

MEASUREMENT OF THE PROTON-PROTON TO ZZX CROSS SECTION AT A CENTER OF MASS ENERGY OF 8 TEV

DISSERTATION

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ABSTRACT

A measurement of the ZZ production in the $\ell^+\ell^-\ell'^+\ell'^-$ channel with pp collisions at $\sqrt{s} = 8$ TeV using the full 2012 dataset amounting to an integrated luminosity of 20 fb^{-1} collected by the ATLAS experiment is presented in this paper. An event is selected when exactly four reconstructed, isolated leptons are found in the final state. Each pair of leptons reconstructed to form a Z boson must have opposite sign and same flavor and have an invariant mass between 66 and 116 GeV. The background contribution is determined using a data-driven technique due to limited Monte Carlo statistics. Limits on the $f_4^\gamma, f_4^Z, f_5^\gamma, f_5^Z$ anomalous triple gauge couplings are also presented.

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Chapter 1

INTRODUCTION

During 2012, the ATLAS detector collected 20.04 fb^{-1} of pp data at a center of mass energy of 8 TeV. Combining the highest energy collisions ever recorded at a human made accelerator with the large amount of data collected allows incredibly precise measurements to be made that can probe the validity of the Standard Model. In the Standard Model (SM) there exist three massive vector bosons that mediate the Weak interaction: the $W^\pm$ and Z bosons with respective masses of 80.4 GeV and 91.2 GeV. This paper will focus specifically on the $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ process, which in the past, due to its very small rate, has been measured with low precision. The high luminosity achieved at the LHC presents a unique opportunity to measure with high precision the cross section of this process and also, with some extrapolation, the inclusive $pp \rightarrow ZZX$ cross section. That being said, the process $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ is significant at the LHC for multiple reasons. A precise measurement of the cross section compared with the SM prediction will provide further verification of the SM's validity as a theory describing fundamental interactions observed in nature. There also exists the opportunity to set tighter limits on the anomalous triple gauge couplings associated with the $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ process, thus limiting the range of beyond SM physics.

This paper will begin with an overview of the SM theory. The physical phenomena it describes including the fundamental interactions and their corresponding particles are discussed along with a brief description of the Higgs mechanism that, when included in the SM, gives rise to particle masses. Also discussed is the Electroweak interaction, of which

the W and Z bosons mediate.

A description of the ATLAS detector and its subsystems is also provided. The characteristics of all systems are mentioned, including but not limited to dimensions, materials and overall purpose.

Lastly, the analysis is presented. Object (μ, e) selection, event selection and the exact process used to reconstruct Z bosons will be discussed in great detail. The tools used to ensure the Monte Carlo matches the data are also discussed. The results of this analysis will be presented along with theoretical predictions and previous measurements.

Chapter 2

THEORY

2.1 The Standard Model

The SM describes physical phenomena observed in nature via three fundamental interactions: the strong, weak and electromagnetic. It is represented by the $SU(3)_{strong} \times SU(2)_{weak} \times U(1)_{EM}$ symmetry groups. All three forces are mediated by gauge bosons. The gluon is the force carrier for the strong interaction that is only felt by particles with color charge such as quarks. The $W^\pm$ and Z bosons are the force carriers for the weak interaction. The $W^\pm$ bosons are responsible for changing leptons into their corresponding neutrinos and vice versa and quark flavor changes and the Z boson is responsible for neutral current interactions. The photon (γ) mediates the electromagnetic interaction. The SM includes three generations of fundamental particles (Fig. 2.1): leptons: electrons, muons and taus, in order of increasing mass and their corresponding neutrinos, quarks: up/down, charm/strange and top/bottom and the force carriers that are described above.

