus any missing energy seen in this analysis is a direct result of imperfections in the reconstruction process or the detector. This coupled with the clean event signature for a $Z \rightarrow ll$ event and

its relatively large production rate mean that it is a good channel to study $\cancel{E}_t$. The plots have been made using $Z \rightarrow ee$ events but this analysis has been also performed in $Z \rightarrow \mu\mu$, where it works equally well.

Two data driven techniques are studied in this thesis: axis resolution and neutrino-fication. The application of these measured scales and resolutions to physics analyses are explored in greater detail in chapter 3.

2.3.2 Data driven $\cancel{E}_t$ resolution functions- axis resolution technique

A particular axis $\mathbf{A}$ is defined from the event topology. The distribution of $\cancel{E}_t$ resolved along this axis, $|\cancel{E}_t| |\mathbf{A}| \cos(\theta)$, denoted by $\cancel{E}_t \cdot \mathbf{A}$, is sensitive to detector resolution and bias. The axes used are either the perpendicular (and for comparison the parallel) axes, or the P_{TZ} direction (and for comparison at right angles to P_{TZ}). The construction of these axes are summarised in figure 2.3.

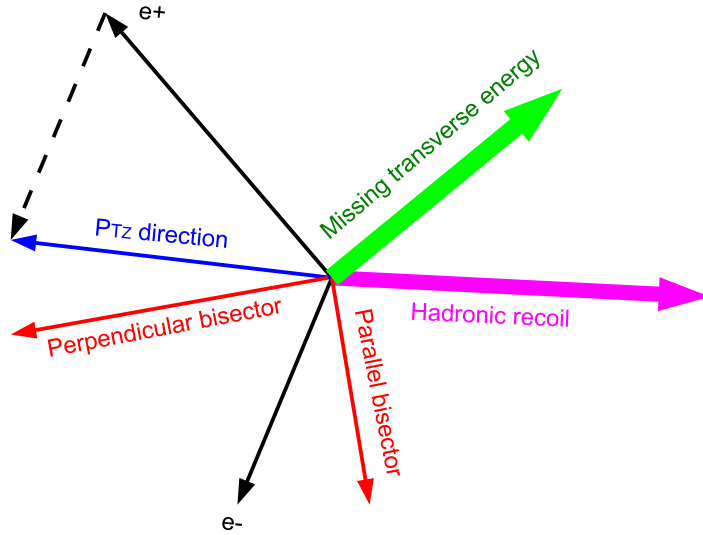


Fig. 2.3: P_{TZ} direction, parallel and perpendicular bisectors in $Z \rightarrow ee$ events

Mathematically, the perpendicular bisector (which may then be normalised) is found by the following:

$$\mathbf{A}_\perp = \frac{\mathbf{P}_{Te+}}{|P_{Te+}|} + \frac{\mathbf{P}_{Te-}}{|P_{Te-}|} \quad (2.5)$$

where P_{T_e} are the momenta of the electron and positron. The parallel bisector $\mathbf{A}_{\parallel}$ is placed at right angles to $\mathbf{A}_{\perp}$. Similarly, P_{TZ} (which also may be normalised) is found by the following:

$$\mathbf{A}_{\mathbf{Z}} = \mathbf{P}_{T_{e+}} + \mathbf{P}_{T_{e-}} \quad (2.6)$$

For comparison, an axis $\mathbf{A}_{\mathbf{AZ}}$ is defined at right angles to $\mathbf{A}_{\mathbf{Z}}$.

More detailed discussion regarding when to use either set of axes is given later in the chapter, but at this point it is sufficient to note that, given the two electrons in a Z decay will have similar energies and for this reason $\mathbf{A}_{\perp}$ and $\mathbf{A}_{\mathbf{Z}}$ (or $\mathbf{A}_{\parallel}$ and $\mathbf{A}_{\mathbf{AZ}}$) will lie very close to one another. Thus all results obtained are very similar regardless of whether $\mathbf{A}_{\perp}$ and $\mathbf{A}_{\parallel}$ or $\mathbf{A}_{\mathbf{Z}}$ and $\mathbf{A}_{\mathbf{AZ}}$ are used.

Using axes to measure bias in MET

The mean values of the distributions $\cancel{E}_t \cdot \mathbf{A}_{\mathbf{Z}}$ and $\cancel{E}_t \cdot \mathbf{A}_{\perp}$ are a measure of the detector scale. If the $\cancel{E}_t$ computation in ATLAS is ideal, these values will be zero in $Z \rightarrow ee$ events and so any deviation from zero suggests a bias in the $\cancel{E}_t$.

Figure 2.4 shows profile plots (the so called ‘Diagnostic plots’) with $\cancel{E}_t \cdot \mathbf{A}_{\mathbf{Z}}$ (figure 2.4(a)) and $\cancel{E}_t \cdot \mathbf{A}_{\perp}$ (figure 2.4(b)) as the y variable. The sum of the electron and positron transverse momenta projected onto the axis is the x variable (an indicator of the energy scale of the event; closely linked to P_{TZ}). This variable represents the hadronic recoil in the event. The diagnostic plot may be used in early data to validate $\cancel{E}_t$ algorithms, as this plot should, in theory, be a flat line through zero regardless of the energy of the lepton system.

$\cancel{E}_t \cdot \mathbf{A}_{\mathbf{Z}}$ and $\cancel{E}_t \cdot \mathbf{A}_{\perp}$ display a clear bias reaching down to about 4 GeV in the region of high hadronic recoil. This can be explained by considering the event topology. $\mathbf{A}_{\mathbf{Z}}$ and $\mathbf{A}_{\perp}$ are designed to be sensitive to the balance between the electrons and the hadronic recoil. It is seen that slightly greater sensitivity to bias is obtained using $\mathbf{A}_{\mathbf{Z}}$ as the resolution axis as it, by construction, lies parallel to the direction of the hadronic recoil from the lepton

system. It must be noted however that this is really an academic point, as the axes $\mathbf{A}_\perp$ and $\mathbf{A}_Z$ lie very close to one another and the observed biases are very similar.

$\cancel{E}_t \cdot \mathbf{A}_{AZ}$ and $\cancel{E}_t \cdot \mathbf{A}_\parallel$ are shown by way of comparison. Such a bias is not seen in these as there is no such mechanism for bias along these axes.

The fact that the observed bias in $\cancel{E}_t \cdot \mathbf{A}_Z$ is negative suggests that either the lepton system energy is being overestimated or the magnitude of the hadronic recoil underestimated. To distinguish between these two, the same plot was made with $Z \rightarrow \mu\mu$ events. The same sign (and also magnitude) bias was seen, suggesting that the problem lies with the hadronic recoil.

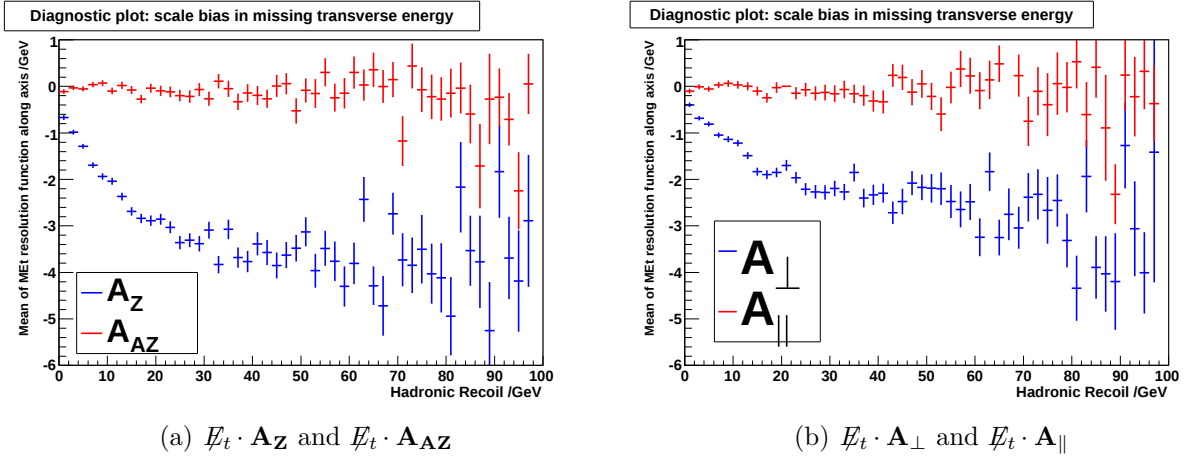


Fig. 2.4: Diagnostic plot for different choice of axes

Figures 2.5 show behaviour of the mean of $\cancel{E}_t \cdot \mathbf{A}_Z$ and $\cancel{E}_t \cdot \mathbf{A}_{AZ}$ with hadronic recoil. The MC comparison $\mathbf{R} \cdot \mathbf{T}(\cancel{E}_t) \cdot \mathbf{A}$ from both $Z \rightarrow ee$ and $W \rightarrow e\nu$ events is superimposed on the plot, and the large bias in $\cancel{E}_t \cdot \mathbf{A}_Z$ is also clearly visible in the Monte Carlo. This result suggests that the cause of the bias is inherent in the ATLAS $\cancel{E}_t$ software and not in the axis resolution methodology.

Investigations were made into the origin of the bias. Firstly, the diagnostic plot was remade except with only the momenta of the real (truth) neutrinos in the event resolved along $\mathbf{A}_\perp$ as the y variable. Only a small bias was seen (< 0.5 GeV) which reveals that the contribution of real neutrinos to the bias is negligible.

Figure 2.6 shows the diagnostic plot separated by jet multiplicity (jets selected using default selection as described in chapter 1). It shows that the bias is greatest in events

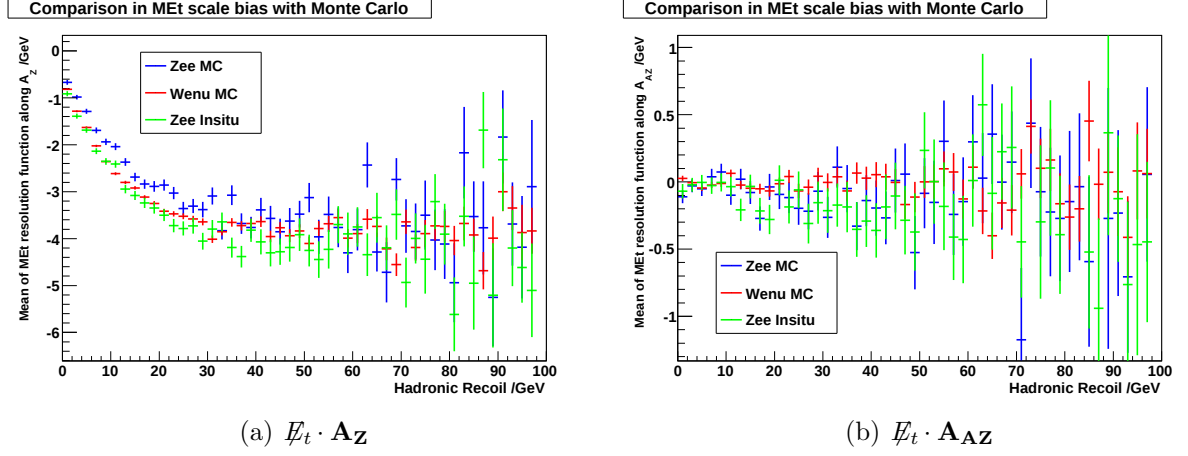


Fig. 2.5: Diagnostic plot compared with Monte Carlo truth in both W and Z events.

with zero jets, which implies the origin of the bias lies with out-of-cone corrections (that is, hadronic deposits which lie outside of reconstructed jets). Such soft deposits can lose too much energy in the upstream material to create any visible energy deposition in the calorimeter. In its current state, the software makes no correction for this effect as it only applies correction factors to the energy deposition that is detected. The bias may be recreated in truth by using a cut on the truth particles (to simulate the loss of energy from those low-energy particles which would not make it to the calorimeters) before using their sum to estimate truth $\cancel{E}_t$. Studies are underway to fully understand this mechanism and correct for it in the $\cancel{E}_t$ algorithms. This effect however may have profound implications for acceptance smearing calculations which is a issue discussed further in the next chapter.

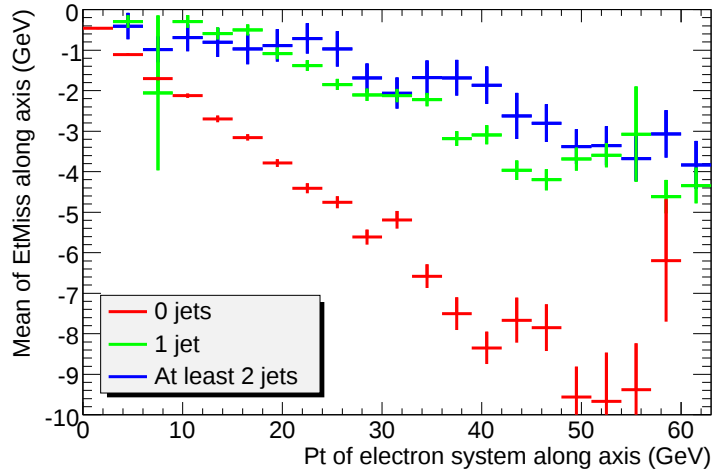


Fig. 2.6: Diagnostic plot split by jet multiplicity

Using axes to measure $\cancel{E}_t$ resolution

In the case of an ideal calorimeter, no missing energy would be seen in $Z \rightarrow ll$ events (other than a contribution from neutrinos originating from heavy jet decays which has been seen to be small). Thus any missing energy that is ‘detected’ from these events must be a result of detector mis-measurement and the spread of its distribution resolved along an axis is interpreted as the calorimeter resolution. The choice of axis to use is an important consideration which is discussed in the next paragraph.

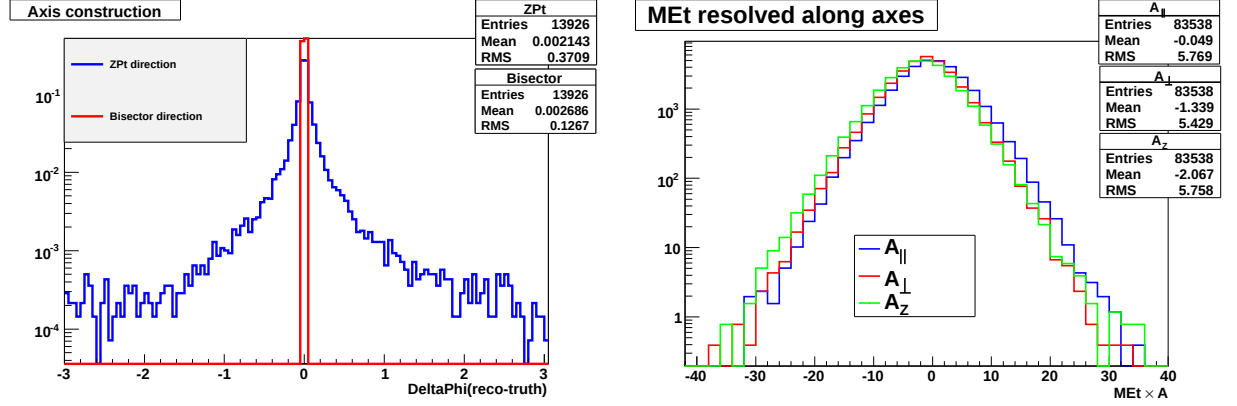
As has already been shown in the previous section, the ATLAS detector is capable of greater accuracy in electron angle measurement than that for momenta. Electrons in general are measured to a much higher precision than other components of a $Z \rightarrow ee$ decay (jets, soft hadronic deposits...). Thus an axis defined from the event topology designed to yield an optimal resolution on $\cancel{E}_t$ may be one whose construction depends solely on electron angles. Thus the axes to use with this purpose in mind are $\mathbf{A}_\perp$ and $\mathbf{A}_\parallel$ as these are constructed from the electron and positron ϕ values alone.

Figure 2.7(a) shows the axis resolution $\mathbf{R}\cdot\mathbf{T}(\text{axis direction})$ for $\mathbf{A}_\perp$ and $\mathbf{A}_Z$. It is seen that $\mathbf{A}_\perp$ (defined by electron angles alone) has better resolution than $\mathbf{A}_Z$ (defined by both the electron angles and P_T), despite these two axes lying close to one another.

Figure 2.7(b) shows how this improved axis resolution translates into an $\cancel{E}_t$ resolution along an axis: the resolution of $\cancel{E}_t \cdot \mathbf{A}_\perp$ (RMS value in the statistics box) is slightly better than for $\cancel{E}_t \cdot \mathbf{A}_Z$. This makes sense as the resolution of a quantity resolved along an axis may be expressed as the quadrature sum of the resolution of the quantity itself and the resolution of the axis direction. It must be noted that $\cancel{E}_t \cdot \mathbf{A}_\perp$ has better resolution than $\cancel{E}_t \cdot \mathbf{A}_\parallel$; the reason for which will be explained later in the chapter.

Parameterising $\cancel{E}_t$ resolution

If we recall that $\cancel{E}_t$ is computed by summing up all energy in the x and y direction in the calorimeter, it is clear that the $\cancel{E}_t$ resolution is driven by the calorimeter energy resolution. Equation 2.4 tells us that this is dependent on the magnitude of the transverse energy deposit and thus the $\cancel{E}_t$ resolution may be parameterised in terms of transverse calorimeter activity.



(a) Axis resolution: a histogram of $\mathbf{R} \cdot \mathbf{T}$ (axis direction)

(b) Resolution of $E_t \cdot \mathbf{A}$ where $\mathbf{A}$ is defined in the legend

Fig. 2.7: E_t resolutions along different axes

A further correction is made to facilitate direct comparison on an equal basis between Z events (2 electrons) and W events (1 electron) by subtracting off the electron contribution. The quantity hadronic activity, $\sum E_{T\text{had}}$, is thus defined as:

$$\sum E_{T\text{had}} = \sum E_T - \sum_{\text{electrons}} |P_{Te}|. \quad (2.7)$$

where $\sum E_T$ is the scalar sum of the energy deposits in the calorimeter cells (weighted for deposit type as described earlier). The distribution of $\sum E_{T\text{had}}$ for $Z \rightarrow ee$ and $W \rightarrow e\nu$ events is shown in figure 2.8. The distributions in $Z \rightarrow ee$ and $W \rightarrow e\nu$ are very similar; the slightly higher values seen in the $Z \rightarrow ee$ sample than in the $W \rightarrow e\nu$ may be attributed to the higher scale of momentum transfer in Z events.

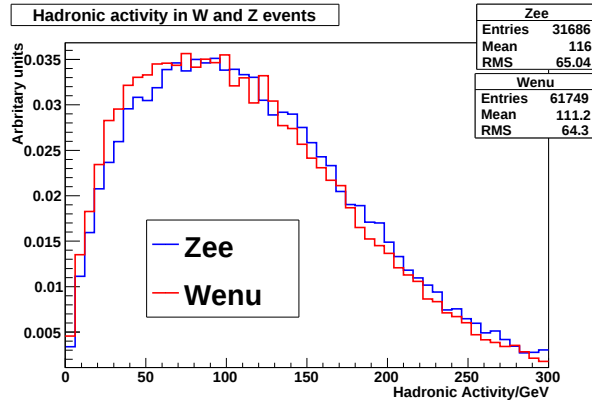


Fig. 2.8: Distribution of hadronic activity in $Z \rightarrow ee$ and $W \rightarrow e\nu$ events.

Distributions in $E_t \cdot \mathbf{A}$ are taken in slices of $\sum E_{T\text{had}}$ in the event. The behaviour of

the RMS values of these distributions tells us how the calorimeter resolution behaves with $\sum E_{T\text{had}}$. The RMS values of $\cancel{E}_t \cdot \mathbf{A}$ (along with the MC $\mathbf{R-T}(\cancel{E}_t \cdot \mathbf{A})$ comparison) are shown in figure 2.9. The plot shows what we would expect, that the absolute resolution of a calorimeter worsens with energy. The distribution follows the form (taken from equation 2.4):

$$\sigma(\cancel{E}_t) = P_0 \sqrt{\sum E_{T\text{had}}} + P_1 \quad (2.8)$$

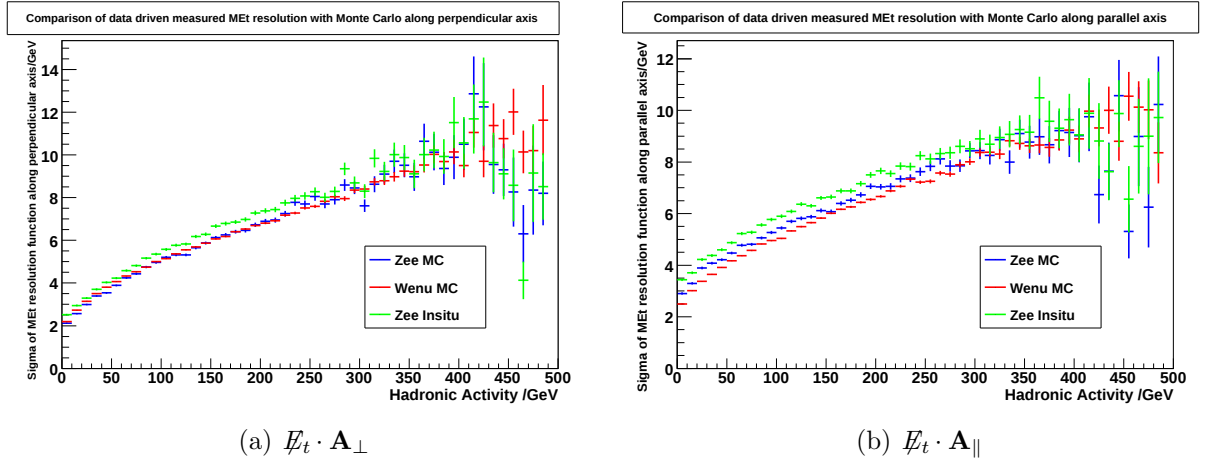


Fig. 2.9: $\sigma(\cancel{E}_t \cdot \mathbf{A})$: detector resolution. The MC (from both $Z \rightarrow ee$ and $W \rightarrow e\nu$ events) $\mathbf{R-T}(\cancel{E}_t \cdot \mathbf{A})$ functions are also shown as a validation of the method. The slightly larger resolution measured in $Z \rightarrow ee$ insitu than $W \rightarrow e\nu$ or $Z \rightarrow ee$ MC is due to the approximation of zero truth $\cancel{E}_t$ in the insitu method.

As was already seen in the global distributions, P_0 was found to be smaller in $\cancel{E}_t \cdot \mathbf{A}_\perp$ than in $\cancel{E}_t \cdot \mathbf{A}_\parallel$. This is due to the contribution of the electron resolution to the $\cancel{E}_t$ resolution. In a $Z \rightarrow ee$ decay, the $\cancel{E}_t$ resolution, σ_{MET} , may be written as follows:

$$\sigma_{\cancel{E}_t}^2 = \sigma_{\text{electrons}}^2 + \sigma_{\text{hadronic}}^2. \quad (2.9)$$

Figure 2.10(a) shows the electron resolution $\sigma_{\text{electrons}}$ determined from $\mathbf{R-T}(P_T(\mathbf{e}) \cdot \mathbf{A})$ when $\mathbf{A}_\perp$ and $\mathbf{A}_\parallel$ are used. It is seen that the electron resolution is larger along $\mathbf{A}_\parallel$ than along $\mathbf{A}_\perp$. This is because, as an artifact of the axis construction as well as the fact that Z bosons in their rest frame decay to back-to-back electrons, the electron component of P_T is largest along $\mathbf{A}_\parallel$ and smallest along $\mathbf{A}_\perp$. As has been described, the *absolute* electron resolution increases with electron P_T and so a large component of electron P_T along an axis

will lead to a worsened electron resolution along that axis.

Figure 2.10(b) shows $\cancel{E}_t \cdot \mathbf{A}$ before ($=\sigma_{\text{MEt}}$) and after ($=\sigma_{\text{hadronic}}$) the electron resolution along the same axis is subtracted off in quadrature. Before the subtraction, the resolution along $\mathbf{A}_{\parallel}$ is the larger, the theory being this is due to the increased electron resolution along this axis. It is seen that after the subtraction, the resolution along $\mathbf{A}_{\perp}$ and $\mathbf{A}_{\parallel}$ now agree as the only effect left is that of hadronic resolution σ_{hadronic} , which ought to be the same along both axes⁴.

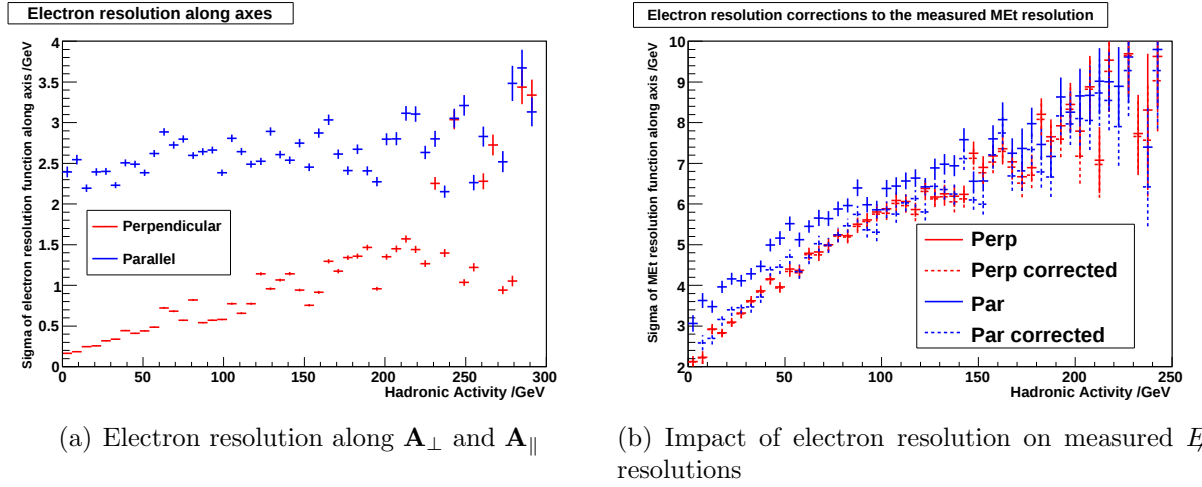


Fig. 2.10: Impact of electron resolution on total $\cancel{E}_t$ resolution

Comparison with different samples

The same analysis was done on the ALPGEN $Z \rightarrow ee + \text{jet}$ and PYTHIA $Z \rightarrow \mu\mu$ samples and the results shown in figure 2.11, showing the resolution behaviour is the same (to within statistical uncertainty) for all three samples. The comparison with $Z \rightarrow ee + \text{jet}$ shows that extra hadronic activity (which is present in these samples) does not affect the scaling of resolution, as these events will tend to fall in the regions with higher x values but the dependence is unchanged. This is good news as it suggests that these results may be extrapolated into events with more jet activity, for example SUSY candidate events. The comparison with $Z \rightarrow \mu\mu$ shows that electrons do not affect the dependence of resolution with hadronic activity (provided the electron contribution to hadronic activity is subtracted

⁴ For this reason, studying the difference in $\cancel{E}_t$ resolution along the two axes could indeed be a method of determining electron resolution from data alone.

off as has been done here).

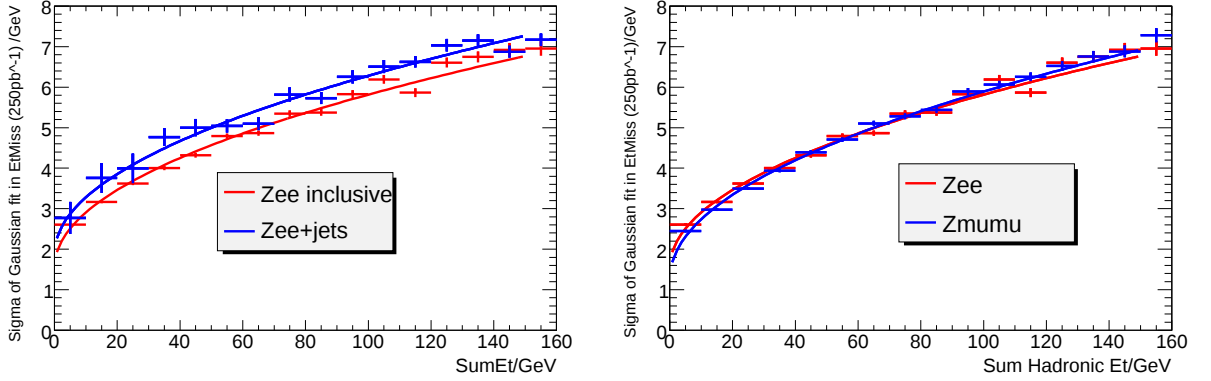


Fig. 2.11: Profile plots of $\sigma(\cancel{E}_t \cdot \mathbf{A})$ against hadronic activity in $Z \rightarrow ee + \text{jet}$ and $Z \rightarrow \mu\mu$ events.

Overall choice of axes for analysis

$\mathbf{A}_Z$ and $\mathbf{A}_{AZ}$ were chosen for the remainder of the analysis. The reason why these and not the $\mathbf{A}_\perp$ and $\mathbf{A}_\parallel$ axes were chosen is that $\cancel{E}_t \cdot \mathbf{A}_Z$ is slightly more sensitive to $\cancel{E}_t$ scale than $\cancel{E}_t \cdot \mathbf{A}_\perp$, which turns out to be the dominant effect on the cross section measurement. This choice of axis turns out to have only a very small impact on the analysis as, as has been mentioned in the preceding sections, the differences between the distributions $(\cancel{E}_t \cdot \mathbf{A}_\perp, \cancel{E}_t \cdot \mathbf{A}_\parallel)$ and $(\cancel{E}_t \cdot \mathbf{A}_Z, \cancel{E}_t \cdot \mathbf{A}_{AZ})$ are small. This of course is providing the axes chosen have sensitivity to scale (so for example, a choice of the x axis would not be satisfactory). Thus the uncertainties on scale and resolution that are quoted in this chapter are those in $\cancel{E}_t \cdot \mathbf{A}_Z$ and $\cancel{E}_t \cdot \mathbf{A}_{AZ}$.

2.3.3 Data driven $\cancel{E}_t$ resolution functions- neutrino-fication technique

Using neutrino-fication to measure $\cancel{E}_t$ resolution

This is an alternative method of measuring $\cancel{E}_t$ resolution in ATLAS without relying on Monte Carlo. The technique relies on the fact that W and Z are actually very similar processes except, to a good approximation, that one of the electrons from a Z event is equivalent to a neutrino in a W event. $\cancel{E}_t$ scales and resolutions in a W event may be approximated by those in a Z event if one of the electrons is ‘neutrino-fied’, that is, if the

event is treated as if the electron was a neutrino as may be seen in figure 2.12.

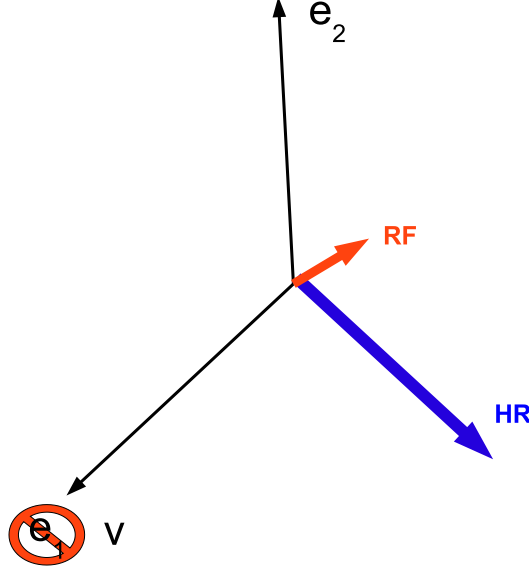


Fig. 2.12: Neutrinofication of a Z event. **RF** is the reconstructed (‘RefFinal’) $\cancel{E}_t$ in the event, and **HR** refers to the hadronic recoil.

In the case of neutrinofication, the truth $\cancel{E}_t$ vector is taken to be:

$$\cancel{E}_t^{\text{true}} = \mathbf{e}_1^{\text{reco}}. \quad (2.10)$$

where the index ‘1’ refers to either electron. Note this involves the assumption of perfect electron resolution with respect to the $\cancel{E}_t$ resolution. Figure 2.10 shows that this, to a good approximation, is the case as the subtraction of electron resolution from the $\cancel{E}_t$ resolution has a small impact on the $\cancel{E}_t$ resolution.

If this Z event was in fact a W event, the reconstructed $\cancel{E}_t$ vector would be found to be the negative vector sum of all other activity in the event⁵, that is to say:

$$\cancel{E}_t^{\text{reco}} = -1 \times (\mathbf{e}_2^{\text{reco}} + \mathbf{HR}) \quad (2.11)$$

⁵ It must be noted at this point that this study is a first approximation, as it uses reconstructed quantities (electrons, $\sum E_T$) only. A refined method is to remove the cells belonging to the electron object and recompute $\cancel{E}_t$ using the remaining cells. This is an ongoing study in ATLAS but is beyond the scope of this thesis.

