THE JET ENERGY SCALE AT ATLAS USING Z+JET EVENTS

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Abstract

Jets, collimated sprays of subatomic particles, are an important component of the final state in high-energy proton-proton scattering. A correct jet energy scale is therefore essential to the success of the ATLAS experiment. In this thesis the missing transverse projection fraction method is used to measure the absolute jet response in Z+jet events where the Z decays into a pair of leptons. This measurement complements similar measurements made using γ+jet events while extending the calibration to lower energies. The possibility of taking advantage of the differing fraction of events in each sample with gluon-initiated jets as a method for deriving a parton-dependent jet response is also explored. Preliminary results are shown to agree with Monte Carlo predictions within their statistical uncertainty.
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Chapter 1

Introduction

1.1 The Standard Model

Richard Feynman has called Quantum Electrodynamics (QED) the jewel of physics [1]. Glashow, Weinberg and Salam were awarded a Nobel Prize in 1979 for their work on unifying the electromagnetic and weak forces. Quantum Chromodynamics (QCD) describes the strong interaction, the force that binds the atomic nucleus together among other things. These forces along with the fundamental particles on which they act make up the Standard Model (SM) of particle physics. While the Standard Model has known shortcomings (it does not explain dark matter, gravity, etc.), it has been very successful in predicting the results of nearly 40 years of experimentation.

The Standard Model is a quantum field theory, where spin-$\frac{1}{2}$ particles\footnote{Spin is an intrinsic, fundamental property of particles} called fermions, listed in Table 1.1, interact via the exchange of force carrying particles with integer spin (bosons), which are listed in Table 1.2. The fermions are further classified into particles with colour charge (quarks) and particles with no colour charge (leptons). The quark flavours are up (u), down (d), charm (c), strange (s), top (t), and bottom (b), while the leptons are known as the electron (e), the muon ($\mu$), and the tau ($\tau$), each with its own neutrino ($\nu_e$, $\nu_\mu$, $\nu_\tau$). These fermions can be categorized into 3 generations which differ only by mass, with ordinary matter being completely made out of the first generation. Finally, every particle has a corresponding oppositely charged anti-particle.

The strong force affects particles carrying a colour charge as the electromagnetic force affects
Table 1.1: Properties of the known spin-$\frac{1}{2}$ fermions in the Standard Model [2]. The quark masses have been estimated using the MS renormalization scheme at a scale $\mu = 2$ GeV, and while the neutrino masses are non-zero, they are small enough that they are approximated as zero for the purposes of this thesis.

particles with electric charge. One significant difference arises from the fact that the strong force does not weaken with increasing distance. As a result of this, quarks can be found only in bound, colour neutral states in nature, a phenomenon known as quark confinement. These colour neutral states are made out of a mixture of so-called valence quarks, which define the particle’s identity, gluons which are exchanged between quarks, and what are known as sea quarks, which are the results of gluons producing quark/anti-quark pairs. For historical reasons, the constituents of the nucleon (neutron or proton) are known as partons. Colour neutral states can be formed by 3 quarks or 3 anti-quarks (baryons), or by a quark and an anti-quark (mesons). The proton and neutron are both baryons, with the proton being a bound state of uud valence quarks, and the neutron being udd. A consequence of quark confinement is that the bare quark masses cannot be directly measured, but must be approximated by observing the bound states and making certain assumptions $^1$.

The neutrinos are a very interesting group, as they possess no electric charge and are colour neutral, so they interact only by the weak force. This leads to a very low probability of interaction. For example a neutrino with an energy of 10 GeV will travel through 10 m of solid iron with an interaction probability of only $3.2 \times 10^{-10}$. Neutrinos have a very small mass so, with the exception of neutrino dedicated physics, the mass can be assumed to be zero, which is reflected in Table 1.1.

$^1$The t quark is the exception, as it decays fast enough that no bound states are formed.
The final piece of the Standard Model puzzle is adding a mechanism which gives particles their mass. In the quest to produce a grand unified theory of everything, the weak and electromagnetic forces were joined. In this new theory the carriers of the weak force (Ws and Zs) were predicted to have zero mass to maintain local gauge symmetry, in contrast to their relatively large mass observed in experiment. This issue was resolved by the addition of a scalar field, which spontaneously breaks the symmetry of the electroweak Lagrangian in the ground state. This mechanism is also used to explain how other fundamental particles in the SM obtain their mass. As a consequence of the addition of this new field, the existence of a new particle, the famous Higgs boson, was predicted. Very recently, both the ATLAS and CMS collaborations at the LHC have announced the discovery of a new boson with a mass of approximately 125 GeV which is consistent with the SM Higgs [3].

### 1.2 Experimental Particle Physics

As most particles are short lived, they must be created in a laboratory to be studied. The average lifetime for most particles is short enough that even if they are created within a detector, the best one can hope to observe is the decay products of the original particle. The LHC and ATLAS (described in Chapter 2) were built for exactly this purpose: the creation of new particles and the detection of their remnants.

Thanks to Einstein’s famous equation, \( E = mc^2 \), we know that energy can be transformed into mass and vice versa. This is one of the properties used in LHC collisions, where bunches of protons are accelerated to over 99\% of the speed of light and collide within a detector, where a variety of new particles can be created. There are advantages and disadvantages to using composite particles.
like protons over more fundamental particles like electrons or muons. One disadvantage that comes from colliding composite particles is that while quarks and gluons from the two protons may collide, other components of the protons will also be ejected. This extra hadronic activity, which is known as the underlying event, deposits energy unrelated to the hard collision of interest. This can complicate the reconstruction of physics objects and global properties of the ‘event’.

While a proton may have an energy of 4 TeV, the amount of energy carried by the particles inside of the proton that actually collide is some unknown fraction of the total. The probability of a specific particle within the proton carrying some fraction of the proton’s total momentum is described by the parton distribution function (PDF). The proton PDF is best measured using accelerators which collide leptons (electrons and positrons) with hadrons (neutrons and protons).

The consequence of this momentum sharing is that with a fixed proton center of mass energy a large range of collision energies can be explored, making machines of this type excellent for discovering new particles. This energy sharing also means that the initial momentum along the beam axis is not known with any certainty. Incoming particles may also carry some small amount of momentum in the plane perpendicular to the beam line due to interactions within the protons and from beam focusing. As this momentum is very small compared to typical collision energies it can be assumed to be zero. With this small assumption conservation of momentum in this transverse plane (transverse momentum, or $P_T$) can be used to detect particles which leave no energy signature in the detector.

1.3 Units and Conventions

In particle physics, charge is traditionally measured in multiples of the magnitude of the electron charge (as seen in Tables 1.1 and 1.2). Unless otherwise specified, mention of a particle will refer to both the particle, and its anti-particle. Energy is measured in a non-SI unit, the electron Volt (eV), which is the amount of energy gained by a particle with unit charge that is accelerated across a potential of 1 volt. One eV is equal to $1.602 \times 10^{-19}$ Joules. Energies in this thesis will typically be much larger than an eV, so gigaelectron volts (GeV, $10^9$ eV), and teraelectron volts (TeV, $10^{12}$ eV) are used. Traditionally in high energy physics the speed of light ($c$) is taken to be unitless and
equal to 1, so that one can use the electron Volt for mass (eV/c^2), momentum (eV/c) and energy (eV).

The probability of a scattering event occurring is quantified by the cross section (\(\sigma\)), which is typically measured in barns (b), where 1 b \(\equiv 1 \times 10^{28}\) m^2. Similarly, recorded data are typically quantified by the integrated luminosity (\(\mathcal{L}\)), which is measured in inverse barns. The total number of events with a cross section of \(\sigma\) in an accumulated dataset with some integrated luminosity \(\mathcal{L}\) can be determined simply by taking the product. This thesis will typically use picobarns (pb, \(10^{-12}\) barns) and femtobarns (fb, \(10^{-15}\) barns) in describing both cross sections and integrated luminosity.
Chapter 2

Experimental setup

The ATLAS (A Torroidal LHC ApparatuS) experiment is located at the Large Hadron Collider (LHC), the largest subatomic particle physics accelerator in the world. Having spent 2011 colliding protons with a center of mass energy of 7 TeV and again in 2012 at 8 TeV, the LHC at the European Organization for Nuclear Research (CERN) is exploring the Standard Model in ways never before possible, as well as searching for physics beyond the Standard Model of particle physics.

2.1 The Large Hadron Collider

Accelerating protons to very high energies is a multi-stage process requiring protons to travel through several different accelerators before they are finally injected into the LHC itself. In general, storage-ring type accelerators have three types of components: magnetic dipoles to bend the beam, quadrupole and higher order magnets to focus the beam, and radio frequency (RF) cavities to accelerate the beam. RF cavities produce a standing radio wave which is controlled in such a way as to consistently accelerate incoming particles. It is this oscillating wave that requires the use of a bunch structure in the beam instead of a continuous stream of particles.

The process starts with the ionization of hydrogen atoms, which are then injected into Linac 2 (a linear accelerator), that uses a radio frequency quadrupole magnet to accelerate protons to 750 keV and provide initial focusing [4]. The protons are then accelerated to 50 MeV by an Alvarez drift tube linac. The protons are then injected into the proton synchrotron (PS) booster, which distributes the protons from the Linac into 3 of its 4 rings, with 2 bunches in each ring. The 6 bunches are
accelerated to 1.4 GeV before they are injected into the Proton Synchrotron (PS). These bunches are then split by tuning the RF cavities into 18 bunches, then 36, then 72 bunches while also being accelerated to 25 GeV. The bunches are now ready for the Super Proton Synchrotron (SPS), which provides acceleration up to 450 GeV. The SPS can handle up to 4 injections from the PS at a time before it injects into the two counter rotating rings of the LHC. The LHC can handle multiple injections from the SPS (2808 bunches requires 12 injections, with the SPS being filled between 2-4 times before each injection).

The 16 RF cavities in the LHC accelerate the beams to the desired energy, a process that may take 20 minutes. These beams are held in precise circular orbits by 1232 superconducting dipoles and several focusing magnets. Additional magnets are used to focus the beams tightly at the collision points. One measure of a collider’s performance is the luminosity, which is the number of particles per unit area per unit time, and is usually given in units of cm\(^{-2}\)s\(^{-1}\). The LHC’s design luminosity is approximately 20 times the maximum luminosity obtained by its predecessor, the Tevatron (\(10^{34}\) cm\(^{-2}\)s\(^{-1}\) vs. 4 x \(10^{32}\) cm\(^{-2}\)s\(^{-1}\)).

The LHC brings these beams of protons into collision inside one of four experiments, situated at different points around the ring. These experiments include ATLAS and the Compact Muon Solenoid (CMS), which are both general purpose detectors. There is also LHCb (LHC beauty), which is an experiment that focuses on b-physics and ALICE (A Large Ion Collider Experiment), that makes use of the LHC’s ability to accelerate not only protons but heavy ions as well (see Fig. 2.1).

2.2 The ATLAS Experiment

2.2.1 The ATLAS Coordinate System

The standard ATLAS coordinate system is used in this thesis with its origin at the centre of the ATLAS detector. The z-axis is oriented along the beam traveling counterclockwise when viewed from above. The positive x direction points towards the center of the ring and the positive y direction points vertically upwards. The azimuthal angle \(\phi\) is defined in the x-y plane, with \(\phi = 0\) along the x axis and increasing in the direction of the positive y axis. The polar angle \(\theta\) is defined with
respect to the positive z axis. A more convenient measure than $\theta$ is the pseudorapidity, which is given by $\eta = -\ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$. The pseudorapidity is an approximation of the rapidity, given by $y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$. For massless particles the pseudorapidity is equal to the rapidity. The pseudorapidity is used because, in contrast to $\theta$, differences in pseudorapidity are invariant under relativistic boosts. This has the advantage of allowing analyzers to obtain information on the scattering angle in the centre of mass frame even while the longitudinal momentum of the colliding particles remains unknown.

2.2.2 ATLAS Detector: Overview

ATLAS is one of two general purpose detectors at the LHC (see Fig. 2.2). It is composed of an inner tracking detector which is surrounded by a solenoidal magnet designed to allow the measurement of the momentum and scattering angle of charged particles. This is hermetically covered by a calorimeter designed to accurately measure the energy of hadrons and electromagnetic particles.
The outer-most subsystem is the muon spectrometer which lies in a magnetic field generated by a toroidal magnet. Detailed information on each of these systems is presented in the following sections.

Figure 2.2: A schematic diagram of the ATLAS detector.

2.2.3 ATLAS Hardware: Inner Detector

The Inner Detector (ID) is made up of three subsystems: the pixel detector, the semiconductor tracker (SCT), and the transition radiation tracker (TRT), which combine to provide tracking information within $|\eta| < 2.5$. These three systems are contained within a solenoidal magnet with an axial field of 2 Tesla. The primary purpose of the inner tracking system is to provide a non-destructive measurement of the momentum of outgoing charged particles as they travel from the interaction point to the calorimeter. The tracker also provides useful information about the scattering angles of charged particles, as well as providing information on particles which decay some distance away from the beam line (B hadrons for example). This is done by measuring the position of the particles at discrete points called hits as they curve through the detector and then reconstructing the path of
CHAPTER 2. EXPERIMENTAL SETUP

the particle. The curvature of this path is determined by the charge of the particle, the strength of the magnetic field and the momentum of the particle.