The SM Lagrangian is defined in Eq. 2.1 and contains a QCD term describing the strong interactions, while all other terms describe the Electroweak interactions (unified description of the electromagnetic and weak sectors). This paper will focus on the Electroweak sector as that is where the $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ process resides. Included in the SM Lagrangian is the Higgs scalar field ϕ , whose presence is required to allow the appropriate particles to acquire mass. A more detailed explanation of the Higgs mechanism is provided in Appendix A. After some algebra and all the appropriate covariant derivatives are applied the physical gauge bosons ($W^\pm, Z, \gamma$) appear along with their masses.

$$\begin{aligned}
\mathcal{L} = & \underbrace{-\frac{1}{4}F_{\mu\nu}^i F^{i\mu\nu} + \sum_r \bar{q}_{r\alpha} i \not{D}_\beta^\alpha q_r^\beta}_{\text{QCD}} + \underbrace{-\frac{1}{4}F_{\mu\nu}^{i(\text{EW})} F^{i\mu\nu(\text{EW})} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu}}_{\text{Electroweak Gauge}} + \\
& \underbrace{(D^\mu \phi)^\dagger (D_\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2}_{\text{Higgs}} + \\
& \underbrace{\sum_m (\bar{q}_{mL}^0 i \not{D} q_{mL}^0 + \bar{l}_{mL}^0 i \not{D} l_{mL}^0 + \bar{u}_{mR}^0 i \not{D} u_{mR}^0 + \bar{d}_{mR}^0 i \not{D} d_{mR}^0 + \bar{e}_{mR}^0 i \not{D} e_{mR}^0)}_{\text{Fermions}} - \\
& \underbrace{\sum_{m,n=1} [\Gamma_{mn}^u \bar{q}_{mL}^0 \tilde{\phi} u_{mR}^0 + \Gamma_{mn}^d \bar{q}_{mL}^0 \phi d_{nR}^0 + \Gamma_{mn}^e \bar{l}_{mL}^0 \phi e_{nR}^0]}_{\text{Yukawa}}
\end{aligned} \tag{2.1}$$

where

$$\begin{aligned}
F_{\mu\nu}^i &= \partial_\mu G_\nu^i - \partial_\nu G_\mu^i - g_s f_{ijk} G_\mu^j G_\nu^k \\
F_{\mu\nu}^{i(\text{EW})} &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g \epsilon_{ijk} W_\mu^j W_\nu^k \\
B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu \\
\tilde{\phi} &\equiv i\tau^2 \phi^\dagger \\
q_{mL}^0 &= \begin{pmatrix} u_m^0 \\ d_m^0 \end{pmatrix}_L, l_{mL}^0 = \begin{pmatrix} e_m^{-0} \\ \nu_m^0 \end{pmatrix}_L \\
\not{D}_\beta^\alpha q_r^\beta &= \gamma_\mu (\partial^\mu \delta_\beta^\alpha + i g_s G^{i\mu} L_\beta^{i\alpha}) q_r^\beta \\
D_\mu \phi &= (\partial_\mu + i g \frac{\tau^i}{2} W_\mu^i + i \frac{g'}{2} B_\mu) \phi \\
D_\mu q_{mL}^0 &= (\partial_\mu + i g \frac{\tau^i}{2} W_\mu^i + i \frac{g'}{6} B_\mu) q_{mL}^0 \\
D_\mu l_{mL}^0 &= (\partial_\mu + i g \frac{\tau^i}{2} W_\mu^i - i \frac{g'}{2} B_\mu) l_{mL}^0 \\
D_\mu u_{mR}^0 &= (\partial_\mu + i \frac{2g'}{3} B_\mu) u_{mR}^0 \\
D_\mu d_{mR}^0 &= (\partial_\mu - i \frac{g'}{3} B_\mu) d_{mR}^0 \\
D_\mu e_{mR}^0 &= (\partial_\mu - i g' B_\mu) e_{mR}^0
\end{aligned} \tag{2.2}$$

The Γ_{mn} matrices describe the Yukawa couplings of the Higgs field to the various flavors of leptons and quarks and $u_{mR}^0, d_{mR}^0, e_{mR}^0$ are the right handed singlet fields (for quarks and

leptons). The W_μ^i and B_μ fields are the gauge fields for the $SU(2)$ and $U(1)$ groups.

Quark interactions are represented by the “QCD” term, self coupling of the gauge bosons is represented by the “Electroweak” term, fermion interactions are represented by the “fermions” term and the Yukawa term represents the Higgs-fermion coupling.