The vector quantity, hadronic recoil $\mathbf{HR}$ is not given in the output of the standard ATLAS reconstruction. It is possible however to calculate it using the negative sum of all other objects in the event, that is:

$$\mathbf{HR} = -1 \times (\mathbf{e}_1^{reco} + \mathbf{e}_2^{reco} + \mathbf{RF}), \quad (2.12)$$

and thus we have

$$\cancel{E}_t^{reco} = \mathbf{e}_1^{reco} + \mathbf{RF}. \quad (2.13)$$

Now we have both ‘truth’ and ‘reconstructed’ $\cancel{E}_t$ in the ‘ W ’ event, a data-driven estimate of $\mathbf{R-T}(\cancel{E}_t)$ may be determined. Given that these are all vector sums, resolution functions, $\mathbf{r}$, in terms of both $|\cancel{E}_t|$ and $\phi(\cancel{E}_t)$ may be obtained. The resolution function in terms of $|\cancel{E}_t|$ is given by the distribution of the following:

$$\mathbf{r}(|\cancel{E}_t|) = |\mathbf{P_T}(\mathbf{e}_1)^{reco} + \mathbf{P_T}(\mathbf{RF})| - |\mathbf{P_T}(\mathbf{e}_1)^{reco}|, \quad (2.14)$$

and is shown in figure 2.13. The agreement between neutrino-fication and $W \rightarrow e\nu$ MC is seen to be quite good (although the limitation of the assumption of perfect electron resolution can be seen as slight disagreement between the two). The agreement between neutrino-fication (or indeed $W \rightarrow e\nu$ $\mathbf{R-T}(\cancel{E}_t)$) and $Z \rightarrow ee$ $\mathbf{R-T}(\cancel{E}_t)$ is worse. The reason for this is that in $Z \rightarrow ee$ events, the truth value of $\cancel{E}_t$ is usually very close to zero. The reconstructed $\cancel{E}_t$ is likely to be larger (due to noise effects being significant compared to the truth value) and so the resolution function is biased toward the positive. This is less of an issue however, as the main concern is that the neutrino-fication reliably estimates the $W \rightarrow e\nu$ $\mathbf{R-T}(\cancel{E}_t)$ (as has been mentioned, this is the analysis in which the resolution functions will eventually be used).

Using the above notation, $\cancel{E}_t \cdot \mathbf{A}_\perp$ and $\cancel{E}_t \cdot \mathbf{A}_\parallel$ may be estimated by:

$$\mathbf{r}_\perp = (\mathbf{e}_1^{reco} + \mathbf{RF})_\perp - \mathbf{e}_{1\perp}^{reco} = \mathbf{RF}_\perp \quad (2.15)$$

and similar for the parallel. This is the same the distributions obtained by just resolving

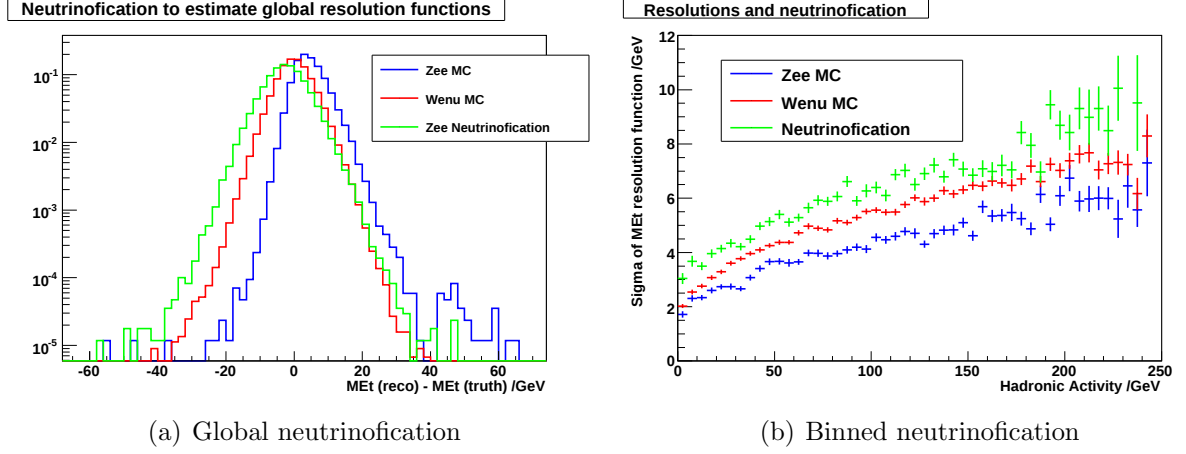


Fig. 2.13: $\cancel{E}_t$ resolution function obtained from neutrinofication of a Z event. $\mathbf{R-T}(\cancel{E}_t)$ in $W \rightarrow e\nu$ and $Z \rightarrow ee$ are shown by way of comparison.

the reconstructed $\cancel{E}_t$ in the event along the axes! Thus the distributions have already been shown in figure 2.9 and good agreement is observed.

Using neutrinofication to measure bias in $\cancel{E}_t$

Neutrinofication, although in its current form is in need of refinement, has an added advantage over using axes. Studies suggest that it may be necessary to study the variation of $\cancel{E}_t$ scale with $|\cancel{E}_t|$ itself. Obviously this creates a problem in Z axis resolution analysis as there is no real $\cancel{E}_t$ in the event. However neutrinofication facilitates the possibility to bin in terms of the ‘true’ $\cancel{E}_t$ as defined by equation 2.10. Figure 2.14 shows such distributions. The following remarks are made regarding this plot:

- Large positive bias at low $\cancel{E}_t$ is seen. This is a consequence of construction: at truth $\cancel{E}_t(x=0)$, $\cancel{E}_t^{\text{reco}}$ is forced to be larger than $\cancel{E}_t^{\text{true}}$ as by construction $\cancel{E}_t^{\text{reco}} > 0$. Thus the y value, the $\mathbf{R-T}(\cancel{E}_t)$ mean, will be forced to be positive.
- The bias becomes steadily lower and falls negative at higher $\cancel{E}_t$. This is an effect currently in the ATLAS reconstruction software (as it is seen both in neutrinofication and MC comparison) which is as of yet not understood⁶.
- The neutrinofication agrees with $\mathbf{R-T}(\cancel{E}_t)$ in the direction and approximate size of

⁶ Note this is NOT due to the direction of smearing from the Jacobian peak in the $\cancel{E}_t$ distribution. That the $\cancel{E}_t$ crosses through zero at approximately the peak position appears to be a coincidence.

the bias. However there is obvious discrepancy in its exact form. This discrepancy eventually causes an unacceptable deviation from the MC calculated acceptances in chapter 3. Neutrinofication must be refined (as touched upon earlier) to be used in a full physics analysis. However this first approximation may be used as a quick check for biases in early $\cancel{E}_t$ calculations.

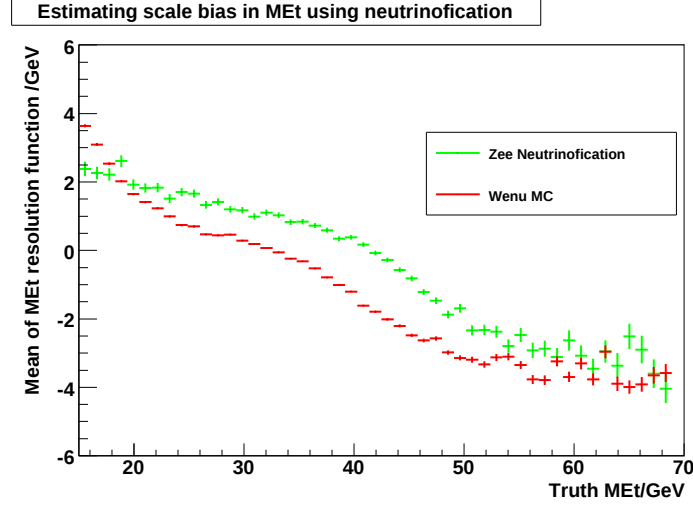


Fig. 2.14: Bias in $\cancel{E}_t$ scale as a function of the size of $\cancel{E}_t$ itself obtained from neutrinofication of a Z event. The $\mathbf{R-T}(\cancel{E}_t)$ $W \rightarrow e\nu$ distribution is shown by way of comparison.

2.4 Estimation of uncertainties

2.4.1 Statistical uncertainties

The statistical uncertainty on the mean, $\epsilon(\bar{x})$, and resolution, $\epsilon(\sigma)$, of a resolution function with N entries, mean $\bar{x}$ and RMS σ are given, by the central limit theorem:

$$\epsilon(\bar{x}) = \frac{\sigma}{\sqrt{N}}, \quad (2.16)$$

and,

$$\epsilon(\sigma) = \sqrt{\frac{\sum_i (x_i - \bar{x})^2}{N}}. \quad (2.17)$$

It is assumed the statistical errors on $\bar{x}$ and σ are similar for both MC and data driven methods, as these result in very similar distributions. The resultant statistical uncertainties

(evaluated as the average on a bin by bin basis) (at 100 pb^{-1}) were observed as small enough to contribute negligibly to the analysis (and are also much smaller than the systematics) and are disregarded from this point onwards.

2.4.2 Systematic uncertainties

Systematic uncertainties on the $\cancel{E}_t$ scale and resolution⁷ are determined by taking the average bin-by-bin absolute deviation between those quantities determined insitu and from the MC-determined $\mathbf{R-T}(\mathbf{x})$ distribution. The binning is in hadronic recoil for the calculation of the scale systematic, and hadronic activity for the resolution systematic as these have been seen to be the driving variables for these two quantities. The number of bins used to determine the average is truncated at the point where statistical fluctuations become large.

Systematic uncertainties on the scale and resolution are quoted as those on $\cancel{E}_t \cdot \mathbf{A}_Z$ and $\cancel{E}_t \cdot \mathbf{A}_{AZ}$, as these are the axes along which $\cancel{E}_t$ is resolved for calculating the acceptance corrections. Two systematic estimators on scale (resolution) are devised:

- Systematic estimator 1 = $\sum_{\text{bins } i} |a_i^{\text{Insitu}} - a_i^{\text{ZMC}}| / \#\text{bins}$
- Systematic estimator 2 = $\sum_{\text{bins } i} |a_i^{\text{Insitu}} - a_i^{\text{WMC}}| / \#\text{bins},$

where a_i is the scale (resolution) measured in bin i .

The systematic estimators on $\bar{x}$ and σ obtained are summarised in table 2.2. The average of the two estimators is given as the total systematic uncertainty on the quantity.

Estimator	$\epsilon(\bar{x})/\text{GeV}$ ($\cancel{E}_t \cdot \mathbf{A}_Z$)	$\epsilon(\bar{x})/\text{GeV}$ ($\cancel{E}_t \cdot \mathbf{A}_{AZ}$)	$\epsilon(\sigma)/\text{GeV}$ ($\cancel{E}_t \cdot \mathbf{A}_Z$)	$\epsilon(\sigma)/\text{GeV}$ ($\cancel{E}_t \cdot \mathbf{A}_{AZ}$)
1	0.477	0.084	0.420	0.642
2	0.223	0.138	0.616	0.616
Average	0.335	0.111	0.518	0.629

Tab. 2.2: Systematic estimators on scales and resolutions. Absolute values in GeV are shown.

⁷ the systematic uncertainty for the electron response has been taken from the W mass note as described earlier.

2.5 Conclusions and recommendations of further work

- For W and Z cross section analyses, it is sufficient to compute resolution functions for electron and $\cancel{E}_t$ P_T alone as angular resolutions are either negligibly small or not relevant to the analysis.
- The standard method of studying electron response is to measure the mean and width of the Z mass peak and relate these quantities to the electron scale and resolution respectively. An alternative may be one briefly mentioned in the chapter; to take the difference between $\cancel{E}_t \cdot \mathbf{A}_Z$ and $\cancel{E}_t \cdot \mathbf{A}_{AZ}$. It may turn out that studying a well understood quantity by using a less well understood quantity is not the best way to go, but perhaps an interesting cross check in any case.
- Using the direction of the Z or alternatively the electron bisector along which to resolve $\cancel{E}_t$ in $Z \rightarrow ee$ events has proved to be valuable as a tool to study calibration of objects in the event. This technique also yields a measurement of $\cancel{E}_t$ resolution functions with small systematic uncertainty. The results are stable in different topologies providing the correct dependencies are accounted for, which is promising for future studies which may attempt to use $Z \rightarrow ee$ to estimate $\cancel{E}_t$ response at, for example, the SUSY scale.
- Neutrino-fication works less well in measuring resolution functions but nevertheless facilitates a measurement of scale bias with respect to $\cancel{E}_t$ itself (not possible using axis resolution). Refinements may be possible to improve accuracy (removing electron clusters and re-computing $\cancel{E}_t$ rather than a crude subtraction of the reconstructed object).
- The diagnostic plot split by jet multiplicity may become a powerful tool to understand hadronic calibration. It allows the separation of the contributions of hard jets and soft hadronic deposits in the $\cancel{E}_t$ calculation. Jet energy scale will probably be well understood in ATLAS with enough data, but few plots allow such a handle on the understanding of soft processes and their impact on $\cancel{E}_t$. In the current detector simulation, this technique has shown that there is currently considerable bias in the

calibration of the soft hadronic recoil.

- Defining parallel and perpendicular regions in a $Z \rightarrow ee$ (or perhaps better, $Z \rightarrow \mu\mu$) event may be used to study Underlying Event models. Comparing these two regions may facilitate separation of hard process and underlying event.
- In early data, comparison between $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ events in this method will assist lepton calibration in the $\cancel{E}_t$ framework, as the results from both types of events should in principle be identical.
- Real data will throw up many problems in $\cancel{E}_t$ not considered in this analysis. For example, pile-up (more than one interaction per bunch crossing) will worsen the $\cancel{E}_t$ resolution. This effect may be quantified (but not removed) by plotting resolution curves at different luminosities. Another ‘real life’ scenario is beam halo, which may be seen as an asymmetry in the ϕ distribution of $\cancel{E}_t$ (allowing for the possibility of it being corrected), due to the lower energy scattered protons being deflected by a larger angle than nominal by the magnetic field of the accelerator.

3. ACCEPTANCE

3.1 A first order acceptance calculation

The definition of an acceptance, A , is as follows:

$$A = \frac{N_{pass}}{N} \quad (3.1)$$

where N is the total number of events predicted at the sample luminosity $\mathcal{L}$ and N_{pass} is the number of these predicted to pass the event selection. It should be re-iterated at this point that the quantity A is alone in the variables considered in the analysis as it will be *determined from MC* (at least to first order) in a real data analysis. There is no way to measure what the truth distribution of a quantity would have been from data alone. For this reason, the results in this section are not scaled to a particular luminosity as the statistical power from the whole sample may be used.

For statistical purposes, the data used in this analysis is filtered by the means of generator level cuts so only events likely to pass the event selection described in section 1.5.2 are in the input files. Thus a filter efficiency referring to the rejection power of the generator cuts must be included and equation 3.1 becomes:

$$A = \frac{N_{pass}}{N_{sample}} \times \frac{N_{sample}}{N} = \frac{N_{pass}}{N_{sample}} \times \epsilon_F \quad (3.2)$$

where N_{sample} is the number of events in the data set (that is, the number of events remaining after filtering) and ϵ_F is the filter efficiency of the sample. This number is given by the Monte Carlo production group, 0.88 and 0.96 for the W and Z PYTHIA samples respectively with negligible associated statistical uncertainty.

Values and uncertainties are quoted for the acceptance of the W and Z samples, A_W and A_Z , as well as their ratio A_Z/A_W as this quantity will be used in the $\mathcal{R}$ analysis.

Table 3.1 shows the rejection power of the event selection on the truth level quantities. The fraction of events remaining after cuts multiplied by ϵ_F is, to first order, the acceptance. It must be noted that this is a first approximation and corrections will be made to this number to obtain the final number to be used in the analysis.

Cut	Z detail	% Z remaining	W detail	% W remaining
Electron P_T	$\times 2$	62.88 (0.19)	$\times 1$	68.30 (0.11)
Electron η	$\times 2$	33.16 (0.13)	$\times 1$	49.10 (0.09)
	+ Z Mass cuts	29.38 (0.12)	+ $\cancel{E}_t$	41.34 (0.08)
Acceptance A		28.21 (0.11)		36.38 (0.07)

Tab. 3.1: First order calculation of acceptance using cuts as detailed in 1.5.2. Absolute statistical uncertainty given in parentheses.

3.2 Binned acceptances

For the purposes of a differential cross section measurement with respect to variable x , one must take the acceptances binned also in x . In fact, accounting for the acceptance variation in different regions of the detector is also important for a global cross section measurement. Figures 3.1 show the variation of acceptance with boson P_T (P_{TB}) and η (η_B). It is seen that the acceptance decreases fairly steadily with increasing η_B . The reason for this is that a forward boson with high pseudo-rapidity will tend to decay into electrons also with high values of η , which are more likely to fail the selection cut of electron $|\eta| < 2.4$.

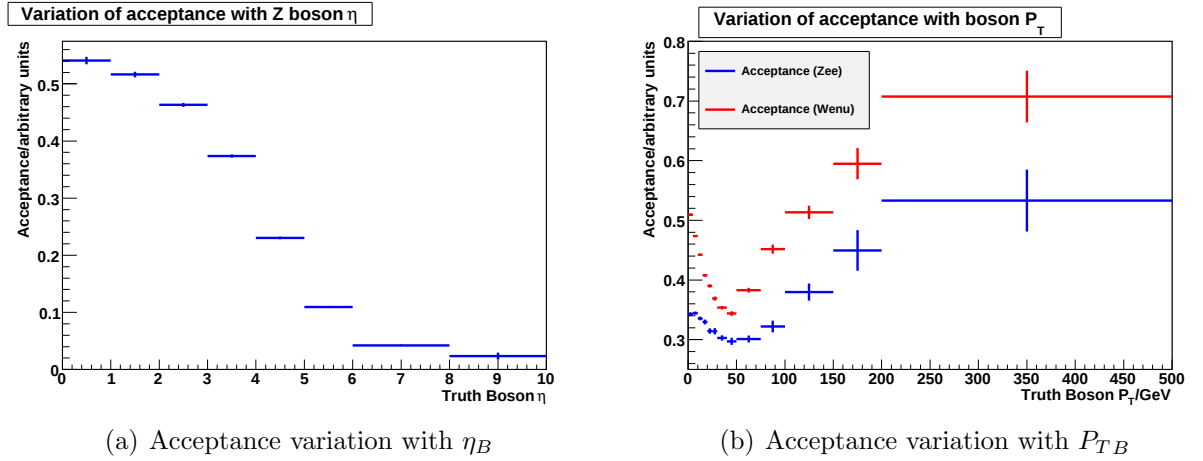


Fig. 3.1: Acceptances (no ϵ_F) with respect to boson kinematic variables.

The explanation for the behaviour with respect to boson P_{TB} (the drop in acceptance at middle values of P_{TB} and subsequent increase in acceptance as P_{TB} is increased further) is more complex and is as follows (consider for simplicity $\eta_B=0$):

- **Zero P_{TB}** (figure 3.2(a)): At $P_{TB}=0$, by conservation of momenta the two decay

electrons must be back to back with equal and opposite P_T .

- **Low P_{TB} region** (figure 3.2(b)): As P_{TB} increases slightly, by conservation of momenta the difference between the two decay electron values of P_T will increase. Thus one is more likely to fail the 25 GeV P_T threshold cut and the acceptance will decrease.
- **Medium P_{TB} region** (figure 3.2(c)): As P_{TB} increases further, at some threshold (at about 45 GeV) the decay electrons will cease to be back to back and will start decaying in the same direction.
- **High P_{TB} region** (figure 3.2(d)): As P_{TB} increases yet further, the electrons will have higher P_T and the acceptance will increase.

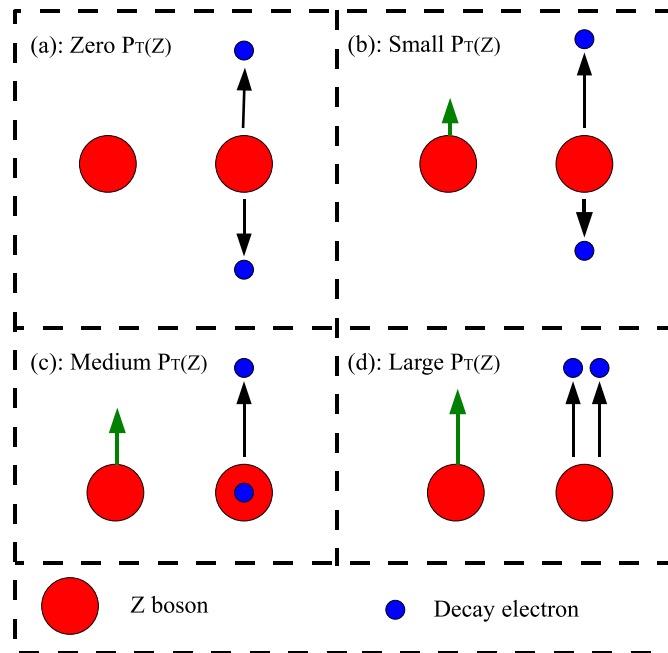


Fig. 3.2: Relation of boson and electron transverse momenta

Obviously, the sensitivity of the cross section measurement to acceptance variation will increase with the number of bins, but it is of vital importance that sufficient events are in each bin so that the statistical uncertainties of both the numerator and denominator in that

bin are under control, otherwise cross sections in certain bins may be wildly mis-calculated (which also has a significant impact on the calculation of a global as well as differential cross section!). Four bins were chosen in P_{TB} and three (one¹) in η_B for $Z \rightarrow ee$ ($W \rightarrow e\nu$) analyses.

3.3 Acceptance corrections

3.3.1 Acceptance and M_Z

As has been described in chapter 1, the process in the so-called $Z \rightarrow ee$ dataset used in this analysis is the the Drell Yan (DY) [29] process. When measuring a cross section, background from other decay channels ($W \rightarrow e\nu$, $t\bar{t}$) will also be present (see chapter 4) in the continuum background formed by the pure photon term. A fit is used to remove such backgrounds. However it is very difficult to distinguish between DY continuum (which could be arguably interpreted as signal or background) and this background from other channels. Due to this difficulty, DY continuum is considered in this analysis to be background, and thus in the fit must be removed along with the other backgrounds before integrating over the signal function to obtain the cross section.

In the interests of comparing like with like, the theoretical cross section (that to which the measurement is compared) must be also corrected to remove the Drell Yan². Figure 3.3 shows the true invariant mass peak from PYTHIA with a signal+background fit: the precise form of the fit is explored in chapter 4 but essentially is a peak function plus an exponentially falling background. The signal function (using the parameters from the overall fit) is also shown.

The correction to be made to the quoted cross section is the ratio between these two functions integrated over the whole region (>67 GeV: the choice of 67 as the lower mass cut is explained in the next paragraph). This ratio is found to be 0.98: thus the quoted

¹ a measurement of η_B is not possible in $W \rightarrow e\nu$ analysis as only missing *transverse* energy is known (see chapter 1).

² it should be noted that equivalently a correction could be made to the acceptance to account for the removal of Drell Yan background, hence the placing of this discussion in this chapter. However in the interests of clarity, the theoretical cross section was modified directly.

PYTHIA cross section in section 1.5.1 of 1143.96 pb^{-1} is corrected to the value of 1121.07 pb^{-1} as the number to which the measurement in chapter 6 must be compared. The systematics on this correction will be absorbed into the systematics obtained on the mass fit, again a topic explored in chapter 4.

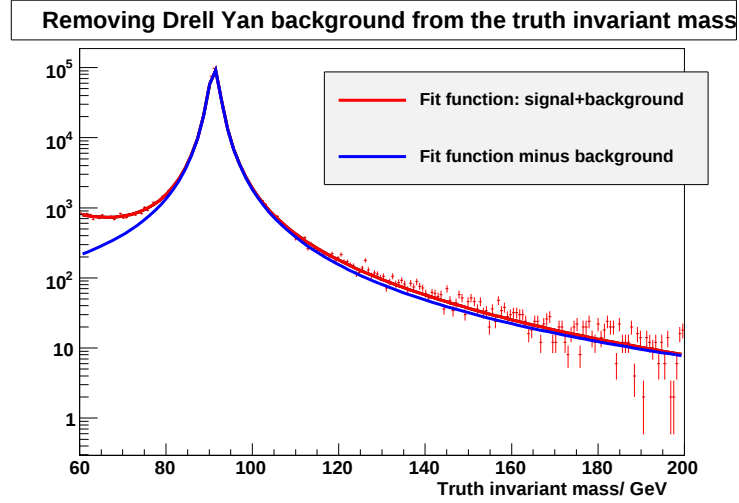


Fig. 3.3: Signal and Signal+DY background invariant mass (as constructed from the two truth leptons) in the Z mass peak region.

The Z term will dominate in the Z mass peak region (90 GeV). Thus when the samples were generated, a filter cut at $M_Z=60$ GeV was used to eliminate too much contamination from γ and γZ interference terms. Other than the choice of having a low energy threshold to reduce continuum background, the precise placement of the cut at 60 GeV was somewhat arbitrarily chosen when the PYTHIA samples were generated. To estimate the impact of this cut on the acceptance, the cut was varied between 60 and 70 GeV (thus altering the denominator in the acceptance equation), and the results are shown in figure 3.4³. Superimposed on the graph is the truth Z lineshape at that value of M_{ll} .

It is observed that the acceptance increases linearly by an amount $\sim 0.1\%$ for each 1 GeV increase in the lower threshold cut. The reason for this is that a higher mass cut will decrease the denominator of equation 3.1 but not the numerator (which has implicit Z invariant mass cuts between 80 and 100 GeV).

³ the acceptance values shown in the plot are lower than the final quoted values as photon merging has not been performed when obtaining these values.

As has been mentioned, the purpose of the lower M_Z cut is to strike a balance between purity and efficiency of Z (as opposed to γ) propagators, although this distinction is somewhat blurred because of the $Z\gamma$ interference term. The cut used for a cross section analysis was chosen to lie at the minimum of the Z lineshape (red) curve, at 67 GeV. Although this choice is somewhat arbitrary, it is a *correction* as opposed to a source of systematic as, as is described in the previous section, the truth mass peak integral over what is considered the signal region accounts for this choice in the predicted cross section it yields.

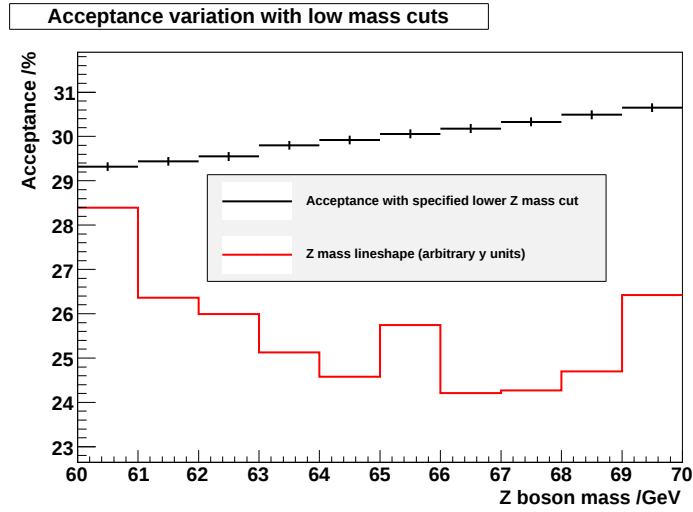


Fig. 3.4: Variation of acceptances as lower mass cut is varied. The Z mass lineshape (in red) is superimposed (scaled to arbitrary y units)

3.3.2 Photon merging

In the truth particles in the dataset used, some photons (the number and kinematics of which are shown in figures 3.5) have a Z or W boson as their parent particle. This is as PHOTOS, the package responsible for FSR⁴, treats FSR photons as if they were emitted from the boson rather than from the electron (as this detail will not affect the final state configuration of the collision). These photons must be distinguished from those originating from Bremsstrahlung, which will detail an electron as their parent.

In the reconstruction process, photons are reconstructed in a very similar manner to electrons except the calorimeter cluster is not required to match a track. However, photons

⁴ the process by which a final state particle radiates another particle (in this case a decay electron radiating a photon).

reconstructed close to electrons are assumed to be due to Bremsstrahlung and thus reconstructed photons will be merged into the electrons if they are found within a certain ΔR distance from them. In the interests of consistency, this procedure must be matched as well as possible at truth level in the acceptance calculations. Thus any FSR photon found in the PYTHIA sample is manually merged (by adding the four-vectors) to its nearest truth electron, providing the electron is within a certain angular separation ΔR , the value of which matching that in the reconstruction procedure.

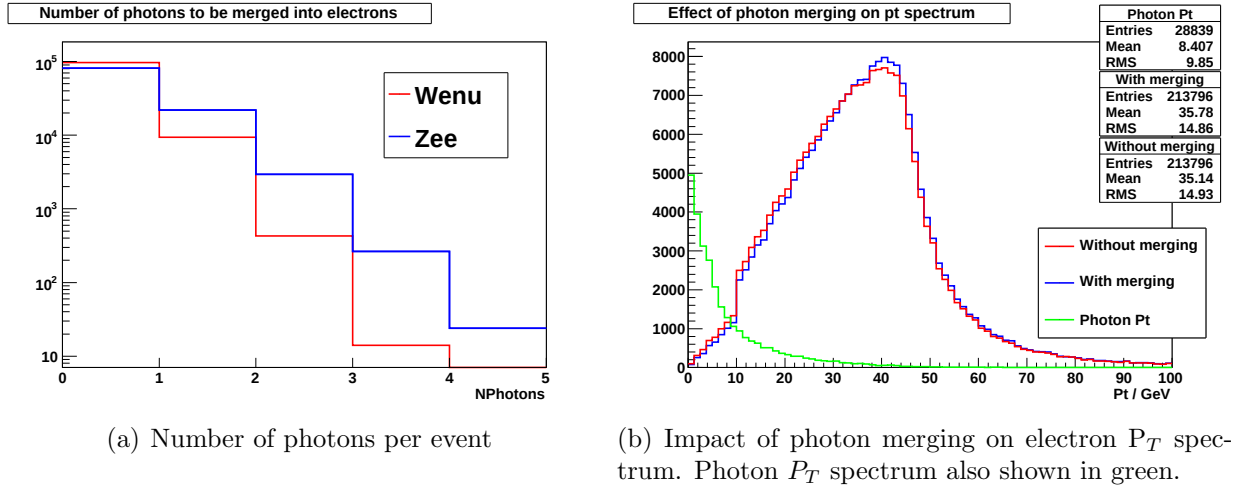


Fig. 3.5: Properties of photons which are documented by PHOTOS as originating directly from the Z boson

Figure 3.6 shows (in black) the Z mass peak M_Z , that is to say, that mass obtained directly from the truth Z boson. The coloured mass peaks are the distributions of M_{ee} , obtained by calculating the invariant mass of the two truth electrons in the event after photon merging has been performed. The variation between the coloured peaks is due to the ΔR cut being varied. The fewer the number of events *below* the threshold cut of 60 GeV, the more successful the merging. That is to say, the aim is to make the peak reconstructed from electrons to look as similar as possible to the peak obtained from the Z boson itself which has a sharp lower mass cut at 60 GeV. With this criteria in mind, it is seen that the higher the merging cut, the better the mass peak, and in fact it is at its best if no cut is used at all. The mass peak is thinner in this case, which makes sense as all objects in the event are now being accounted for. However, it must be kept in mind that the point is to match the truth procedure to the reconstruction procedure, which can't merge photons at a

large distance from electrons.

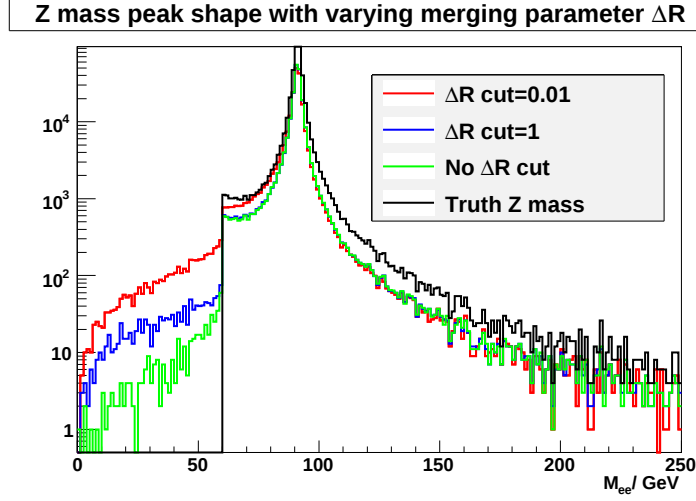


Fig. 3.6: Impact of photon merging cut on the Z invariant mass spectrum.

In the reconstruction process, the photons in question will be merged into the electrons if they are found within a certain ΔR distance from them, and for consistency this must be matched at truth level in the acceptance calculation. To find the ideal placement of the ΔR cut to use at truth level, a distribution of ΔR between all *reconstructed* electrons and photons in $W \rightarrow e\nu$ events was made, which can be seen in figure 3.7.

The first minimum in the distribution is the ‘resolution’ of the ATLAS detector, that is, the spatial separation below which the electron and photon will not be distinguished from one another. The histogram entries in the distribution below this minimum are ΔR values between electrons/photons and themselves. Thus truth FSR⁵ photons closer to truth electrons than this ΔR separation must be manually merged in. Zooming into the plot, the minimum is seen to occur at $\Delta R \simeq 0.15$. The merging is performed by adding the Lorentz vectors of any photons within this angular separation to the closest truth electron.