Both the pixel detector and the SCT make use of electron-hole pairs that are created in a semiconductor as a charged particle passes through it. These electrons are collected by electrodes which record the hits. The pixel barrel detector is composed of three concentric cylinders, where the innermost cylinder is situated 50.5 mm away from the beam line and the outer-most cylinder is 150 mm from the beam [5]. The pixel detector also includes two endcaps, with each endcap being composed of three individual layers. In total the pixel detector is made up of 1744 silicon pixel modules, each module being further subdivided into 47,232 pixels, where most pixels are 50 \( \mu m \) by 400 \( \mu m \) with the 400 \( \mu m \) aligned with the beam line. This configuration allows for an intrinsic detector resolution of approximately 10 \( \mu m \) in \( r\phi \) and about 115 \( \mu m \) in \( z \) [6].

The SCT consists of 4 cylinders in the barrel, ranging from a radius of 299 mm to 560 mm, along with two endcaps which consist of nine layers each. Each module consists of two silicon strip detectors glued together with a stereo angle of 40 mrad, providing a resolution of 17 \( \mu m \) in the \( \phi \) direction and 580 \( \mu m \) in the \( z \) direction.

The TRT consists of nearly 300,000 gas filled ‘straw’ tubes with a radius of 4 mm. Charged particles ionize the gas, and the electrons are collected on a central anode wire. The TRT provides 30 hits per track on average, with a resolution of approximately 130 \( \mu m \) per straw. While the TRT is used for tracking, it can also be used to identify particles. Relativistic charged particles also emit so-called transition radiation as they cross the boundary between two materials with different dielectric constants. The amount of energy a particle loses through this transition radiation depends on the Lorentz factor of the particle [7], so one can use the number of straws along a track with a large energy deposited in them to identify particles with a large relativistic \( \gamma \), such as electrons.

2.2.4 ATLAS Hardware: Calorimeter

Calorimetry is a term whose origin lies in thermodynamics. In high energy physics, calorimeters are detectors that, through destructive processes, absorb the energy of incoming particles and then
measure this absorbed energy. This process can give information about individual objects in an event (energy of outgoing electrons, jets, etc.), and also information about the event in general, like missing transverse energy (MET), which may signify the presence of a neutrino or some new particle beyond the Standard Model. Calorimeters are generally discussed in two broad categories: electromagnetic calorimeters and hadronic calorimeters, where each type is optimized to measure the energy of a specific type of particle. This section begins with a description of the processes electromagnetic objects (photons, electrons, positrons) undergo as they traverse the calorimeter, followed by a description of the electromagnetic calorimeter in ATLAS. The following section describes hadronic calorimetry in general and hadronic calorimetry as is it used in ATLAS.

**Electromagnetic Calorimeter**

Electromagnetic calorimetry is focused on measuring the energy of photons and electrons. For both types of particles, the primary interaction mechanism depends on the energy of the particle in question. For photons, the dominant process at low energies is the photoelectric effect, where a photon is absorbed and an electron is emitted. The cross section for this process scales with $Z^n$, where $Z$ is the atomic number of the material, and $n$ has a value between 4-5 [8]. The cross section varies as $E^{-3}$, making this process important only for low energy photons. The second most important process at low energies is Raleigh scattering, which is the coherent scattering of photons by atomic electrons. While this process affects the spatial distribution of photons, it does not contribute to the energy deposition of the photon as no energy is lost in the process.

In the intermediate energy range ($E_{\text{photon}} \approx 10^5 - 10^7$ eV) Compton scattering becomes important. This is the process in which a photon liberates an atomic electron, scattering it (preferentially) in the direction of the photon. A photon may Compton scatter many times before it is finally absorbed via the photoelectric effect, liberating numerous electrons in the process. The cross section for Compton scattering decreases more slowly as a function of energy than for the photoelectric effect ($1/E$ opposed to $1/E^3$), but at higher energies the importance of Compton scattering does decrease significantly.

At photon energies above twice the mass of the electron, the dominant photon interaction process quickly becomes electron/positron pair production. This process occurs mainly in the electric
field of atomic nuclei, but it may also take place in the presence of any charged particle. The cross section for pair production rises with energy and asymptotically approaches a plateau. By combining these processes, one can define an average path length, $\lambda_0$, which is the distance a photon travels on average between interactions.

The dominant energy loss mechanism for charged particles depends on the energy and mass of the particle in question. In the low energy regime, energy is lost by ionizing the material in which the charge carrier is traveling. The rate at which electrons lose energy by ionization is given by

$$- \frac{dE}{dx} = \frac{4CZ}{A\beta^2} \left( \ln \left( \frac{\gamma m_e c^2}{2I} \right) - \beta^2 - \frac{\delta^*}{2} \right), \tag{2.1}$$

where $C$ is a constant, $Z$ and $A$ are the atomic number and weight of the material, $I$ is the mean ionization energy of the material, and $\delta^*$ is a material dependent term that describes the amount that the electrons in the material screen the transverse electric field of the electron [7]. In this equation $\gamma$ is the Lorentz factor, given by $\gamma = 1/\sqrt{1-\beta^2}$ where $\beta$ is given by $\beta = v/c$. The equation describing ionization energy loss for positrons is slightly different, due to the different cross sections for Möller and Bhabha scattering. At higher energies, the dominant process becomes bremsstrahlung, where the charged particle radiates photons primarily in the forward direction ($\langle \theta_i \rangle \approx m_e c^2 / E$). The energy

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fractional_energy_loss.png}
\caption{Fractional energy loss per radiation length in lead as a function of electron or positron energy. Taken from Ref. [2].}
\end{figure}
at which the amount of energy loss via bremsstrahlung is equal to the energy lost through ionization is called the critical energy, $\epsilon$. For particles other than the electron with mass $m$ the critical energy scales as $(m/m_e)^2$, which means that for particles heavier than an electron bremsstrahlung becomes important only at very high energies. The energy loss of an electron or positron by bremsstrahlung can be defined as follows,

$$\frac{dE}{dx} = \frac{E}{X_0},$$

(2.2)

where $X_0$ is the radiation length, a property of the material that varies approximately as $Z^2$. The fractional energy loss per radiation length of electrons and positrons through these mechanisms in lead is shown in Fig. 2.3. It can also be shown that at high energy the average path length of a photon is related to the radiation length ($\lambda_0 = 9/7X_0$).

As electron interactions may produce photons, and photon interactions may produce electrons, one can imagine a situation where these newly produced secondary particles themselves produce new particles. So as an electromagnetic particle enters a medium, several generations of new electromagnetic particles are produced traveling in the same general direction as the original particle, and this is known as an electromagnetic shower. A simple model of this showering process can be made by assuming that electrons produce a new bremsstrahlung photon after a distance $X_0$ and that a photon will pair produce after covering the same distance. In this model, after a particle with some energy $E$ has showered some depth $nX_0$ into the medium, the shower will be composed of $2^n$ particles with an average energy of $E/n$. At some point the energy per particle will be too low to produce new particles, and the shower will terminate. As the processes involved in an EM shower tend to be forward, overall the shape of the shower tends to be quite narrow. This narrow shape is characterized by the Moliere radius defined by $\rho_M = mc^2\sqrt{4\pi/\alpha X_0}/\epsilon_c$, inside which more than 90% of the energy deposited by the shower is contained on average.

The electromagnetic calorimeter in ATLAS is an example of what is known as a sampling calorimeter, where the calorimeter is built out of alternating layers of some high $Z$ material that produces the shower (absorber) and some sensitive material to measure the energy deposited (active). The ATLAS EM calorimeter uses lead as the absorber and liquid argon (LAr) as the active material. To eliminate any cracks and provide full coverage in the $\phi$ coordinate, the absorber and active layers have been arranged into an accordion-like geometry, which can be seen in Fig. 2.5. The EM
calorimeter consists of a barrel unit ($|\eta| < 1.475$), and two planar end-caps ($1.375 < |\eta| < 3.2$). A presampler is used to account for energy lost in the inactive material between the interaction point and the EM calorimeter ($|\eta| < 1.8$). To contain the entire EM shower, the calorimeter is designed to be more than $24X_0$ deep in the central region and greater than $26X_0$ in the endcaps [9]. The EM calorimeter’s fine granularity in the central region ($|\eta| < 2.5$) provides information on the shape of the shower in the early stages, helping to separate photons from the hadronic background, notably $\pi^0$s decaying to two photons.

**Hadronic Calorimeter**

In many ways hadronic calorimetry is very similar to electromagnetic calorimetry: incoming particles interact with the detecting material, producing secondary particles which continue to produce a shower. As the electromagnetic force affects all charged particles, charged hadrons will lose energy by ionizing and exciting the material just like electrons. For charge carriers that are heavier than electrons, the energy loss is described by the Bethe-Bloch formula, which can be written as

$$-\frac{dE}{dx} = \frac{2CZ}{A\beta^2} \left( \ln \frac{2m_e c^2 \gamma^2 \beta^2}{I} - \beta^2 \frac{\delta}{2} \right)$$  \hspace{1cm} (2.3)
Hadrons may also interact with atomic nuclei through the strong force, allowing the formation of secondary hadrons along with the electrons and photons produced in the EM interactions. These nuclear interactions are the dominant mechanism for hadronic energy loss. Event by event, nuclear interactions vary much more than their EM counterparts. The most likely interaction is nuclear spallation [8], which is characterized by a rapid cascade of nucleons followed by a slower, evaporative stage where lower energy particles continue to be released.

After a hadron travels some distance through the calorimeter, it will lose energy through one of the processes described above, producing secondary particles. This distance has some average value, the interaction length $\lambda_I$, which is analogous to the average path length of the photon. While these showers are generally composed of a large number of charged and neutral pions, a wide array of particles can in fact be produced. This leads to large fluctuations in shower composition from one shower to the next. The particles produced in one interaction may be predominantly $\pi^0$s and $\eta$s, which would later decay into $\gamma\gamma$ creating electromagnetic sub-showers inside of the hadronic shower. This is called EM energy. In another interaction particles may decay into $\mu$s and $\nu$s, which
can escape the detector, so called escaped energy. On average, $O(50\%)$ of the energy will be EM energy, $O(25\%)$ will be visible, non-EM energy, $O(25\%)$ will be absorbed during nuclear breakup (invisible energy), and $O(2\%)$ will be escaped energy.

In comparison to the very narrow EM showers discussed in Sec. 2.4, hadronic showers are quite wide due to the large contribution of the nuclear interactions, and also penetrate much deeper into the calorimeter. While these differences in shape can be used to distinguish EM objects from hadronic ones, larger calorimeters are required to contain the energy carried by incoming hadrons. By longitudinally segmenting the calorimeter, additional shower development information can be obtained, and additional calibration can be performed.

![Calorimeter layout within the ATLAS detector.](image)

Figure 2.6: Calorimeter layout within the ATLAS detector.

The hadronic calorimeter, like the EM calorimeter, is divided into a barrel section and two end-caps (see Fig. 2.6). The barrel section is further subdivided into a central barrel region and two
extended barrel regions. Unlike the EM calorimeter, the hadronic calorimeter makes use of different technologies for these regions. In the barrel region ($|\eta| < 1.6$) a sampling calorimeter known as the Tile Calorimeter (TILE) is used, with steel as the absorber and scintillating plastic tiles as the active material. When a charged particle travels through the plastic tile, scintillation light is emitted. This light is then collected by wavelength shifting fibers, and read out by photo-multiplier tubes. At $\eta = 0$, the hadronic calorimeter is designed to be approximately $7 \lambda_f$ thick, which along with the $\sim 3 \lambda_f$ thick EM calorimeter contains the majority of hadronic showers [9]. The endcap uses a copper-LAr sampling calorimeter known as the Hadronic Endcap Calorimeter (HEC), which uses a more traditional parallel plate layout, in contrast to the accordion used in the EM calorimeter.

The very forward region ($3.1 < |\eta| < 4.9$) is covered by the Forward Calorimeter (FCAL), which is a LAr sampling calorimeter with a copper and tungsten absorber, for the EM and hadronic sections, respectively.

### 2.2.5 ATLAS Hardware: Muon Spectrometer

Muons are 200 times heavier than electrons, and as a consequence they will not lose large amounts of energy due to bremsstrahlung unless they have much higher energies. Since they are also unaffected by the strong force, they will travel much further through matter before being completely absorbed. This means that because muons penetrate much farther than other final state particles, they can be easily identified because they are alone. The muon spectrometer is essentially a large tracking system, with its own magnetic field created by large superconducting air-core toroids. In the central region, position measurements are performed by Monitored Drift Tubes (MDTs), which measure the ionization of a gas as a muon travels through them (similar to the TRT) [11]. In the endcap, a similar technology is used (multiwire proportional chamber or WPCs), in which a muon ionizes a gas between 2 plates, and the electrons are collected on wires.

The muon spectrometer also features a stand-alone triggering system (see Sec. 2.2.6), which contributes additional hits along the muon track. In the central region, the trigger system is made up out of Resistive Plate Chambers (RPCs), where the charge is collected by 2 parallel plates. The triggering in the endcaps is done by Thin Gap Chambers (TGCs) which are similar to the RPCs, the difference being the pitch of the collection wires. The electron drift velocity in RPCs is much faster.
than the drift velocity in MDTs, making this technology well suited to deliver the fast response time needed by the triggering system.

2.2.6 Triggers

At design luminosity the LHC will produce 40 million interactions per second in ATLAS, with each event requiring on average 1.5-2 Megabyte of computer disk and/or tape to store. While recording every single event is not necessary, rare events of interest should not be lost. To deal with this issue, ATLAS has adopted a sophisticated 3 level trigger system that filters the approximately 20 million collisions per second down to a few hundred events of interest per second. The first trigger level is a hardware based trigger known as the L1 trigger, which makes decisions based on the multiplicity of particles with momentum above a transverse momentum threshold. The L1 trigger also associates regions of interest with these locally triggered objects. In the second level trigger, L2, reconstruction algorithms are run only over the regions of interest to save time, and calibrations are applied. If a set of calibrated objects passes the L2 thresholds they are passed to the third level, the event filter (EF). The event filter uses the fully reconstructed and calibrated event to make a final series of selection requirements. Both L2 and the event filter are implemented on dedicated CPU clusters.