The Z_μ field identified as the Z boson is defined as

$$Z_\mu = \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2 + g'^2}} \equiv \cos \theta_W W_\mu^3 - \sin \theta_W B_\mu \quad (2.3)$$

and the A_μ field identified as the photon is defined as

$$A_\mu = \frac{g'W_\mu^3 + gB_\mu}{\sqrt{g^2 + g'^2}} \equiv \sin \theta_W W_\mu^3 + \cos \theta_W B_\mu \quad (2.4)$$

where the Weinberg angle is defined as:

$$\cos \theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \quad (2.5)$$

and the W_μ^1, W_μ^2 fields are identified as the $W^\pm$ boson. As the symmetry is spontaneously broken the W and Z bosons acquire unique masses defined in Eq. 2.6 and Eq. 2.7 respectively.

$$M_W^2 = \frac{g^2 \eta^2}{2} \quad (2.6)$$

$$M_Z^2 = \frac{g^2 \eta^2}{2 \cos^2 \theta_W} = \frac{M_W^2}{\cos^2 \theta_W} \quad (2.7)$$

where η is the Higgs potential vacuum expectation value of 246 GeV.

Using the relationship defined in Equation 2.7, if one experimentally measures θ_W (Weinberg angle) and M_W , M_Z is predicted to be 89.3 GeV which is in agreement with the measured Z mass of 91.2 GeV. The same can be said for M_W and θ_W . This agreement between predicted and experimentally measured values is a remarkable success of electroweak theory.

2.2 The Higgs Boson

The $pp \rightarrow ZZ X \rightarrow l^+ l^- l^+ l^-$ process is an irreducible background to a search for a heavy Higgs boson and is therefore important to measure. In July of 2012 ATLAS and CMS both

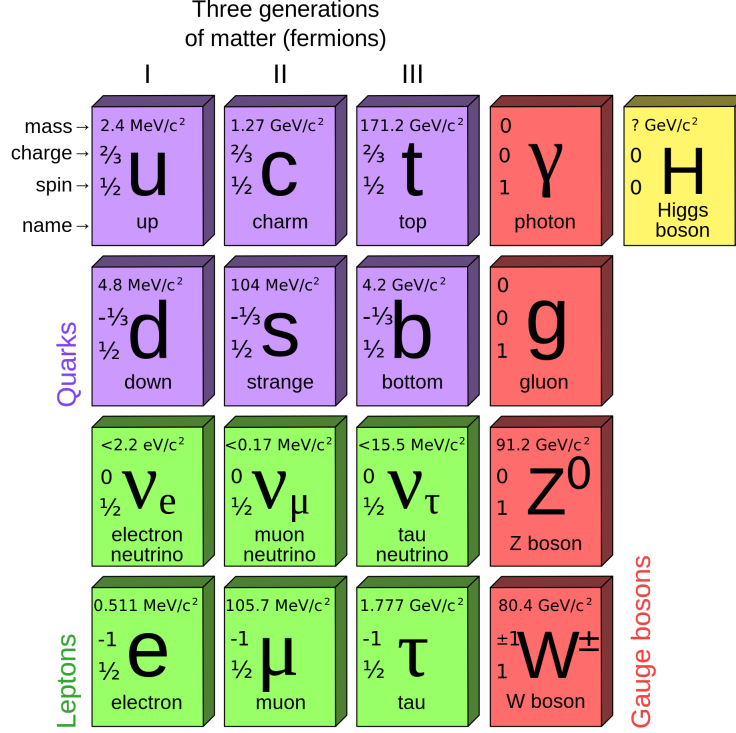


Figure 2.1: The elementary particles of the SM. Included is the Higgs boson, which as of July 2012 has a measured mass of approximately 126 GeV.

observed an excess of events at a mass of approximately 126 GeV (Figs. 2.2 and 2.3). As of March 6th, 2013 the combined signal strength ($\mu = \frac{\sigma}{\sigma_{SM}}$ where σ_{SM} is the cross section predicted by the SM) of all Higgs channels was measured to be $1.43 \pm 0.16 \pm 0.14$ at a mass of 125.5 GeV [4]. As recently as April 16th, 2013 a spin study was performed yielding results showing that the resonance observed resembles a spin 0 state, with an exclusion of the spin 1 state due to the $H \rightarrow \gamma\gamma$ process and Landau-Yang theorem, and an exclusion of the spin 2 state at a confidence level above 95 % [5]. So far this resonance appears to resemble the SM Higgs boson. Since this particle has a mass less than twice that of the Z boson it falls outside of the measured region defined in this paper.