The systematic uncertainty on the merging procedure is chosen to be the difference between the calculated acceptance with different ΔR cuts centered round the chosen cut of 0.16 (cuts of 0.14 and 0.18 are chosen as these could arguably also be the position of the minima). The absolute impact of this on the acceptance (when quoted in percent), which is also taken to be the systematic uncertainty, was 0.03 (0.06) for W (Z) events and 0.001

⁵ truth photons originating from Bremsstrahlung are already merged into the electrons at truth level by PHOTOS and so merging these photons in also would be double counting.

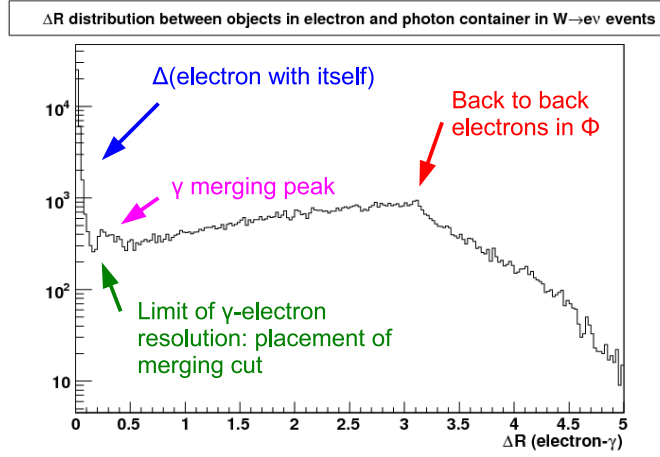


Fig. 3.7: ΔR distribution between objects in the electron and photon container in $W \rightarrow e\nu$ events

on the acceptance ratio (which shows that the fractional systematic uncertainty due to this effect partially cancels in the ratio).

The overall impact of the merging on the acceptance is to increase it as a consequence of the increased electron P_T values. The modification to acceptance value⁶ due to photon merging, with the parameters optimised as above, is found to be 1.24 % for W events and 1.42% for Z events, which is understandably larger as there are two electrons in $Z \rightarrow ee$ and only one in $W \rightarrow e\nu$.

3.3.3 Resolution corrections

In the preceding sections the acceptance has been calculated by running the truth level quantities through the event selection. However, in the case of a data derived measurement of a physics quantity such as a cross section, it is the reconstructed quantities to which these cuts are actually applied. Thus a correction of truth to reconstructed quantity must be made.

It will not be possible to simply apply the event selection on the reconstructed quantities to calculate acceptance, as certain regions are not well modelled (very small P_T electrons or E_t), and some particles are lost altogether (such as those escaping down the beam pipe). Additional unwanted factors such as efficiency bias also distort the reconstructed spectrum

⁶ note this is a correction, not a systematic.

(see section 3.3.3) and would affect the acceptance measurement.

Resolution functions mapping truth to reconstructed values are used to calculate the correction associated with detector response to be made to acceptance. It must be noted at this point that this method is outlined as an *early data strategy only*. A more precise and correct method is to do this by modifying the Monte Carlo directly, a strategy discussed in section 3.5.

Resolution functions need to be determined from data, otherwise the purpose of event smearing is defeated as a MC estimate of the reconstructed distribution could just be used. This is unsatisfactory as it would not just be relying on MC for the truth distribution, but also assuming that the detector response had been simulated correctly. Techniques for obtaining these functions have already been detailed in chapter 2, and this section addresses the procedure of event smearing itself.

Methodology

General smearing technique

The calculation is split up into two loops summarised in figure 3.8: the first to obtain resolution functions⁷ $\mathbf{r}(\mathbf{w})$ dependent on a certain variable w in this MC test, or in real data⁸ the data driven equivalent $\mathbf{r}'(\mathbf{w})$. The second loop smears the truth values (from distribution $\mathbf{T}$) event by event using a random number generated from either the $\mathbf{r}(\mathbf{w})$, $\mathbf{r}'(\mathbf{w})$ distributions themselves (default) or a fit over them (discussed later). The smearing creates a new distribution $\mathbf{R}_s$ which, after correcting for other biases (such as efficiency), should lie on top of the reconstructed distribution $\mathbf{R}$. In this study the same event sample is used for both loops but in real data the collected data will be used to derive $\mathbf{r}'(\mathbf{w})$ and the MC sample will be used for the event smearing.

⁷ in the form $\mathbf{R}-\mathbf{T}(\mathbf{x})$ as defined at the beginning of chapter 2.

⁸ a MC test of the real data procedure is described later in the chapter.

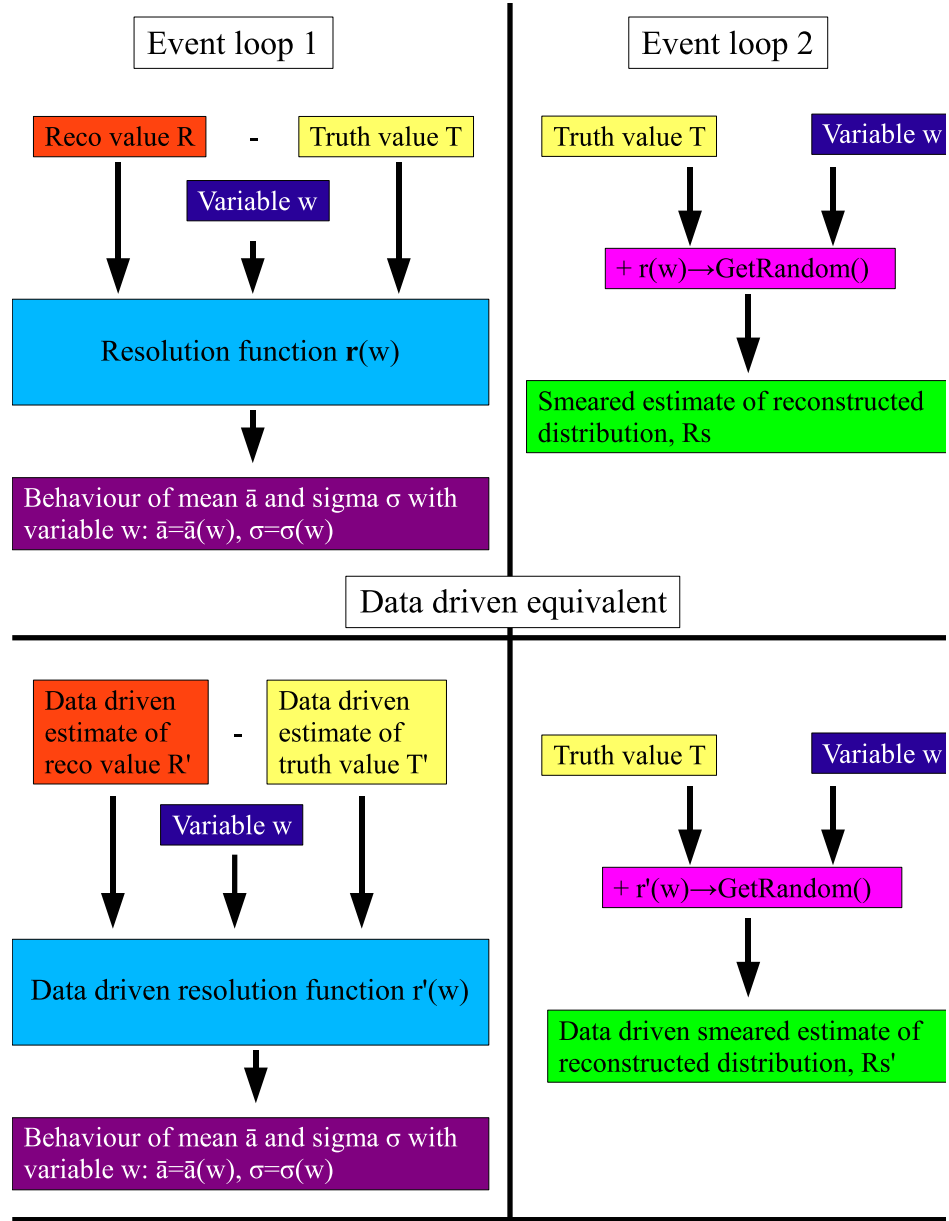


Fig. 3.8: Smearing methodology. Note the definition of the distributions $\mathbf{r}$, $\mathbf{T}$ and $\mathbf{R}_s$.

Systematics on smearing strategy

The systematic uncertainty from the smearing strategy was determined from the following elements. The actual numbers obtained from electron P_T and $\cancel{E}_t$ smearing are shown in the relevant sections.

- **Binning:** As has been described, resolution functions are taken differentially⁹ in bins of variable(s) w (and v). Object smearing works most effectively if the bin width in w is of similar size to the object resolution. However, the object resolution varies with event topology, so there is some ambiguity on the choice of bin width. The systematic associated with bin width was determined by comparing the final calculated acceptance using the default bin width x and that using $2x$.
- **Range:** In the first loop (constructing the resolution functions), some lower P_T cut must be made on the truth and reconstructed values (electron P_T and $\cancel{E}_t$). Whatever choice is made will, to some degree, bias the final function but the alternative (using no cuts and including, for example, very low energy reconstructed electrons) is even more unappealing. Symmetric cuts on reconstructed and truth quantities at 15 GeV (for both $\cancel{E}_t$ and electron P_T) were chosen as the default, as these should represent fairly those <25 GeV electrons which are smeared into the selected sample, whilst cutting out the very low P_T objects (which can have very discontinuous resolution functions). The systematic from this choice was estimated by comparing the final measured acceptance with those obtained from resolution functions determined from (equally sensible) symmetric cuts at 20 GeV.
- **Fit or histogram** The default method for smearing is to use a random number generator directly from the resolution function. This has the advantage of being sensitive to non-Gaussian tails (from genuine physics effects such as Bremsstrahlung) that may be present in the function. However, this has the problem of also picking up statistical fluctuations in the resolution function as well as non-Gaussian tails from selection bias when producing the resolution function. A systematic is thus quoted on this choice

⁹ see $\cancel{E}_t$ smearing section.

by comparing the acceptance results with those determined from using a Gaussian fit over the resolution function.

Smearing electron P_T

The strategy used for electron smearing¹⁰ was to smear the magnitude of the electron P_T , as is seen in figure 3.9 by a resolution function, that is, to perform a scalar transformation. The resolution function $\mathbf{r}(\mathbf{w})$ in this analysis is of the form $\mathbf{R}-\mathbf{T}(\mathbf{x})$ (defined in section 2.1), but in real data this will be replaced by a data driven equivalent method such as studying the Z boson invariant mass as described in chapter 2. The appropriate variable to bin both the electron P_T scales and resolutions is the electron P_T itself, as has been seen in figure 2.2(b).

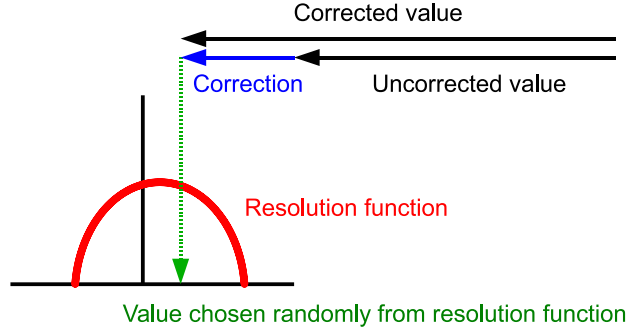
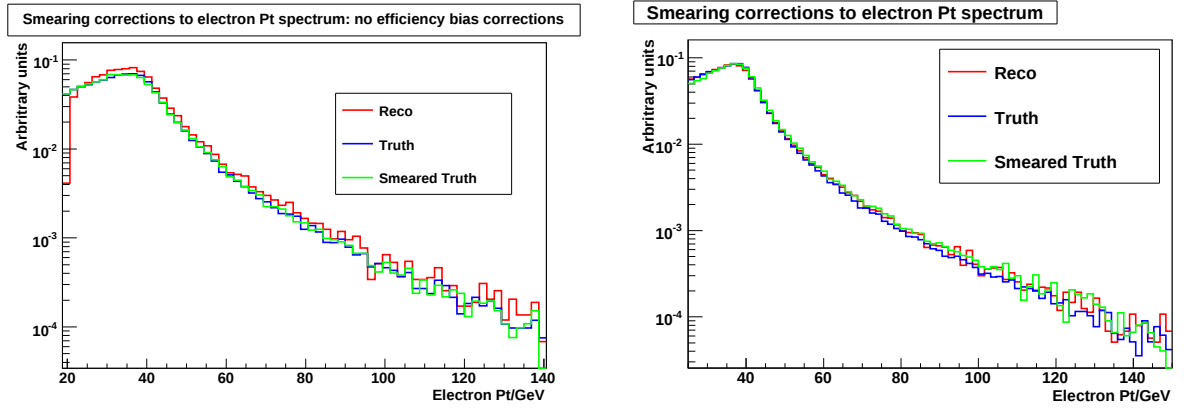


Fig. 3.9: Smearing methodology (a)- scalar

Figure 3.10(a) shows the $\mathbf{T}$, $\mathbf{R}$ and $\mathbf{R}_s$ distributions for electron P_T (in $W \rightarrow e\nu$ events, although similar results are seen in $Z \rightarrow ee$) as per the procedure described in figure 3.8. The left plot has some considerable bias between $\mathbf{R}$ and $\mathbf{R}_s$, particularly at low P_T . This is due to the variation of the trigger and reconstruction efficiencies with $\mathbf{R}$, which is particularly noticeable at low P_T due to the turn on curve in efficiency (see chapter 5). This point is purely academic as the variation of efficiency is already factored directly in for the cross section analysis and folding it in here would be double counting the effect.

¹⁰ recall in the earlier chapter it was seen that smearing electron η is not necessary due to the very high detector resolution on this quantity.

However, for the peace of mind of the reader, figure 3.10(b) shows the same distributions when the efficiency bias has been folded in. It is seen that this produces an $\mathbf{R}_s$ distribution much close to $\mathbf{R}$ than the unsmeared distribution $\mathbf{T}$, shown more clearly in figure 3.11 which shows the bin-by-bin difference between these distributions. One point to note from this exercise is that the efficiency variation with P_T is by far the dominant effect on the spectrum when compared to the impact of the electron scale and resolution.



(a) Distributions $\mathbf{R}$, $\mathbf{T}$ and $\mathbf{R}_s$ in $W \rightarrow e\nu$ with no correction for trigger and reconstruction bias

(b) Distributions $\mathbf{R}$, $\mathbf{T}$ and $\mathbf{R}_s$ in $W \rightarrow e\nu$ events after correction for trigger and reconstruction bias

Fig. 3.10: P_{T_e} distributions in $W \rightarrow e\nu$ events before and after smearing procedure.

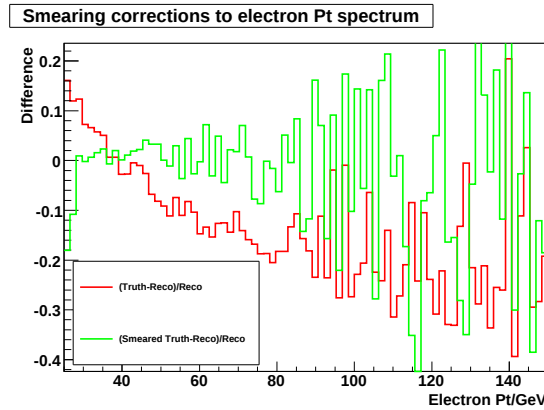


Fig. 3.11: Fractional residual differences between $\mathbf{R}_s$ and $\mathbf{R}$ (green) P_{T_e} distributions (trigger bias included). Initial difference between $\mathbf{R}$ and $\mathbf{T}$ is shown for comparison in red.

Systematics on electron P_T smearing procedure

The systematics shown in table 3.2 are those obtained from the elements described earlier in the chapter. It is seen that the systematic uncertainties associated with binning and

the lower P_{T_e} cut are very small. The impact of using a Gaussian fit to approximate the electron resolution for smearing however is large. Figure 3.12 shows the electron $\mathbf{R-T}(P_T)$ resolution as determined in the fifth bin of electron P_T (25-27.5 GeV). The fit is inconsistent with the histogram as it doesn't describe the non-Gaussian Bremsstrahlung lower side tail of the distribution, which leads to the large systematic on the acceptance associated with using a Gaussian approximation. Thus a Gaussian approximation is not used as a source of systematic as it is concluded preferable to use a random number generator from the resolution function rather than a fit for electron P_T smearing.

The overall (fractional) systematic used for electron smearing strategy is taken to be the quadrature sum of the other elements mentioned in table 3.2: 0.10% ($Z \rightarrow ee$), 0.08% ($W \rightarrow e\nu$) and 0.02% (ratio). It is thus seen that this systematic cancels out to some extent in the acceptance ratio.

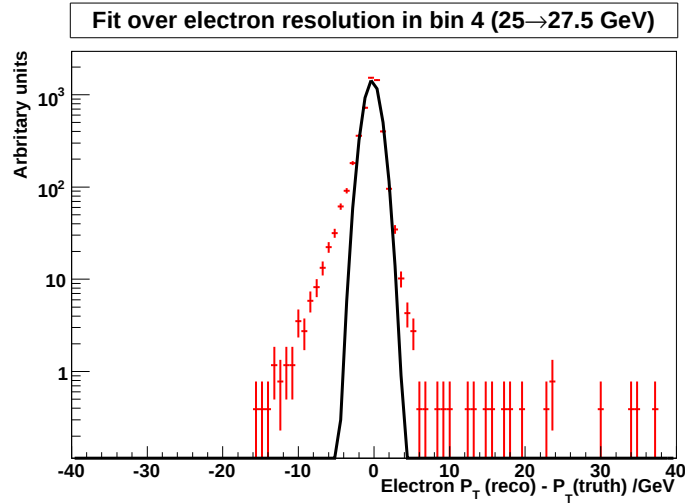


Fig. 3.12: Electron $\mathbf{R-T}(P_T)$ resolution as determined in the fifth bin of electron P_T with a Gaussian fit. The plot shows that a Gaussian resolution approximation for electrons is not appropriate.

Smearing $\cancel{E}_t$

Two different strategies were implemented in the case of $\cancel{E}_t$ smearing. The first, to use a global smearing like that detailed in the electron case. The second strategy was component smearing.

Systematic source	$W \rightarrow e\nu$ impact	$Z \rightarrow ee$ impact	A_Z/A_W impact
Double binning	0.001	0.001	negligible
Lower P_T cut	0.03	0.03	0.0002
Using fit	0.08	0.75	0.02
Quadrature sum (excluding systematic from fit)	0.03 (0.08%)	0.03 (0.10%)	0.0002 (0.02%)

Tab. 3.2: Evaluation of systematics on smearing strategy for electron P_T (absolute values quoted and acceptance values are quoted in percent). The quadrature sum is also quoted in parentheses as a fractional percent of the quantity. Note that the statistical uncertainty on the acceptance is 0.13 ($Z \rightarrow ee$) and 0.08 ($W \rightarrow e\nu$), and the impact of electron smearing is -1.04 ($Z \rightarrow ee$) and 0.67 ($W \rightarrow e\nu$).

Component smearing

The P_T vector of the object is resolved along two chosen axes (in figure 3.13 the x and y axes are chosen for demonstration but in reality it could be any) and resolution smearing is performed along these axes. The resolution functions must be the correct function *along that particular axis*. The smeared components are then recombined to obtain an overall smeared P_T using the following procedure (as has been justified in chapter 2, the axes $\not{E}_t \cdot \mathbf{A}_Z$ and $\not{E}_t \cdot \mathbf{A}_{AZ}$ are chosen as the axes to smear along, and the quantities are defined in figure 3.14).

The components of $\not{E}_t$ parallel and perpendicular to the P_{TZ} direction ($\not{E}_t \cdot \mathbf{A}_Z$ and $\not{E}_t \cdot \mathbf{A}_{AZ}$) are given as follows:

$$\not{E}_t^Z = \not{E}_t \cdot \mathbf{A}_Z = |\not{E}_t| \cos \alpha, \quad (3.3)$$

$$\not{E}_t^{AZ} = \not{E}_t \cdot \mathbf{A}_{AZ} = |\not{E}_t| \sin \alpha, \quad (3.4)$$

It is these quantities which are smeared, altering both the angle and the magnitude of the $\not{E}_t$ vector:

$$\not{E}_t^{Z'} = |\not{E}_t'| \cos \alpha', \quad (3.5)$$

$$\not{E}_t^{AZ'} = |\not{E}_t'| \sin \alpha', \quad (3.6)$$

where

$$\not{E}_t' = \sqrt{(\not{E}_t^{Z'})^2 + (\not{E}_t^{AZ'})^2} \quad (3.7)$$

The components of the smeared $\not{E}_t$ vector along the x and y axes are given by

$$P_x = \not{E}_t' \cos \theta' \quad (3.8)$$

$$P_y = \not{E}_t' \sin \theta' \quad (3.9)$$

where from the diagram it can be seen by inspection that

$$\theta' = \alpha' - \alpha + \theta \quad (3.10)$$

Thus the smeared $\not{E}_t$ vector size and angle, $\not{E}_t'$ and α' , may be obtained.

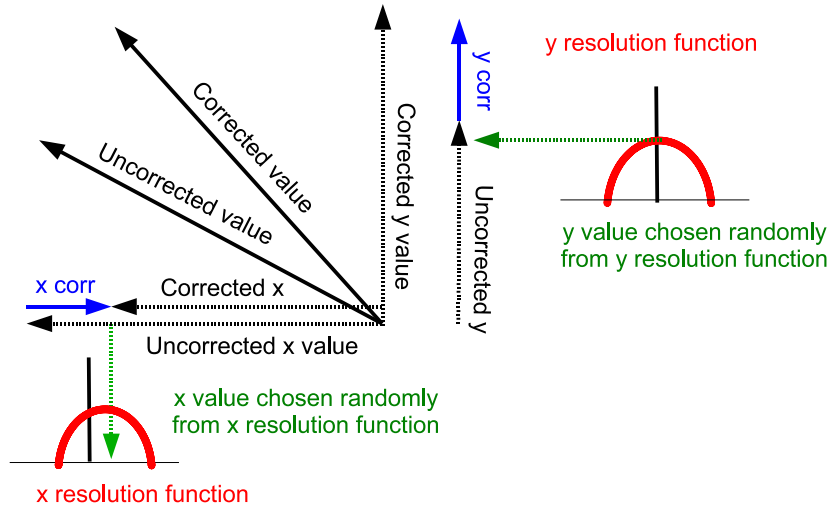


Fig. 3.13: Smearing a quantity along component axes.

Initial problems with $\not{E}_t$ smearing

Similar methodology as that used in the electron case was attempted with the $\not{E}_t$ distributions, except the $\not{E}_t$ response was binned in terms of hadronic activity as opposed to P_T .

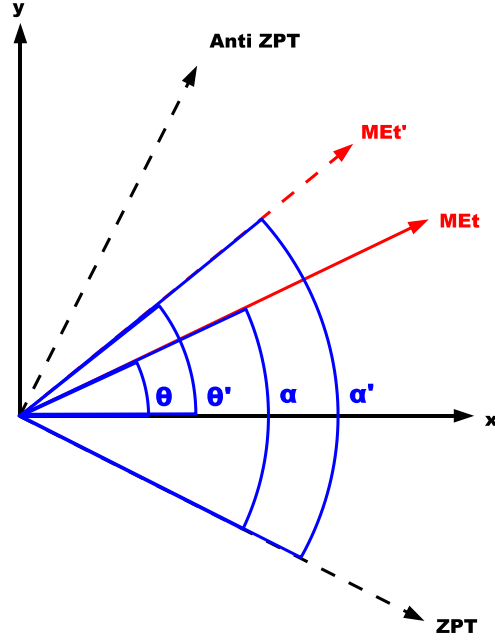


Fig. 3.14: Recombination of a quantity smeared along component axes.

The resultant distributions are shown in figure 3.15. It must be noted that no efficiency correction has been made in these distributions. There are two worrying aspects of this plot. The first being that $\mathbf{R}$ and $\mathbf{T}$ lie almost on top of each other. The second is that $\mathbf{R}_s$ lies very far away from $\mathbf{R}$.

Figure 3.16 shows a toy Monte Carlo study, where $\mathbf{T}$ is smeared on an event by event basis by a random number generated from Gaussian functions of the form $G(\bar{x}, \sigma) = G(0, 6)$ and $G(-3, 0.01)$ (numbers in GeV). It is seen that a Gaussian function with $\sigma = 6$ GeV will smear the $\cancel{E}_t$ distribution much more than what is observed in $\mathbf{R}$ in figure 3.15. Indeed, if another toy MC study is used to manually smear $\mathbf{T}$ with a random number generated from a Gaussian function, the σ value found to allow $\mathbf{R}_s$ to lie on top of $\mathbf{R}$ is less than 1 GeV, clearly much smaller than the known ATLAS $\cancel{E}_t$ simulated resolution of ~ 6 GeV.

Figure 3.17 outlines a theory as to how this has occurred. Given that the peak is *Jacobian*, and thus asymmetric, smearing will indeed flatten the peak but will preferentially shift events toward the steep side of the peak (in the diagram shown this is on the right)¹¹. If a negative

¹¹ it is important to note this is **not** the same as saying that, on an event by event basis, $\cancel{E}_t$ values will

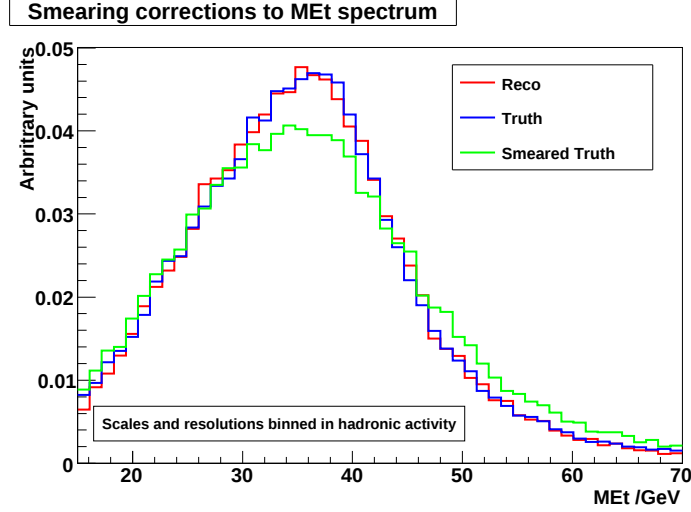


Fig. 3.15: E_t distributions in $W \rightarrow e\nu$ events (Athena release 13) before and after smearing procedure (response binned in hadronic activity).

scale bias is also present, as is the case in E_t scale, this may to some extent cancel out the effect of resolution and the final scaled and smeared distribution may, co-incidentally if the effects of smearing and bias are of similar but opposite magnitude, lie very close to the original distribution. Thus if the scale bias is not accounted for correctly, for example if it depends on a different variable, this could cause the ‘over-smearing’ effect seen in figure 3.15.

To test this hypothesis, one must separate out the effects of scale and resolution which have, in the case of E_t , been seen to depend on different variables. Independent corrections must be applied for scale and resolution to $\mathbf{T}$ and a strategy for doing so is outlined in figure 3.18.

get preferentially shifted upwards. The E_t resolution function is (to a good approximation) symmetric and events will be equally shifted upwards and downwards. The shifting of the peak shape is an artifact of the number density of events in E_t space prior to smearing.

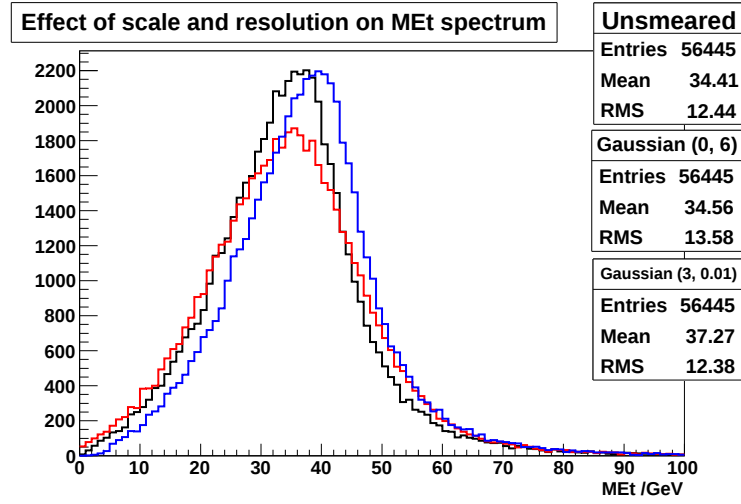


Fig. 3.16: E_t distributions in $W \rightarrow e\nu$ events smeared using a random number generated from a Gaussian function (black) with parameters as defined in the statistics boxes. The effect of $G(-3, 0.01)$ is to shift the peak (blue) and $G(0, 6)$ flattens and widens it (red).

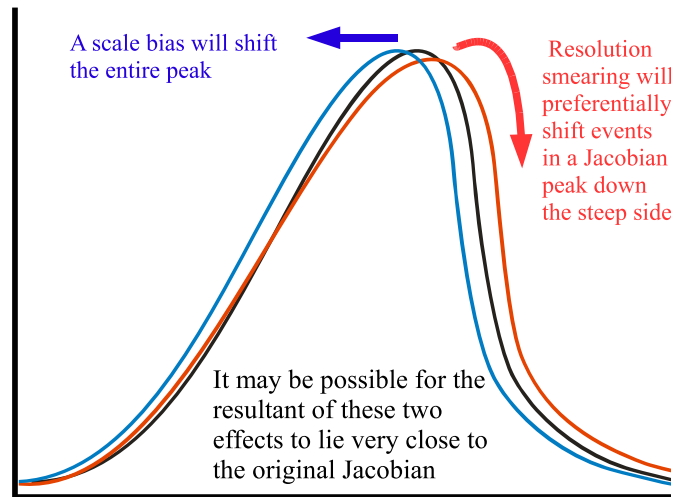


Fig. 3.17: Effect of resolution and scale bias on a Jacobian peak

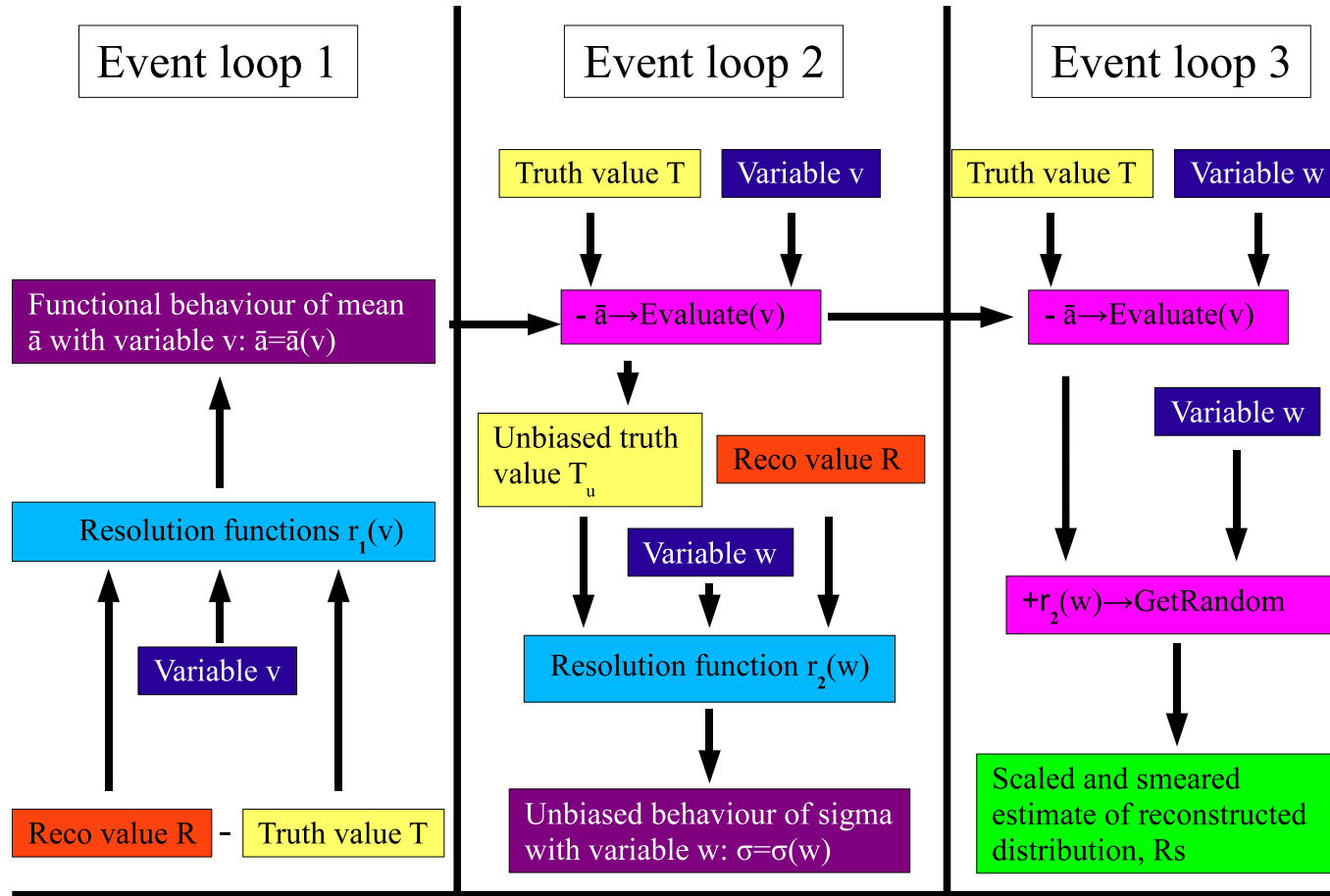


Fig. 3.18: Strategy to apply unbiased corrections of scale and resolution to T . Note the definitions of variables v and w .