As a compromise between the high rate at which some event types of interest occur and the need to reduce the data recording rate to a manageable level some triggers are prescaled. Prescaling involves randomly selecting a predefined fraction of the total events selected by the trigger. This provides an unbiased sub-sample which is an accurate representation of the whole. By weighting the selected events by the prescale factor the total number of events can be retrieved.
Chapter 3

Physics Object Reconstruction

3.1 Clustering

Clustering is the process of grouping together calorimeter cells which are deemed to contain energy originating from the same particle. ATLAS uses two different clustering algorithms depending on the particle type [12].

3.1.1 Sliding Window Clusters

The first type of clustering is known as a sliding window algorithm, where a collection of cells with a fixed size in $\eta$-$\phi$ space is associated with each particle candidate. This sliding window type cluster is used for EM objects.

For EM clustering, the calorimeter is divided into 0.025 x 0.025 cells ($\eta$ x $\phi$) and cluster seeds are located, where a cluster seed is defined as a 5 x 5 window with a local maximum in contained transverse energy ($E_T$) that is above a set threshold (3 GeV). The position of the pre-cluster is defined as the energy weighted barycenter of this cluster, found using a 3 x 3 sub window. Finally another window of fixed size is constructed around this center, where the dimensions of the window depend on the particle hypothesis (sizes are shown in Table 3.1.1). These window sizes are optimized to contain most of the energy of the incoming particle, while avoiding as much noise and background as possible. The window size used for photons further depends on whether or not the
<table>
<thead>
<tr>
<th>Particle Type</th>
<th>Barrel</th>
<th>Endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>3 x 7</td>
<td>5 x 5</td>
</tr>
<tr>
<td>Converted photon</td>
<td>3 x 7</td>
<td>5 x 5</td>
</tr>
<tr>
<td>Unconverted photon</td>
<td>3 x 5</td>
<td>5 x 5</td>
</tr>
</tbody>
</table>

Table 3.1: Cluster sizes ($\eta$-$\phi$) used for electrons, photons, and converted photons.

The asymmetry seen in the window sizes for converted and unconverted photons in the barrel comes from the bending of the charged particle tracks in the magnetic field.

### 3.1.2 Topological Clusters

Topological (topo) clustering is an algorithm where cells are grouped together based on how significant the deposited energy is relative to the expected noise. In ATLAS, three-dimensional topo clusters are used as seeds in the jet reconstruction algorithms (see Sect. 3.2). In contrast to the fixed dimensions of the sliding window algorithm this process can lead to a wide variety of shapes, allowing the clusters to adapt to minimize the effects of noise.

The topo clustering algorithm begins by creating a list of cluster seeds, where the energy contained in a seed cell must have a signal to noise ratio above some threshold, $t_{seed}$. The noise in this case can be a combination of electronic noise and a contribution for other activity in the same beam crossing (in-time pile-up) or the previous beam crossings (out-of-time pile-up). Beginning with the seed with the highest signal to noise ratio, neighboring cells are now considered. If a neighboring cell has a signal to noise ratio above some level, $t_{neighbor}$, it is combined with the seed cluster and its neighbor are checked. This process continues until no neighboring cells remain. A final step of adding all cells adjacent to a cluster above some 3rd threshold $t_{cell}$ completes the clusters. In ATLAS, the clustering thresholds are 4-2-0 ($t_{seed} - t_{neighbor} - t_{cell}$), where $t_{cell} = 0$ represents no requirements on the final stage, i.e. all neighbors are added at the last step.
3.2 Jets

When colliding protons, there will be events where some combination of quarks and gluons will interact and be ejected in opposite directions. At first, this may seem impossible as particles may only exist in colour neutral states (see Sec. 1.1). As the partons travel further apart, the energy stored in the colour field between the quarks grows large enough that a quark/anti-quark pair is produced. This process will be repeated, continuing until the available energy decreases below the pair-producing threshold. The resulting quarks combine to form stable hadrons. This process is known as fragmentation, and the end result is a collimated spray of colour neutral hadrons roughly in the direction of each of the initial partons. As this shower of hadrons reaches the calorimeter, it will produce a secondary calorimeter shower, as was described in Sec. 2.2.4.

This is a very complicated process, with multiple steps between the hard collision and the energy deposited in the calorimeter. Many different algorithms have been developed to reconstruct these energy deposits into a form that may be more readily compared with theory predictions. The outputs of these algorithms are known as jets. These jet algorithms may be run over a variety of input objects, and at various stages of the showering process. It is therefore useful to define the different development stages as parton level (before hadronization), particle level (after hadronization but before propagation through the detector) and calorimeter level jets, as seen in Fig. 3.2.

![Diagram showing the progression of a jet from parton level to calorimeter level.](image)

There are several criteria to consider while searching for an ideal jet clustering algorithm. Jet
algorithms should be insensitive to soft (low $p_T$) radiation, as the rate that soft gluons are emitted diverges in a fixed order QCD calculation (infrared safe). Jet algorithms should also produce the same final jet topology regardless of whether or not the initial parton splits into two high-energy partons (collinear safe). For more details see Ref. [13]. One algorithm that satisfies these criteria and that is used by ATLAS is the anti-$k_T$ algorithm. Many different input objects can be used by this algorithm, such as tracks, calorimeter clusters and truth particles (in Monte Carlo samples). This thesis focuses on jets constructed from the topo clusters described in Sec. 3.1.2.

To begin the algorithm, all relevant objects are considered to be pseudo jets. Then, a distance parameter $d_{i,j}$ is calculated for each pair of pseudo jets $i$ and $j$, where $d_{i,j}$ is defined by

$$d_{i,j} = \min \left( p_{ti}^{-2}, p_{tj}^{-2} \right) \frac{\Delta_{ij}^2}{R^2}. \quad (3.1)$$

In this equation, $p_{tj}$ is the transverse momentum of the $j$th pseudo jet, $\Delta_{ij}$ is the distance between pseudo jet $i$ and $j$ in $\eta\phi$ space, and $R$ is a size parameter. Similarly a distance parameter for individual pseudo jets to the beam direction is defined as

$$d_{i,B} = p_{ti}^{-2}. \quad (3.2)$$

If the lowest $d$ is a pseudo jet pair, the pseudo jets are combined to form a new pseudo jet. If the lowest value is instead a single pseudo jet, that jet is added to a list a completed jets. This process is repeated until no pseudo jets remain. More details can be found in Ref. [14].

### 3.3 Muons

Muon reconstruction begins by fitting straight lines through nearby muon hits in the muon spectrometer, creating muon segments. Track segments in the outermost layer of the muon spectrometer are then iteratively associated with segments in the middle and inner layers of the spectrometer until a full track is reconstructed. These tracks are extrapolated to the interaction point, taking into account the energy loss in the calorimeter and multiple scattering. This is known as the Muonboy algorithm which is part of the Staco muon family of reconstruction algorithms, and results in a so-called stand alone muon [15].
The muon momentum resolution can be improved by using tracking information from the inner detector as well as the muon spectrometer (combined muons). Staco combined muons are created by performing a statistical combination of the independently reconstructed inner detector and muon spectrometer muons. An alternative scheme (Muid) creates combined muons by an independent algorithm which makes use of hits in both sub-detectors [16].

3.4 Missing Transverse Energy

The imbalance in momentum (or energy) produced in a collision is a useful quantity to measure. A large imbalance can be caused by some high energy particle escaping detection (e.g., neutrino), while a small imbalance may indicate a mismeasurement. In Sec. 1.2 the consequences of protons being composite particles was briefly discussed. It was noted that in hadron colliders one can observe conservation of momentum only in the plane transverse to the beam line, so momentum imbalance along the beam line contains no useful information. This is why missing transverse energy (MET or $E_{miss}^T$) is usually discussed.

The $E_{miss}^T$ can be constructed using a variety of inputs, ranging from the inputs used in the jet reconstruction algorithm to the reconstructed and calibrated jets themselves. This thesis focuses on using $E_{miss}^T$ based on topological clusters. The general formula for calculating the $E_{miss}^T$ is

$$E_{miss}^T = - \sum E_{cluster}^x$$

(3.3)

where $E_{miss}^x$ is the $x$ component of the missing transverse energy, with the analog also calculated in the $y$-direction.

This process can be slightly complicated by muons, which deposit only a small fraction of their energy in the calorimeter while passing through the calorimeter. Two different strategies have been adopted to account for muons. The first method uses the momentum of the fully reconstructed muon (using information from the inner detector and muon spectrometer) to determine the initial momentum of the muon. In a separate step the amount of energy deposited by the muon in the calorimeter is estimated and subtracted, to avoid double counting. In the second strategy, the muon momentum used in the calculation of $E_{miss}^T$ is calculated using only hits in the muon spectrometer. As this measurement is made after the muon has traveled through the calorimeter, no further corrections
are needed. In this thesis, muons have been accounted for in the $E^{\text{miss}}_T$ calculation using the second method.
The purpose of the jet energy scale correction is to calibrate the jet energy measured in the calorimeter back to the particle level energy. This makes the results independent of the detector so they can be more readily compared to theory. Jets are the most common objects created in ATLAS, and as such are very important in a wide variety of physics measurements and searches for new phenomena. This provides a strong motivation for deriving and monitoring the jet energy scale. A successful jet energy scale determination corrects for escaped/invisible energy, dead material, algorithm effects etc. The dominant component of the jet energy scale is the calorimeter jet response, which can be determined using a variety of *in-situ* techniques.

### 4.1 Jet Energy Scale in ATLAS

ATLAS currently supports two types of calorimeter based jets. Both types begin with ‘EM scale’ calibrated clusters, where the ‘EM scale’ sets the correct energy for electrons and photons. In the first scheme, these clusters are assembled into jets before any corrections are applied. Alternatively the local calibration scheme applies an additional energy-dependent correction at the cluster level before assembling clusters into jets (Local Cluster Weighting or LCW jets). Monte Carlo studies have been done, which are used to determine the probability of a cluster being electromagnetic or hadronic in nature in bins of $|\eta|$, energy, depth of the energy deposit and shape of the energy deposit. Clusters which are identified as being hadronic clusters have an additional weight applied to them to account for escaped/invisible energy. This is done to artificially increase the calorimeter’s
response to purely hadronic energy deposits, improving the jet energy resolution.

The calibration process begins after the jet reconstruction. The current calibration scheme used by ATLAS is shown in Fig. 4.1. A Monte Carlo based correction is applied to correct for additional pile-up energy, and then the direction of the jet is corrected to the measured primary vertex. Another Monte Carlo correction is introduced to perform an initial scale calibration. This correction is different for EM scale jets and LCW jets.

Figure 4.1: Calibration scheme for jets in ATLAS. Copied from Ref. [17].

Figure 4.2: Calibration scheme for jets in ATLAS. Copied from Ref. [18]
In the final step, an in-situ correction is applied to data. Many different techniques can be used to derive this final correction, each having its own advantages and disadvantages. In general, in situ techniques make use of events where a jet recoils against some well measured particle, a photon or leptonically decaying Z boson, for example. Momentum balance in the transverse plane can then be used to obtain a correct calibration [18]. The large cross section for the production of dijets and multi-jets is also exploited to extend the calibration to higher energies and larger pseudorapidity.

The study in this thesis focuses on using Z+jet events to determine the jet energy scale. While Z+jet events occur less frequently than γ+jet events, they provide complementary information. One advantage in Z+jets is that the sample remains pure down to very low $p_T$, in contrast to γ+jet which suffers from a large dijet contamination at low energies. As the LHC luminosity increases, the trigger prescale factors on low energy γ+jet events also increase, reducing the sample size and increasing the statistical uncertainty on the measurements of the jet energy scale at low energies in this channel. Another motivation for looking at both γ and Z+jet samples is the different rates of light-quark and gluon initiated jets in these two samples, where light-quarks are quarks with a mass less than the mass of a b-quark. Gluon initiated jets tend to be composed of a larger number of lower energy particles than quark jets, and they therefore tend to be larger in area and more shallow in depth than light-quark-initiated jets. This leads to gluon jets having a lower calorimeter response than light-quark jets [19]. By separating the quark and gluon response, one would be able to create a sample-dependent jet energy scale which should reduce the uncertainty on the calibration.

### 4.2 Jet Response

The largest correction to the jet energy scale is the absolute jet response component. The jet response describes how the calorimeter responds to both the hadrons and the electromagnetic objects within jets. For a single incident hadron, the response can be simply described by

$$r(E) = f_{em}(E)e + [1 - f_{em}(E)]h,$$

where $f_{em}$ is the fraction of the shower energy that is electromagnetic, and $e$ and $h$ are the calorimeter’s responses to EM and hadronic energy, respectively. This EM fraction term can be approximated by

$$f_{em}(E) = \left( \alpha_0 + \alpha_1 \ln \frac{E}{E_{scale}} \right) \ln \frac{E}{E_{scale}},$$

where

\[
\begin{align*}
\alpha_0 & = 0.40, \\
\alpha_1 & = 0.66,
\end{align*}
\]
where $E_{\text{scale}} \approx 1$ GeV [8].

A jet at particle level may already contain particles that will decay electromagnetically, and this must be accounted for. The response for an entire jet may then be described by

$$j(E) = w_h \cdot r(w_h \cdot E) + w_e \cdot e(w_e \cdot E)$$

where $w_e$ and $w_h$ are respectively the fractions of the particle level jet which will decay electromagnetically and hadronically. Some assumptions may now be made. First of all it can be assumed that the calorimeter’s response to single deposits of EM and hadronic energy ($e$ and $h$) are energy independent. With the additional assumption that the fraction of electromagnetically decaying particles at particle level is also energy independent it can be shown that the jet response can be parametrized by

$$j(E) = b_0 + b_1 \ln \frac{E}{E_{\text{scale}}} + b_2 \ln^2 \frac{E}{E_{\text{scale}}}$$

where constants have been absorbed into new constants $b_0$, $b_1$ and $b_2$.