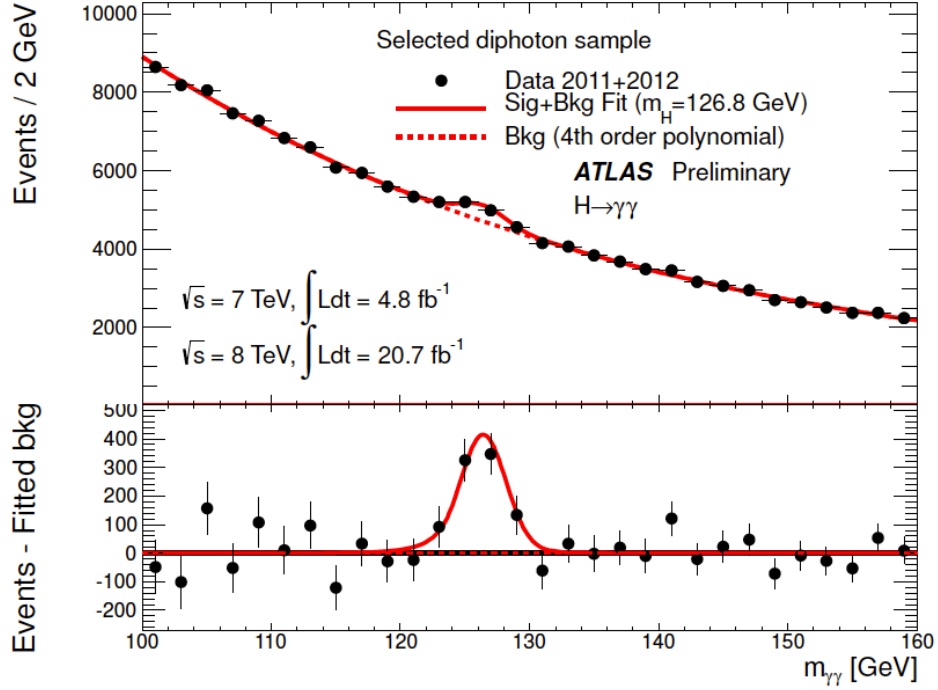


Figure 2.2: Distribution of the $\gamma\gamma$ reconstructed mass [1].

2.3 Parton Distribution Functions

At the LHC, protons are accelerated and collide with one another at high energies. It is therefore important to be able to accurately model these proton-proton interactions. The proton is made of two up quarks (u) and one down quark (d) however there exist within the proton gluons and virtual pairs of quarks known as sea quarks. This means that during a proton-proton collision there are many different interactions that can occur.

Parton distribution functions (PDFs) describe the probability of finding a parton of flavor i (quark or gluon) carrying a fraction x (Bjorken scaling variable) of the proton's momentum with the energy scale of the collision being defined as Q . The PDFs can be measured using Deep Inelastic Scattering processes such as $e^\pm p \rightarrow e^\pm X$ to probe the substructure of hadrons. Structure functions ($f_i(x, Q^2)$) are then defined for gluons and each flavor of quark (sea and valence) present within the hadrons. Each structure function can