Testing new procedure with MC

The new procedure was first tested using simple $\mathbf{r}(\mathbf{w})$, $\mathbf{r}(\mathbf{v})$ distributions but will be extended to the data driven equivalents $\mathbf{r}'(\mathbf{w})$ and $\mathbf{r}'(\mathbf{v})$ later. One must carefully choose variables v and w so that an accurate scale $\mathbf{a}(\mathbf{v})$ and smearing $\mathbf{r}_2(\mathbf{w})$ is applied. In chapter 2 it was seen that the sensible variable $\mathbf{w}$ to parameterise resolution $\mathbf{r}_2$ is the hadronic activity $\sum E_{T\text{had}}$, as seen in figure 2.9. The correct variable for scale $\mathbf{a}$ is either the magnitude of the $\cancel{E}_t$ itself (as may be seen in figure 2.14) or the hadronic recoil when $\cancel{E}_t$ is resolved along the axis of the boson transverse momenta P_{TZ} (as may be seen in figure 2.5). The latter scenario (denoted ‘axis resolution’) requires component smearing whereas the former is achieved by global smearing (denoted ‘neutrinofication’).

Figure 3.19 shows the smeared distributions when the resolution functions are binned in these variables. We see in these cases $\mathbf{R}$ is, for the most part, successfully recovered. Residual differences remain (thought to be due to efficiency bias: a reflection of the efficiency affecting the electron P_T distribution which is of course correlated to the neutrino P_T spectrum).

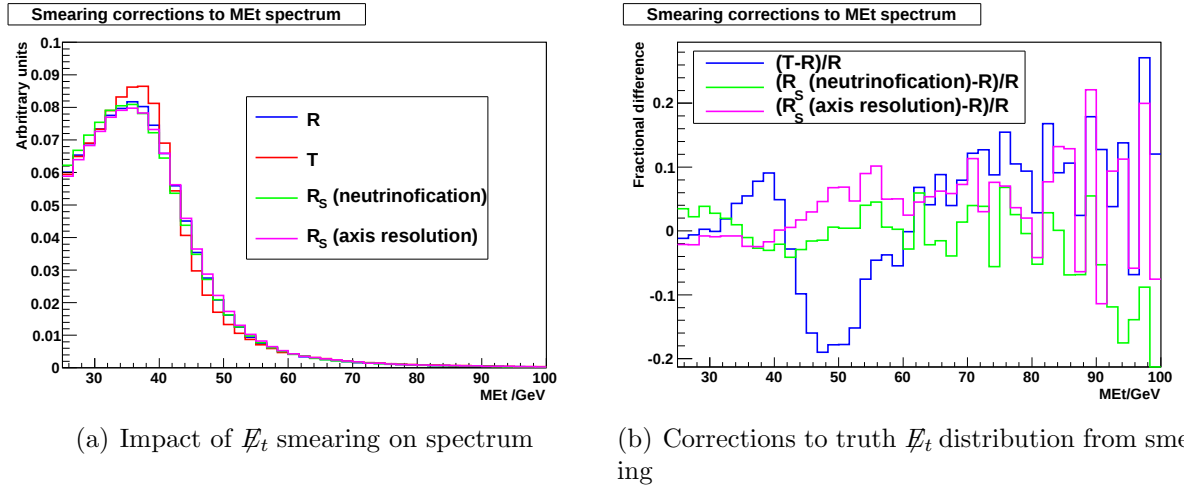


Fig. 3.19: $\mathbf{T}$, $\mathbf{R}$ and $\mathbf{R}_s$ for $\cancel{E}_t$ (using MC derived resolution functions $\mathbf{r}_1(\mathbf{v})$ and $\mathbf{r}_2(\mathbf{w})$ to test smearing procedure). $\mathbf{R}_s$ (neutrinofication) and $\mathbf{R}_s$ (axis resolution) refer to the smeared truth distributions using resolution functions obtained from neutrinofication and axis resolution respectively.

Data driven comparison

The same procedure was tested using resolution functions $\mathbf{r}'$ derived from data driven methods. Two methods were explored, following the procedure shown in figure 3.18:

- Procedure (a) (‘axis resolution’):

$\Rightarrow \cancel{E}_t \cdot \mathbf{A}_Z$ and $\cancel{E}_t \cdot \mathbf{A}_{AZ}$ used to obtain $\mathbf{r}_1(\mathbf{v})$ and $\mathbf{r}_2(\mathbf{w})$ along $\mathbf{A}_Z$ and $\mathbf{A}_{AZ}$ where v =hadronic recoil and w =hadronic activity.

$\Rightarrow$ Truth value of $\cancel{E}_t \cdot \mathbf{A}_Z$ and $\cancel{E}_t \cdot \mathbf{A}_{AZ}$ in a $W \rightarrow e\nu$ event scaled if necessary¹² and smeared as according to these values.

• **Procedure (b) (‘neutrino-fication’):**

$\Rightarrow$ Neutrino-fication in a $Z \rightarrow ee$ event performed to obtain $\mathbf{r}_1(\mathbf{v})$ and $\mathbf{r}_2(\mathbf{w})$ where $v=|\cancel{E}_t|$ and w =hadronic activity.

$\Rightarrow$ Truth $\cancel{E}_t$ in a $W \rightarrow e\nu$ event globally scaled and smeared as according to these values.

The resultant smeared distributions for $\cancel{E}_t$ are shown in figure 3.20. Procedure (a) is seen to have recovered well the distribution $\mathbf{R}_s$, but biases still remain in the neutrino-fication based smearing (procedure (b)). This is due to the data-driven resolution function not describing perfectly the detector response. However, the real test of the data driven smearing is shown by the overall impact on the calculated acceptances, described in the next section.

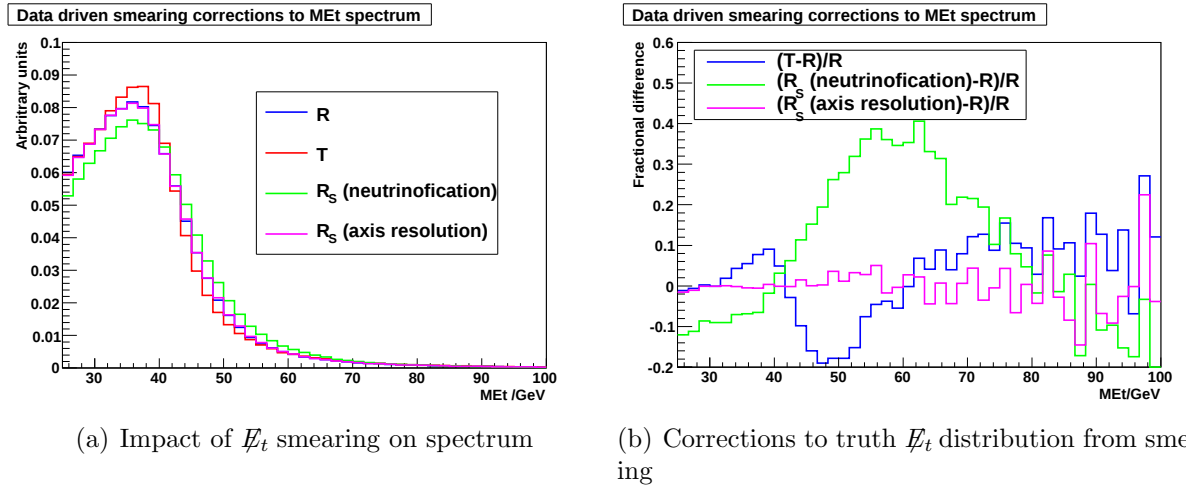


Fig. 3.20: $\mathbf{T}$, $\mathbf{R}$ and $\mathbf{R}_s$ for $\cancel{E}_t$ (using data derived resolution functions $\mathbf{r}_1(\mathbf{v})$ and $\mathbf{r}_2(\mathbf{w})$ to test smearing procedure)

Systematics on $\cancel{E}_t$ P_T smearing procedure

The systematics shown in table 3.3 are those obtained from the elements described in section

¹² scaling along the $\mathbf{A}_{AZ}$ in this MC study is not in fact necessary as there is no statistically significant bias along this axis.

3.3.3. It is seen that, as for the electron case, the systematic uncertainties associated with binning and range are very small. Unlike the electron case, $\cancel{E}_t$ response is estimated by applying a scale and a resolution effect separately. Thus the impact of using a fit over a histogram rather than the histogram itself may be quoted separately for scale and resolution.

The systematic used for $\cancel{E}_t$ smearing strategy (excluding the systematics obtained by comparing different smearing procedures, which is discussed in the next section) is taken to be the quadrature sum of the elements mentioned for the electron case, summarised in table 3.3: 0.62% for both A_W and the acceptance ratio (as A_Z is not a source of systematic in $\cancel{E}_t$ smearing).

Systematic source	A_W impact	A_Z/A_W impact
Double binning	0.01	0.0002
Lower P_T cut	0.18	0.004
Using fit in resolution	0.14	0.003
Using fit for scale	0.001	Negligible
Quadrature sum	0.23 (0.6%)	0.005 (0.6%)

Tab. 3.3: Absolute systematics from $\cancel{E}_t$ smearing strategy on $W \rightarrow e\nu$ acceptance (when quoted in percent) and the acceptance ratio. The statistical uncertainty on the acceptance is 0.08%, and the impact of $\cancel{E}_t$ smearing is -0.15%. The fractional percentage systematic on the quadrature sum (as a ratio of the quantity) is given in parentheses.

Final impact of smearing on acceptances

The event selection code (cuts at 25 GeV on both electrons and $\cancel{E}_t$) was then run on the unmodified quantities (electron P_T and $|\cancel{E}_t|$), and the same quantities after smearing. The difference in acceptance between these two cases was calculated and table 3.4 summarises the results. The following observations were made:

- The effect of electron smearing is larger in $Z \rightarrow ee$ events (about 1.0%) than for $W \rightarrow e\nu$ (0.7%). This is hardly surprising, as there are twice the number of electrons in $Z \rightarrow ee$ than in $W \rightarrow e\nu$ events¹³.

¹³ although this doesn't necessarily translate into a 1:2 ratio between the acceptance impact as the two decay electron kinematics are correlated.

- It is seen that, for $W \rightarrow e\nu$ events, the smearing correction in E_t ($\sim 0.2\%$) is a smaller correction than for the electron correction ($\sim 0.7\%$). This is not a reflection of the size of the scale bias and resolution in E_t compared to that for electrons, but it is instead due to the previously described cancellation of the scale and resolution in this particular $W \rightarrow e\nu$ sample, leading to the truth and reconstructed distributions lying very close to each other. For this reason, it is not a fair comparison to look at the systematic uncertainty on the acceptance E_t smearing compared to its impact, as another configuration of E_t scale and resolution may not cancel one another out and the impact of smearing could be much larger.
- The systematic on E_t smearing evaluated from the difference in acceptance between MC ($\mathbf{r}$) and data driven ($\mathbf{r}'$) smearing is seen to be 0.05% for procedure (a). The corresponding systematic for procedure (b) is seen to be unacceptably large. This is assumed to be due to the limitation of the neutrino-fication method (as it stands-as has been mentioned refined methods involving cluster removal are currently being investigated) in accurately estimating scale bias in E_t (as can be seen in figure 2.14) and the method was rejected at this point as a reliable one for such precise studies as truth smearing. Thus a systematic of 0.05% , taken from procedure (a) alone, on the smearing strategy¹⁴ was chosen.
- The difference in acceptance of 0.08% between procedures (a) and (b) in MC is taken as another source of systematic.

The systematic uncertainties (averaged over bins) of the scales and resolutions are evaluated in chapter 2 but summarised in table 3.5¹⁵. Table 3.6 shows the effect of systematic uncertainties on the lepton and E_t responses (as determined in chapter 2) on the calculated acceptances. Upwards systematic shifts on the response (ie, $\bar{x} + \Delta x$) only have been shown but downwards shifts have been seen to give similar results (in the opposite direction). The statistical uncertainty on the detector response (again, as determined in chapter 2) has been

¹⁴ note this does not include the systematic associated with the smearing procedure determined earlier, nor the determination of scale and resolution themselves, which are discussed in the next section.

¹⁵ as a percentage of the total value as opposed to an absolute quantity as in chapter 2.

Analysis	Electron smearing	$\cancel{E}_t$ smearing	ΔA %
$W \rightarrow e\nu$	MC	None	-0.67
$Z \rightarrow ee$	MC	None	-1.04
$W \rightarrow e\nu$	None	MC (proc a)	-0.15
$W \rightarrow e\nu$	None	Data driven (proc a)	-0.11
$W \rightarrow e\nu$	None	MC (proc b)	-0.08
$W \rightarrow e\nu$	None	Data driven (proc b)	+1.08
$W \rightarrow e\nu$	MC	MC (proc a)	-0.79
$Z \rightarrow ee$	MC	N/A	-1.04

Tab. 3.4: Impact of smearing on computed acceptances. The statistical uncertainty on the acceptance is 0.13% for $Z \rightarrow ee$ events and 0.08% for $W \rightarrow e\nu$ events.

neglected in this section as it has negligible impact on the acceptance in comparison to the systematic uncertainties. The systematic obtained on scale is consistent with the jet energy scale uncertainty assumed in the sample, which is set at $\sim 5\%$ (see chapter 1).

Quantity	Scale systematic %	Resolution systematic %
Electron	0.2%	0.7%
$\cancel{E}_t \cdot \mathbf{A}_Z$	14.9 %	9.7 %
$\cancel{E}_t \cdot \mathbf{A}_{AZ}$	N/A	9.7 %

Tab. 3.5: Summary of detector responses (percentage values averaged bin by bin shown). Note the fractional scale systematic along $\mathbf{A}_{AZ}$ is not applicable as the $\cancel{E}_t$ is not scaled in this direction (there is no mechanism for bias along this axis).

Analysis	Electron scale	Electron resolution	$\cancel{E}_t$ scale	$\cancel{E}_t$ resolution	ΔA %
$W \rightarrow e\nu$	central+sys	central	central	central	<0.01
$W \rightarrow e\nu$	central	central+sys	central	central	<0.01
$Z \rightarrow ee$	central+sys	central	central	central	<0.01
$Z \rightarrow ee$	central	central+sys	central	central	<0.01
$W \rightarrow e\nu$	central	central	central+sys	central	0.11%
$W \rightarrow e\nu$	central	central	central	central+sys	0.11%

Tab. 3.6: Deviation of acceptances when taking into account systematic uncertainties on detector scale and resolutions, from acceptances which are computed from ‘centrally smeared’ quantities.

3.4 Estimation of systematic uncertainties

3.4.1 Experimental uncertainties

The experimental uncertainties on the acceptance calculation originate from detector response, photon merging and the choice of the lower boundary cut on M_Z . Systematic esti-

mators were devised to account for uncertainties both on the smearing procedure and those on the measurements of the detector response itself. These have been discussed in detail through the chapter, but the numerical results are summarised in table 3.7. The total systematic uncertainty from these on the acceptances was evaluated as the quadrature sum of the sources in the table.

Estimator	Value
$Z \rightarrow ee$ analysis	
Photon merging parameter	0.06 (0.20%)
Impact of electron scale uncertainty on acceptance	negligible
Impact of electron resolution uncertainty on acceptance	negligible
Estimated impact of electron smearing procedure on acceptance	0.03 (0.10%)
$\sqrt{\text{Quadrature sum}}$	0.08 (0.22%)
$W \rightarrow e\nu$ analysis	
Photon merging parameter	0.03 (0.08%)
Impact of electron scale uncertainty on acceptance	negligible
Impact of electron resolution uncertainty on acceptance	negligible
Impact of $\cancel{E}_t$ scale uncertainty on acceptance	0.11 (0.30%)
Impact of $\cancel{E}_t$ resolution uncertainty on acceptance	0.11 (0.30%)
Comparison of acceptance with MC and data driven $\cancel{E}_t$ smearing	0.05 (0.14%)
Comparison with acceptance between two methods of $\cancel{E}_t$ smearing	0.08 (0.22%)
Estimated impact of electron smearing procedure on acceptance	0.03 (0.08%)
Estimated impact of $\cancel{E}_t$ smearing procedure on acceptance	0.23 (0.62%)
$\sqrt{\text{Quadrature sum}}$	0.30 (0.80%)
$\mathcal{R}$ analysis (A_Z/A_W)	
Photon merging parameter	0.001 (0.12%)
Impact of electron scale uncertainty on acceptance ratio	negligible
Impact of electron resolution uncertainty on acceptance ratio	negligible
Impact of $\cancel{E}_t$ scale uncertainty on acceptance ratio	0.002 (0.30%)
Impact of $\cancel{E}_t$ resolution uncertainty on acceptance ratio	0.002 (0.30%)
Comparison of acceptance with MC and data driven $\cancel{E}_t$ smearing	0.001 (0.14%)
Comparison with acceptance between two methods of $\cancel{E}_t$ smearing	0.002 (0.22%)
Estimated impact of electron smearing procedure on acceptance	0.0002 (0.02%)
Estimated impact of $\cancel{E}_t$ smearing procedure on acceptance	0.005 (0.62%)
$\sqrt{\text{Quadrature sum}}$	0.006 (0.80%)

Tab. 3.7: Summary of experimental absolute systematic uncertainties (fractional uncertainties quoted in parentheses) on acceptance (quoted in percent) for $W \rightarrow e\nu$ and $Z \rightarrow ee$ and the acceptance ratio A_Z/A_W .

It must be noted that the photon merging procedure is the source of the dominating experimental systematic uncertainty on the acceptance for $Z \rightarrow ee$ analysis, and the $\cancel{E}_t$ smearing procedure for $W \rightarrow e\nu$ and $\mathcal{R}$ analysis.

3.4.2 Theoretical uncertainties

The theoretical uncertainties on the acceptance are taken from a study by Matthias Schott [47] and are evaluated from the same PYTHIA signal samples as used in this analysis. The systematics from the following effects were evaluated and the final result is summarised in table 3.8:

- **PDFs:** evaluated by the Hessian method: producing a data set for each of the 44 eigenvector sets of CTEQ 6.6 PDF predictions[48], and rerunning the analysis on each of these. This forms the dominant theoretical uncertainty on the cross section measurements.
- **ISR:** Initial State Radiation generates P_T of the vector boson and can affect the decay kinematics. The systematic uncertainty associated with this effect was evaluated by turning on and off ISR in PYTHIA and was seen to form the sub-dominant uncertainty.
- **Higher order corrections:** PYTHIA is a LO (Born level) generator and so FEWZ [49] was used to calculate next-to-next LO QCD matrix element corrections to the cross section. This was used to estimate the associated systematic effect on the acceptance.
- **Intrinsic K_T** Altering PYTHIA settings allows an estimate of the effect of partons inside the proton having a intrinsic transverse momenta (which would alter the P_T distribution of the boson and thus the acceptance).
- **Hadronisation and multiple parton interactions (MPI):** Generator level predictions are compared when the hadronisation¹⁶ and MPI¹⁷ models were turned on or off. These were found to have a negligible effect on the acceptance.
- **QED and electroweak corrections:** Systematic uncertainties on the acceptance from these was evaluated by altering PHOTOS settings.

¹⁶ fragmentation of gluon radiation from the hard process

¹⁷ more than one hard parton-parton interaction in the collision

Effect	Impact on $W \rightarrow e\nu$	Impact on $Z \rightarrow ee$	Impact on $\mathcal{R}$
Total	2.06%	2.44%	1.27%

Tab. 3.8: Summary of theoretical percentage uncertainties[47] on the calculated acceptance in PYTHIA.

3.4.3 Summary of acceptances and associated uncertainties

Table 3.9 summarises the evaluated acceptances along with their associated uncertainties.

The following notes were made from the results:

- The theoretical uncertainties for both $Z \rightarrow ee$ and $W \rightarrow e\nu$ are larger than the experimental ones.
- The experimental systematic uncertainty to $Z \rightarrow ee$ acceptance calculation is actually smaller than the statistical one, as electron resolution effects are very small (so even a large relative systematic uncertainty on electron response only has a small impact on the final calculated acceptance). However, it is just a matter of collecting more statistics (which could be done) to obtain a smaller statistical uncertainty. However, as the overall statistical uncertainty in the cross section is calculated to be much smaller than the systematic, this was considered to be unnecessary.
- The experimental systematic uncertainty for $W \rightarrow e\nu$ was larger than that for $Z \rightarrow ee$. The reason for this is the systematic associated with $\cancel{E}_t$ smearing is much larger, for reasons explored in the chapter.
- The experimental systematic uncertainty on the acceptance ratio is of very similar size to that for $W \rightarrow e\nu$. The reason for this is that the systematic associated with smearing electrons is very small compared to that with smearing $\cancel{E}_t$, which is the dominant source of uncertainty for $W \rightarrow e\nu$ and thus also $\mathcal{R}$. In addition, the effect of smearing the electron in $W \rightarrow e\nu$ cancels out to some extent with that of smearing one of the electrons in $Z \rightarrow ee$, leaving the effect of smearing one electron and the $\cancel{E}_t$ in the $\mathcal{R}$ calculation remaining: the same as smearing $W \rightarrow e\nu$ alone.
- Theoretical uncertainties cancel to some extent in the acceptance ratio and the systematic uncertainty on this quantity is approximately half of that for $W \rightarrow e\nu$ and

$Z \rightarrow ee$ individually.

	$A_{W \rightarrow e\nu}$	$A_{Z \rightarrow ee}$	$A_{Z \rightarrow ee}/A_{W \rightarrow e\nu}$
Acceptance %	36.82	30.44	0.83
Statistical uncertainty ^a %	0.22%	0.41%	0.46%
Systematic uncertainty (experimental) %	0.80%	0.22%	0.80%
Systematic uncertainty (theory) %	2.06%	2.44%	1.27%

^a Statistical uncertainty on $Z \rightarrow ee$ and $W \rightarrow e\nu$ combined using standard error propagation to obtain the statistical uncertainty on their ratio (needed for a calculation of $\mathcal{R}$).

Tab. 3.9: Summary of evaluated acceptances (quoted as a fraction of the quantity in percent) along with associated uncertainties.

3.5 Conclusions and recommendations of further work

- Detector acceptance varies significantly for different final state kinematics and it is thus important to fold in these dependencies for a cross section calculation.
- A large (and thus necessary) correction to the acceptance is photon merging. The recommended photon merging parameter evaluated in this thesis is $\Delta R=0.15$, although the measured acceptance has been seen to be stable with other (reasonable) choices.
- Electron smearing has been seen to be a stable procedure (although it has been seen that a Gaussian approximation to the electron resolution function is not acceptable) but care must be taken as the electron efficiencies are a much more dominant factor affecting the P_T spectrum than the detector response. The systematic due to electron smearing in MC is very small. Obviously electron smearing using resolution functions measured from M_{ee} as opposed to $\mathbf{R-T}(P_{Te})$ needs to be implemented.
- Neutrinofication as it has been presented here does not describe the detector response accurately enough to be used for event smearing. Current techniques are being investigated to perform neutrinofication and recompute the $\cancel{E}_t$ variables when the electron clusters have been removed. Using the resultant resolution functions for $\cancel{E}_t$ smearing may then be re-attempted.

- As has been shown in the chapter, E_t smearing is not straightforward because E_t is a sum over detected activity from all objects. This leads to dependence of E_t scale and resolution on different factors which is what leads to the troublesome cancelling out of the two effects seen in this analysis. The chapter shows that axis resolution is promising as a technique to smear E_t *providing* the procedure is carefully designed to account for resolution, bias and the impact of these on each other. The impact of the systematic from the E_t response determination has in fact only a small impact on the measured acceptance and the systematic mainly comes from the smearing procedure itself. In early data, hidden E_t biases not present in MC simulation are sure to be present. Care must be taken to ensure that these are found otherwise event smearing will give incorrect results.

A proposal to make the procedure of E_t smearing more stable is to smear the E_t constituents (electrons, jets...) separately, and to recombine the smeared objects to estimate the total smeared E_t . The detector response to each of these objects is driven by well understood variables, and so different effects should not cancel when this method is used. Studies are underway into smearing electrons and jets separately. However, as has been seen in chapter 2, the detector response to hard jets and soft recoil is quite different. Thus for these techniques to work, resolution functions for both types of hadronic deposit are required. Techniques such as those seen in chapter 2, such as axis resolution for different jet multiplicities, may provide powerful tools in obtaining such functions.

- It has been mentioned in the chapter that event smearing will be used in first data as it is a quick way to estimate the impact of detector response on the analysis. A full treatment includes firstly using the measured resolution functions to *understand* the detector response and then using this understanding to modify the detector simulation. Although the process may be speeded up by using fast simulation, this feedback however is not one that can be performed on a short time scale. For this reason, smearing methods need to be refined and their stability improved for early data analyses.

-
- The systematic uncertainty on the acceptance in $Z \rightarrow ee$ and $W \rightarrow e\nu$ due to event smearing (which is larger in $W \rightarrow e\nu$ due to the difficulties with E_t smearing) is smaller than the evaluated theoretical uncertainty (which is driven by the uncertainty due to PDFs). However the theoretical systematic uncertainty for the acceptance ratio is smaller than that for the $Z \rightarrow ee$ and $W \rightarrow e\nu$ acceptances individually.
 - The (percentage) systematic uncertainty on the acceptance ratio may be approximated by that on smearing $W \rightarrow e\nu$.

4. BACKGROUND DETERMINATION

The background distributions (excluding the background from QCD) in this analysis are determined from simulation¹. The determination of QCD background in Monte Carlo is more complicated due to its large cross section and associated large statistical uncertainties. Table 4.1 describes the dominant mechanisms forming backgrounds to the signal $Z \rightarrow ee$ and $W \rightarrow e\nu$ events, and Table 4.2 shows the number of events surviving each cut (as detailed in chapter 1) of the W and Z event selection. The following notes are made:

- $W \rightarrow e\nu$ and in particular $Z \rightarrow ee$ analysis has a high signal to background ratio.
- Backgrounds other than QCD are small. Thus relying on the (well understood) MC predictions for their simulation is a valid procedure.
- The numbers obtained for the QCD channel have a huge statistical uncertainty and should be considered unreliable.
- Tighter electron identification cuts would increase the signal-background ratio. However, this is deemed unnecessary at 100 pb^{-1} , as there is also the requirement to keep as many signal events as possible. This strategy may not be adopted in real data; MC does not predict well how much QCD background there will actually be and event selection will need to be re-optimised once data arrives.

	$W \rightarrow e\nu$	$Z \rightarrow ee$
$W \rightarrow e\nu$		A jet fakes an electron and $\cancel{E}_t$ is either mis-reconstructed or small
$Z \rightarrow ee$	One electron is not reconstructed (and large $\cancel{E}_t$ is reconstructed)	
$W \rightarrow \tau\nu$	τ decays into a lepton	Negligible
$Z \rightarrow \tau\tau$	One τ decays leptonically, while the other is not identified (can fake $\cancel{E}_t$)	Both τ particles decay leptonically
$t\bar{t}$	One top decays leptonically	Both tops decay leptonically
QCD dijets	One jet fakes an electron and $\cancel{E}_t$ is large (mis-measured jets)	Both jets fake electrons

Tab. 4.1: Expected mechanisms forming backgrounds to signal channels

¹ details of the datasets used are given in chapter 1.

	$W \rightarrow e\nu$	$Z \rightarrow ee$	$Z \rightarrow \tau\tau$	$W \rightarrow \tau\nu$	$t\bar{t}$	QCD
$W \rightarrow e\nu$						
None	1035285 (1017)	109821 (331)	112837 (336)	512459 (716)	20549 (143)	1.03×10^{10} (1.01×10^5)
Trigger	535902 (732)	76700 (277)	4813 (69.4)	26200 (162)	4627 (68)	7.86×10^6 (2.8×10^3)
Offline electron, P_T	471445 (687)	26447 (163)	3399 (58.3)	18934 (138)	1955 (44.2)	5.31×10^6 (2.3×10^3)
+ η cuts	444084 (666)	30224 (174)	2790 (52.8)	18068 (134)	2052 (45.3)	4.8×10^6 (2.19×10^3)
+ IsEM (medium)	419767 (648)	36774 (192)	2790 (52.8)	17231 (131)	3677 (60.6)	1.25×10^6 (1.12×10^3)
+ $\cancel{E}_t > 25\text{GeV}$	353182 (594)	312 (17.7)	678 (26)	10490 (102)	3139 (56)	3.4×10^4 (184)
% contribution	87.9	0.08	0.17	2.61	0.78	8.46
$Z \rightarrow ee$						
	1035285 (1017)	109821 (331)	112837 (336)	512459 (716)	20549 (143)	1.03×10^{10} (1.01×10^5)
Trigger	535902 (732)	76700 (277)	4813 (69.4)	26200 (162)	4627 (68)	7.86×10^6 (2.8×10^3)
2 offline electrons, P_T	26739 (164)	40299 (201)	530 (23)	1376 (37.1)	1406 (37.5)	4.11×10^5 (641)
+ η cuts	24842 (158)	35042 (187)	470 (21.7)	1283 (35.8)	1334 (36.5)	3.65×10^5 (604)
+ IsEM (medium)	4952 (70.4)	29256 (171)	64 (8)	151 (12.3)	216 (14.7)	1.76×10^4 (133)
+ Mass cuts	47 (6.86)	26552 (163)	0 (0)	3 (1.73)	34 (5.83)	<1256 (35)
% composition	0.18	99.68	0	0.01	0.13	0

Tab. 4.2: Number of events surviving selection cuts (at 100pb^{-1}) with quoted statistical uncertainties (QCD is scaled to 100pb^{-1} and $Z \rightarrow \tau\tau$ includes 13% double counting as this luminosity is not available in these channels).

4.1 Backgrounds to the $W \rightarrow e\nu$ decay mode

Figure 4.1 shows the transverse mass distribution of W signal and backgrounds after event selection. Unlike the Z mass peak (see next section), this is not enough of a discriminating variable (as in, there is no clear signal distribution either above or in a different region to the background) to fit and estimate the background contamination. In data, each background to $W \rightarrow e\nu$ must be evaluated separately to estimate the number of background events remaining after signal selection.

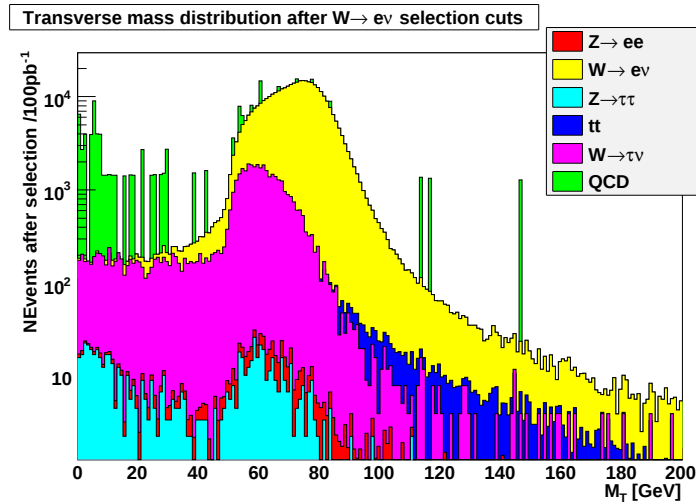


Fig. 4.1: Transverse mass distribution for selected events in a $W \rightarrow e\nu$ analysis. The spikes in the QCD background are due to a lack of statistics (combined with a large scaling factor to account for the cross section of the process).

4.1.1 Data driven estimation of dominant backgrounds to $W \rightarrow e\nu$

The dominant background to $W \rightarrow e\nu$, as may be seen in table 4.2, is that from QCD. The other backgrounds are both minor and well understood from a generator point of view, and thus it is reasonable to rely on estimation of these from the MC samples².

In section 5.2.4 a short study into a data-driven estimation of QCD background to Z events (although a similar treatment for W events is possible) is described. The conclusion of this study was that a full treatment of data driven QCD background estimation is unprac-

² Figure 4.1 shows that $t\bar{t}$ actually becomes the dominant background at higher transverse mass which suggests that it will increase at higher jet multiplicity. In fact, $t\bar{t}$ has been seen to become the dominant background at ~ 3 jet multiplicity, and so for a W +jet study the $t\bar{t}$ background must be treated more carefully (studies have been done into estimating this using b-tagging)[7]

tical as a study *in MC* due to lack of statistics, and rather than adopting ad-hoc means to circumvent this problem it is best to wait until data is available when the QCD background will be obtained ‘for free’! For sake of completeness however, three recommendations for estimation of QCD background to $W \rightarrow e\nu$ in real data are outlined.