### 4.3 $E_T^{\text{miss}}$ Projection Method

The Missing $E_T$ Projection Fraction (MPF) method is a technique for measuring the jet response in-situ that has previously been used with success by the DØ collaboration [20]. Contrary to other in-situ methods, the MPF does not directly use any jet information but instead uses only a well measured probe and the $E_T^{\text{miss}}$. This has the advantage of removing any reliance on the jet reconstruction from the calibration, making the measurement independent of the jet algorithm used. The MPF is also unaffected by pile-up to first order.

To derive the MPF, begin by considering the parton level momentum balance in a $Z$+jet event at the Born level

$$\vec{p}_T^Z + \vec{p}_T^q = 0,$$  \hspace{1cm} (4.5)

where $\vec{p}_T^Z$ is the transverse momentum of the Z boson and $\vec{p}_T^q$ is the transverse momentum of the quark or gluon. For a perfect calorimeter and neglecting effects due to the fragmentation process, the measured quantities would also balance, giving

$$E_T^{Z,\text{measured}} + E_T^{\text{jet,measured}} = 0,$$  \hspace{1cm} (4.6)
where $E_T$ is the transverse energy of the particles, defined as

$$
\vec{E}_T = \frac{E}{\cosh(\eta)} \hat{p}_T.
$$

(4.7)

This however is not the case, as some energy is lost in the measurement due to the calorimeter response to hadrons leading to some imbalance, given by

$$
\vec{E}^Z_{T, \text{measured}} + \vec{E}^\text{jet, measured}_T = -\vec{E}^\text{miss}_T
$$

(4.8)

where $\vec{E}^\text{jet, measured}_T$ is given by

$$
\vec{E}^\text{jet, measured}_T = j(E_\text{jet}) \vec{E}^\text{jet}_T.
$$

(4.9)

When the $Z$ decays into electrons $\vec{E}^Z_{T, \text{measured}}$ is given by

$$
\vec{E}^Z_{T, \text{measured}} = e\vec{E}^{e_1}_T + e\vec{E}^{e_2}_T
$$

(4.10)

where $e$ is the EM response and $e_1$ and $e_2$ are the two electrons. It can be assumed that the EM energy scale is well measured, and as the electron mass is small relative to the energies being explored, it can be approximated as zero, leading to

$$
\vec{E}^Z_{T, \text{measured}} = e\vec{E}^{e_1}_T + e\vec{E}^{e_2}_T = \vec{p}^{e_1}_T + \vec{p}^{e_2}_T = \vec{p}^Z_T.
$$

(4.11)
In the case where the $Z$ boson decays into a pair of muons $E_{T}^{\mu_{1}\mu_{2}}$ is given by

$$E_{T}^{\mu_{1}\mu_{2}} = p_{T}^{\mu_{1}} + p_{T}^{\mu_{2}} = p_{T}^{Z}. \tag{4.12}$$

As a final step, by ignoring fragmentation effects and approximating the jet as being massless, project Eq. 4.12 in the direction of the $Z$ and obtain

$$j(E_{jet}) = 1 + \frac{p_{T}^{Z} \cdot E_{T}^{\text{miss}}}{(p_{T}^{Z})^2}. \tag{4.13}$$

While this is the form of the MPF used when deriving the jet response, the relation to the response can be seen more clearly by first noting that $E_{T}^{\text{miss}}$ can be written as

$$E_{T}^{\text{miss}} = -p_{T}^{Z} - \sum' E_{T} \tag{4.14}$$

where $\sum'$ signifies a sum over all activity in the calorimeter other than the $Z$, and $p_{T}^{Z}$ is used for the reasons previously described. Using this definition of the MET, the response can be written as

$$j(E_{jet}) = -\frac{\sum' E_{T} \cdot \hat{n}_{Z}}{p_{T}^{Z}} \tag{4.15}$$

where $\hat{n}_{Z}$ in a unit vector in the direction of $p_{T}^{Z}$. It is now clear that the MPF balances all hadronic activity against the $Z$ boson. Since all activity outside of the $Z$+jet system (pile-up, underlying event) is $\phi$ symmetric with respect to the $Z$ when averaged over many events, the terms in $\sum'$ associated with this activity cancel out, leaving only the jet.
Chapter 5

Determining the Jet Energy Scale

5.1 Data Samples

As described in Sec. 4.1, the jet calibration scheme used in ATLAS which is based on Monte Carlo simulations involves a final energy scale calibration to account for differences observed between data and the Monte Carlo prediction. This thesis makes use of 6.2 fb$^{-1}$ of 8 TeV data, which was recorded by the ATLAS detector between April 12th, 2012 and August 28th, 2012. Results derived using this data set are compared to simulated data samples. In this study the nominal Monte Carlo sample has been generated with POWHEG, a next-to-leading order 2 parton - 2 parton generator [21]. These events are then passed to PYTHIA 8, which calculates the fragmentation process using the Lund String Model [22]. The set of particles generated by PYTHIA then pass through a full detector simulation provided by GEANT 4 [23].

5.2 Selection Criteria

5.2.1 Lepton Selection

Electrons

In order to determine the response, well measured leptons from the Z decay must first be identified. To be considered, events must pass the lowest unprescaled single electron transverse momentum based trigger, which includes a cut on the hadronic core isolation of 1 GeV. The isolation cut reduces the rate of jets faking electrons, reducing the trigger rate. On the 19th of April, 2012, the
lowest non-prescaled trigger threshold moved from 22 GeV to 24 GeV to cope with the increasing luminosity (and hence pileup) being delivered by the LHC. Isolation cuts may be applied to physics objects requiring that the energy or momentum contained within a cone of a specified radius centered on the object (excluding the object itself) must be below some threshold. On the first of May, one such cut was added to the trigger, requiring that the energy within an isolation cone of radius 0.2 contain no more than 10% of the electron’s energy to further reject hadronic fakes.

ATLAS has three predefined levels of electron selection: loose++, medium++, and tight++. The medium++ selection is used in this analysis. These definitions include a variety of cuts ensuring that the shape of the energy deposit within the calorimeter is consistent with an electromagnetic shower. One such cut is applied to the relative energy deposited by the object in the hadronic calorimeter to the EM calorimeter. This cut takes advantage of the different shower depths expected for electrons and hadrons. A similar cut is applied restricting the fraction of the total energy of the deposit that is contained in the third layer of the EM calorimeter. As previously mentioned (see Chap. 2), hadronic showers also tend to be much wider than their electromagnetic counterparts. To take advantage of this fact, cuts are applied which limit the root mean square of the energy deposit in pseudorapidity in both the strip and second layers of the EM calorimeter. Furthermore a second isolation criterion is applied, where a 3x7 and a 7x7 sliding window cluster are both centered on the energy deposit and a requirement on the ratio of the energy contained within these two clusters is applied. Finally to reduce hadronic fakes which are dominated by a neutral pion decaying into a pair of photons, a limit on the ratio of the energies in the two highest energy strips in the EM calorimeter is enforced. Each of these cuts has been optimized to obtain a pile-up independent signal acceptance efficiency and background rejection. These cuts vary in bins of energy and $\eta$, while also varying between the levels of electron identification (see Appendix D).

The medium++ selection also requires a track to be tightly matched to the energy deposit in the calorimeter ($\Delta \eta < 0.005$). The track must have at least 2 hits in the pixel detector, and in the central region at least one of these hits must be in the inner-most layer of the pixel detector (B-layer) to remove converted photons where an electron is lost. Tight++ electrons have additional cuts to match the track to the energy deposit in $\phi$ and on the electron’s energy over momentum ratio, which vary with energy and $\eta$. Finally, the medium++ and tight++ selection criteria have a loose requirement on the number of high threshold hits in the TRT to further reject fakes.
Additional cuts have been added to the medium++ selection to ensure high quality electrons. Electrons are required to have a transverse momentum greater than 20 GeV to further reduce hadronic fakes. Electrons must also be within the central region of the calorimeter which is covered by the tracking system ($|\eta| < 2.47$), excluding the crack region between the barrel and endcap in the EM calorimeter ($1.37 < |\eta| < 1.55$). Relative energy and momentum isolation criteria are also applied, requiring that the energy in a cone of radius 0.3, excluding the electron, is less than 15% of the electron energy and that the sum of the momentum of tracks measured by the tracker in a cone of radius 0.3 around the electron track is less than 14% of the electron’s momentum.

Cuts are applied to ensure that the electrons originate from the same vertex. To determine which vertex is to be associated with the hard collision, the square of the momentum of all tracks coming from each vertex is summed, and the vertex with the largest momentum is chosen as the primary vertex. An additional cut requiring at least 3 tracks to be associated with the selected vertex is applied. Electron tracks must originate within 1 mm of the primary vertex in the $z$ direction. The reconstructed electron track must also come within 10 times the detector resolution of the primary vertex. Finally electrons must be found using the cluster based electron finding algorithm.

**Muons**

Events which have passed the lowest non-prescaled transverse momentum isolated muon trigger of 24 GeV are considered. Only combined Staco muons have been used (see Sect. 3.3). To ensure the quality of the fit in the inner detector, the reconstructed track may only travel through at most two layers of the combined pixel/SCT system without having recorded a hit. To ensure a well measured vertex position the inner most layer of the pixel detector must have a recorded hit. Finally, in the central region covered by the TRT, at least six hits are required in the TRT.

In addition to track-quality based cuts, muons must pass a momentum-based isolation cut, similar to the one used for electrons, in a cone of radius 0.2 around the muon ($p_T^{0.2} / p_T^\mu < 0.2$), along with cuts on the transverse momentum ($p_T > 20$ GeV) and the pseudorapidity ($|\eta| < 2.4$). A cut on the origin of the muons is applied to suppress contamination from heavy quark decays requiring the reconstructed muon track to pass within 1 mm from the primary vertex in the $z$ direction, and be
within 10 times the detector resolution in the radial direction. To remove muons which come from cosmic rays no two muons with a distance of closest approach to the primary vertex greater than 0.5 mm can be back to back ($\Delta\phi > 3.1$).

### 5.2.2 Jet Selection

Jets are reconstructed using 4-2-0 topo clusters and the anti-$k_t$ algorithm with size parameter $R = 0.6$ (see Chap. 3.2). As leptons leave energy deposits inside the calorimeter, they are also reconstructed as jets by the ATLAS software. To remove these false jets, any jet closer than $\Delta R = 0.3$ to an electron or $\Delta R = 0.1$ to a muon is removed from the list of jets. A small fraction of events may be affected by noise bursts in the calorimeter, affecting the measurement of the jet energy (bad jets). Jets which land in problematic regions of the calorimeter may also be mismeasured (ugly jets). Events with bad or ugly jets are removed to avoid biasing the response measurement.

![Leading jet $p_T$ spectrum at EM scale for data and the Monte Carlo prediction using the $Z\rightarrow ee$ selection.](image)

Figure 5.1: Leading jet $p_T$ spectrum at EM scale for data and the Monte Carlo prediction using the $Z\rightarrow ee$ selection.

The jet vertex fraction is used to determine from which vertex a reconstructed jet originated. The jet vertex fraction is the fraction of the jet momentum associated with tracks in the inner detector that are within the jet definition and that originated from the primary vertex. The jet with the
highest transverse momentum (leading jet) is required to have a jet vertex fraction greater than 0.5.

In the derivation of the MPF method it was assumed that the transverse momentum of the Z boson and the parton are equal and opposite, but this is not always the case. In addition to Z+jet events, there are events where the outgoing parton may radiate a second parton, known as final state radiation (FSR). There are also events where incoming partons radiate a gluon known as initial state radiation (ISR), again ruining the assumption. To eliminate these effects, events with a second reconstructed jet with a high jet vertex fraction (over 0.5) and a large $p_T$ (above 12 GeV and above 30% of the Z’s $p_T$) are rejected. Any event with more than 2 jets after the lepton removal are also rejected. The leading jet $p_T$ spectrum after completing this selection is shown in Figs. 5.1 and 5.2 for electrons and muons respectively.

### 5.2.3 Z Selection

Events are required to have exactly two same flavour leptons which pass the criteria listed above. These leptons must be oppositely charged and are required to have a combined mass within 25 GeV
of the Z mass peak at 91 GeV (see Figs. 5.3 and 5.4). A very clean Z mass peak is seen in both decay channels. An additional cut requiring the Z boson to be back to back with the leading jet further
removes events with significant IFS and FSR. This cut is nominally set to require the difference in $\phi$ between the Z and the leading jet to be greater than 2.9. The resulting $p_T^Z$ distributions can be seen in Figs. 5.5 and 5.6. The Z bosons are found to be back-to-back with the $E_T^{\text{miss}}$, which is consistent with the $E_T^{\text{miss}}$ originating from a jet energy mismeasurement (see Figs. 5.7 and 5.8).

![Figure 5.5: $p_T^Z$ distributions as seen in data and the Monte Carlo prediction after applying the $Z\rightarrow ee$ selection criteria.](image)

**5.3 Measuring the Jet Energy Scale**

The jet energy scale must be measured in bins to capture the dependence on the particle level jet energy (see Eq. 4.4). As this study focuses on jets in the very central region of the detector ($|\eta| < 0.8$) the transverse momentum of the Z boson is chosen as a suitable measure of the true jet $p_T$. Within each energy bin, the response is first fit with a Gaussian function within a window of three times the root mean square of the distribution centered on the arithmetic mean ($\bar{x}$). A new fitting region centered on the mean of this Gaussian and extending three standard deviations in each direction is defined. To reduce the effect of any potential unphysical tails in the response distribution, which may affect the response measurement, the arithmetic mean and fitted mean are then compared. If the arithmetic mean is found to be significantly different from the fitted mean ($\text{abs}(\bar{x} - \mu) > 0.1$) the
Figure 5.6: $p_T^Z$ distributions as seen in data and the Monte Carlo prediction after applying the $Z \rightarrow \mu\mu$ selection criteria.

Figure 5.7: $\Delta\phi$ between the leading jet and the $E_T^{miss}$ as seen in data and the Monte Carlo prediction, after applying the $Z \rightarrow ee$ selection criteria.
fitting region on the side of the distribution with the tail is reduced by $1 - \frac{\text{abs}(\bar{x} - \mu)}{\sigma}$. A second Gaussian fit is performed within this reduced fitting region. The measured response distribution and the resulting fit for a single $p_T$ bin are shown in Fig. 5.9.

The response is measured using the first 6.2 fb$^{-1}$ of 8 TeV data taken in 2012. To determine the residual in-situ jet energy scale (JES) correction (see Sec. 4.1) the jet response is also measured using a Monte Carlo sample. The Monte Carlo sample has been generated using POWHEG, a next-to-leading order generator, and then showered using PYTHIA 8. The measured response and relative data/MC response for jets at EM scale can be seen using both $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ in Figs. 5.10 and 5.11, respectively. The response of jets constructed with locally calibrated clusters (see Sec. 4.1) as determined using $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ can be seen in appendices A and C respectively. During jet reconstruction in ATLAS, only jets with energy above some predetermined threshold are stored (10 GeV in this study). This results in an unphysical rise in the measured response at low $p_T^Z$ as jets with low response are not stored.
Figure 5.9: Response measurements are binned in $p_T^Z$. Shown is the measured response in the 2012 8 TeV data in the $Z\rightarrow\mu\mu$ channel with $80 \text{ GeV} < p_T^Z < 100 \text{ GeV}$ at EM scale. The Gaussian fit is overlaid on the data.

5.4 Systematic Uncertainties

Differences between the measured MPF response in data and the Monte Carlo prediction may be due to a mismodeling of the detector, directly influencing the measured response. Differences may also be caused by mismodeling effects which directly affect the MPF method itself (e.g. the amount of initial state or final state radiation emitted). A selection of parameters is varied, and the variation of the relative data/Monte Carlo predicted responses is used to assess the impact of these effects on the measurement. The effects studied in this thesis are:

1. Initial- and final- state radiation, varied by changing the requirements on the sub-leading jet $p_T$ and the $\Delta\phi(Z,\text{jet})$

2. Modeling in the simulation of the electron energy scale and of the resolution for leptons

3. Modeling of the jet energy resolution

4. Purity of the $Z$ sample
Figure 5.10: Comparison of the MPF response to EM scale jets as measured in the $Z \rightarrow \mu\mu$ channel. Results are shown for both data and a Monte Carlo sample which was produced with POWHEG and showered using PYTHIA 8. The ratio between data and the Monte Carlo prediction is shown in the lower inset. The statistical uncertainties of the individual measurements have been propagated to the ratio.

5. The amount of pile-up

6. Quality of the simulation models
Figure 5.11: Comparison of the MPF response to EM scale jets as measured in the $Z\rightarrow ee$ channel. Results are shown for both data and a Monte Carlo sample which was produced with POWHEG and showered through PYTHIA 8. The ratio between data and the Monte Carlo prediction is shown in the lower inset. The statistical uncertainties of the individual measurements have been propagated to the ratio.

5.4.1 Initial- and Final-state Radiation

Variation of the Sub-leading Jet Cut

To ensure that the $Z$ boson’s transverse momentum is an accurate representation of the leading jet’s momentum, events with additional jets with large momentum are vetoed. The sub-leading jet cut is varied between a looser value ($p^{jetz}_T < 12 \text{ GeV} + 0.1 \times p^Z_T$ or $p^{jetz}_T < 0.4 \times p^Z_T$) and a tighter value.
Figure 5.12: Variation of the MPF caused by changing the sub-leading jet cut in $Z \rightarrow \mu\mu$ for both data and the Monte Carlo prediction. Here Loose corresponds to a cut requiring the sub-leading jet $p_T$ to be less than $12 \text{ GeV} + 0.1 * p_T^Z$ or less than $0.3 * p_T^Z$. Tight corresponds to a cut requiring the sub-leading jet $p_T$ to be less than $10 \text{ GeV}$ or less than $0.2 * p_T^Z$. The statistical uncertainties of the individual measurements have been propagated to the ratio.

($p_T^{\text{jet}2} < 10 \text{ GeV}$ or $p_T^{\text{jet}2} < 0.2 * p_T^Z$). The effect of these variations on the measured EM scale jet response using the $Z \rightarrow \mu\mu$ selection can be seen in Fig. 5.12, and is shown to be quite small. The variation of the data to Monte Carlo prediction, which is the quantity put in to the jet calibration, can be seen in Fig. 5.13. With the exception of the lowest energy bin, the Monte Carlo prediction seems to do an excellent job of modeling the variations in response, with the largest variations being on
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Figure 5.13: Double ratio variations in data / Monte Carlo prediction caused by varying the sub-leading jet cut (J2). Definitions for Loose and Tight are consistent with those used in Fig. 5.12. The statistical uncertainties of the individual measurements have been propagated to the ratio.

the order of one percent. The effect of varying these cuts on the measured MPF response at LCW scale for Z→μμ can be seen in Fig. A.2. The effect on the response as measured in Z→ee at EM scale (see Fig. B.2) and LCW scale (Fig. C.2) have also been studied.

Variation of the Delta Phi Cut

The derivation of the MPF response shown in Sec. 4.3 relies heavily on the assumption that the parton and the Z boson have equal and opposite transverse momentum (see Eq. 4.5). In events with high-energy initial state radiation this assumption may not always be true. It has been shown in the analysis of γ+jet events that vetoing events where the jet and the photon are not produced back-to-back in ϕ significantly reduces the effects of initial state radiation [24]. In this thesis a similar approach is taken, where the Z boson is required to be produced back-to-back with the jet. The Δφ cut is treated very similarly to the sub-leading jet cut, where this cut is varied between a looser (Δφ(Z, jet) > 2.8) and tighter (Δφ(Z, jet) > 3.0) value. The effect that this variation of the cut has on the measured EM scale jet response using the Z→μμ selection can be seen in Fig. 5.14. The
resulting variations in the data to Monte Carlo prediction ratio, shown in Fig. 5.15, are seen to be larger than the variations seen when varying the subleading jet cut. The largest variations are still within one and a half percent. The effects of varying the $\Delta\phi$ on the measurement of the jet energy scale at LCW scale and also in the electron channel at both EM and LCW scale may be seen in Figs. A.4, B.4, and C.4 respectively.

Figure 5.14: Variation of the MPF caused by changing the $\Delta\phi$ cut in $Z \rightarrow \mu\mu$ for both data and the Monte Carlo prediction. Here, Loose corresponds to a cut requiring the opening angle in $\phi$ between the leading jet and the reconstructed Z to be greater than 2.8. Tight corresponds to requiring that the opening angle must be greater than 3.0. The statistical uncertainties of the individual measurements have been propagated to the ratio.
Figure 5.15: Double ratio variations in data / Monte Carlo prediction caused by varying the cut on the opening angle between the leading jet and the Z boson. Definitions for Loose and Tight are consistent with those used in Fig. 5.14. The statistical uncertainties of the individual measurements have been propagated to the ratio.

5.4.2 Lepton Energy Scale and Resolution

Smearing of the Lepton Energy

The electron reconstruction algorithm has been found to have a better energy resolution in the Monte Carlo prediction than in data. This is corrected by applying a Gaussian smearing factor to simulated electrons. A similar approach is used to correct the simulated muon $p_T$ resolution to match the data. The effects of varying the amount by which the energy of the electrons is shifted up and down within the uncertainty of the energy resolution in the data, and the effect on the resolution are found to be quite small (see Fig. 5.16). The muon $p_T$ smearing is also shifted up and down within the uncertainty of the resolution measurement, and the results may be seen in Fig. 5.17. The effect of lepton smearing on the measurement of the LCW jet energy scale is also studied, and the results may be seen in the appendix of this thesis.
In addition to the base EM energy scale which has been determined using test beam and Monte Carlo samples, a residual in-situ electron energy scale correction is applied. This energy scale is calibrated using the known Z, Y, and J/ψ mass peaks and the decays of these particles into an electron-positron pair [25]. This has been updated with 2011 and 2012 data. The electron energy scale is varied up and down within its uncertainty and the effect on the measured EM scale jet response is found to be less than one percent over the energy range considered (see Fig. 5.18).
5.4.3 Jet Energy Resolution

The jet energy resolution has been measured in-situ in ATLAS using dijet events. The measured jet energy resolution in data has been found to agree with the jet energy resolution seen in the Monte Carlo prediction [26]. The uncertainty of this measurement has been propagated to the uncertainty on the measured jet energy scale by smearing the jet energy in the Monte Carlo sample. The energy is smeared using a random number sampled from a Gaussian distribution centered at one, with a width given by $\sigma = \sqrt{(\sigma_{Data} + \Delta \sigma_{Data})^2 - \sigma_{Data}^2}$, where $\sigma_{Data}$ and $\Delta \sigma_{Data}$ are the measured jet...
Figure 5.18: Effect of varying the electron energy scale on the measurement of the MPF response of EM scale jets using the $Z \rightarrow ee$ selection. The statistical uncertainties of the individual measurements have been propagated to the ratio.

energy resolution and its uncertainty, respectively. The difference in measured response before and after smearing can be seen in Fig. 5.19, and this difference is taken as the systematic uncertainty due to the jet energy resolution.
5.4.4 *Z* Sample Purity - Dilepton Mass Cut

To ensure that the sample is as pure a *Z*-jet sample as possible, a cut requiring the selected leptons to have a combined invariant mass within 25 GeV of the *Z* mass peak has been applied. This cut is varied to include dilepton masses within 15 GeV or 35 GeV of the *Z* mass to assess the effects of any jets which may pass the *Z* → *ee* selection criteria. The resulting response measurement for EM scale jets using the *Z* → *µµ* selection can be seen in Fig. 5.20, while the effect on the relative data to Monte Carlo predicted response can be seen in Fig. 5.21. The effect of varying the *Z* mass cut is
found to be quite small, on the order of a few parts per thousand. The same result can be seen while using the $Z\rightarrow \mu\mu$ selection (see Fig. 5.22).

### 5.4.5 Pile-Up

To estimate the effect of pile-up on the measurement of the jet response using the MPF method, the stability of the jet response measurement as measured in different pile-up conditions is studied.
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**Figure 5.21:** Effect of varying the $Z$ mass cut on the relative data to Monte Carlo predicted EM scale jet energy scale response in $Z \rightarrow \mu\mu$. The statistical uncertainties of the individual measurements have been propagated to the ratio.

The amount of in-time pile-up present in a given event is generally measured using the number of reconstructed interaction vertices (NPV). The impact of in-time pile-up on the measurement of the jet response is studied by measuring the MPF in samples with different numbers of reconstructed vertices (NPV $\leq 10$ and NPV $> 10$). This separates the dataset into two subsets with approximately the same number of events (see Fig. 5.23). The amount of out-of-time pile-up is quantified by using *in-situ* measurements of the luminosity to obtain the average number ($\mu$) of visible pp interactions per bunch crossing; this average is taken over a lumi-block, where a lumi-block represents approximately two minutes of data taking. More specifically, $\mu$ is given by

$$\mu = L \cdot 0.00636/N_{\text{bunches}},$$  

(5.1)

where $L$ is the instantaneous luminosity in $mb^{-1}s^{-1}$ and $N_{\text{bunches}}$ is the number of bunches in the current fill of the LHC. The effect of $\mu$ on the measured response has been studied by separating the data into two samples of approximately the same size labeled high-$\mu$ and low-$\mu$ (see Fig. 5.24). High and low are defined as being greater than or less than 16, and events where $\mu$ is equal to 16 are considered low-$\mu$. 

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Figure 5.22: Effect of varying the Z mass cut to a looser and tighter values on the measured EM scale MPF response in $Z \rightarrow e e$. The statistical uncertainties of the individual measurements have been propagated to the ratio.

It should be noted that $\mu$ is affected by both in-time and out-of-time pile-up. The measured responses at high/low $\mu$ and NPV can be seen in Fig. 5.25, while the effect on the relative data to the Monte Carlo predicted response can be seen in Fig. 5.26. As these two quantities are highly correlated, the uncertainty is estimated by taking the largest variation up and down of the relative response between $\mu$ and NPV.

5.4.6 Monte Carlo Generator

The response derived in the Monte Carlo sample is dependent on the underlying model used in generating the simulated data. This study uses events generated with POWHEG, a next-to-leading order two-parton to two-parton event generator [21]. The uncertainty associated with this choice has been studied by deriving the MPF response using a second Monte Carlo sample which has been generated using Alpgen, a leading order multi-parton generator, and subsequently showered using HERWIG/JIMMY, which uses a cluster hadronization model. This model takes advantage of the fact that the partons within the hadronic shower combine into colour-less groups with an invariant mass distribution which in independent of the scale at which the original process occurred [27]. The
Figure 5.23: Number of reconstructed vertices per event using the $Z \rightarrow \mu \mu$ selection.