Strategy 1: Using the photon trigger [15]

- Use a photon trigger (which will select electromagnetic calorimeter clusters above a certain energy threshold) to select a sample with high purity of QCD events.
- This sample will be kinematically very similar to the $W \rightarrow e\nu$ background sample: a QCD sample containing jets which have passed the electron trigger, but will have much lower ‘signal contamination’ of $W \rightarrow e\nu$.
- Fit the $\cancel{E}_t$ distribution of this sample to obtain the $\cancel{E}_t$ distribution shape of events with QCD jets faking electrons.
- Use the electron trigger to obtain a $W \rightarrow e\nu + \text{QCD (jet fakes)}$ sample.
- Normalise the previously obtained shape to the tail of the $\cancel{E}_t$ distribution of this sample (largely free of $W \rightarrow e\nu$) to estimate the total number of QCD events passing $W \rightarrow e\nu$ selection.

Strategy 2: Studying discriminating variables [50]

- Certain identification cuts may be reversed to obtain a QCD enriched sample.
- The distribution of a variable which has discrimination power between QCD and $W \rightarrow e\nu$ (for example, electron isolation or $\cancel{E}_t$) is measured.
- The contribution to this distribution from the signal may be obtained from other means (using simulation or studying the distribution in another decay channel). For example, the electron isolation distribution in $W \rightarrow e\nu$ may be obtained by assuming it is the same in $Z \rightarrow ee$ (which has much lower background).
- Template fitting over this signal plus background is used to estimate the remaining background contribution to the distribution and thus to the channel.

Strategy 3: Fake rates (as described in chapter 5)

- Obtain a set of probabilities $\mathbf{P}$ of jets faking electrons.

- Select a sample with at least one jet and $\cancel{E}_t$ (which will be largely dominated by QCD).
- Weight each jet with the probability $\mathbf{P}$ of it faking an electron and obtain the expected number of QCD events after $W \rightarrow e\nu$ selection.

4.2 Backgrounds to the $Z \rightarrow ee$ decay mode

Figure 4.2 shows the invariant mass distribution (as constructed from the two decay electrons) of Z signal and backgrounds after event selection, which may be used as a discriminating variable with which to estimate signal and background fractions. The strategy in $Z \rightarrow ee$ background estimation is to perform a global fit over signal+background which then enables the estimation of background contamination in the Z mass range (80→100 GeV). The development of the fit function is non trivial and is described in the next section. All backgrounds are used in the development of the fit function with the exception of QCD background (as previously justified).

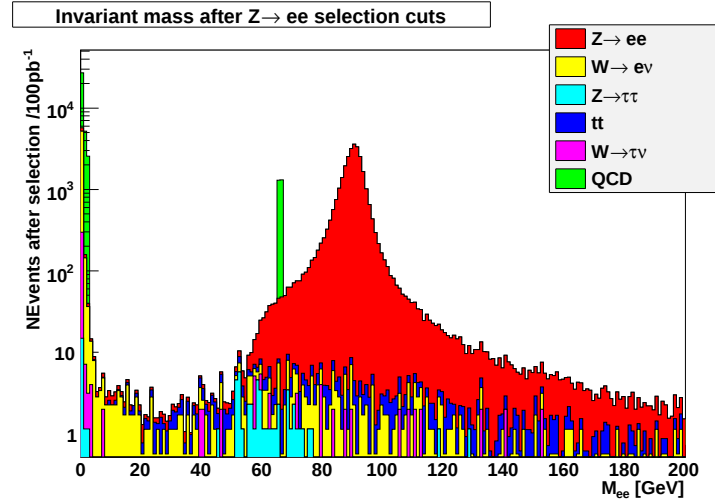


Fig. 4.2: Invariant mass distribution for selected events in a Z analysis. Histograms displayed are cumulative. All samples are run over the correct (100 pb^{-1}) luminosity apart from the dijet sample which had to be scaled and the $Z \rightarrow \tau\tau$ which (deliberately) includes 13% duplicated events (100 pb^{-1} not available): justification for this is given in the next section. It must be noted that there is a filter bias in the signal sample at 60 GeV, which explains the sharp cut-off of some events below this value.

4.2.1 Fitting using χ^2 minimisation

The fits were performed over the sum of samples, each of which initially had a (different) weighting W to scale it to a certain luminosity (100 pb^{-1}). However, the trouble with fitting over a sum of weighted samples is as follows:

- The fit is performed over the sum of the weighted samples, with the i^{th} bin content $N_i W$ and statistical uncertainty $W\sqrt{N_i}$. Consider the case where the signal sample is small with a weighting of 1, and the small background continuum is a large sample which has a correspondingly small weighting ($\ll 1$). The resultant histogram will be a signal with very large error bars ($\sqrt{N_i}$) and a background with very small error bars ($W\sqrt{N_i}$). The result of this will be that the small background will be over-represented in a χ^2 minimisation fit. That is, in this example, although the χ^2 is a fair test of goodness of fit, it is minimising with respect to the wrong region of the distribution and a good fit in the peak region may be sacrificed to accommodate a good fit in the tails of the distribution.
- The alternative is to scale the bin uncertainties to a quantity reflected by the bin content (statistical uncertainty in the i^{th} bin = $\sqrt{N_i}$). This would result in statistical fluctuations in the sample being either under- or over-estimated with respect to the bin content and so the χ^2 value given by the fit, although minimising with respect to the correct region of the distribution, would be an unfair test of goodness of the fit.
- The purpose of the procedure is to develop a fit which should be reliable once data (which obviously will not be weighted!) arrives. The first scenario presented has the problem that the fit is minimising with respect to the wrong thing and the fit developed may not describe the data correctly. The problem with the second scenario however, is that the χ^2 test is not a good test of the accuracy of the fit.
- The conclusion of the above is that it is impossible³ to correctly develop a fit using χ^2 minimisation when using a sum of weighted samples and the only solution is to run

³ although it must be noted that the above described problems ought only to be of significance if very large or small weightings are used.

over the number of each type of event needed for the luminosity stated. This was done for all samples used in the development of the fit function apart from QCD, which was not⁴ used in the fitting development in any case. One sample ($Z \rightarrow \tau\tau$) had some (13%) duplicate events artificially introduced due to this requirement.

4.2.2 Building the Z mass peak fitting function

Truth term

The truth invariant mass distribution (determined by calculating the invariant mass of two truth electrons) of the Z boson is modelled by:

→ A Breit-Wigner function which accounts for the lineshape of the Z boson (a result of the matrix element calculation) [51] (chapter 9)

→ multiplied by a parton luminosity term (ad-hoc) which accounts for the falling probability of $q\bar{q}$ collisions producing an object of mass M with energy [51] (chapter 7)

→ added to a falling exponential which accounts for the DY continuum background (described in chapter 3 where the photon (or photon- Z interference) is the propagator.

The function built from the above is as follows:

$$f_{\text{truth}}(M) = \frac{N_0}{(M - M_0)^2 + (\frac{\Gamma}{2})^2} \times M^{-\beta} + Ae^{-BM}, \quad (4.1)$$

where the parameters are defined as:

- M : x axis variable: truth invariant mass of the Z
- N_0 : Normalisation of peak
- M_0 : On-shell mass of the Z
- Γ : Width of the Z mass peak
- β : controls the exponential decay of the parton luminosity term

⁴ luckily, as developing a fit over QCD+signal sample will have inherent problems due to the very large weighting required for the QCD.

- A : controls the height of the background
- B : controls the exponential decay of the DY continuum

Figure 4.3 shows the truth Z mass peak reconstructed from two truth electrons, with the fit of equation 4.1. It should be noted that Γ does not converge on the accepted SM value of ~ 2.5 [28]. It in fact converges on a value slightly larger (~ 2.7). The reason for this is that the PYTHIA sample contains γZ interference (which has the effect of widening the Z mass peak) whereas the PDG value does not.

This observation becomes relevant later in the chapter, when fitting the reconstructed distribution. As the Z width is a well known quantity, it would have otherwise made sense to fix the Z mass peak width at the measured SM value when performing the overall fit. However, as there is also γZ contributing to the width, it is not clear what to fix it to. Therefore the Γ parameter was allowed to float in the fit⁵.

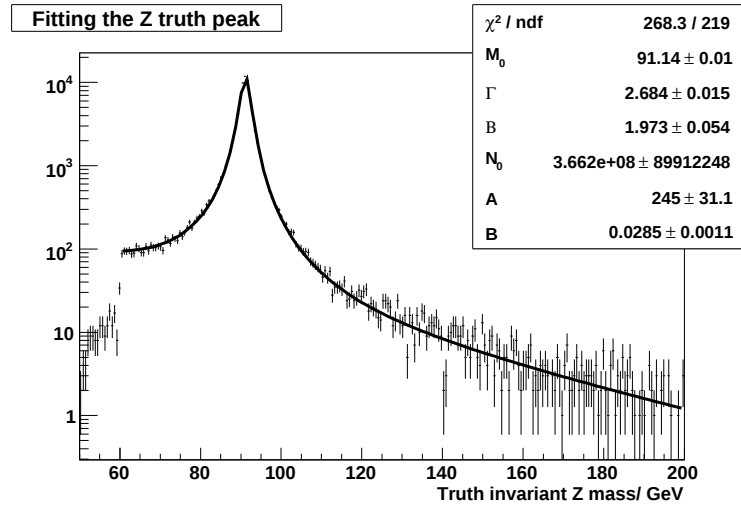


Fig. 4.3: Truth invariant Z mass fitting to equation 4.3

Detector resolution term

The next piece of the puzzle is to incorporate the detector resolution into the analysis. Figures 4.4 show the mass resolution (that is to say, the $\mathbf{R-T}(M_{ee})$ distribution) with two different fits attempted. The figure shows the better model out of a Gaussian and Crystal

⁵ in fact, it is seen that whether the Γ parameter is or is not allowed to float does not significantly affect the overall fit integral.

Ball (CB) fit is the CB (which is essentially a Gaussian function with an exponential tail strapped onto one side):

$$f_{\text{resolution}}(\Delta_0) = \begin{cases} N_1 e^{-\left(\frac{(\Delta-\Delta_0)^2}{2\sigma^2}\right)} & \text{for } \left(\frac{\Delta-\Delta_0}{\sigma}\right) > -\alpha \\ N_1 a \left(b - \frac{\Delta-\Delta_0}{\sigma}\right)^{-n} & \text{for } \left(\frac{\Delta-\Delta_0}{\sigma}\right) \leq -\alpha, \end{cases} \quad (4.2)$$

where

$$a = \left(\frac{n}{|\alpha|}\right)^{-n} \cdot \exp\left(-\frac{|\alpha|^2}{2}\right), \quad (4.3)$$

and

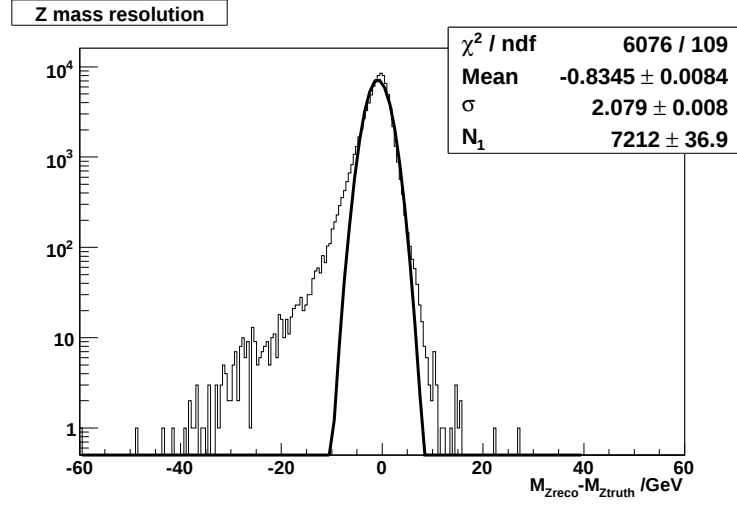
$$b = \frac{n}{|\alpha|} - |\alpha|, \quad (4.4)$$

where the parameters are defined as follows:

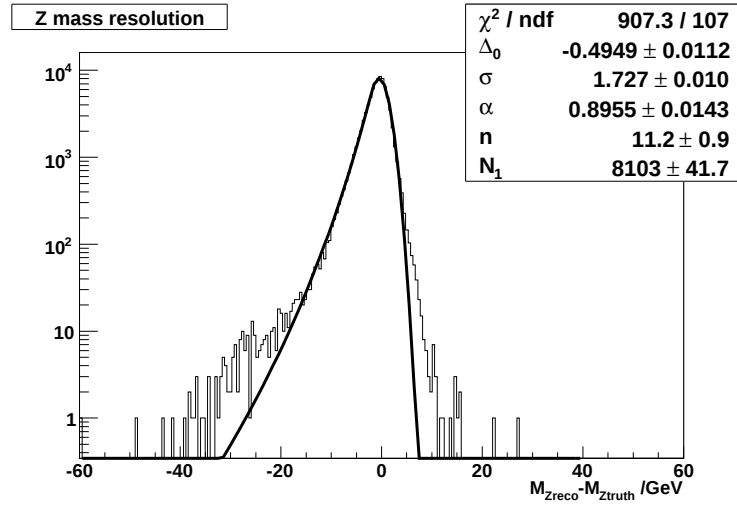
- Δ : x axis variable, $M_Z^{\text{reco}} - M_Z^{\text{truth}}$
- Δ_0 : Mean value of $M_Z^{\text{reco}} - M_Z^{\text{truth}}$ (as described in chapter 2, this is sensitive to the electron scale)
- α : Parameter controlling which side and region of the Gaussian peak to strap the exponential tail to
- n : Controls exponential decay
- σ : Width of Gaussian resolution peak (as described in chapter 2, this is sensitive to the electron resolution)
- N_1 : Normalisation of function

The asymmetry of the CB function is used to model the Bremsstrahlung tail⁶ on the distribution. This is the dominant effect on the distribution (the mean value is well below 0). A small number of high tail events may be seen in figures 4.4; thought to be caused by selection bias. However such subtleties in the exact resolution function used are seen (later in the chapter) to contribute negligibly to the analysis.

⁶ described in section 2.2.



(a) Z mass resolution fitting using a Gaussian fit



(b) Z mass resolution fitting to equation 4.2

Fig. 4.4: Mass resolution fitting using Gaussian and Crystal Ball fits.

Background fitting

The background function (in the absence of QCD) is modelled by an exponential decay

$$f_{\text{background}}(M) = Ae^{-Bx} \quad (4.5)$$

Reconstructed distribution

The overall function fitted to the reconstructed distribution is a convolution of the truth term and the resolution term, added to a background function. The background exponential decay term in the truth function is taken out of the convolution as it will be absorbed by the background function which describes the background from other decays as well as the DY continuum. For the purposes of training this fit, all backgrounds (excluding QCD) are included in the reconstructed distribution.

Once the fit is made, the functional form of the background (non $Z \rightarrow ee$ channels and the DY continuum) is known and the expected number of background events may be subtracted from the overall fit to obtain the number of signal events in the Z mass peak region, $M_{ee}=80\text{-}100$ GeV (alternatively the signal function may be directly integrated over this range). The overall form of the fit is as follows:

$$f(M) = ((\text{Breit-Wigner} \times \text{Parton Luminosity}) \otimes \text{Crystal Ball}) + \text{Background} \quad (4.6)$$

$$= (f_{\text{truth}} \otimes f_{\text{resolution}}) + f_{\text{background}} \quad (4.7)$$

where the exact form of the components in the above equation are as those determined earlier in the chapter.

Figure 4.5(a) shows the fit of signal+background samples to equation 4.6. By eye, the fit seems to be a very good one (a small deviation from the fit in the invariant mass region close to 60 GeV is due to generator filter bias). However the χ^2/N_{DOF} value of 1.54 is fairly large. Figure 4.5(b) shows the χ^2 value for each bin x (that is, the fit evaluated at x minus the histogram bin content at x , divided by the uncertainty on the histogram bin). It can be seen that the fit is slightly overestimating the peak height, and underestimating the width

of the peak, leading to the oscillating fluctuation in the region 80-95 GeV. This is what leads to the reasonably large χ^2 value.

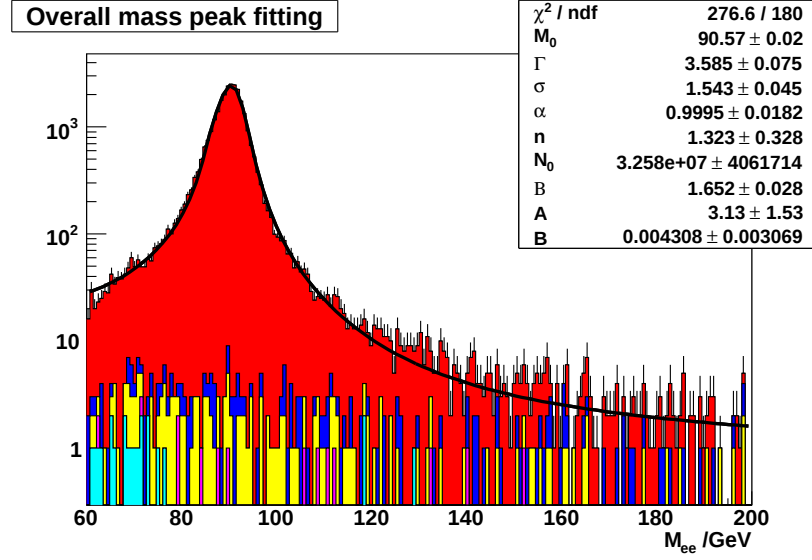
The problem with this particular fit is there are three terms in the equation which cause a lower number of entries on the high mass side than the low mass side: the parton luminosity term, the Crystal Ball resolution function and the exponentially falling background. This confuses the fit somewhat as it has three different functions causing the same effect and it finds it difficult to separate out the effect of each. However, as table 4.3 shows, replacing the Crystal Ball by a symmetric Gaussian or removing the parton luminosity term (in the hope that the exponential background would absorb this dependence) leads to a worsened χ^2 value⁷, justifying the original choice of fit. For this reason, the three separate falling functions were kept but the Crystal Ball exponential tail was constrained quite heavily, the constraint numbers coming from those obtained in figure 4.4(b). These constraints on the fit function may be what causes the deviation between the histogram and the fit in the peak region.

It is also noted that the fitted Γ parameter of 3.6 is larger than that found when fitting over the truth function (figure 4.3) of 2.9, and also the fitted σ parameter of 1.5 is smaller than that found (1.7) when fitting the resolution function (figure 4.4). The reason for this is that the truth width is to some extent ‘swallowed’ by the resolution function. To test this hypothesis, the truth width was fixed to the value of 2.9 and the fit repeated. It was seen that both the χ^2 value and fit integral were almost unchanged by this procedure. Thus it was deemed unnecessary to ‘separate out’ the effects of resolution and truth width, seeing as this would not affect final parameters.

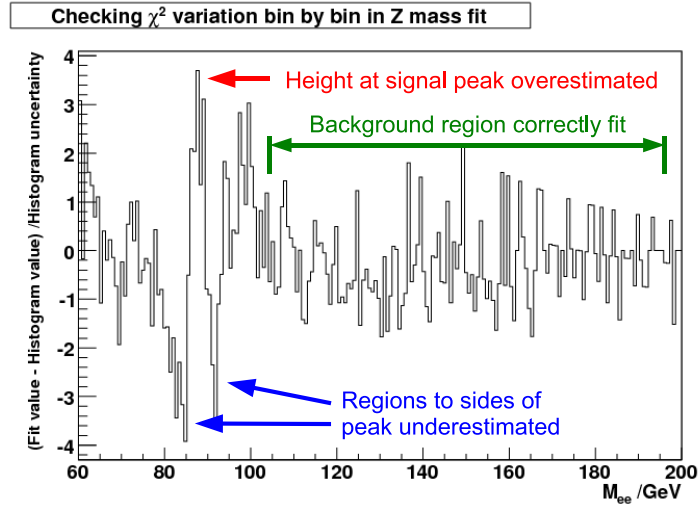
Table 4.3 shows the χ^2 values and the deviation from the default fit if the fitting procedure is varied somewhat (changing binning, fit range.....). It is observed that, despite the (consistently) high χ^2 values, the fit gives a very stable integral, and in fact the deviation from the total fit function from the total histogram integral is small. This may be explained by again examining figure 4.5(b); although oscillation is seen in the peak region, the deviations average out around zero and in fact will yield the correct peak integral and

⁷ although it must be noted that these variations still yield stable integral fits, an observation exploited in chapter 5.

the fit was thus deemed to be suitable for a cross section measurement⁸.



(a) Signal and background distributions with the fit of equation 4.6. All samples are truncated at 100 pb^{-1} apart from the $Z \rightarrow \tau\tau$ sample which includes a few (13%) duplicated events. The colour coding is the same as for figure 4.2 and plots are cumulative.



(b) χ^2 bin by bin using fit of equation 4.6

Fig. 4.5: Fitting to signal and background distributions of Z invariant mass M_{ee} .

⁸ of course for measuring, for example, the Z mass width this fit would be unsatisfactory.

4.2.3 Evaluation of systematic uncertainties from background subtraction in Z events

Systematics were evaluated from two main sources; the fitting procedure and the background subtraction:

- **Fitting:** The input fit functions, fitting range and binning were varied. The percentage deviation of the signal integral due to these variations were used to calculate the systematic uncertainty.
- **Background subtraction:** The input background fraction (excluding dijet background) was manually scaled and the fit re-performed. Again the percentage deviation of the signal integral was used in systematics calculation. This was also useful to simulate the impact of additional QCD background that will be present in real data.

Systematic	Variation	Comments	$ \Delta\text{integral} \%$	χ^2/N_{DOF}
Overall	None	Default fit: Crystal ball $\otimes$ Breit-Wigner $\times$ Parton Luminosity + Exponential background	N/A	1.54
	Histogram ^a	Counting number of events in histogram	1.03	N/A
Fit function	Gaussian resolution	Swapping Crystal Ball resolution term for a Gaussian	1.14	3.04
	No parton luminosity	Removing parton luminosity term (this and the above used in efficiency determination)	0.01	2.93
Binning	Double #Bins	Default of 0.7 GeV per bin	0.34	1.16
	Halve #Bins		0.25	2.38
Fit range	70-200 GeV	Default of 60-200	0.50	1.45 ^b
	60-150 GeV		0.16	1.95
Background	$\uparrow 50 \%$	Drell Yan continuum still in sample	0.17	1.57
	$\uparrow 100 \%$		0.23	1.58
	zero		0.31	1.49

Tab. 4.3: Systematics calculation for the mass peak fitting and background subtraction. Deviations from the default integral are quoted in percent of the integral.

^a comparison of histogram integral to total fit integral.

^b it is seen here that a lower mass cut of 70 GeV yields a slightly better χ^2 value. However this was not used as the default lower cut as it results in slightly more unstable fit integral results.

Apart from the overall comparison in the first section in table 4.3, each section (those separated by horizontal lines) corresponds to a different and independent source of systematic uncertainty. The systematic contribution from each section was taken as its average integral deviation (fourth column in the table). However, each section is considered an independent source of systematic uncertainty. Thus, the overall uncertainty in the analysis from mass fitting and background subtraction was calculated by summing in quadrature these contributions:

$$\sigma_{\text{total}} = \sqrt{\langle \sigma_{\text{Fit Function}}^2 \rangle + \langle \sigma_{\text{Binning}}^2 \rangle + \langle \sigma_{\text{Fit Range}}^2 \rangle + \langle \sigma_{\text{Background}}^2 \rangle}. \quad (4.8)$$

Using the above equation, an overall systematic uncertainty of 1.26% is obtained. The deviation between the signal function integral and counting the number of events in the peak made from the $Z \rightarrow ee$ sample only should include all of these systematics. As was expected, the evaluated systematic is larger than this comparison of 1.03%.

4.3 Conclusions and recommendations of further work

- Backgrounds other than QCD to both $Z \rightarrow ee$ and $W \rightarrow e\nu$ have been seen to be small. Given that they are also well understood from a MC perspective, this thesis recommends that it is acceptable to estimate their contribution to $W \rightarrow e\nu$ from MC. Their contribution to $Z \rightarrow ee$ may be estimated by fitting the invariant mass distribution.
- The background from QCD is not well predicted in MC and thus is not included in this analysis. Data driven methods exist to estimate its contribution to $W \rightarrow e\nu$ but it is best to tune these on real data as opposed to MC. The QCD contribution to $Z \rightarrow ee$ is expected again to be removed by invariant mass fitting, although is difficult to ‘second guess’ the exact form this background should take and thus the developed fits have been designed to be flexible with this requirement in mind.
- The systematic associated with $Z \rightarrow ee$ background removal from the mass fitting

procedure developed in the chapter has been seen to be acceptably small and it is expected this should not change with the inclusion of QCD background, as the systematic obtained by varying the background level has been seen to be small.

5. EFFICIENCIES

5.1 Electrons and efficiencies

As has been detailed in chapter 1, $Z \rightarrow ee$ and $W \rightarrow e\nu$ events in ATLAS will trigger through a single electron trigger (for example, what is in Athena version 14 called e22i which essentially requires one isolated triggered electron above 22 GeV), that is to say, only one electron needs to pass the trigger for the event to be written to storage. One ($W \rightarrow e\nu$) or two ($Z \rightarrow ee$) electrons must be reconstructed by the electron reconstruction algorithms for the event to be used in the analysis. In this chapter, the techniques developed to measure the efficiency of the e22i trigger chain (with respect to offline) and the electron reconstruction (with respect to the best available estimate of truth) using the tag and probe technique are described.

5.2 Calculation of an efficiency using the tag and probe technique

5.2.1 Basic Methodology

The so-called ‘tag and probe’ method uses $Z \rightarrow ee$ events to determine the single electron trigger efficiencies, ϵ_T , as well as the offline electron reconstruction efficiencies, ϵ_R , from data (although the same method may equally be applied to other decays, for example $Z \rightarrow \mu\mu$ to measure muon efficiencies).

Tag and probe in this context consists of using one fully triggered and reconstructed electron to tag the event, and investigating the properties of the additional electron (if any) in the event. More specifically, a diagnostic sample of size N_1 is defined by requiring at least one electron candidate to satisfy tag requirements. A control sample of size N_2 is defined by additionally requiring that the second electron satisfies the probe requirements. The tag and probe requirements for both reconstruction and trigger efficiencies are displayed in table 5.1.

Once the background levels in each sample, B_1 and B_2 have been determined (see later in the chapter), N_1 and N_2 may be used to extract the single electron efficiency as follows.

$$\epsilon = \frac{N_2 - B_2}{N_1 - B_1}, \quad (5.1)$$

with associated binomial uncertainty,

$$\sigma(\epsilon) = \sqrt{\frac{\epsilon(1-\epsilon)}{N_1}} \quad (5.2)$$

Method	Level	Tag condition N ₁		Probe condition N ₂	
		Electron 1	Electron 2	Electron 1	Electron 2
T&P	L1	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	OL(X)	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	OL(X)+L1 _{OL}
	L2	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	OL(X)+L1 _{OL}	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	OL(X)+L1 _{OL} +L2 _{OL}
	EF	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	OL(X)+L1 _{OL} +L2 _{OL}	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	OL(X)+L1 _{OL} +L2 _{OL} +EF _{OL}
	Overall Trigger	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	OL(X)	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	OL(X)+L1 _{OL} +L2 _{OL} +EF _{OL}
	Reconstruction	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	Opposite hemisphere cluster	OL(T)+L1 _{OL} +L2 _{OL} +EF _{OL}	Cluster+OL(X)
truth	L1	tr+OL(X) _{tr}		tr+OL(X) _{tr} +L1 _{tr}	
	L2	tr+OL(X) _{tr} +L1 _{tr}		tr+OL(X) _{tr} +L1 _{tr} +L2 _{tr}	
	EF	tr+OL(X) _{tr} +L1 _{tr} +L2 _{tr}		tr+OL(X) _{tr} +L1 _{tr} +L2 _{tr} +EF _{tr}	
	Overall Trigger	tr+OL(X) _{tr}		tr+OL(X) _{tr} +L1 _{tr} +L2 _{tr} +EF _{tr}	
	Reconstruction	tr		tr+OL(X) _{tr}	

Tab. 5.1: Tag and probe requirements. Standard kinematic selection is applied on objects ($P_T < 25$ GeV and fiducial η as defined in chapter 4). The symbols in the table represent the following:

- T&P: efficiency as will be measured in data using the tag and probe technique
- truth: truth efficiency without tag and probe
- OL(X): Offline reconstructed electron passing electron identification cuts=X where X refers to loose/medium/tight requirements
- OL(T): Offline reconstructed electron passing tight IsEM cuts
- L1: Level 1 trigger candidate
- L2: Level 2 trigger candidate
- EF: Event filter trigger candidate
- Cluster: calorimeter topological cluster
- tr: truth electron
- a_b : object Y matched up to object X to within a certain tolerance ΔR .

5.2.2 Truth comparison

The requirements for a truth comparison efficiency (for the purpose of systematic evaluation), are also shown in table 5.1. This is given by just ‘counting electrons’, that is to say, counting the percentage of truth electrons within the fiducial η/P_T space that trigger/are reconstructed offline.

Two problems lie in the calculation of the above as a comparison to tag and probe:

- Only one electron is required in the above. This makes it impossible to calculate certain variables (such as M_{ee}).
- When computing a differential efficiency, the efficiency dependence on a given variable (for example, probe P_T) is measured. In the above, this variable must be taken from truth and not from offline (which is the case in tag and probe) which causes a discrepancy when comparing efficiency distributions.

The solution adopted by some to counteract these problems was (in the example of ϵ_T) to take two truth electrons, match them up to offline electrons and then to complete the analysis. The problem in this was that the ‘truth tag and probe’ is then artificially forced to be very similar to the actual tag and probe efficiency (less than 0.1% difference), and thus perhaps is not a reliable indicator of a systematic uncertainty! For this reason, the ‘counting electrons’ method was used for systematic calculations.

5.2.3 Angular matching

The determination of an efficiency requires matching the probe object up to its tag counterpart (for example, matching an offline object to its L1 candidate). Two objects are considered to be matched if the angular distance, ΔR , between them is smaller than a certain specified tolerance. The ΔR parameter is chosen to be the minimum of a distribution of ΔR between all probe candidates and their tag counterparts, marking the difference between a good match and combinatorial background.

Table 5.2 shows the final matching parameters chosen. Matching parameters are chosen

similarly for truth matching, and are not necessarily the same (although they are in the current release) as for the offline matching. The numbers have to be validated for each Athena release (and vary from version to version).

Level	ΔR parameter (to offline)	ΔR parameter (to truth)
L1	0.2	0.2
L2	0.15	0.15
EF	0.1	0.1
cluster	0.1	0.1

Tab. 5.2: ΔR matching parameters between electron candidates and offline/truth.

5.2.4 Treatment of background

Background contamination in the efficiency determination from tag and probe is largely due to jets faking electron candidates (offline or trigger). Recalling the equation 5.1 for calculating a tag and probe efficiency:

$$\epsilon = \frac{N_2 - B_2}{N_1 - B_1} \quad (5.3)$$

where N_1 and N_2 are as defined before, and B_1 and B_2 are the sizes of the backgrounds to N_1 and N_2 respectively, the background to both the tag sample (N_1) and probe sample (N_2) must be determined. Table 5.3 summarises the requirements for N_1 and N_2 in the efficiency determination and describes the mechanism giving rise to the signal and major backgrounds (as determined from chapter 4) to these samples.

For reasons discussed in chapter 4, full QCD background treatment is not included in this MC analysis. However, a proposal of how to treat this particular background in the framework of ϵ_T (can be extended to ϵ_R) determination is given below.

	N ₁	N ₂
Offline		
$Z \rightarrow ee$	electron + topocluster	Two electrons
$W \rightarrow e\nu$	electron + jet causing topocluster	electron + jet faking electron
$W \rightarrow \tau\nu$	electron from τ + jet causing topocluster (or vice versa)	electron from τ + jet faking electron (or vice versa)
$Z \rightarrow \tau\tau$	electron from τ + topocluster from τ	two electrons from τ
$t\bar{t}$	electron from top decay + topocluster from top decay	two electrons from top decay
QCD	jet faking electron + topocluster from jet	two jets faking electrons
Combinatorics from $Z \rightarrow ee$	electron + cluster (jets or conversions)	electron + jet faking electron / conversion
Trigger		
$Z \rightarrow ee$	two electrons	electron + electron passing trigger
$W \rightarrow e\nu$	electron + jet faking electron	electron + jet fake passing electron trigger
$W \rightarrow \tau\nu$	electron from τ + jet faking electron (or vice versa)	electron from τ + jet fake passing electron trigger (or vice versa)
$Z \rightarrow \tau\tau$	two electrons from τ	electron from τ + τ electron passing electron trigger
$t\bar{t}$	two electrons from top decay	electron from top decay + top decay passing electron trigger
QCD	two jets faking electrons	jet faking electron + jet fake passing electron trigger
Combinatorics from $Z \rightarrow ee$	electron + fake electron (jets or conversions)	electron + fake electron passing electron trigger

Tab. 5.3: Signal and background to N₁ and N₂ in efficiency determination.