Figure 5.24: Average number of visible pp interactions per bunch crossing using $Z \rightarrow \mu \mu$ selection.
Figure 5.25: Effect of pile-up on the MPF response as measured in $Z \rightarrow \mu\mu$. High / low NPV is defined by a NPV being greater or less than 10, and high / low $\mu$ is defined as being greater or less than 16.

response calculated using both samples can be seen in Fig. 5.27, and the difference between these two samples has been taken as an asymmetric systematic uncertainty.

5.4.7 Results

All sources of systematic uncertainty discussed in this chapter have been added in quadrature. The resulting total systematic uncertainty along with the individual components may be seen in Fig. 5.28 for the EM scale. The systematic uncertainty is large (4-6%) in the lowest $p_T$ bin (17-22 GeV),
where the jet reconstruction threshold of 10 GeV has the largest effect on the measurement. It is also large in the highest $p_T$ bin (400-800 GeV) where statistics are quite low. Uncertainties are 2-3% for jets in the 22-50 GeV range before dropping to less than 1% for 50-400 GeV. Fig. 5.28 also shows the data to Monte Carlo prediction ratio (lower inset in Fig. 5.10), along with the combined statistical uncertainty on the measurements. Data and Monte Carlo simulations are found to agree within uncertainty.

All sources of systematic uncertainty discussed in this section have also been determined for LCW scale jets using Z+jet events where the Z decays to a pair of muons (see appendix A). The contributions are summed in quadrature and the final results are shown in Fig. 5.29. While there is a smaller uncertainty associated with jet energy resolution for LCW jets, the pile-up uncertainty is larger leading to a total systematic uncertainty which is comparable to that of EM scale jets. The reduction in size of the effect of jet energy resolution on the jet energy response may be a direct consequence of the improved jet energy resolution associated with LCW jets. One possible explanation of the larger pile-up uncertainty for LCW jets is that the LCW algorithm may be identifying pile-up energy within the jet as being hadronic energy and giving it additional weight.
Figure 5.27: The MPF has been measured with Monte Carlo samples generated by both POWHEG which has been showered using Pythia, and Alpgen showered using Herwig. The difference between Monte Carlo samples is taken to be a systematic uncertainty associated with the Monte Carlo generator choice.

Both EM and LCW scale jets have been measured using Z+jet where the Z decays to a pair of electrons (see appendices B and C). The combined systematic errors for are shown in Figs. 5.32 and 5.33 respectively. POWHEG+PYTHIA has been found to predict a lower jet response than is observed in data at both EM and LCW scale. For EM scale, POWHEG+PYTHIA predicts a jet response which is on the order of one to two percent lower than the response measured in data in the
two lowest $p_T$ bins. For events with $p_T^Z$ greater than 27 GeV the predicted value agrees with data within statistical uncertainty. At LCW scale the discrepancy is larger, nearly five percent at low $p_T$, only beginning to agree with data for $p_T^Z$ greater then 70 GeV. Attempts to resolve this issue include varying the electron selection from medium++ to tight++, and tightening the electron energy and $p_T$ isolation requirements to 10% of the measured lepton value in order to better eliminate jets faking electrons. While these additional requirements remove a large number of events (from approximately 36 000 to 28 000 using LCW jets in **POWHEG+PYTHIA** sample), they have very little effect on the data to Monte Carlo predicted response measurement (see fig. 5.30).

While the **POWHEG+PYTHIA** sample does not agree with data, the Alpgen+**HERWIG/JIMMY** sample does reproduce the jet response at both EM and LCW scales in this channel (see Figs. B.13 and C.13). In a second attempt to resolve this issue a sample generated with a third independent event generator has been studied. Sherpa is a leading order multi-parton generator which uses the
Figure 5.29: Combined systematic uncertainties on the measurement of the residual in situ jet energy scale correction at LCW scale in $Z \rightarrow \mu\mu$. Black points represent the data / Monte Carlo prediction ratio.

Despite this disagreement the combined systematic uncertainty obtained at EM scale is on the order of one to two percent for jets in the intermediate $p_T$ range (35-200 GeV) (Fig. 5.32). The dominant sources of uncertainty in this region are due to pile-up and the disagreement between the two Monte Carlo generators which have been compared to data. While the EM jet response measurement has a relatively small systematic uncertainty, the LCW scale measurement suffers from the large discrepancy between the different Monte Carlo generators. The total combined systematic uncertainty is on the order of five percent at low $p_T$ and between one to three percent between 40-150 GeV.
Figure 5.30: Jet response at LCW scale using the MPF method on Zee+jet event. Nominal isolation refers to an energy isolation cut requiring less than 15% of the electron energy within a cone of radius 0.3 and less than 14% of the track $p_T$ in a cone of radius 0.3. Tight isolation requires less than 10% of the electrons energy and track $p_T$ within a cone of radius 0.3. The statistical uncertainties of the individual measurements have been propagated to the ratio.
Figure 5.31: Jet response at LCW scale using the MPF method on Zee+jet event. Results derived using data, Sherpa, POWHEG+PYTHIA and Alpgen+HERWIG/JIMMY are compared.
Figure 5.32: Combined systematic uncertainties on the measurement of the residual in-situ jet energy scale correction at EM scale in $Z\rightarrow\text{ee}$. Black points represent the data / Monte Carlo ratio.
Figure 5.33: Combined systematic uncertainties on the measurement of the residual in situ jet energy scale correction at LCW scale in $Z \rightarrow ee$. Black points represent the data / Monte Carlo ratio.
Chapter 6

Separating the Quark and Gluon Responses

6.1 Motivation

Differences in the fragmentation of light-quarks and gluons lead to a parton-dependent jet energy scale [19]. As gluon-initiated jets tend to contain a higher number of low energy particles (see Fig. 6.1), they are expected to have a lower average response. For EM scale jets the response difference between quark- and gluon-initiated jets is expected to be on the order of 5-10% for jets at low $p_T$ (up to 100-200 GeV [28]). Failing to account for this will affect both the uncertainty on the measured jet energy scale, as well as the measured jet energy resolution. By measuring the jet energy scale using independent samples with different fractions of gluon-initiated jets one should be able to extract this difference in response. In this thesis, the jet energy scale measured in $(Z\rightarrow \mu\mu)$+jet events (described in the previous section) is compared with the response measured in a $\gamma$+jet sample.

6.2 Separation

Measurements of the jet response using $\gamma$+jet or Z+jet samples are in fact measurements of combinations of the quark- and gluon-initiated jet response. The measured response can be written as

$$R_X = R_{\text{gluon}} f_{\text{gluon}} X + R_{\text{quark}} f_{\text{quark}} X,$$  \hspace{1cm} (6.1)
CHAPTER 6. SEPARATING THE QUARK AND GLUON RESPONSES

Figure 6.1: Differences in number of tracks and track width vs. $p_T$ between quark- and gluon-initiated jets. In this study width $W$ is defined as $W = \Sigma p_T x \Delta R_i / \Sigma p_T_i$. Plots taken from Ref. [19].

where $R_X$ is the measured response in an X+jet sample, $R_{\text{gluon}}$ and $R_{\text{quark}}$ are the gluon and quark jet responses, and $f_X^{\text{gluon}}$ and $f_X^{\text{quark}}$ are the fractions of X+jet events where the jet is initiated by a gluon or a quark, respectively. $f_X^{\text{gluon}}$ and $f_X^{\text{quark}}$ are taken from Monte Carlo simulations, while $R_X$ can be determined from either data or Monte Carlo samples. By measuring the response using two samples with known and different parton compositions ($\gamma$ and $Z$+jet in this study), the response of quark and gluon jets may be separated by rearranging Eq. 6.1 into

$$R_{\text{gluon}} = \frac{R_Z f_{\text{quark}}^Z - R_{\gamma} f_{\text{quark}}^{\gamma}}{f_{\text{gluon}}^Z - f_{\text{gluon}}^{\gamma}} \tag{6.2}$$

$$R_{\text{quark}} = \frac{R_Z f_{\text{gluon}}^Z - R_{\gamma} f_{\text{gluon}}^{\gamma}}{f_{\text{quark}}^Z - f_{\text{quark}}^{\gamma}} \tag{6.3}$$

6.3 $\gamma$+jet

Photons create electromagnetic showers inside of the calorimeter, in much the same way as electrons (see Sec. 2.2.4). As a result of this, photon reconstruction has many points in common with
electron reconstruction. Photon candidates are selected using a sliding window clustering algorithm (see Sec 3.1.1). To remove events where a jet fakes a photon, photons are required to pass a set of so called ‘tight’ requirements. These tight requirements are similar to the tight electron requirements. Furthermore the energy contained within a cone of radius 0.4 around the photon, excluding the energy of the photon itself, is required to be less than 3 GeV to avoid jets faking photons.

Figure 6.2: Comparison of the MPF response to EM scale jets in the Z→µµ and γ+jet channels determined using Monte Carlo simulation. γ+jet results are calculated using a pure Pythia8 sample, while Z→µµ results are calculated using a sample generated using Powheg and subsequently showered using Pythia8.
In order to keep the samples as consistent as possible, the requirements imposed on the jet (size, jet vertex fraction, bad/ugly jets) have been chosen to be consistent with those used in the Z+jet samples. To remove photons from the jet collection, any jet closer than $\Delta R = 0.3$ to the reconstructed photon is removed from the jet collection. To reduce the effects of ISR and FSR, the photon is required to be produced back-to-back in the transverse plane with the leading jet ($\Delta \phi > 2.9$) and events with a high $p_T$ second jet (above 15 GeV and above 30% of the photon’s $p_T$) are rejected. Upon passing this selection, events are sorted into bins of photon $p_T$, where the response is measured using the same procedure described in Sec. 5.3. To accommodate the low statistics at low $p_T$ due to the large prescaling in $\gamma$+jet trigger, larger $p_T$ bins have been used for this case. The resulting response measurements, as well as the response measured in $Z \to \mu\mu$ using these larger bins, for Monte Carlo simulations can be seen in Fig. 6.2.

### 6.4 Monte Carlo

The use of this method to isolate the quark- and gluon-initiated jet responses requires a knowledge of the quark/gluon composition of each sample.

Truth particle information in the Monte Carlo sample is used to identify the partonic origin of jets, where jets are classified according to the highest energy parton within the jet definition at generator level. This successfully tags all jets in the Monte Carlo samples, and the resulting sample compositions can be seen in Fig. 6.3.

The samples are divided into quark and gluon sub-samples, and a measurement of quark and gluon jets which have been showered using Pythia 8 can be performed, the results of which are shown in Fig. 6.4. As $\gamma$+jet is very nearly a pure quark jet sample (see Fig. 6.6), the truth tagged gluon response in this channel has a very large statistical uncertainty.
Figure 6.3: Inclusive quark/gluon composition of the leading jet as seen in $\gamma$+jet and $Z$+jet samples for events having passed the nominal selection criteria for pure Pythia8 and Powheg+Pythia8 samples, respectively.
Figure 6.4: Response of jets which have been tagged as being initiated by either a quark or a gluon, shown for the $\gamma$ and Z+jet MC samples.
Figure 6.5: MPF response to EM scale jets measured in both $\gamma$+jet and $Z$+jet. The response has been fit using the functional form shown in Eq. 4.4.
CHAPTER 6. SEPARATING THE QUARK AND GLUON RESPONSES

To reduce the effects of statistical fluctuations on the determination of a parton-dependent jet response the measured responses in both $\gamma$ and Z+jet have been fitted using the functional form of the response in Eq. 4.4 (seen in Fig. 6.5). The value of the fitted function at the central value of each bin is taken to be the true response. The fraction of jets initiated by gluons within each $p_T$ bin used to measure the response is then determined. To further reduce the effects of any statistical fluctuations, the $p_T$ dependence on the fraction of jets initiated by gluons in Z+jet has been fitted to an inverted exponential ($ae^{b/x}$) which follows the data (see Fig. 6.6). There is no noticeable trend in the $\gamma$+jet sample, so the data points themselves have been used.

The quark and gluon responses are separated using the process discussed in Sec. 6.2. A rough analysis is performed in order to estimate the effect of the statistical uncertainty associated with the measurement of the jet response in the $\gamma$ and Z+jet channels. The measured jet response within all $p_T$ bins is shifted up within the uncertainty on the mean of the Gaussian by which it was obtained. These raised values are then fitted once again using the functional form of the response in Eq. 4.4. New fits are also performed upon varying the measured values down by one sigma. The parton-dependent jet response reconstructions are performed using each of these varied fits and the differences between each varied curve and the nominal values are taken to be independent sources of uncertainty. The uncertainties are added in quadrature, and the largest error (up or down) is taken as a new symmetric error for that bin. The resulting parton-dependent responses and error bars can be seen in Fig. 6.7.

The reconstructed gluon jet response agrees with the measured truth tagged gluon response within uncertainty, although due to the relatively low number of gluon initiated jets in both samples the error bars on the reconstructed values are rather large (on the order of 4%). The statistical error bars on the reconstructed gluon jet response are also large (4-5%) despite the small size of the statistical errors on the measured $\gamma$ and Z+jet response (0.5-1%). The reconstructed quark jet response also agrees with the truth tagged quark response within statistical uncertainty over the entire $p_T$ range considered.
Figure 6.6: Fraction of jets initiated by gluons as a function of $p_T$ for both $\gamma$ and $Z$+jet events.
CHAPTER 6. SEPARATING THE QUARK AND GLUON RESPONSES

Figure 6.7: Comparison of the truth tagged quark and gluon jet responses to the quark and gluon responses which have been reconstructed using the Z and γ+jet response curves.
### 6.5 Data

The $\gamma$+jet selection described above has been used to determine the MPF response using 6.2 fb$^{-1}$ of 8 TeV 2012 data (Fig. 6.8). Due to the large number of $\gamma$+jet events at low $p_T^\gamma$, low threshold triggers have been highly prescaled. To take advantage of these low trigger thresholds as well as the low prescaling of higher energy triggers, events have been separated into $p_T^\gamma$ bins with events in each bin being required to pass a selected trigger. To reduce the effect of possible trigger inefficiencies at the trigger threshold, the lower range of each $p_T$ bin has been selected to be 5-10 GeV above the corresponding trigger threshold. Additional weight is applied to events within each bin in order to undo the prescaling.