Estimation of dijet background using fake rates

The purpose of this study¹ was to develop a technique to estimate and subtract the QCD background present in the tag and probe trigger efficiency determination. As has been shown in chapter 4, the difficulty with estimation of QCD background in MC is due to lack of statistics, which is sufficient to be a major source of systematic uncertainty. To obtain any reasonable statistics, an unfeasibly large simulated sample must be made, due to the low probability of a jet faking an electron but the large cross section of the QCD process. The sample used (see table 1.4) is already heavily filtered, but lowering the filter efficiency to allow an increased probability of jets in the dataset faking electrons runs the risk of biasing the sample. One technique explored to circumvent this problem of lack of MC statistics in addition to providing a data-driven method of QCD background estimation is a ‘fake rate’ one. The methodology is summarised in figure 5.1.

In a first loop over events, the probability of a given jet faking an electron at trigger level was calculated by looking for a reconstructed jet (after overlap removal - see event selection in chapter 1) and a trigger electron candidate reconstructed within $\Delta R=0.4$ of one another. This configuration is assumed to be caused by a jet faking the electron candidate. The number of such instances was stored as a fraction of the number of all jets in the sample, as a function of the jet P_T and truth type (b , c , light)². This fraction is taken to be the ‘fake rate’- the probability of a jet faking an electron.

In the second event loop, a tight electron plus at least one jet was used to tag the event. The corresponding probability of the jet faking the electron candidate was applied as a weighting when filling an invariant M_{e-jet} histogram. A correction (determined from MC) from the measured jet P_T to its expected P_T if it was to be reconstructed as an electron (which is very different) was made when calculating M_{e-jet} .

The above histogram is called the ‘data histogram’, as the electron tag used in this method will be used in real data to trigger the event. This procedure has the additional advantage of also obtaining the $W \rightarrow e\nu$ background to $Z \rightarrow ee$ ‘for free’. The resultant

¹ Athena release 12 study.

² thanks for Mike Flowerdew for providing these

histogram is the estimation of the $\text{QCD}+W \rightarrow e\nu$ background to N .

As a Monte Carlo comparison to the proposed data procedure above, no tag electron requirement was made, and all jets in the event were weighted as according to their probability of faking the electron candidate when filling the $M_{jet-jet}$ invariant mass histogram. A smooth background spectrum was obtained (labelled as ‘MC’), as opposed to the statistics-limited spectrum which would be obtained without using fake rates.

The estimated backgrounds using fake rates (both with and without an electron tag) at the L1 trigger level with the signal peak for comparison are shown in figures 5.2. The peak of the distribution at 50 GeV is an artifact of filter level cuts on jet P_T as well as the trigger turn on at 20 GeV. The method predicts that, even in the worst case signal to background ratio in the trigger analysis (that is, N_1 at L1, which suffers from the highest background contamination), the signal still dominates over the background. Obviously the signal:background ratio will be much higher for the reconstruction efficiency calculation (see next section). It is harder to estimate rates for higher levels of the trigger using the ‘data’ method as, even using fake rates, statistics are still not sufficient (even using the full sample of ~ 2 million QCD events).

The above proposal has been briefly outlined with the purpose of discussing a method that may be used in real data, it must be stressed that, due to lack of statistics, such methods carry high systematic uncertainty in MC (not even considering trying to complete the study in a differential perspective). This means that, whilst useful for a ‘proof of principle’ study, the method cannot be taken seriously as a projection for expected background in data. The conclusion is that such studies are best left until data arrives and for this reason, this method was not continued in Athena version 14 or folded into the cross section analysis.

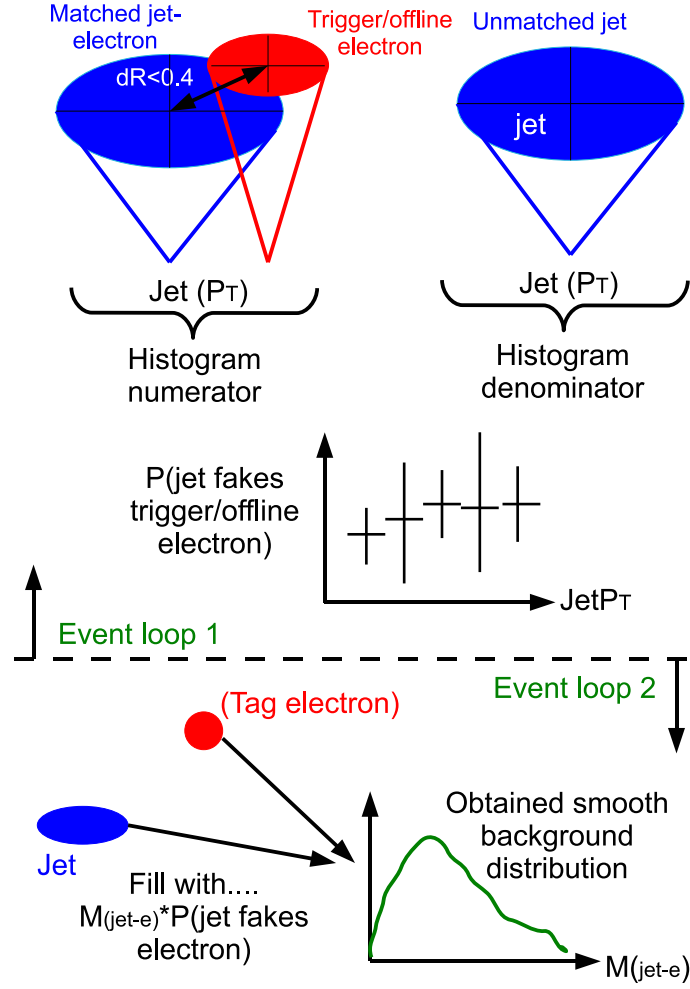
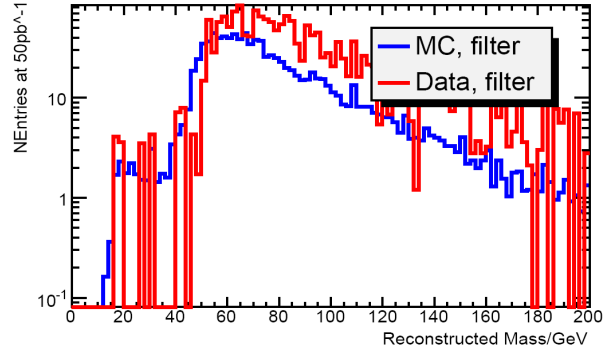
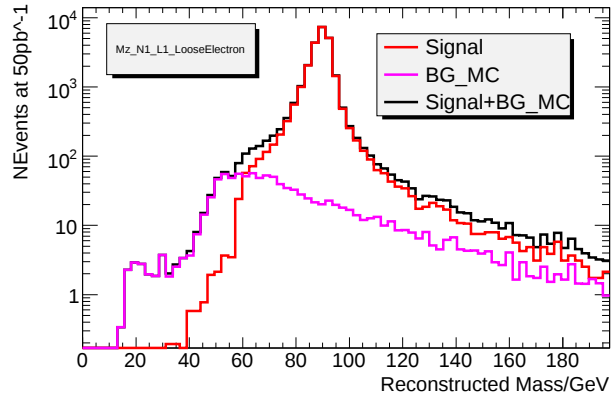


Fig. 5.1: Summary of fake rate method to estimate QCD background to N_1 and N_2 .



(a) Background estimation to N_1 at L1 using fake rates for the ‘MC’ and ‘Data’ method



(b) Signal + background to N_1 at L1 (estimated using fake rates for the ‘MC’ method)

Fig. 5.2: Estimating background (to N_1 at L1) using fake rates.

Treatment of other backgrounds

Analogous to the method developed in chapter 4, a signal+background fit over the invariant mass peak (when all samples other than QCD were used) was implemented to remove the expected background contamination to N_1 and N_2 . The constituents of the background to these quantities has been summarised in table 5.3. The combinatorial background is particularly relevant in the case of ϵ_R at N_1 , where the requirement is simply an electron plus a cluster not necessarily matched to an electron. However, many of these electron-cluster combinations are removed by the cuts on the Z mass.

Figure 5.3 shows signal and background (excluding the dijet background which needs special treatment- see previous section) after N_1 and N_2 requirements. As is to be expected

due to the loose (electron+cluster) criteria, N_1 for ϵ_R has by far the highest background contamination. The other three distributions in the figure have a much lower background level due to the tighter selection (two offline electrons plus additional trigger requirements in the case of the lower two plots). These look similar to the plots obtained for the overall background (chapter 4), where the background distribution is small enough to be reliably be modelled by a falling exponential.

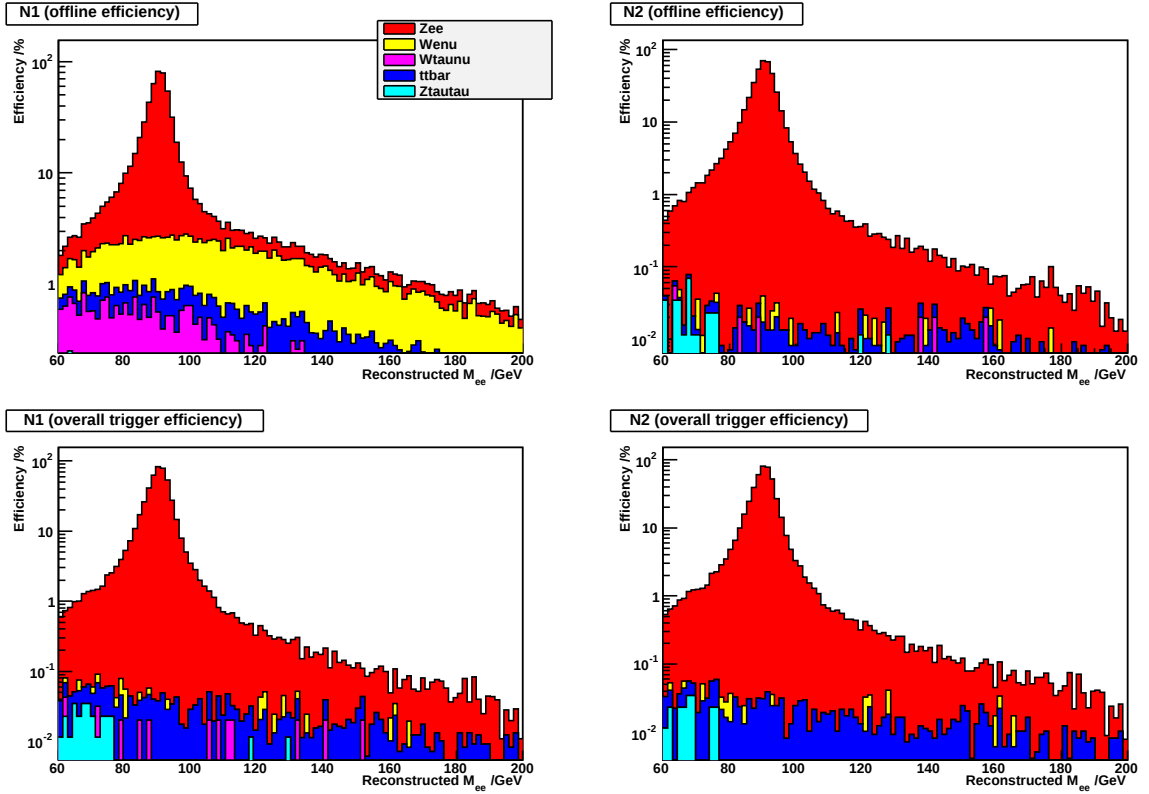


Fig. 5.3: Signal and dominant backgrounds (excluding that from dijets) to N_1 and N_2 in efficiency determination.

To estimate the size of the background to N_1 and N_2 , a method of sideband subtraction was considered but unfortunately the background shape includes a local maximum at ~ 90 GeV which is underneath the signal peak. This makes sideband subtraction difficult, and thus a global fit (signal + background) was used. The general form of the fit used is that developed in chapter 4:

$$N = (f_{\text{truth}} \otimes f_{\text{resolution}}) + f_{\text{background}}. \quad (5.4)$$

However, as may be seen in the upper left hand plot of figure 5.3, the background distribution to N_1 for the ϵ_R is not simply a falling exponential. In fact, a Landau fit over the background distribution gives a better χ^2 value, as may be seen in figure 5.4.

However, the problem with using a Landau fit for this particular distribution is that, as previously mentioned, the $W \rightarrow e\nu$ background peaks right underneath the signal peak. The reason for this is a combination of the requirement that the cluster is in the opposite hemisphere, and in addition to the double 25 GeV cuts on both the electron and cluster this causes a peak at high invariant mass in the $W \rightarrow e\nu$ sample (which of course has a real electron with jacobian peak at 40 GeV and a cluster caused by hadronic deposit).

The overlay of the signal and background peaks is problematic for the fitting procedure as it causes instabilities in the fit. This may in fact be seen in the Landau fit in figure 5.4, that the fit is trying to shift the peak position and width (which it can do by altering the Landau peak height and width to compensate) to allow a reasonable fit on the background tails. In fact it should do the opposite: the background fit (low statistics) should be sacrificed (if necessary) to allow a reasonable signal fit (high statistics).

The systematic uncertainty on the final measured efficiency stemming from this effect is unacceptably large and this method was rejected as a feasible background subtraction method. Instead, the following proposals are made for a real data strategy:

- Use selection cuts (on the offline electrons and clusters) at 15 GeV whenever possible. This will shift the background peak to below the Z mass peak and then a Landau background fit will be stable (or a simple exponential may be used to fit the region above the mass peak). However this will only work when trigger threshold *below 15 GeV* is used, otherwise the ϵ_T (which must have consistent cuts with those used in the ϵ_R determination if using the two numbers to calculate a cross section, for example) will not be reliably measured. This strategy may not be used when using tag and probe to calculate, for example, the efficiency of the e22i trigger.
- Refine the fit and use a highly constrained Landau fit over the background, constraints coming from a data driven study of the predicted background shape. For example, the precise fitting function for the $W \rightarrow e\nu$ background is determined in a high electron- $\cancel{E}_t$

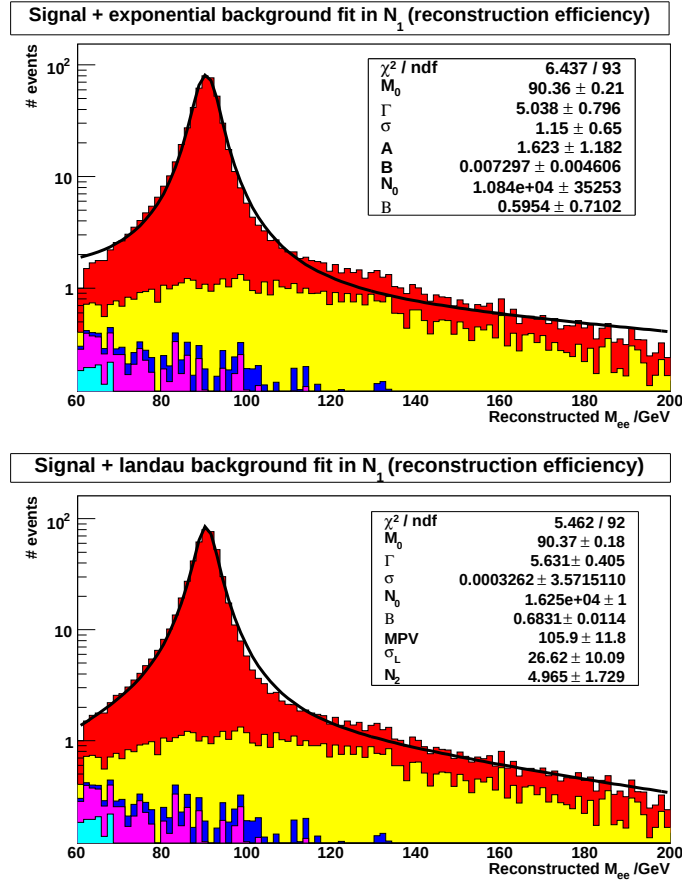


Fig. 5.4: Signal + background (exponential or Landau) functions in fit over N_1 for ϵ_R .

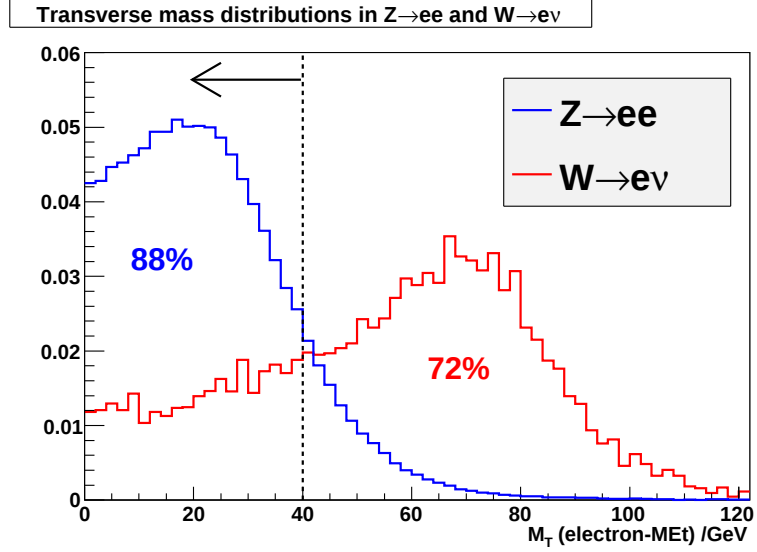
transverse mass (M_T) region (which should be largely signal free- see figure 4.1), and the shape used to fit the background in the low M_T region.

- Use additional cuts to remove the bulk of the $W \rightarrow e\nu$ background.

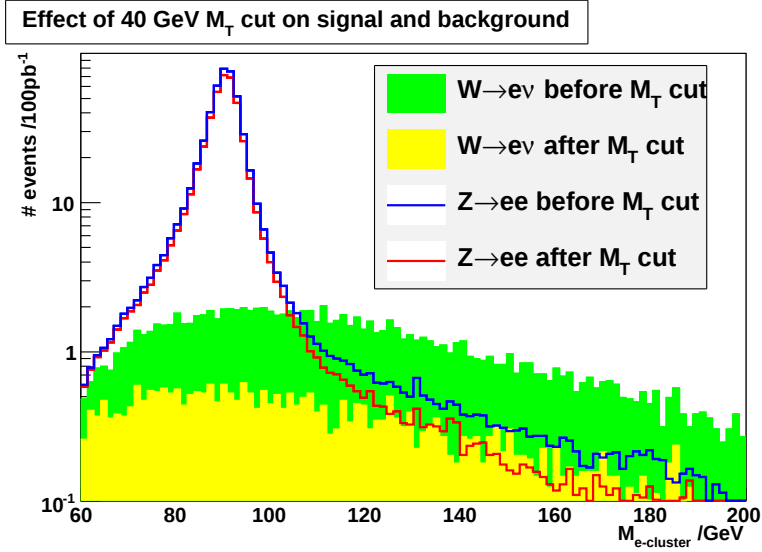
The last option is the one chosen in this analysis. A cut on transverse mass (constructed from $\cancel{E}_t$ and the electron) was chosen to reduce to some extent the $W \rightarrow e\nu$ background. Figure 5.5(a) shows the transverse mass distribution in $W \rightarrow e\nu$ and $Z \rightarrow ee$ events along with the proposed position of the cut. It must be noted that these M_T distributions are distorted somewhat due to the preselection cut requiring that the cluster is at an angle $\phi > 3\pi/4$ away from the tag electron. The figure shows that an M_T cut at 40 GeV would reduce the $W \rightarrow e\nu$ contamination whilst retaining most of the signal.

Figure 5.5(b) shows the impact of the transverse mass cut at 40 GeV on the $W \rightarrow e\nu$ background to N_1 of the ϵ_R . The cut is seen to have negligible effect on the $Z \rightarrow ee$ mass

peak in the signal region and thus should not bias the signal efficiency. The systematics discussed in the next section are those obtained when an M_T cut is used.



(a) M_T (electron- E_t) distributions (drawn normalised) in $Z \rightarrow ee$ and $W \rightarrow e\nu$ distributions along with proposed position of cut (distorted due to bias from pre-selection cuts)



(b) Impact of M_T cut on signal and background invariant mass (M_{ee}).

Fig. 5.5: Investigation of M_T cut to improve signal-noise ratio for N_1 in reconstruction efficiency.

5.2.5 Factorisation of efficiencies

ϵ_T is determined assuming the electron under consideration is reconstructed offline. For performance studies it is desirable to study the efficiency of each trigger level separately and

ϵ_T with respect to offline is given thus:

$$\epsilon_{OL}^{Trigger} = \epsilon_{OL}^{OL+L1+L2+EF} \quad (5.5)$$

$$= \epsilon_{OL}^{OL+L1} \times \epsilon_{OL+L1}^{OL+L1+L2} \times \epsilon_{OL+L1+L2}^{OL+L1+L2+EF} \quad (5.6)$$

$$= \epsilon^{L1} \times \epsilon^{L2} \times \epsilon^{EF} \quad (5.7)$$

$$(5.8)$$

where the superscripts denote the object of which efficiency is being measured, and the subscripts the object(s) with respect to the efficiency is being measured. The equation demonstrates that the product of the efficiencies of each level is equal to the overall ϵ_T with respect to offline.

ϵ_R is (ideally) determined with respect to truth (that is, the efficiency of a reconstructed electron given that an electron originating from a $Z \rightarrow ee$ decay was created in the collision). Sadly, in real data truth variables won't be available in the ntuple! A very good approximation is to determine ϵ_R with respect to a calorimeter topological cluster (topocluster); a three dimensional calorimeter local energy maximum from which electron reconstruction algorithms may seed. A truth electron above 25 GeV will create a topocluster within a ΔR distance of 0.1 with 99.98%³ efficiency.

$$\epsilon_R = \epsilon_{\text{truth}}^{\text{electron}} \simeq \epsilon_{\text{cluster}}^{\text{electron}} \quad (5.9)$$

ϵ_R and ϵ_T are calculated independently and may be multiplied together to give the overall efficiency, ϵ for a lepton. Recalling that the analysis is using a *single* electron trigger, the efficiency for a W or Z **event** triggering (at least one electron) and passing full reconstruction (all electrons) are given by equations 5.10 and 5.11 respectively, where subscripts 1 (and 2 in the case of Z analysis) identify the electrons in the event.

$$\epsilon_W = \epsilon_{R1} \epsilon_{T1} \quad (5.10)$$

³ number determined from MC study on 100 pb^{-1} of $Z \rightarrow ee$ events

$$\epsilon_Z = \epsilon_{R1}\epsilon_{R2}(1 - (1 - \epsilon_{T1})(1 - \epsilon_{T2})) \quad (5.11)$$

5.3 Results

5.3.1 Global efficiency

Table 5.4 summarises the results for the single lepton ϵ_R and ϵ_T (after background subtraction using the standard fit) for a medium IsEM electron.

Level	Measured efficiency/%
Electron Trigger	96.38 (0.10)
Electron Reconstruction	87.22 (0.19)

Tab. 5.4: ϵ_R and ϵ_T as measured by tag and probe. The statistical uncertainties are shown in parentheses for an integrated luminosity of 100 pb^{-1} .

5.3.2 Differential efficiencies

Neither ϵ_R nor ϵ_T is uniform in all regions of the detector nor independent of the event kinematics. The variation of efficiency with respect to the probe lepton P_T and η is accounted for in this analysis.

Figure 5.6 shows the distribution of ϵ_T with respect to the probe P_T for different trigger chains (‘menus’). A ‘turn on curve’ is seen which is the characteristic shape for any threshold trigger or cut. A sharp increase in the efficiency is seen at the P_T threshold, which is at different levels for the different trigger menus. Efficiencies are given a finer binning in this region as the rate of change is larger.

As has been mentioned, the tag and probe method gives stable results for different choices (within reason) of trigger menu and also electron selection, with the requisite that consistency is maintained in the cross section calculation. For example, figure 5.7 shows the turn on curves for ϵ_T and ϵ_R with respect to loose, medium and tight electron criteria. It is seen that ϵ_R drops as the electron selection is tightened, which makes sense as more true electrons are missed. However, ϵ_T does the opposite as it is being measured *with respect to* the offline. For an accurate cross section measurement it is possible to use all criteria (as

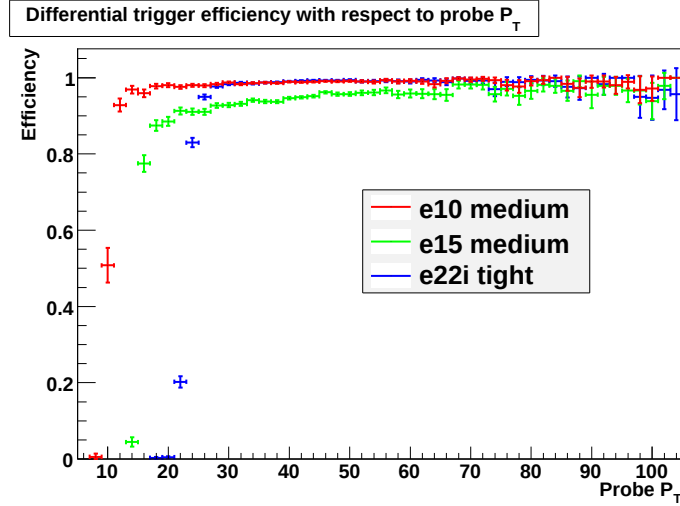


Fig. 5.6: ϵ_T as a function of probe P_T for different trigger menus. The threshold trigger candidate P_T of each menu is the number within the name given in the legend

long as background levels are not too high and statistics are not too low), as long as the cross section selection is performed with respect to the same criteria.

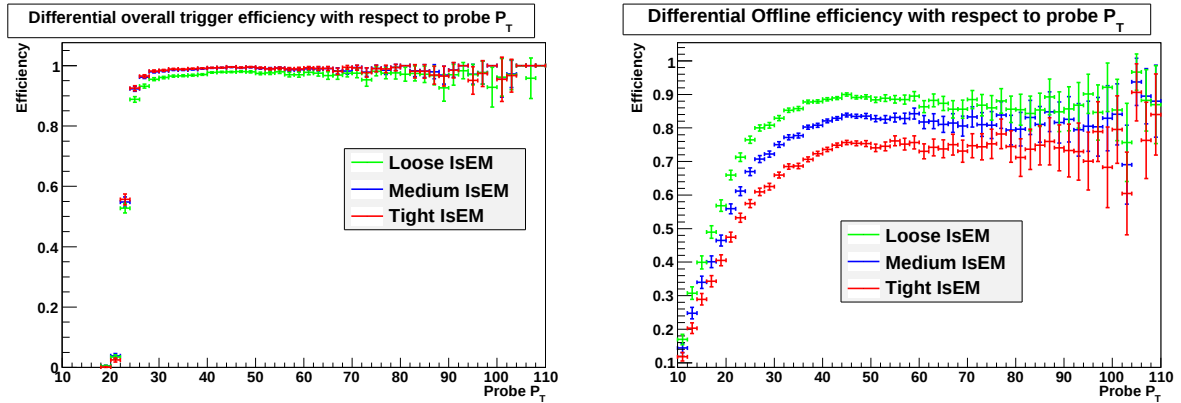


Fig. 5.7: Differential efficiencies with respect to probe P_T for different IsEM reconstruction criteria. For the (e22i) trigger efficiency (left hand side plot), the medium IsEM efficiency is almost under the tight (barely visible).

The differential efficiency with respect to probe η is a useful tool in understanding the detector, as it maps out the detector topology. The efficiency is particularly sensitive to material distributions in the detector (extra material will increase the probability of Bremsstrahlung, for example, which will lower the efficiency). Figure 5.8 shows the distributions of ϵ_R and ϵ_T (separated by level) with respect to probe η . Figure 5.9 shows the material distribution in η in the inner detector, as this affects the efficiency. Several features are noted:

- A slow drop in ϵ_R in the endcaps ($\eta > 1.5$). This is due to less efficient tracking in this region (the TRT coverage ceases at $\eta=2.0$, and in the forward regions there is more material for the electrons to travel through, as can be seen in figure 5.9).
- A sharp drop in both ϵ_R and ϵ_T in the region $1.37 < \eta < 1.52$. This is due to less efficient regions of the detector where the inner detector cabling leaves the detector. It also marks the gap between the barrel and endcap region.
- A small drop in the region $\eta \simeq 0.7$ thought to be due to electromagnetic calorimeter structural effects.
- A drop in ϵ_T (L2) in the central η region. This is thought to be due to a inactive region (a space between positive and negative η was introduced to reduce occupancy) in the TRT (which affects L2 as this is the first trigger level where TRT tracking is implemented).

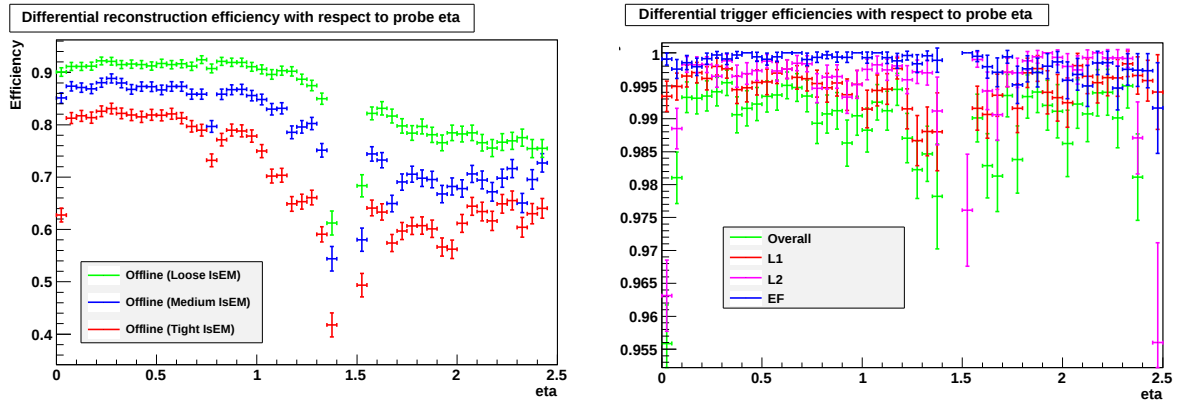


Fig. 5.8: Reconstruction and trigger (shown level by level) efficiencies versus probe P_T and η as measured by tag and probe.

The efficiency shapes vary too irregularly to be fit properly, so it is proposed that binned efficiencies are to be used to fold into a cross section. The binning of the efficiencies was chosen carefully to reflect these local variations as well as being of different size to allow for differing statistics in each bin. The bin edges chosen for this analysis (100 pb^{-1}) are summarised in table 5.5, although local variations will vary between Athena releases and the binning may be changed to accommodate this.

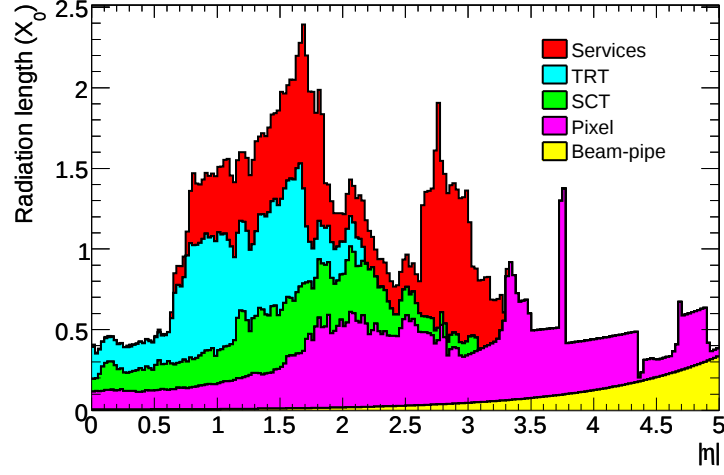


Fig. 5.9: Material distribution at the exit of the ID envelope, including the services and thermal enclosures (taken from [34])

To account for correlation between probe η and P_T , a two (or higher if necessary) dimensional map of the efficiencies is used to calculate a cross section, an example (using much finer binning than that used in practice) of which may be seen in figure 5.10. Figures such as these will be studied in early data to spot correlation of efficiency dependence between different variables.

$ \eta /P_T$	25 $\rightarrow$ 30	30 $\rightarrow$ 35	35 $\rightarrow$ 40	>40
Offline				
0.0 $\rightarrow$ 0.7	4941.05 (4113.07)	5819.1 (5329.04)	6455.45 (6015.05)	13873 (13139.5)
0.7 $\rightarrow$ 0.9	1422.21 (1069.03)	1667.83 (1454.28)	1873.55 (1664.31)	4061.83 (3754.42)
0.9 $\rightarrow$ 1.37	3268.65 (2265.84)	3879.96 (3301.51)	4355.56 (3831.47)	9331.94 (8468.85)
1.52 $\rightarrow$ 2.4	5513.64 (3710.22)	6430.81 (5141.3)	7306.51 (6087.41)	15861.5 (13757.4)
Trigger				
0.0 $\rightarrow$ 0.7	4161.96 (4020.37)	5426.43 (5257.07)	6469.53 (6296.26)	16437.4 (16058.9)
0.7 $\rightarrow$ 0.9	1124.57 (1078.42)	1467.19 (1422.6)	1754.65 (1706.94)	4555.03 (4447.86)
0.9 $\rightarrow$ 1.37	2567.39 (2453.97)	3397.33 (3265.13)	4093.51 (3952.32)	9942.45 (9640.52)
1.52 $\rightarrow$ 2.4	4107.2 (3791.57)	5550.41 (5143.65)	6840.69 (6397.95)	16987 (15949.6)

Tab. 5.5: Binning chosen for a 100 pb^{-1} analysis with N_1 (N_2) events in each bin.

5.3.3 Effect of hadronic activity

For an analysis involving additional jets in the final state topology (for example, a $\mathcal{R}$ + jets cross section measurement), it is important to study the effect of additional hadronic activity

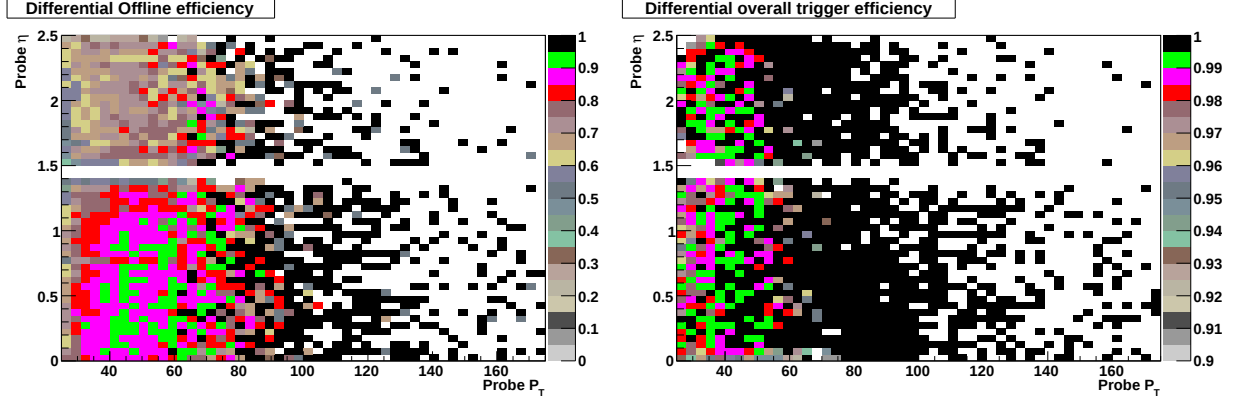


Fig. 5.10: Two dimensional reconstruction and trigger efficiencies versus probe P_T and η as measured by tag and probe (fine binning).

on the efficiency. ALPGEN (interfaced with HERWIG in this case) is more appropriate as a generator for the studies of hard jets than PYTHIA as it generates hard jets by matching matrix element calculations to the parton shower. PYTHIA generates jets using parton showering only, and for this reason ALPGEN $Z \rightarrow ee + \text{jets}$ samples 1.4 were used in this small study. A more detailed description regarding exactly how the samples were produced and the differences between PYTHIA and ALPGEN results for this channel is given in [7].

Efficiency was expected to vary with hadronic activity as both the trigger and reconstruction algorithms include cuts on isolation (as was detailed in the introductory section of this chapter), which is of course correlated with additional jets in the event. The purpose of the study was to look for variation of efficiency with ‘jet-like’ variables, and to find those variables that represented best this dependency. Out of those studied, the variables where the highest variation was seen were ΔR (angular separation between the electron and the closest jet), jet multiplicity and hadronic activity (as defined in chapter 2). The dependencies on these variables are shown in figure 5.11, and it is noted that a fairly heavy dependency on these is seen in both ϵ_R and ϵ_T .

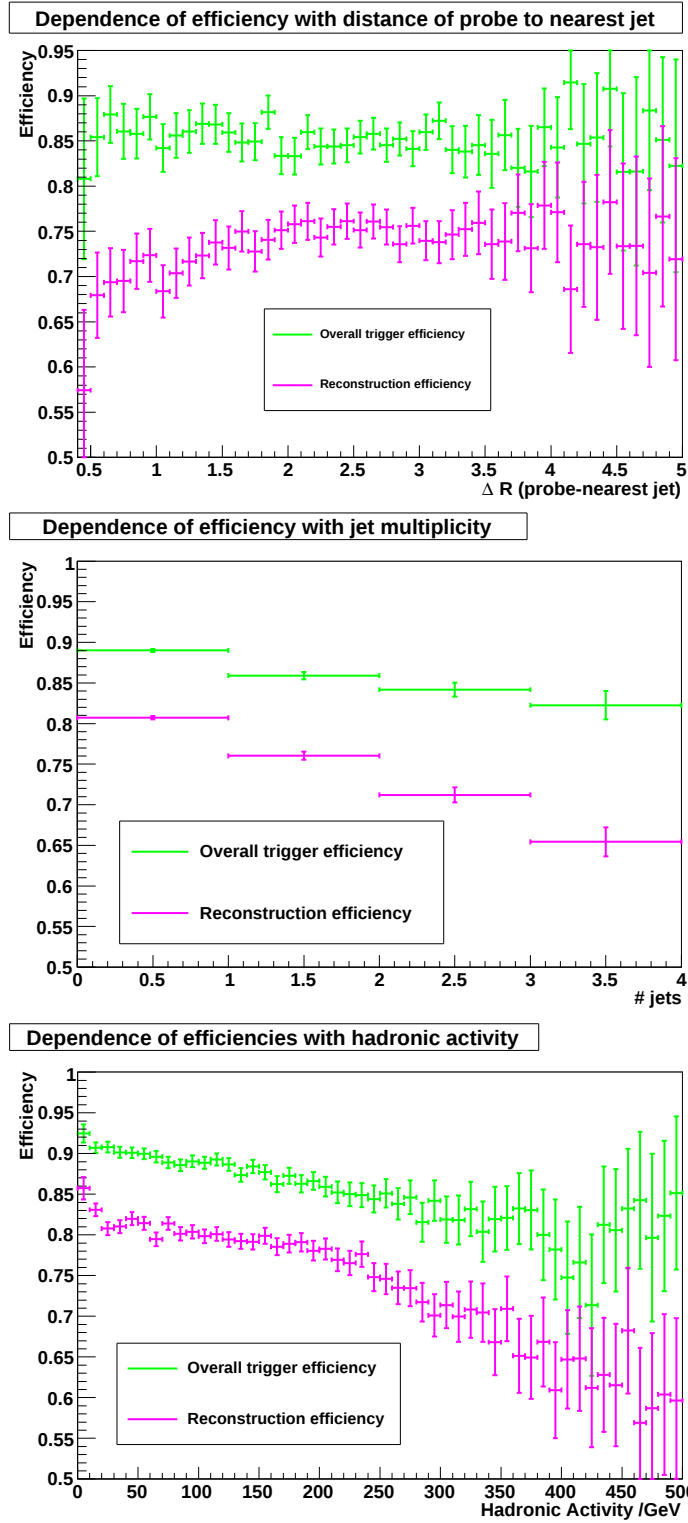


Fig. 5.11: Dependency of ϵ_R and ϵ_T on jet-like variables

A problem encountered with using tag and probe in $Z \rightarrow ee$ to measure the variation of efficiencies with jet-like variables is that these can be correlated to ‘electron-like’ variables. This is clear in the context of a $Z \rightarrow ee$ decay which may be considered as two electrons recoiling against one or more jets.

To give an example of such a correlation, figure 5.12(a) shows the variation of ϵ_T with ΔR made in Athena release 12. A drop in efficiency is seen at high ΔR which isn’t seen in the release 14 plot of figure 5.11 which does not make sense at first glance - the requirement that the probe electron lies far away from a jet should not affect the efficiency. However, imposing this requirement biases the sample toward those events where the electron falls in the end-caps. In release 12 a spacepoint tracking bug meant that the L2 efficiency was substantially lower in this region, which may be seen in figure 5.12(b).

If jet dependencies such as that with ΔR are blindly measured in $Z \rightarrow ee$ and applied to a different event topology ($W \rightarrow e\nu$, SUSY scenarios...) without taking account of such correlations problems could arise. Plots such as that shown in 5.10 (with a jet variable on one of the axes) must be studied to check for such correlations. The recommendation from this study is that, if the dependency of efficiency on ‘jet-like’ variables is to be folded into an analysis, it must be done in an N-dimensional matrix form so that the ‘electron-like’ variables and possible correlations are also accounted for.

5.4 Evaluation of systematic uncertainties

5.4.1 Sources of uncertainty

Comparison with MC truth:

The major systematic handle on this method has been taken from comparison to MC truth efficiency. As has been discussed, a ‘truth tag and probe’ procedure is forced to be artificially close to the tag and probe efficiency so just the ‘truth efficiency’ (tag and probe requirements summarised in table 5.1) was used.

The tag and probe results obtained were compared with truth efficiency in $Z \rightarrow ee$ events. This comparison of $Z \rightarrow ee$ tag and probe with $Z \rightarrow ee$ MC gives a handle on the tag and

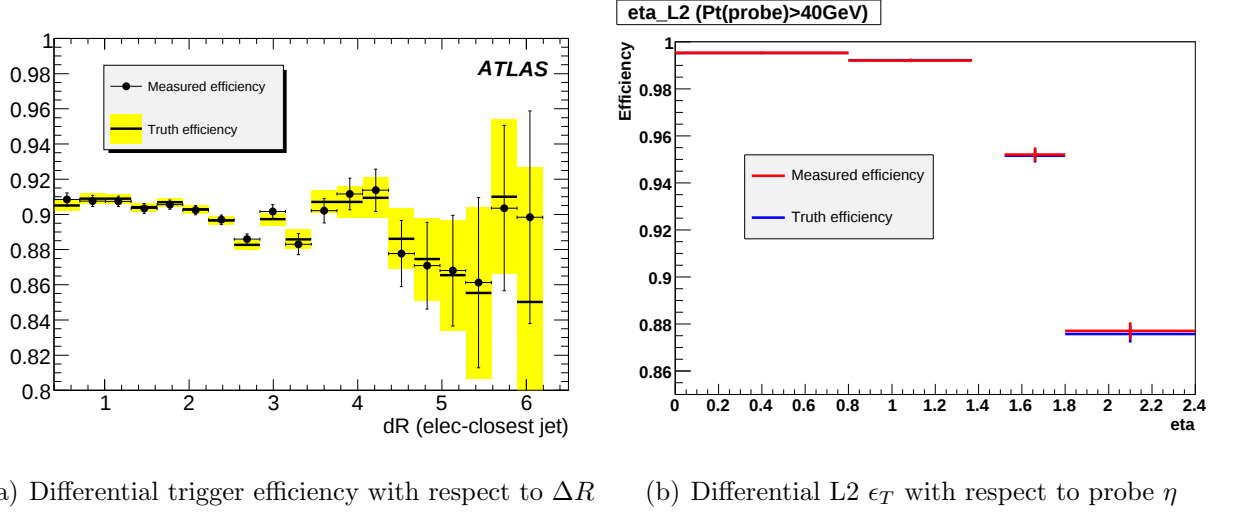


Fig. 5.12: Studying jet-electron correlations in Athena release 12. The effect of the endcap space-point bug in the L2 trigger can be seen as a reflection in the overall trigger efficiency with respect to ΔR .

probe method itself, and also includes all systematics on the mass fitting procedure as the truth efficiency calculation does not have background and so thus does not require a mass fit. The absolute overall percentage impact was evaluated at 0.04 (0.23)% for ϵ_R (ϵ_T). The number for ϵ_R was seen to be unexpectedly small, which is discussed in the next section.

It was hoped that the average deviation between insitu and truth efficiencies would be smaller if this quantity was evaluated differentially with probe η and P_T . However this was seen not to be the case, and the reason for this is the change of the combinatorical background shape in different regions of probe P_T . Figure 5.13 shows the signal+combinatorial background shape for N_1 for different probe P_T bins. Note that this is made using the $Z \rightarrow ee$ sample *only*, and thus all background shape is attributed to combinatorics (and a small amount of DY).

The background is seen to be on the low mass side of the peak for low probe P_T regions and on the high mass side for high probe P_T . This effect is understood as low P_T probes will tend to make low invariant mass pairs with clusters and vice versa. It causes problems for the background fit function which is trained on an exponentially falling background (such as that seen in the middle P_T region). However no more time was spent on this as a study in

MC as it is expected that, firstly, the precise behaviour of combinatorial background is not well understood in MC, and secondly, this effect is likely to be washed out with the inclusion of QCD background in any case. The following procedures are advocated when real data arrives:

- **Scenario 1:** Dijet background swamps combinatorics in N_1 and a simple exponential parameterisation of the background may be used.
- **Scenario 2:** Variation is again seen in the background shape with respect to probe P_T (or other variables). The fitting is given different functions (for example, Landau, exponential and quadratic although the precise forms are to be determined once real data is available) to fit, and the best χ^2 dictates which is used in that bin.

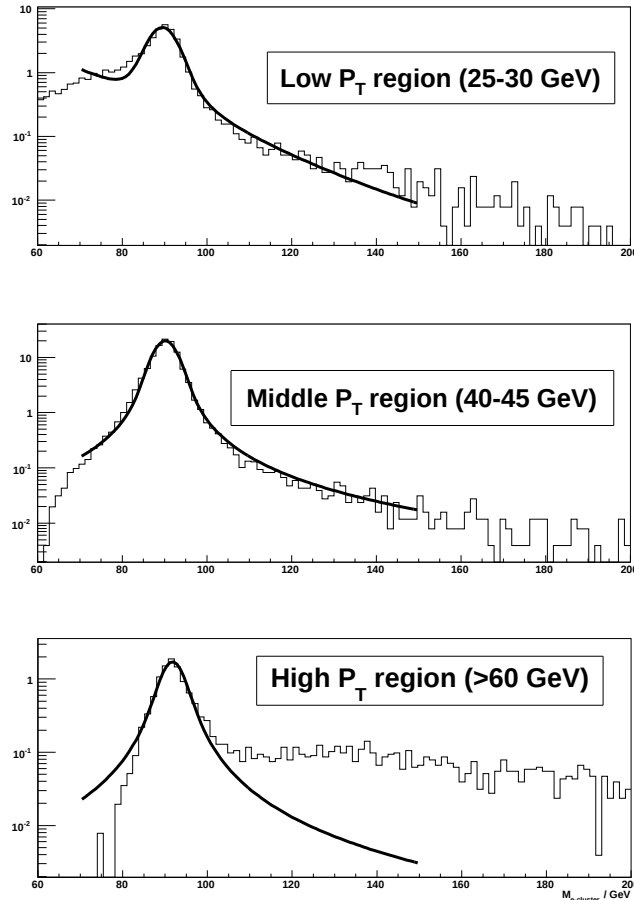


Fig. 5.13: Variation of combinatorial background shape to N_1 of ϵ_R in different regions of probe P_T .

Comparison of $Z \rightarrow ee$ MC with $W \rightarrow e\nu$ MC gives an additional insight into the validity of using a $Z \rightarrow ee$ derived efficiency in a $W \rightarrow e\nu$ analysis (comparison with $Z \rightarrow ee$ tag and probe was not used as this would be double counting other effects such as the mass fitting procedure). The overall percentage difference between these two numbers was found to be 1.04 (-0.10) % for ϵ_R (ϵ_T). The large difference in the global difference between these numbers in the reconstruction efficiency is partly due to the different kinematics (electron P_T distribution and thus turn on curves) in $Z \rightarrow ee$ and $W \rightarrow e\nu$ events. For this reason, it is necessary to use differential efficiencies when applying tag and probe efficiencies measured from $Z \rightarrow ee$ events to $W \rightarrow e\nu$ analysis. The systematic uncertainty was then derived as the average (absolute) difference evaluated over bins. This number was evaluated at 0.34 (0.25) % for ϵ_R (ϵ_T).

Background subtraction

The global impact of background subtraction ($\epsilon(\text{background subtraction implemented}^4) - \epsilon(\text{no background subtraction implemented})$) on the global efficiency is -0.06% for ϵ_T and 2.44% for ϵ_R . The size of systematics discussed below must be considered with respect to this quantity. The impact is larger for ϵ_R due to the large combinatorical background (B_1) to N_1 (discussed in the previous section) which does not cancel with B_2 .

It must be noted that the numbers quoted above are global, but vary depending on the event topology which is seen when studying efficiency in a differential perspective. For example, background subtraction has more of an effect on the measured efficiency when more jets are present in the event. The size of the impact of background subtraction on ϵ_R for different numbers of reconstructed jets in the event is shown in figure 5.14. This plot is made from the signal sample only, so as to show the impact of additional jets on the combinatorical background. More jets will increase the value of N_1 and thus lower the efficiency in the absence of background subtraction, as is seen in the plot. Thus if efficiencies are extrapolated to regions of higher jet multiplicity, care must be taken to treat accordingly

⁴ using the default fit function and including all predicted backgrounds other than QCD.

the different systematics arising from this effect in each bin.

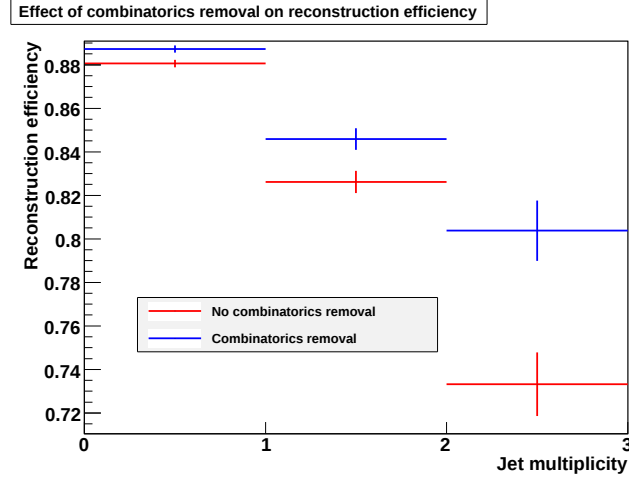


Fig. 5.14: Effect of combinatorial background removal on ϵ_R as a function of number of reconstructed jets in the event

The separate sources of systematic uncertainty on the efficiency determination arising from background fitting and subtraction are considered below. Including such numbers in the overall determination of the efficiency systematic would be double counting (it is already implicit in the MC-truth comparison- see next section- as the truth calculation does not have background and thus does not require a mass fit). These numbers are used to check the validity of the tag and probe- truth comparison as a source of systematic, as well as monitoring stability (the idea is to design a flexible fit where the number of degrees of freedom may be reduced to cut down processing time if necessary).

- Fitting function:** The systematics determined on the fit function in chapter 4 may not be used for the efficiencies as deviations from the signal integral due to imperfections in the choice of fit function will often be in the same direction and thus, to some extent, may cancel out in the ratio N_1/N_2 used to calculate efficiency. For this reason, in the interests of minimising computing time, a simpler fit may be acceptable when calculating an efficiency (which is not the case when counting events to make a cross section measurement in $Z \rightarrow ee$).

To give two examples, the effect of using a Gaussian instead of a Crystal Ball is 0.33 (-0.37)%, and the impact of removing the parton luminosity term is 0.09 (0.09)% on ϵ_R (ϵ_T). The default fit chosen was as follows:

$$f_{\text{truth}} = \text{Breit Wigner} \quad (5.12)$$

$$f_{\text{resolution}} = \text{Gaussian} \quad (5.13)$$

$$f_{\text{background}} = \text{Falling exponential} \quad (5.14)$$

- **Mass cuts:** The mass cuts over which the integral was calculated were varied, from (80, 100), (75, 100), (80, 105) GeV. The average percentage impact of this was 0.05% on ϵ_T and 0.60% on ϵ_R .
- **Fitting range:** The range over which the fit was performed was varied, from (60, 120), (60, 150), (60, 200), (70, 120), (70, 200) GeV. The lower cut was not moved lower as this is where the generator level filter cut is applied. The average (absolute) percentage variation of the fitting range was found to be 0.21% on ϵ_T and 0.41% on ϵ_R .
- **Background level:** A comparison was made between fitting the entire sample (including all backgrounds apart from QCD) and the ‘signal sample’ only (which of course includes combinatorial background). The difference in measured efficiency between these two samples was -0.04% and -1.22% on ϵ_T and ϵ_R respectively.

The overall systematic taken from these elements is their quadrature sum:

$$\sqrt{0.33^2 + 0.09^2 + 0.6^2 + 0.41^2 + 1.22^2} = 1.46\% \text{ for } \epsilon_R,$$

$$\sqrt{0.37^2 + 0.09^2 + 0.05^2 + 0.21^2 + 0.04^2} = 0.44\% \text{ for } \epsilon_T.$$

It has been noted that, for ϵ_T , the systematic introduced by background removal is larger than its actual impact (0.06%). Despite this however, background removal was still performed as the purpose of this analysis is to prepare the methods to be used when real data arrives. In real data, QCD background will be present in the tag and probe samples and thus the impact of background removal is expected to be significantly larger.

As mentioned earlier, the systematic from the mass fitting procedure is absorbed by the systematic evaluated by comparing MC measured efficiencies to those measured using tag and probe. To avoid double counting, both of these systematic sources may not be included in the calculation of the overall systematic uncertainty on tag and probe.

The small difference of 0.04% between $Z \rightarrow ee$ truth and tag and probe evaluated ϵ_R is much smaller than the systematic from the mass fitting procedure evaluated in the previous section. This is thought to be co-incidental (perhaps a cancelling out between mass fitting and other systematics) and so the quadrature sum of the mass fitting uncertainties (1.46%) considered in section 5.4.1 is taken instead as a source of systematic.

In the case of ϵ_T , the systematic uncertainty of 0.23% from comparison with $Z \rightarrow ee$ MC is of comparable size to the systematic uncertainty evaluated from the mass fit (0.44%). Thus the mass fit systematic is not included explicitly (to avoid double counting) and instead the MC truth comparison used as the evaluated systematic.

Kinematic bias from tag selection

A potential bias in the tag and probe method is the tag selection (described in table 5.1) biasing the kinematics of the events in the tag sample. To give an example, events with larger calorimeter activity will have lower electron efficiency (as they are more likely to fail isolation cuts) and are therefore more likely not to be present in the tag sample. Calorimeter activity is a global event characteristic independent of the electron variables and thus may bias the tag and probe efficiency measurement. To estimate the size of this bias from data alone, the following variables were constructed:

$$\epsilon_1 = \frac{\sum_i (N_i \cdot \epsilon_i)}{\sum_i N_i} \quad (5.15)$$

$$\epsilon_2 = \frac{\sum_i (N_i^{\text{tag}} \cdot \epsilon_i)}{\sum_i N_i^{\text{tag}}} \quad (5.16)$$

where i is the bin of the histogram, ϵ_i is the measured efficiency (trigger or offline) in that bin, N_i is the number of events in the bin *in the absence of pre-selection* and N_i^{tag} is the

number of events in the bin after tag selection. The distributions of ϵ_i , N_i and N_i^{tag} (after tag selection for ϵ_T and ϵ_R calculation) are shown in figure 5.15. It is seen that the tag selection biases the distribution toward lower values of calorimeter activity. The difference between ϵ_1 and ϵ_2 (as integrated over the range shown in the plot) is 0.04% and 0.33% for the trigger and reconstruction efficiencies respectively⁵. The lower systematic associated with ϵ_T is due to the lack of dependence of ϵ_T on the quantity in question (calorimeter activity). The numbers quoted have been taken as the systematic uncertainties due to this bias.

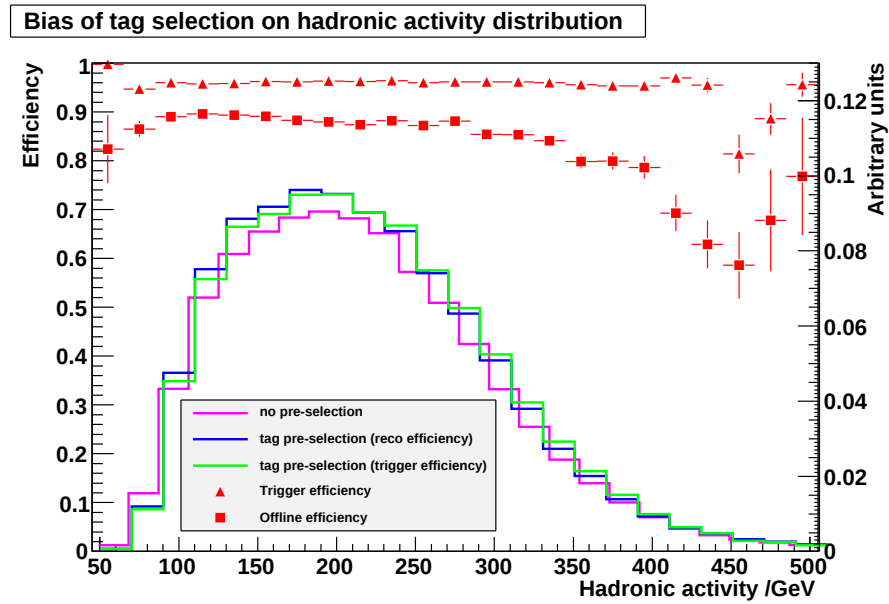


Fig. 5.15: Distributions of calorimeter activity before and after tag selection. The efficiencies in the same bin of calorimeter activity are superimposed on the same plot.

Charge asymmetry:

The efficiency calculated with positively and negatively charged probe samples was found to be the same to within statistical uncertainty, although it is of vital importance that this is checked in early data.

⁵ Not surprisingly, the bias is larger for the ALPGEN $Z \rightarrow ee + \text{jet}$ sample which has a higher reach into jet multiplicity, where the effect is most prevalent. This must be taken into account for an analysis explicitly dependent on jet variables.

5.4.2 Overall systematic uncertainty

The overall systematic uncertainty on the efficiency was chosen to be the quadrature sum of the uncertainties discussed above: Thus for ϵ_R :

$$\sigma_{sys} = \sqrt{\sigma_{\text{mass fitting}}^2 + \sigma_{W \rightarrow e\nu \text{ MC}}^2 + \sigma_{\text{kinematic}}^2} \quad (5.17)$$

$$= \sqrt{1.46^2 + 0.34^2 + 0.33^2} \quad (5.18)$$

$$= 1.53\%, \quad (5.19)$$

and for ϵ_T :

$$\sigma_{sys} = \sqrt{\sigma_{Z \rightarrow ee \text{ MC}}^2 + \sigma_{W \rightarrow e\nu \text{ MC}}^2 + \sigma_{\text{kinematic}}^2} \quad (5.20)$$

$$= \sqrt{0.23^2 + 0.25^2 + 0.04^2} \quad (5.21)$$

$$= 0.34\%. \quad (5.22)$$

5.5 Conclusions and recommendations of further work

- Efficiencies vary significantly with the event kinematics. It is necessary to account for these variations particularly if applying tag and probe determined efficiencies to a $W \rightarrow e\nu$ analysis due to the slightly different kinematics in these events to that in $Z \rightarrow ee$.
- The driving source of systematic uncertainty in tag and probe efficiency determination from $Z \rightarrow ee$ is the background removal in N_1 for ϵ_R calculation. This is due to the background from $W \rightarrow e\nu$ peaking underneath the signal peak. The method implemented in this analysis is to use additional cuts on M_T as this removes much of the background without distorting the measured efficiencies. More investigation could be done into other discriminating variables to remove more efficiently the $W \rightarrow e\nu$ background to this distribution, for example cutting on both M_T and $\cancel{E}_t$.

Other methods have been discussed into how to remove or otherwise deal with the $W \rightarrow e\nu$ background, for example either constraining the fit or allowing a choice of

different fits. For choosing the procedure to be used, it is preferable to wait for real data as the inclusion of QCD background will certainly affect the background distributions. A first order investigation has been made into the distribution of QCD background to ϵ_T determination and the conclusion of this is that it will fall exponentially underneath the invariant mass signal peak.

- Again, once real data is available, the analysis may be improved by allowing a floating fit to cope with the shift in the combinatorical background shape in different bins of P_T . This should facilitate closer agreement between insitu and MC measured differential efficiencies than that observed in this analysis.
- It has been shown that additional hadronic activity in the event will lower the measured efficiencies. For analyses more focused on jet activity, thought must be given as to how best to fold in this effect taking care to treat correctly the additional correlation between hadronic and leptonic kinematics, as well as the different background shapes to N_1 and N_2 in different jet topologies. This is particularly complex when implementing tag and probe measured efficiencies from $Z \rightarrow ee$ into, for example, a SUSY analysis which lies in a very different region of phase space (multiple jets and $\cancel{E}_t$).
- An additional source of systematic uncertainty on the tag and probe method is bias in the tag sample due to certain events not passing the tag requirements, and a recommendation has been made for a method of estimating the systematic uncertainty due to this effect.

6. GLOBAL CROSS SECTIONS AND THE RATIO $\mathcal{R}$

As discussed in chapter 1, the purpose of this analysis is to study the feasibility of measuring the inclusive cross sections for W and Z boson production and subsequent decay in the electron channel:

$$\sigma_W = \sigma_W \cdot \mathbf{Br}(W \rightarrow e\nu), \quad (6.1)$$

$$\sigma_Z = \sigma_Z \cdot \mathbf{Br}(Z \rightarrow ee), \quad (6.2)$$

as well as the ratio between these quantities:

$$\mathcal{R} = \frac{\sigma_W \cdot \mathbf{Br}(W \rightarrow e\nu)}{\sigma_Z \cdot \mathbf{Br}(Z \rightarrow ee)}. \quad (6.3)$$

In this section the overall evaluation of the W and Z cross sections and their ratio $\mathcal{R}$ are evaluated with their associated uncertainties. Uncertainties are evaluated at an integrated luminosity¹ of 100 pb^{-1} . Comparisons are made with the input cross sections (after filter cuts) given by the generator (given in chapter 1): 11764.6 for $W \rightarrow e\nu$ and 1121.07 for $Z \rightarrow ee$ (correction made to the input generator value due to removal of DY continuum- see chapter 3).

Two sets of systematic uncertainties are evaluated in the analysis: a full set of systematics which yields a predicted systematic uncertainty for when real data is available, and a so called ‘reduced systematic uncertainty’ (shown in parentheses) which excludes those systematics which are not a real source of uncertainty in this MC study. The reason for quoting this second set is to provide a check of the method; that the calculated cross section from the reconstructed quantities matches the input cross section to within evaluated uncertainties. The systematics excluded are:

- Luminosity uncertainty: Will obviously be present in real data but a known luminosity is used in the MC datasets so this is not a source of uncertainty in this study.
- Theoretical uncertainty on the acceptance (see chapter 3). Choices such as those

¹ other than the uncertainty on the acceptance which is evaluated using the whole set of samples (signal plus backgrounds), as will be done in a real data measurement.

outlined in section 3.4.2 will affect the generated sample and will cause a discrepancy between the generation truth (used to calculate the acceptance) and the absolute truth. However the purpose of this study is to correct the generated reconstructed quantities back to the generated truth, and so this effect will cancel out in a MC sample but not in real data.

- QCD background uncertainty for reasons detailed in chapter 4 (although this to some extent in Z analysis will be absorbed by the uncertainty quoted from fitting the M_Z peak). Systematics on background estimation in $W \rightarrow e\nu$ are not included, although the systematic associated with background fitting and removal in $Z \rightarrow ee$ are considered.

Thus, the systematic uncertainties that are included in the calculation of the reduced systematic are those from experimental acceptance (chapter 3), efficiencies (chapter 5) and background fitting and subtraction in $Z \rightarrow ee$ (chapter 4).

6.1 Global evaluation of cross sections

6.1.1 W channel

The cross section for a $W \rightarrow e\nu$ event triggering on a single electron trigger is measured by

$$\sigma(W \rightarrow e\nu) = \frac{N_W - B_W}{\mathcal{L} \cdot \epsilon^R \cdot \epsilon^T \cdot A_W}, \quad (6.4)$$

with associated (absolute) uncertainty $\sigma(\sigma(W \rightarrow e\nu))$ defined as:

$$\frac{\sigma^2(\sigma(W \rightarrow e\nu))}{\sigma^2(W \rightarrow e\nu)} = \frac{\sigma^2(N_W - B_W)}{(N_W - B_W)^2} + \frac{\sigma^2(\mathcal{L})}{\mathcal{L}^2} + \frac{\sigma^2(\epsilon^R)}{(\epsilon^R)^2} + \frac{\sigma^2(\epsilon^T)}{(\epsilon^T)^2} + \frac{\sigma^2(A_W)}{A_W^2} \quad (6.5)$$

where

- N_W = Number of signal events passing $W \rightarrow e\nu$ event selection reconstructed in the detector

- B_W = Number of background events passing $W \rightarrow e\nu$ event selection reconstructed in the detector
- $\mathcal{L}$ = Luminosity of the sample
- ϵ^R = Reconstruction efficiency **for the electron**
- ϵ^T = Trigger efficiency **for the electron**
- A_W = Detector acceptance for $W \rightarrow e\nu$ events

and $\sigma(\text{quantity})$ is the absolute (statistical or systematic) uncertainty on the quantity. Note that the assumption is made that none of the uncertainties are correlated with one another.

Table 6.1 summarises the cross section determination in the $W \rightarrow e\nu$ channel and table 6.2 summarises the uncertainties on the relevant quantities for the calculation. The quantities along with their associated uncertainties have been determined in the preceding chapters, apart from the luminosity uncertainty of 10% which is given externally by the LHC machine group [52] as a prediction for first data, although in later data this is expected to decrease to a few percent through a combination of improved understanding of the LHC and also dedicated luminosity measurements performed by the ATLAS luminosity monitors [53][54].