As mentioned, at very low $p_T^\gamma$, $\gamma$+jet suffers from dijet contamination. In these events one of the jets passes all of the photon selection criteria. As this 'fake' photon is in fact a jet, it has a lower response than a true photon, causing the measured response to be artificially higher than the true jet response. This is observed in Fig. 6.8 for events where the $p_T$ of the photon is less than 60 GeV.

By combining the in-situ jet response measurements with the Monte Carlo based measurements of the jet composition of the two samples, a measurement of the parton-dependent jet response in data is made. The results, in Fig. 6.9, show a difference in the response of quark-initiated jet and gluon-initiated jets of 11% for 50 GeV jets. This difference decreases to as low as seven to eight percent at 150 GeV. The statistical uncertainties have been estimated using the same technique used in the purely Monte Carlo response separation. The statistical errors on the gluon-initiated jet response are quite large, ranging from 2-5% between 50 and 150 GeV. The resulting parton-

<table>
<thead>
<tr>
<th>Trigger Threshold (GeV)</th>
<th>$p_T^\gamma$ Range (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>25 - 45</td>
</tr>
<tr>
<td>40</td>
<td>45 - 65</td>
</tr>
<tr>
<td>60</td>
<td>65 - 85</td>
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<tr>
<td>80</td>
<td>85 - 110</td>
</tr>
<tr>
<td>100</td>
<td>110 - 125</td>
</tr>
<tr>
<td>120</td>
<td>125 - inf</td>
</tr>
</tbody>
</table>

Table 6.1: Binned $\gamma$+jet trigger thresholds.
Figure 6.8: Comparison of the MPF response to EM scale jets in the $Z \rightarrow \mu \mu$ and $\gamma + \text{jet}$ channels as measured using $6.2 \text{ fb}^{-1}$ of 8 TeV data.

dependent response curves are compared to Monte Carlo predictions in Fig. 6.10.
Figure 6.9: Reconstructed quark and gluon response. Results have been calculated using Monte Carlo to derive the fraction of jets initiated by gluons, and using $6.2 \text{ fb}^{-1}$ of 8 TeV data to derive the $Z$ and $\gamma$ sample jet responses.
Figure 6.10: Data Monte Carlo comparison between parton-dependent jet responses.
Chapter 7

Conclusion

Jets are the most abundantly produced physics objects created in high-energy proton-proton collisions. As a result, a precise knowledge of the jet energy scale is essential to the success of ATLAS. In this thesis the jet energy scale is measured using the missing transverse energy projection fraction method applied to Z+jet events. Cases where the Z boson decays into an electron-positron pair, as well as into a pair of muons are considered. In both cases the jet response has been determined using jets which have been reconstructed at EM and LCW scale. In all cases, in-situ results are found to agree with simulation within uncertainty.

This study will be extended to include the full 20 fb$^{-1}$ of 8 TeV data taken in 2012. Along with a reduction on the statistical uncertainty of the response measurement, the varying pile-up conditions on the additional data will allow for better exploration of the effects of pile-up on the measurement itself. The full data set may also be large enough to allow for accurate measurements of the jet response in the forward regions of the calorimeter, which would be combined with dijet and gamma jet measurements to decrease the uncertainty on the jet energy scale at larger pseudorapidities.

Jets initiated by gluons tend to contain a higher number of lower energy particles compared to jets initiated by light quarks. This results in gluon-initiated jets having a lower response. By comparing response measurements performed in channels with different fractions of events being initiated by gluons, a parton-dependent jet response can be obtained. In this thesis a Monte Carlo based study has been performed using γ+jet and Z+jet samples, as well as a preliminary data-based measurement. While results consistent with expectation have been achieved, large statistical errors
are present in the gluon jet response measurement due to the low fraction of gluon jets in the $\gamma$+jet sample. Improved parton-dependent responses may be obtained by including additional jet response measurements derived in channels with differing quark/gluon composition (dijets for example).
Appendix A

MPF Response at LCW scale in $Z \rightarrow \mu\mu$

The LC scale jet response at ATLAS has been measured using the missing transverse energy projection fraction technique using $Z$+jet events where the $Z$ subsequently decays into a pair of muons. This measurement has been performed using a 6.2 fb$^{-1}$ sample of 8 TeV pp data collected in 2012. The results are compared to a Monte Carlo sample which has been generated using Powheg+Pythia. A variety of studies have been performed to evaluate the systematic uncertainties associated with these measurements. This appendix contains figures displaying the details of these studies, the results of which are summed together and shown in Fig. 5.29.
Figure A.1: Comparison of the MPF response to LCW scale jets as measured in the Z→μμ channel. Results are shown for both data and a Monte Carlo sample which was produced with Powheg and showered using Pythia 8. The ratio between data and the Monte Carlo prediction is shown in the lower inset. The statistical uncertainties of the individual measurements have been propagated to the ratio.
Figure A.2: Variation of the LCW scale MPF response caused by changing the sub-leading jet cut using $Z \to \mu \mu$ events for both data and the Monte Carlo prediction. Here Loose corresponds to a cut requiring the sub-leading jet $p_T$ to be less than $12 \text{ GeV} + 0.1 \times p_T^Z$ or less than $0.4 \times p_T^Z$. Tight corresponds to a cut requiring the sub-leading jet $p_T$ to be less than $10 \text{ GeV}$ or less than $0.2 \times p_T^Z$. 
Figure A.3: Double ratio variations in data / Monte Carlo prediction caused by varying the sub-leading jet cut (J2). Definitions for Loose and Tight are consistent with those used in Fig. A.2.
Figure A.4: Variation of the MPF caused by changing the $\Delta \phi$ cut in $Z \to \mu\mu$ for both data and the Monte Carlo prediction. Here Loose corresponds to a cut requiring the opening angle in $\phi$ between the leading jet and the reconstructed $Z$ to be greater than 2.8. Tight corresponds to requiring that the opening angle must be greater than 3.0.
Figure A.5: Double ratio variations in data/MC prediction caused by varying the cut on the opening angle between the leading jet and the Z boson. Definitions for Loose and Tight are consistent with those used in Fig. A.4.
Figure A.6: The reconstructed muon momentum in the Monte Carlo sample is ‘smeared’ to account for the differences in resolution in the muon $P_T$ measurement between data and the Monte Carlo prediction. The amount by which the simulated muon $p_T$ is smeared is varied and found to have very little effect on the measured MPF response.
Figure A.7: Effect of smearing the Monte Carlo jet energy resolution within the uncertainty on the resolution observed in data on the MPF response.
Figure A.8: The possibility of signal contamination is explored by varying the size of the window around the Z mass which is considered to be a Z boson. The Loose selection requires the reconstructed Z boson to have a mass within 35 GeV of the Z pole mass at 91 GeV. The Tight selection requires that the Z mass is within 15 GeV of the pole mass.
Figure A.9: Double ratio variation in the data / Monte Carlo prediction response caused by varying the Z mass cut for LCW scale jets using $Z\rightarrow \mu\mu +$ jet events.
Figure A.10: Effect of pile-up on the MPF response as measured in $Z \rightarrow \mu\mu$. High / low NPV is defined by a NPV being greater or less than 10, and high / low $\mu$ is defined as being greater or less than 16.
Figure A.11: Effect of pile-up on the relative data / Monte Carlo prediction MPF response. Definitions of how the quantities are varied can be seen in Fig. A.10.
Figure A.12: The MPF has been measured with Monte Carlo samples generated by both Powheg which has been showered using Pythia and Alpgen showered using Herwig. The difference between Monte Carlo samples is taken to be a systematic uncertainty on the current calibration scheme used in ATLAS.
Figure A.13: Combined systematic uncertainties on the measurement of the residual in situ jet energy scale correction at LCW scale in $Z \rightarrow \mu\mu$. Black points represent the data / Monte Carlo prediction ratio.
Appendix B

MPF Response at EM scale in $Z \rightarrow ee$

The EM scale jet response at ATLAS has been measured using the missing transverse energy projection fraction technique using $Z+\text{jet}$ events where the $Z$ subsequently decays into a pair of electrons. This measurement has been performed using a 6.2 fb$^{-1}$ sample of 8 TeV pp data collected in 2012. The results are compared to a Monte Carlo sample which has been generated using Powheg+Pythia. A variety of studies have been performed to evaluate the systematic uncertainties associated with these measurements. This appendix contains figures displaying the details of these studies, the results of which are summed together and shown in Fig. 5.32.
Figure B.1: Comparison of the MPF response to EM scale jets as measured in the $Z \rightarrow ee$ channel. Results are shown for both data and a Monte Carlo sample which was produced with Powheg and showered using Pythia 8. The ratio between data and the Monte Carlo prediction is shown in the lower inset. The statistical uncertainties of the individual measurements have been propagated to the ratio.
Figure B.2: Variation of the MPF caused by changing the subleading jet cut in $Z \rightarrow ee$ for both data and the Monte Carlo prediction. Here Loose corresponds to a cut requiring the subleading jet $P_T$ to be less than $12$ GeV + $0.1 \times P_T^Z$ or less than $0.4 \times P_T^Z$. Tight corresponds to a cut requiring the subleading jet $P_T$ to be less than $10$ GeV or less than $0.2 \times P_T^Z$. 
## APPENDIX B. MPF RESPONSE AT EM SCALE IN $Z \rightarrow ee$

Figure B.3: Variations in data / Monte Carlo prediction ratio caused by varying the subleading jet cut (J2). Definitions for Loose and Tight are consistent with those used in Fig. B.2.
Figure B.4: Variation of the MPF caused by changing the $\Delta\phi$ cut in $Z\rightarrow ee$ for both data and the Monte Carlo prediction. Here Loose corresponds to a cut requiring the opening angle in $\phi$ between the leading jet and the reconstructed $Z$ must be greater than 2.8. Tight corresponds to requiring that the opening angle must be greater than 3.0.
Figure B.5: Variations in data / Monte Carlo prediction ratio caused by varying the cut on the opening angle between the leading jet and the Z boson. Definitions for Loose and Tight are consistent with those used in Fig. B.4.
Figure B.6: Variation of the MPF caused by changing the $\Delta \phi$ cut in $Z \rightarrow ee$ for both data and the Monte Carlo prediction. Here Loose corresponds to a cut requiring the opening angle in $\phi$ between the leading jet and the reconstructed $Z$ must be greater than 2.8. Tight corresponds to requiring that the opening angle must be greater than 3.0.
APPENDIX B. MPF RESPONSE AT EM SCALE IN Z→ ee

Figure B.7: The reconstructed electron energy in Monte Carlo simulation is ‘smeared’ to account for the differences in resolution in the electron energy measurement between data and the Monte Carlo prediction. The amount by which Monte Carlo simulated electron energy is smeared is varied and found to have very little effect on the measured MPF response.
Figure B.8: Jets in Monte Carlo generated samples have been found to have a better resolution than jets in data. To account for this the jet energy in Monte Carlo simulation is ‘smeared’ to better simulate the resolution seen in data.
Figure B.9: The possibility of signal contamination is explored by varying the size of the window around the Z mass which is considered to be a Z boson. The Loose selection requires the reconstructed Z boson to have a mass within 35 GeV of the Z pole mass at 91 GeV. The Tight selection requires that the Z mass is within 15 GeV of the pole mass.
Figure B.10: Only very small variations in the ratio of the data / Monte Carlo prediction MPF responses are seen while varying the Z mass cut.
Figure B.11: Effect of pile-up on the MPF response as measured in $Z \to ee$. High / low NPV is defined by a NPV being greater or less than 10, and high / low $\mu$ is defined as being greater or less than 16.
Figure B.12: Effect of pile-up on the relative data / Monte Carlo prediction MPF response. Definitions of how the quantities are varied can be seen in Fig. /refZeeEMPile.
Figure B.13: The MPF has been measured with Monte Carlo samples generated by both Powheg which has been showered using Pythia and Alpgen showered using Herwig. The difference between Monte Carlo samples is taken to be a systematic uncertainty on the current calibration scheme used in ATLAS.
Figure B.14: Combined systematic uncertainties on the measurement of the residual in situ jet energy scale correction at EM scale in Z→ee. Black points represent the data / Monte Carlo prediction ratio.
Appendix C