Quantity	Value
N_W	367672
B_W	14493
ϵ^R (%)	87.22
ϵ^T (%)	96.38
A_W (%)	36.82
$\mathcal{L}$	100 pb ⁻¹

Tab. 6.1: Quantities necessary for the evaluation of cross section (W analysis).

Thus the cross section for $W \rightarrow e\nu$ is evaluated as follows (central value $\pm$ statistical uncertainty $\pm$ systematic (reduced systematic) uncertainty):

$\sigma(W \rightarrow e\nu) = 11411 \pm 40 \pm 1186 \text{ (223) pb}$ (deviation from the input MC of -354 pb: -3.05%).
--

Quantity	Statistical uncertainty %	Systematic uncertainty %
$\sigma(N_W - B_W)/N_W - B_W$	0.17	N/A
$\sigma(\epsilon^T)/\epsilon^T$	0.10	0.31
$\sigma(\epsilon^R)/\epsilon^R$	0.19	1.75
$\sigma(A_W)/A_W$ (theory)	N/A	2.06
$\sigma(A_W)/A_W$ (experimental)	0.22	0.80
$\sigma(\mathcal{L})/\mathcal{L}$	N/A	10
$\sqrt{\text{Quadrature sum as in equation 6.5}}$	0.35	10.40 (1.96)

Tab. 6.2: Fractional (quoted in percent) systematic and statistical uncertainties relevant to $W \rightarrow e\nu$ cross section calculations evaluated at 100 pb^{-1} . Note that the quadrature sum stated is the fractional uncertainty (in %) on the cross section. The reduced systematic uncertainty is shown in parentheses.

Discussion

It is seen that the measured cross section differs from the input MC cross section more than the evaluated reduced uncertainty (statistical+systematic) allows. The reason for this is that global efficiencies and acceptances were used. The efficiencies in particular contribute to this effect as they are determined from $Z \rightarrow ee$ and applied to $W \rightarrow e\nu$ events (which have different electron P_T spectra, for example). It may be seen later in the chapter that the cross section is computed to be much closer to the input value if differential efficiencies are used. However, the discussion of uncertainties (independent of central quantities) is still valid for a global analysis. The following aspects (only considering the systematic uncertainties which are by far the dominant source at 100 pb^{-1}) were noted:

- The total uncertainty by far swamps the reduced uncertainty, mainly due to the large uncertainty on the luminosity.
- Even at a relatively small sample of 100 pb^{-1} , the statistical uncertainty is dominated by the systematic uncertainty.
- The dominant uncertainty to the cross section measurement is the luminosity, followed by that originating from the (theoretical) uncertainty on the acceptance A . The dominant uncertainty in the reduced group is from ϵ_R , resulting from background removal in N_1 (see chapter 5).
- As has been discussed, a data driven QCD background estimation has not been in-

cluded in this analysis and thus the above numbers are in absence of a systematic uncertainty from this effect. Systematics from MC studies are very large (up to 100%) but in real data when sufficient statistics are available these are expected to shrink.

6.1.2 Z channel

The production cross section for a $Z \rightarrow ee$ event is given by (with symbols defined as before)

$$\sigma = \frac{N_Z - B_Z}{\mathcal{L} \cdot \epsilon_Z^R \cdot \epsilon_Z^T \cdot A_Z}, \quad (6.6)$$

with the probability of both electrons in a $Z \rightarrow ee$ event being reconstructed:

$$\epsilon_Z^R = \epsilon_1^R \cdot \epsilon_2^R, \quad (6.7)$$

and the probability of either electron in the $Z \rightarrow ee$ event triggering the event:

$$\epsilon_Z^T = \epsilon_1^T + \epsilon_2^T - (\epsilon_1^T \cdot \epsilon_2^T). \quad (6.8)$$

The associated statistical uncertainty, $\sigma(\sigma(Z \rightarrow ee))$ on the cross section measurement is thus as follows:

$$\frac{\sigma^2(\sigma(Z \rightarrow ee))}{\sigma^2(Z \rightarrow ee)} = \frac{\sigma^2(N_Z - B_Z)}{(N_Z - B_Z)^2} + \frac{\sigma^2(\mathcal{L})}{\mathcal{L}^2} + \frac{\sigma^2(\epsilon_Z^R)}{(\epsilon_Z^R)^2} + \frac{\sigma^2(\epsilon_Z^T)}{(\epsilon_Z^T)^2} + \frac{\sigma^2(A_W)}{A_W^2}. \quad (6.9)$$

The uncertainties on the efficiencies $\sigma(\epsilon)$ are evaluated in two use cases: binned and unbinned analysis. In the case of the binned analysis, ϵ_1 and ϵ_2 are assumed to be uncorrelated, and the uncertainty on the overall efficiency of the event $\sigma(\epsilon_Z)$ is given by the following:

$$\sigma(\epsilon_Z^R) = \sqrt{(\epsilon_2^R)^2 \sigma^2(\epsilon_1^R) + (\epsilon_1^R)^2 \sigma^2(\epsilon_2^R)}, \quad (6.10)$$

and

$$\sigma(\epsilon_Z^T) = \sqrt{(1 - \epsilon_2^T)^2 \sigma^2(\epsilon_1^T) + (1 - \epsilon_1^T)^2 \sigma^2(\epsilon_2^T)}. \quad (6.11)$$

In the global case, a global efficiency $\epsilon_1 = \epsilon_2 = \epsilon$ is used for ϵ_R and ϵ_T (thus causing 100%

correlation between the two electron efficiencies), and the above equations become:

$$\sigma(Z \rightarrow ee) = \frac{N_Z - B_Z}{\mathcal{L} \cdot (\epsilon^R)^2 \cdot \epsilon^T (2 - \epsilon^T) \cdot A_Z}, \quad (6.12)$$

$$\frac{\sigma^2(\sigma(Z \rightarrow ee))}{\sigma^2(Z \rightarrow ee)} = \left(\frac{\sigma(N_Z - B_Z)}{N_Z - B_Z} \right)^2 + \left(\frac{\sigma(\mathcal{L})}{\mathcal{L}} \right)^2 + \left(\frac{2\sigma(\epsilon^R)}{\epsilon^R} \right)^2 + \left(\frac{2\sigma(\epsilon^T) \cdot (1 - \epsilon^T)}{\epsilon^T (2 - \epsilon^T)} \right)^2 + \left(\frac{\sigma(A_Z)}{A_Z} \right)^2. \quad (6.13)$$

Table 6.3 summarises the cross section determination in the $Z \rightarrow ee$ channel and table 6.4 summarises the uncertainties on the relevant quantities for the calculation.

Quantity	Value
N_Z	26760
B_Z	218
ϵ_Z^T (%)	99.87
ϵ_Z^R (%)	76.07
A_Z (%)	30.44
$\mathcal{L}$	100 pb ⁻¹

Tab. 6.3: Quantities necessary for the evaluation of cross section (Z analysis).

Quantity %	Statistical uncertainty %	Systematic uncertainty %
$\sigma(N_Z - B_Z)/N_Z - B_Z$	0.61	1.26
$2\sigma(\epsilon^T) \cdot (1 - \epsilon^T)/\epsilon^T(2 - \epsilon^T)$	0.007	0.02
$2\sigma(\epsilon_R)/\epsilon_R$	0.38	3.51
$\sigma(A_Z)/A_Z$ (theory)	N/A	2.44
$\sigma(A_Z)/A_Z$ (experimental)	0.41	0.22
$\sigma(\mathcal{L})/\mathcal{L}$	N/A	10
$\sqrt{\text{Quadrature sum as in equation 6.13}}$	0.83	10.95 (3.73)

Tab. 6.4: Fractional (quoted in percent) systematic and statistical uncertainties relevant to $Z \rightarrow ee$ cross section calculations evaluated at 100 pb⁻¹. The reduced systematic uncertainty is shown in parenthesis.

Thus the cross section for $Z \rightarrow ee$ is evaluated as follows (central value $\pm$ statistical uncertainty $\pm$ systematic (reduced systematic) uncertainty):

$$\sigma(Z \rightarrow ee) = 1147.9 \pm 9.5 \pm 125.7 \text{ (42.9) pb}$$

(deviation from the input MC of 26.2 pb: 2.3%).

Discussion

The measured cross section agrees with the input to within the quoted reduced systematic+statistical uncertainty. Given that the efficiencies and acceptances are measured from the same sample to the one to which they are applied, unlike in the $W \rightarrow e\nu$ case, a significant deviation from this measured number is not seen when binned efficiencies are used. The following conclusions were made from the measurement:

- Again the luminosity provides the dominant source of systematic uncertainty in the cross section measurement
- For $Z \rightarrow ee$ analysis the sub-dominant source of systematic uncertainty is ϵ_R , which is the dominant source of uncertainty in the reduced total uncertainty.
- Similarly to $W \rightarrow e\nu$, the statistical uncertainty is much smaller than the systematic. However, the fractional statistical uncertainty in $Z \rightarrow ee$ is larger than that for $W \rightarrow e\nu$, for the simple reason that, at a given luminosity, more $W \rightarrow e\nu$ than $Z \rightarrow ee$ events will be available.
- The fractional uncertainty for the trigger efficiency is lower in $Z \rightarrow ee$ than in $W \rightarrow e\nu$. This originates from the $(1-\epsilon_T)$ term that may be seen in equation 6.13, which is small as the trigger efficiency is close to 1. The physical interpretation of this is, for a high efficiency, nearly all $Z \rightarrow ee$ events will trigger the event as $Z \rightarrow ee$ has two electrons and therefore two ‘chances’ of passing the trigger, and thus the overall efficiency will be very high.
- The fractional uncertainty from reconstruction efficiency is larger in $Z \rightarrow ee$ as *both* electrons have to be reconstructed and thus the overall efficiency will be lower.
- It must be noted that it is not a fair comparison to look at the total systematic uncertainty in $Z \rightarrow ee$ compared to that in $W \rightarrow e\nu$, as the systematic uncertainty on QCD background estimation (which is expected to be larger for $W \rightarrow e\nu$ as there is no discriminating variable for a neat signal+fit technique such as M_Z in $Z \rightarrow ee$) is included. However, given any reasonable systematic from QCD background estimation

in $W \rightarrow e\nu$, the results suggest that the systematic uncertainty on the two channels should be comparable, although probably slightly smaller in $Z \rightarrow ee$.

6.2 Evaluation of $\mathcal{R}$

$\mathcal{R}$ is defined thus:

$$\mathcal{R} = \frac{\sigma(W \rightarrow e\nu)}{\sigma(Z \rightarrow ee)}. \quad (6.14)$$

The same luminosity run will be used to select both W and Z events. Thus the luminosity values cancel and $\mathcal{R}$ is given by:

$$\mathcal{R} = \frac{N_W - B_W}{N_Z - B_Z} \cdot \frac{\epsilon_Z^R \epsilon_Z^T}{\epsilon^R \epsilon^T} \cdot \frac{A_Z}{A_W} \quad (6.15)$$

$$= \frac{N_W - B_W}{N_Z - B_Z} \cdot \frac{(\epsilon^R)^2 (1 - (1 - \epsilon^T)^2)}{\epsilon^R \epsilon^T} \cdot \frac{A_Z}{A_W} \quad (6.16)$$

$$= \frac{N_W - B_W}{N_Z - B_Z} \cdot \epsilon_R (2 - \epsilon_T) \cdot \frac{A_Z}{A_W}. \quad (6.17)$$

The associated uncertainty is evaluated as follows:

$$\frac{\sigma_{\mathcal{R}}^2}{\mathcal{R}^2} = \frac{\sigma^2(N_W - B_W)}{(N_W - B_W)^2} + \frac{\sigma^2(N_Z - B_Z)}{(N_Z - B_Z)^2} + \frac{\sigma^2(\epsilon_R)}{\epsilon_R^2} + \frac{\sigma^2(\epsilon_T)}{(2 - \epsilon_T)^2} + \frac{\sigma^2(A_Z/A_W)}{(A_Z/A_W)^2}. \quad (6.18)$$

The terms from equation 6.17 with their associated errors in equation 6.18 are tabulated in tables 6.5 and 6.6.

Quantity	Value
$N_Z - B_Z$	26542
$N_W - B_W$	353179
ϵ^R (%)	87.22
$2 - \epsilon^T$ (%)	1.04
A_Z/A_W	0.83

Tab. 6.5: Quantities necessary for the evaluation of $\mathcal{R}$.

Quantity	Statistical uncertainty %	Systematic uncertainty %
$\sigma(N_Z - B_Z)/N_Z - B_Z$	0.17	1.26
$\sigma(N_W - B_W)/N_W - B_W$	0.61	N/A
$\sigma(\epsilon^T)/(2 - \epsilon^T)$	0.09	0.29
$\sigma(\epsilon^R)/\epsilon^R$	0.19	1.75
$\sigma(A_Z/A_W)/A_Z/A_W$ (theory)	N/A	1.27
$\sigma(A_Z/A_W)/A_Z/A_W$ (experimental)	0.46	0.80
$\sqrt{\text{Quadrature sum as in equation 6.18}}$	0.81	2.65 (2.32)

Tab. 6.6: Fractional systematic and statistical uncertainties (quoted in %) relevant to determination of $\mathcal{R}$ (calculations evaluated at 100 pb^{-1}). Reduced systematic uncertainty shown in parenthesis.

Thus the value of $\mathcal{R}$ is evaluated as follows (central value $\pm$ statistical uncertainty $\pm$ systematic (reduced systematic) uncertainty):

$$\mathcal{R} = 9.94 \pm 0.08 \pm 0.26 \text{ (0.23)}$$

(deviation from the input Monte Carlo of -0.55 : -5.4%).

Discussion

The evaluated value of $\mathcal{R}$ does not agree with the input value to within reduced systematic+statistical uncertainty. The reason for this is, again, that it uses a global efficiency which affects, in particular, the $W \rightarrow e\nu$ component of the calculation. This discrepancy is solved by using binned efficiencies (see next section). The following aspects (common to both binned and global analysis) were noted:

- The contribution of the uncertainty due to the trigger efficiency in the evaluation of $\mathcal{R}$ is similar to that in the $W \rightarrow e\nu$ analysis. Mathematically, this is because $2-\epsilon_T$ is of similar magnitude to ϵ_T (as it is close to 1). Intuitively, this is because it is almost certain that a Z event will trigger the chain used (e22i) and so the trigger efficiency uncertainty is less important in the analysis of these events (and indeed, this may be seen in equation 6.13 where the contribution of the trigger efficiency in $Z \rightarrow ee$ scales with $1-\epsilon_T$).
- The contribution of the uncertainty due to the reconstruction efficiency in the evaluation of $\mathcal{R}$ is the same as that in the $W \rightarrow e\nu$ analysis. The reason for this is different for that in the case of the trigger efficiency: in this case, the uncertainty due to the reconstruction efficiency partially cancels out between $Z \rightarrow ee$ and $W \rightarrow e\nu$ events.
- The experimental uncertainty on the acceptance is very similar in an $\mathcal{R}$ evaluation to that in $W \rightarrow e\nu$, for reasons discussed in chapter 3.
- The theoretical uncertainty on the acceptance is about half the contribution in an evaluation of $\mathcal{R}$ in an evaluation in either $Z \rightarrow ee$ and $W \rightarrow e\nu$. In other words, this uncertainty partially cancels in the ratio.
- Obviously, the luminosity uncertainty completely cancels in the ratio.

Thus, the reduced systematic uncertainty (including the efficiencies and experimental acceptance systematics) is of similar size for $\mathcal{R}$ than in both $W \rightarrow e\nu$ and $Z \rightarrow ee$. However the total systematic uncertainty (which will be the one used in practice) is significantly

smaller, due to the complete cancellation of luminosity systematic and partial cancellation of theoretical acceptance uncertainties.

6.2.1 Refined evaluation of cross sections

The deviation of the above results (for $W \rightarrow e\nu$ and $\mathcal{R}$) from the input results is larger than the evaluated uncertainty. The reason for this is due to the variation of acceptance and efficiency in the detector. To account for the non-uniformity of the detector, each event in the cross section calculation is assigned a weighting (efficiency $\epsilon \times$ acceptance A) appropriate to its kinematics. The variables chosen have been discussed in the various performance chapters, but are summarised in table 6.7. Two variables have been chosen to represent the variation of each variable but this is by co-incidence; any number of variables may be used. The precise binning chosen has been described in the chapter pertaining to that particular variable.

Quantity	Variable	Motivation
ϵ	electron P_T (P_{Te1}, P_{Te2})	Accounts for the turn on curves in electron efficiency. In $Z \rightarrow ee$ events there are two electrons and so there are two labels accounting for the electron P_T values.
	electron η (η_{e1}, η_{e2})	Accounts for the local variation in electron efficiency in different regions of the detector. Again there are two labels accounting for the two electrons in $Z \rightarrow ee$ events.
A	Boson P_T (P_{TB})	Accounts for the variation in acceptance with boson P_T due to the decay electron kinematics.
	Boson η (η_B)	As above. Note that this quantity is only used in Z analysis as it cannot be measured in a W decay.

Tab. 6.7: Variables chosen to represent kinematical dependencies of variables used in cross section determination.

A 6 dimensional matrix is constructed to hold the weightings to be assigned to the events. Each cell of the matrix is associated with a particular ($P_{Te1}, P_{Te2}, \eta_{e1}, \eta_{e2}, P_{TB}, \eta_B$) label (for $W \rightarrow e\nu$ events, the P_{Te2} , η_{e2} and η_B dimensions of the matrix only have one bin as these variables are nonsensical). A cell is incremented every time an event with the

appropriate label is counted in the analysis.

Each cell of the matrix (identified by the variable i) has its own unique weighting, $W_i = (\epsilon_i A_i)^{-1}$ where ϵ_i is the efficiency assigned to that cell and A_i is the acceptance. The number of events in each cell, N_i , multiplied by the cell weighting W_i is the cell contribution (before scaling to a luminosity) to the cross section, C_i .

Thus, the total cross section, σ_T , is given by:

$$\mathcal{L} \cdot \sigma_T = \sum_i C_i - \sum_i B_i \cdot W_i, \quad (6.19)$$

where $\mathcal{L}$ is the luminosity of the sample, B_i is the number of background events in the cell and C_i is given by:

$$C_i = N_i \cdot W_i, \quad (6.20)$$

The above equations imply that to obtain the total cross section, one must sum the entries C_i of every cell in the matrix and then remove the sum of the expected backgrounds $\sum_i B_i W_i$ from that sum. Or equivalently, fill a separate histogram for each cell, each with a weighting W_i , and sum to obtain one final histogram, the integral of which minus the estimated background contribution should be the total cross section.

The actual strategy of the analysis (which is again an equivalent procedure) is to fill one histogram event by event using the weighting W_i which is determined for that particular event. Background estimation (including weighting) $B_i \cdot W_i$ in the overall histogram is performed by using a signal + background fit (the form of which is determined in chapter 1). The integral of the signal function in the histogram divided by the luminosity is the measured cross section.

To perform the fit correctly, the statistical uncertainty of each bin of the histogram has to be set to $\sqrt{\sum_N W_N}$, where N is the number of times the bin is filled and W_N is the weighting used when the bin is filled for the N^{th} time. This keeps the relative size of the error with respect to the bin content (which is essentially what a χ^2 minimises) constant and thus estimates correctly the statistical significance of each bin even when the bins are

scaled by a weighting.

The statistical uncertainty on the total cross section, $\sigma(\sigma_T)$, is taken by standard error propagation from equation 6.19:

$$\mathcal{L}^2 \cdot \sigma^2(\sigma_T) = \sigma^2 \left[\sum_i ((N_i - B_i) \cdot W_i) \right] \quad (6.21)$$

$$= \sum_i [(\sigma(W_i) \cdot (N_i - B_i))^2 + (\sigma(N_i - B_i) \cdot W_i)^2] . \quad (6.22)$$

where $\sigma(x)$ is taken to be the statistical uncertainty on that quantity x .

The above cannot be evaluated unless the background contribution in each bin, B_i is known. This would require a full fit over each bin which would be most undesirable as, firstly it would place huge constraints on how many events are in each bin to get a reasonable fit, and secondly would introduce an unacceptable amount of systematic uncertainty into the final result.

The solution to this was to assume a low background level, $B_i \ll N_i^2$. The justification for this approximation is as follows:

- The background is indeed very small. This can be seen clearly in the mass plots, and background fits suggest that the background is at the 1% level. Using typical numbers from a global cross section analysis, this shows the percentage impact on the statistical uncertainty would be less than 1% of the statistical uncertainty itself.
- The additional systematic uncertainty which would be caused by introducing a mass fitting in each cell would swamp this small extra unknown in statistical uncertainty (which at 100 pb^{-1} is by far the smaller source of uncertainty).

The above equation then reduces to

$$\mathcal{L}^2 \cdot \sigma^2(\sigma_T) = \sum_i [(\sigma(W_i) \cdot N_i)^2 + (\sigma(N_i) \cdot W_i)^2] , \quad (6.23)$$

² note that this approximation is only made in calculating the statistical uncertainty on the cross sections, not the cross sections themselves!

which can be easily calculated by summing over the matrix elements C_i .

It must be noted, to find (for example) a differential efficiency with respect to boson P_T , all that is needed to be done is to project the matrix along the chosen axis, and all bin contents along with their associated uncertainties will be automatically computed correctly.

Using this analysis the cross sections (central value $\pm$ statistical uncertainty $\pm$ systematic (reduced systematic) uncertainty) were again determined (systematic uncertainties taken from the global case):

$$\sigma(W \rightarrow e\nu) = 11806 \pm 39 \pm 1186 \text{ (223) pb}$$

$$(42 \text{ pb (0.35\%) away from input value})$$

$$\sigma(Z \rightarrow ee) = 1132.1 \pm 7.7 \pm 125.7 \text{ (42.9) pb}$$

$$(10.4 \text{ pb (0.92\%) deviation from input value})$$

$$\mathcal{R} = 10.43 \pm 0.02 \pm 0.26 \text{ (0.23)}$$

$$(-0.06 \text{ (0.56\%) away from input value})$$

Discussion

Both the evaluated cross sections and their ratio agree with prediction to within reduced systematic+statistical uncertainty when using binned quantities for the analysis. The following conclusions were made from the measurement:

- Using binned acceptance and efficiencies has facilitated the determination of the $W \rightarrow e\nu$ cross section (and therefore a measurement of $\mathcal{R}$) to within the allowed statistical + systematic uncertainty.
- The statistical uncertainty when using binned weightings is smaller (although comparable) than for a global determination.
- The systematic uncertainty quoted on the measurement is that taken from the global measurement.

6.3 Conclusions and recommendations of further work

The recommendations below do not include those on the separate elements of the analysis, as these have been discussed in the relevant chapters. However those notes pertaining to the results obtained in this chapter and potential uses of the cross section calculation are discussed below.

- For the three quantities evaluated in this analysis ($\sigma(W \rightarrow e\nu)$, $\sigma(Z \rightarrow ee)$ and $\mathcal{R}$), the statistical uncertainty at 100 pb^{-1} (which is below the percent level in all three cases) has been evaluated to be much smaller than the systematic uncertainty. The systematic uncertainty is approximately 10 (11)% for $\sigma(W \rightarrow e\nu)$ ($\sigma(Z \rightarrow ee)$) (dominated by luminosity uncertainty: without this, the cross section uncertainties are 3-4%), and less than 3% for $\mathcal{R}$. The sub-dominant systematic uncertainties are that from theoretical acceptance and the uncertainty associated with the evaluation of ϵ_R .
- Some systematic uncertainties (in particular, that due to the luminosity, but also those from theoretical acceptance) have been seen to partially cancel in the ratio. No source of uncertainty has a significantly bigger impact on $\mathcal{R}$ than in $\sigma(W \rightarrow e\nu)$ or $\sigma(Z \rightarrow ee)$.
- Using binned weightings makes the difference between measurements which are unacceptably far from their predicted value, and those that are correct within uncertainties.
- The systematic uncertainty quoted in the binned analysis is taken from the global case (although, on each of the quantities separately the systematic quoted is that averaged bin by bin so the variation of systematic bin-by-bin is to some extent accounted for). An extension to the study could be to calculate the systematic uncertainty in each bin and combine to obtain a better estimate of the systematic uncertainty.
- The advantage of the analysis in the way it was structured is, as has been mentioned, that it is straightforward (at least, for a basic calculation!) from this stage to make a differential cross section measurement with respect to boson P_T or η . One needs to sum along one of the dimensions of the matrix and the uncertainties along with variation of ϵ and A with kinematics will be calculated correctly. However, dedicated

studies will also be needed to calculate the systematic uncertainties when viewed in a differential perspective as mentioned in the previous point.

- For the purposes of statistical uncertainty evaluation, the assumption of small background to $Z \rightarrow ee$ was made in this analysis (bin by bin fluctuations of background level may be neglected) so as to avoid having to perform multiple fits. However, in real data, if the QCD background does turn out to be large, it may be necessary for a fit to be evaluated in each bin of the matrix for the $Z \rightarrow ee$ analysis. However, if QCD does turn out to dominate over $W \rightarrow e\nu$ as a background to $Z \rightarrow ee$, the situation should be simplified somewhat as QCD background does not peak underneath M_Z in the way that $W \rightarrow e\nu$ does (see chapter 5 for a more complete discussion), and a falling exponential may be used as the background parameterisation in each bin which should simplify the fit.
- As was mentioned in the introductory chapter of this work, an evaluation of $\mathcal{R}$ is a very useful tool when viewed in a differential perspective. Studying $\mathcal{R}$ as a function of jet multiplicity (or another variable connected with hadronic activity) has potential as a new physics search. This work has started to investigate certain variables (efficiencies, resolutions) in a jet-differential perspective, and these preliminary studies could be extended into making such a measurement.
- Again, as was mentioned in chapter 1, it may be interesting at the LHC to study the implications on PDFs of such a high energy regime. $\mathcal{R}$ may provide a window into such analysis, as it could be sensitive to b-quark PDFs contributing to Z but not W production, which will affect the value of $\mathcal{R}$ (when compared to, for example, its value measured at the Tevatron). Due to the high statistics expected at the LHC and the low systematic uncertainty on $\mathcal{R}$ predicted by this work this may be possible.

7. CONCLUSIONS

This analysis has developed methods using Z events to understand from data the detector response and efficiency, as well as techniques for folding in such quantities to measure σ_W , σ_Z and $\mathcal{R}$ along with their predicted uncertainties for an early data scenario (100 pb^{-1}). The techniques have been developed to measure these quantities with the aim of not relying, whenever possible, on MC simulation. Specific conclusions and suggestions for further work have been given at the end of each chapter, and a summary of the conclusions is given below.

Using certain axes along which to resolve $\cancel{E}_t$ in $Z \rightarrow ee$ events has been shown to be valuable as a tool to study calibration of objects in the event. This technique also yields a measurement of $\cancel{E}_t$ resolution functions with small systematic uncertainty, although neutrino-fication in the form discussed in this thesis works less well and in fact leads to unacceptably large systematic uncertainty in event smearing.

The $\cancel{E}_t$ resolution functions obtained from axis resolution yield acceptance corrections with reasonable systematic uncertainty, although significantly larger than that obtained for the electron case. If $\cancel{E}_t$ smearing is to be used, care must be taken that the effects of $\cancel{E}_t$ scale and resolution are treated as according to the guidelines recommended in this thesis. Smearing $\cancel{E}_t$ constituents separately may be a more stable procedure, although the differing detector responses to different types of hadronic deposit that have been seen in this work must be accounted for.

Despite these difficulties, the systematic uncertainty on the acceptance in $Z \rightarrow ee$ and $W \rightarrow e\nu$ due to event smearing (which is larger in $W \rightarrow e\nu$ than in $Z \rightarrow ee$ due to the difficulties with $\cancel{E}_t$ smearing) is smaller than the evaluated theoretical uncertainty (which is driven by the uncertainty due to PDFs). However the theoretical systematic uncertainty for the acceptance ratio is smaller than that for the $Z \rightarrow ee$ and $W \rightarrow e\nu$ acceptances individually. Other sources of systematic uncertainty in the acceptance calculation are those from DY removal and photon merging, although this work concludes that both of these contribute minimally to the total acceptance systematic.

This thesis concludes it is acceptable to estimate backgrounds other than QCD to $W \rightarrow e\nu$ from MC. Data driven methods exist to estimate the contribution of QCD to $W \rightarrow e\nu$ but, for reasons discussed, it is recommended that these are tuned on real data. The background

to $Z \rightarrow ee$ may be estimated with small systematic uncertainty by fitting the invariant mass distribution.

Background removal forms the driving source of systematic uncertainty in tag and probe efficiency determination. The background from $W \rightarrow e\nu$ is particularly problematic as it peaks underneath the signal peak which causes particular difficulty when fitting N_1 for ϵ_R . The variation of combinatorical background in different kinematical regions also creates problems. Methods have been discussed or implemented to circumvent these problems, although it is recommended that these techniques are tuned on real data as the inclusion of QCD background will certainly affect the background distributions (a fake rate study discussed suggests it will be exponentially falling) under the signal peak. An additional source of systematic uncertainty on the tag and probe method is bias in the tag sample due to certain events not passing the tag requirements, and a recommendation has been made for a method of estimating the systematic uncertainty due to this effect.

The variation of detector efficiencies in different kinematic regions has been considered. In particular, the variation with probe P_T and η has been folded into the analysis as this was considered necessary. The variation of efficiency with hadronic activity has been investigated in a qualitative manner and recommendations made regarding the treatment of this effect in an analysis involving jets in the signal sample.

The use of binned weightings has facilitated correct (within uncertainties) MC measurements of σ_W , σ_W and $\mathcal{R}$ along with projected uncertainties at 100 pb^{-1} . The statistical uncertainties obtained on the cross sections are predicted to be below the percent level, and have been evaluated to be much smaller than the systematic uncertainties which are predicted to be at the 10-11% level. The sub-dominant sources of systematic uncertainty after the luminosity are the theoretical acceptance calculation and ϵ_R . Some systematic uncertainties have been seen to completely (luminosity) or at least partially cancel (acceptance) in the cross section ratio, which has a predicted total systematic uncertainty of less than 3%.

8. APPENDIX: GLOSSARY OF ACRONYMS, ABBREVIATIONS AND COMMONLY USED SYMBOLS

A : Acceptance	MC : Monte Carlo
ATLAS : A Toroidal Lhc ApparatuS	N₁ : Denominator for efficiency calculation (size of tag sample)
A_⊥ : Perpendicular axis	N₂ : Numerator for efficiency calculation (size of probe sample)
A_∥ : Parallel axis	N_{DOF} : Number of Degrees Of Freedom
A_Z : Axis pointing parallel to P_{TZ}	NLO : Next to Leading Order
A_{AZ} : Axis pointing perpendicular to P_{TZ}	ϕ : Azimuthal angle
B : Background	PDF : Parton Density Function
BSM : Beyond the Standard Model	P_T : Transverse momentum
cone04 : Cone jet algorithm with size=0.4	P_{TB} : Boson transverse momentum
D-Y : Drell Yann	QCD : Quantum ChromoDynamics
ΔR : Angular separation	$\mathcal{R}$: Ratio between the cross sections of $W \rightarrow e\nu$ and $Z \rightarrow ee$, $\sigma(W \rightarrow e\nu)/\sigma(Z \rightarrow ee)$
η : Pseudo-rapidity	R(x) : Reconstructed distribution of x
η_B : Boson pseudo-rapidity	R_{s(x)} : Smeared truth distribution of x
ϵ_F : Filter efficiency	R-T(x) : Monte Carlo estimate of the detector response of x
ϵ_R : Electron Reconstruction efficiency	x^{reco} : Reconstructed quantity x
ϵ_T : Electron Trigger efficiency	RefFinal or RF : $\cancel{E}_t$ reconstructed with the default ATLAS algorithm
$\sum \mathbf{E}_T$: Scalar sum of calorimeter deposits	RMS : Root Mean Square
E_{COM} : Centre of mass energy	RoI : Region of Interest
EM : Electro-magnetic	σ : Cross section, uncertainty or RMS
EF : Event Filter	SCT : SemiConductor Tracker
FSR : Final State Radiation	SM : Standard Model
γ : photon	$\sum \mathbf{E}_{T\text{had}}$: Weighted scalar sum of hadronic calorimeter cell deposits
Γ : Branching fraction	SUSY : SuperSYmmetry
HR : Hadronic recoil	τ : Tau lepton
ID : Inner Detector / IDentification	t ($\bar{\mathbf{t}}$): top (anti top) quark
IsEM : Electron identification criteria	T(x) : True distribution of variable x
ISR : Initial State Radiation	TRT : Transition Radiation Tracker
$\mathcal{L}$: Integrated Luminosity	ν : neutrino
L1 : Level 1	V : Massive Vector Boson (W or Z)
L2 : Level 2	W : Weighting $(\epsilon \times A)^{-1}$
LHC : Large Hadron Collider	x^{true} : Monte Carlo truth quantity x
LO : Leading Order	
$\cancel{E}_t$: Missing transverse energy	
$\cancel{E}_t \cdot \mathbf{A}$: The distribution of missing transverse energy resolved along an axis	
μ : muon	
M_{ee} : Invariant mass of the Z boson as constructed from the two decay electrons	
M_Z : Invariant mass of the Z boson	

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