MPF Response at LCW scale in Z→ ee

The LC scale jet response at ATLAS has been measured using the missing transverse energy projection fraction technique using Z+jet events where the Z subsequently decays into a pair of electrons. This measurement has been performed using a 6.2 fb$^{-1}$ sample of 8 TeV pp data collected in 2012. The results are compared to a Monte Carlo sample which has been generated using Powheg+Pythia. A variety of studies have been performed to evaluate the systematic uncertainties associated with these measurements. This appendix contains figures displaying the details of these studies, the results of which are summed together and shown in Fig. 5.33.
Figure C.1: Comparison of the MPF response to LCW scale jets as measured in the $Z \to ee$ channel. Results are shown for both data and a Monte Carlo sample which was produced with Powheg and showered using Pythia 8. The ratio between data and the Monte Carlo prediction is shown in the lower inset. The statistical uncertainties of the individual measurements have been propagated to the ratio.
Figure C.2: Variation of the MPF caused by changing the subleading jet cut in $Z \rightarrow ee$ for both data and the Monte Carlo prediction. Here Loose corresponds to a cut requiring the subleading jet $P_T$ to be less than $12 \text{ GeV} + 0.1 * P_T^Z$ or less than $0.4 * P_T^Z$. Tight corresponds to a cut requiring the subleading jet $P_T$ to be less than $10 \text{ GeV}$ or less than $0.2 * P_T^Z$. 
Figure C.3: Variations in data / Monte Carlo prediction ratio caused by varying the subleading jet cut (J2). Definitions for Loose and Tight are consistent with those used in Fig. C.2.
Figure C.4: Variation of the MPF caused by changing the Δφ cut in $Z \rightarrow ee$ for both data and the Monte Carlo prediction. Here Loose corresponds to a cut requiring the opening angle in φ between the leading jet and the reconstructed Z must be greater than 2.8. Tight corresponds to requiring that the opening angle must be greater than 3.0.
Figure C.5: Variations in the data / Monte Carlo prediction ratio caused by varying the cut on the opening angle between the leading jet and the Z boson. Definitions for Loose and Tight are consistent with those used in Fig. C.4.
Figure C.6: Variation of the MPF caused by changing the Δφ cut in Z→ee for both data and the Monte Carlo prediction. Here Loose corresponds to a cut requiring the opening angle in φ between the leading jet and the reconstructed Z must be greater than 2.8. Tight corresponds to requiring that the opening angle must be greater than 3.0.
Figure C.7: The reconstructed electron energy in the Monte Carlo sample is ‘smeared’ to account for the differences in resolution in the electron energy measurement between data and the Monte Carlo prediction. The amount by which the simulated electrons are smeared is varied and found to have very little effect on the measured MPF response.
Figure C.8: Jets in the Monte Carlo sample have been found to have a better resolution than jets in data. To account for this, the jet energy in the Monte Carlo sample is ‘smeared’ to better simulate the resolution seen in data.
Figure C.9: The possibility of signal contamination is explored by varying the size of the window around the Z mass which is considered to be a Z boson. The Loose selection requires the reconstructed Z boson to have a mass within 35 GeV of the Z pole mass at 91 GeV. The Tight selection requires that the Z mass is within 15 GeV of the pole mass.
Figure C.10: Only very small variations in the ratio of the data / Monte Carlo predicted MPF responses are seen while varying the Z mass cut.
Figure C.11: Effect of pile-up on the MPF response as measured in $Z\rightarrow ee$. High / low NPV is defined by a NPV being greater or less than 10, and high / low $\mu$ is defined as being greater or less than 16.
Figure C.12: Effect of pile-up on the relative data / Monte Carlo predicted MPF response. Definitions of how the quantities are varied can be seen in Fig. /refZeeLCPile.
Figure C.13: The MPF has been measured with Monte Carlo samples generated by both Powheg which has been showered using Pythia and Alpgen showered using Herwig. The difference between Monte Carlo samples is taken to be a systematic uncertainty on the current calibration scheme used in ATLAS.
Figure C.14: Combined systematic uncertainties on the measurement of the residual in situ jet energy scale correction at LCW scale in $Z \rightarrow ee$. Black points represent the data / Monte Carlo prediction ratio.
Appendix D

Medium Electron Selection

In this thesis electrons are required to pass the medium++ selection. Contained within this appendix are the details on the energy/$\eta$ dependent cuts associated with the medium++ selection. Some of these cuts take advantage of the relative sizes of the hadronic interaction length and the electron radiation length, which leads to the tendency of hadronic showers to penetrate deeper into the calorimeter. These cuts include the ratio of energy contained in the EM calorimeter as compared to the hadronic calorimeter (see Table D.1) and the fraction of the total energy contained in the final layer of the EM calorimeter (see Table D.2). Other cuts take advantage of the relative narrowness of EM showers compared to hadronic showers. One such cut puts restrictions on the ratio of the energy contained in a 3x7 cluster as compared to a 7x7 cluster centered on the energy deposit (see Table D.3). Cuts are also applied on the RMS width of the energy deposit in $\eta$ in the strip layer (Table D.5) and middle layer (Table D.4) of the EM calorimeter. A final cut to remove neutral pions which decay into a pair of photons is applied, which uses the narrow strips of the inner most layer of the EM calorimeter to distinguish a one EM object shower Vs. a two EM object shower (Table D.6).
| $E_T$ | $|\eta|$ | 0.0-0.1 | 0.1-0.6 | 0.6-0.8 | 0.8-1.15 | 1.15-1.37 | 1.37-1.52 | 1.52-1.81 | 1.81-2.01 | 2.01-2.37 | 2.37-2.47 |
|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| < 5 GeV | 0.0-0.1 | 0.12800 | 0.15600 | 0.15200 | 0.11600 | 0.15600 | 0.04275 | 0.13200 | 0.15200 | 0.15600 | 0.14000 |
| 5-10 GeV | 0.12800 | 0.15600 | 0.15200 | 0.11600 | 0.15600 | 0.04275 | 0.13200 | 0.15200 | 0.15600 | 0.14000 |
| 10-15 GeV | 0.03225 | 0.03225 | 0.03075 | 0.03575 | 0.02575 | 0.02575 | 0.04275 | 0.04325 | 0.04525 | 0.04325 | 0.03675 |
| 15-20 GeV | 0.02925 | 0.02925 | 0.02775 | 0.03175 | 0.02375 | 0.03875 | 0.03875 | 0.04025 | 0.03425 | 0.03825 | 0.02975 |
| 20-30 GeV | 0.02425 | 0.02425 | 0.02275 | 0.02575 | 0.01975 | 0.01975 | 0.02725 | 0.02725 | 0.02725 | 0.02725 | 0.01975 |
| 30-40 GeV | 0.02275 | 0.02275 | 0.02125 | 0.01975 | 0.01825 | 0.01825 | 0.02425 | 0.02575 | 0.02425 | 0.02425 | 0.01675 |
| 40-50 GeV | 0.01825 | 0.01825 | 0.01975 | 0.01525 | 0.01675 | 0.01675 | 0.02125 | 0.02275 | 0.01975 | 0.01675 |
| 50-60 GeV | 0.01825 | 0.01825 | 0.01975 | 0.01525 | 0.01675 | 0.01675 | 0.02125 | 0.02275 | 0.01975 | 0.01675 |
| 60-70 GeV | 0.01825 | 0.01825 | 0.01975 | 0.01525 | 0.01675 | 0.01675 | 0.02125 | 0.02275 | 0.01975 | 0.01675 |
| 70-80 GeV | 0.01825 | 0.01825 | 0.01975 | 0.01525 | 0.01675 | 0.01675 | 0.02125 | 0.02275 | 0.01975 | 0.01675 |
| > 80 GeV | 0.01825 | 0.01825 | 0.01975 | 0.01525 | 0.01675 | 0.01675 | 0.02125 | 0.02275 | 0.01975 | 0.01675 |

Table D.1: Cuts on the fraction of the electron candidate energy contained in the hadronic calorimeter for medium++ electrons.
Table D.2: The maximum fraction of the electrons energy which can be present in the 3rd layer of the EM calorimeter.
Table D.3: Cuts on the ratio of energy contained within a 3x7 cluster as compared to a 7x7 cluster for medium++ electrons.
Table D.4: Cuts on the RMS width of the energy deposit in $\eta$ of the energy deposition in the middle layer of the EM calorimeter for medium++ electrons.
Table D.5: Cuts on the RMS width of the energy deposit in $\eta$ of the energy deposition in the strip layer of the EM calorimeter for medium++ electrons.

| $E_T$ | $|\eta|$ | 0.0-0.1 | 0.1-0.6 | 0.6-0.8 | 0.8-1.15 | 1.15-1.37 | 1.37-1.52 | 1.52-1.81 | 1.81-2.01 | 2.01-2.37 | 2.37-2.47 |
|-------|----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| < 5 GeV | 0.0-0.1 | 3.48    | 3.48    | 3.78    | 3.96    | 4.20    | 9999.   | 4.02    | 2.70    | 1.86    | 9999.   |
| 5-10 GeV | 0.0-0.1 | 3.18    | 3.18    | 3.54    | 3.90    | 4.02    | 9999.   | 3.96    | 2.70    | 1.80    | 9999.   |
| 10-15 GeV | 0.0-0.1 | 2.85    | 2.85    | 3.2     | 3.4     | 3.6     | 9999.0  | 3.7     | 2.4     | 1.72    | 9999.0  |
| 15-20 GeV | 0.0-0.1 | 2.76    | 2.76    | 2.92    | 3.3     | 3.45    | 9999.0  | 3.67    | 2.4     | 1.72    | 9999.0  |
| 20-30 GeV | 0.0-0.1 | 2.5     | 2.5     | 2.65    | 3.0     | 3.2     | 9999.0  | 3.3     | 2.15    | 1.49    | 9999.0  |
| 30-40 GeV | 0.0-0.1 | 2.5     | 2.5     | 2.65    | 3.0     | 3.2     | 9999.0  | 3.3     | 2.15    | 1.49    | 9999.0  |
| 40-50 GeV | 0.0-0.1 | 2.5     | 2.5     | 2.65    | 3.0     | 3.2     | 9999.0  | 3.3     | 2.15    | 1.49    | 9999.0  |
| 50-60 GeV | 0.0-0.1 | 2.5     | 2.5     | 2.65    | 3.0     | 3.2     | 9999.0  | 3.3     | 2.15    | 1.49    | 9999.0  |
| 60-70 GeV | 0.0-0.1 | 2.5     | 2.5     | 2.65    | 3.0     | 3.2     | 9999.0  | 3.3     | 2.15    | 1.49    | 9999.0  |
| 70-80 GeV | 0.0-0.1 | 2.5     | 2.5     | 2.65    | 3.0     | 3.2     | 9999.0  | 3.3     | 2.15    | 1.49    | 9999.0  |
| > 80 GeV  | 0.0-0.1 | 2.5     | 2.5     | 2.65    | 3.0     | 3.2     | 9999.0  | 3.3     | 2.15    | 1.49    | 9999.0  |
### Table D.6: Cuts on the ratio in the energy between the two most energetic strips medium++ electrons.

| $E_T$ | $|\eta|$ | 0.0-0.1 | 0.1-0.6 | 0.6-0.8 | 0.8-1.15 | 1.15-1.37 | 1.37-1.52 | 1.52-1.81 | 1.81-2.01 | 2.01-2.37 | 2.37-2.47 |
|-------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| < 5 GeV | | 0.640 | 0.600 | 0.560 | 0.36 | 0.24 | -9999.0 | 0.320 | 0.640 | 0.760 | -9999.0 |
| 5-10 GeV | | 0.640 | 0.600 | 0.560 | 0.36 | 0.24 | -9999.0 | 0.320 | 0.640 | 0.760 | -9999.0 |
| 10-15 GeV | | 0.8 | 0.8 | 0.79 | 0.61 | 0.6 | -9999.0 | 0.65 | 0.86 | 0.85 | -9999.0 |
| 15-20 GeV | | 0.83 | 0.83 | 0.825 | 0.7 | 0.65 | -9999.0 | 0.75 | 0.9 | 0.89 | -9999.0 |
| 20-30 GeV | | 0.835 | 0.835 | 0.835 | 0.8 | 0.8 | -9999.0 | 0.8 | 0.9 | 0.91 | -9999.0 |
| 30-40 GeV | | 0.835 | 0.835 | 0.835 | 0.8 | 0.8 | -9999.0 | 0.8 | 0.9 | 0.91 | -9999.0 |
| 40-50 GeV | | 0.835 | 0.835 | 0.835 | 0.8 | 0.8 | -9999.0 | 0.8 | 0.9 | 0.91 | -9999.0 |
| 50-60 GeV | | 0.835 | 0.835 | 0.835 | 0.8 | 0.8 | -9999.0 | 0.8 | 0.9 | 0.91 | -9999.0 |
| 60-70 GeV | | 0.835 | 0.835 | 0.835 | 0.8 | 0.8 | -9999.0 | 0.8 | 0.9 | 0.91 | -9999.0 |
| 70-80 GeV | | 0.835 | 0.835 | 0.835 | 0.8 | 0.8 | -9999.0 | 0.8 | 0.9 | 0.91 | -9999.0 |
| > 80 GeV | | 0.835 | 0.835 | 0.835 | 0.8 | 0.8 | -9999.0 | 0.8 | 0.9 | 0.91 | -9999.0 |
Appendix E

Jet Response Distributions

This appendix contains the fit results for the jet response in each bin considered for both EM and LCW scale jets. Results are shown using Z→ee and Z→μμ for both data and the nominal Monte Carlo sample (Powheg+Pythia).
Figure E.1: Bin by bin EM scale jet response distributions as seen in $Z \rightarrow \mu \mu$ data. The x-axis is the measured response while the y-axis is the number of events measured.
Figure E.2: Bin by bin EM scale jet response distributions as seen in Z→µµ Monte Carlo. The x-axis is the measured response while the y-axis is the number of events measured.
Figure E.3: Bin by bin LC scale jet response distributions as seen in $Z \rightarrow \mu \mu$ data. The x-axis is the measured response while the y-axis is the number of events measured.
Figure E.4: Bin by bin LC scale jet response distributions as seen in $Z \rightarrow \mu\mu$ Monte Carlo. The x-axis is the measured response while the y-axis is the number of events measured.
Figure E.5: Bin by bin EM scale jet response distributions as seen in Z→ee data. The x-axis is the measured response while the y-axis is the number of events measured.
Figure E.6: Bin by bin EM scale jet response distributions as seen in Z→ee Monte Carlo. The x-axis is the measured response while the y-axis is the number of events measured.
Figure E.7: Bin by bin LC scale jet response distributions as seen in Z→ee data. The x-axis is the measured response while the y-axis is the number of events measured.
Figure E.8: Bin by bin LC scale jet response distributions as seen in Z→ee Monte Carlo. The x-axis is the measured response while the y-axis is the number of events measured.
Bibliography