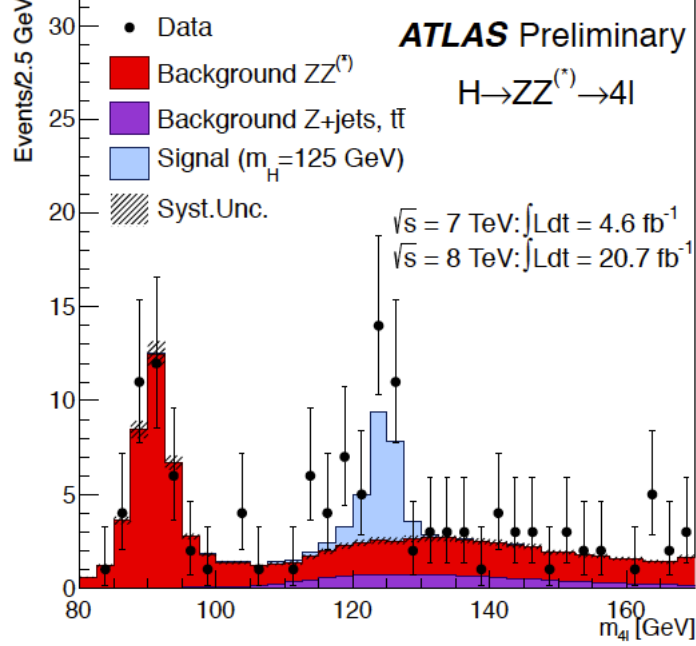


Figure 2.3: Distribution of the $\ell^+\ell^-\ell'^+\ell'^-$ reconstructed mass [2].

be used to determine the contribution to the total cross section due to each interacting quark and/or gluon. The parton distribution function is then the sum of all the structure functions.

2.4 Standard Model $pp \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ Production

The SM electroweak sector described by the non-abelian gauge group $SU(2)_L \times U(1)_Y$ has proven to successfully describe experimental observations. That being said, the process $ZZ \rightarrow l^+l^-l^+l^-$ is a significant process at the LHC for multiple reasons. A precise measurement of the cross section compared with the SM prediction will provide further verification of the SM's validity as a theory describing fundamental interactions observed in nature. In the past a precise measurement of this process was unfeasible as it was suppressed by the branching fraction of the Z bosons decaying into leptons. With the current data collected at ATLAS this is no longer a limitation. The primary amplitudes of ZZ production are seen in figure 2.4.

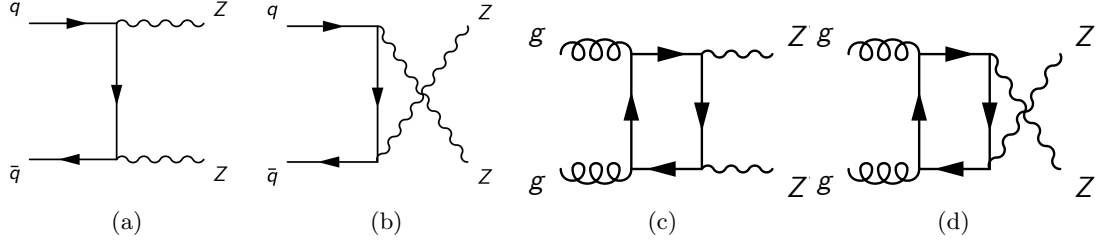


Figure 2.4: The tree level feynman diagrams of primary modes of ZZ production at the LHC. The $q\bar{q}$ initial state production modes (figures (a) and (b)) account for approximately 94% of the total ZZ cross section while the gg modes (figures (c) and (d)) account for the rest of the cross section.

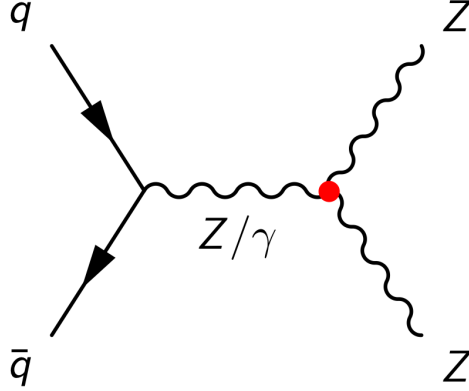


Figure 2.5: The diagram above shows ZZ s-channel production via an anomalous triple gauge coupling vertex which is currently forbidden in the SM

The $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ process can also help probe new physics beyond the SM. It could be a final state of a heavy Higgs boson where $m_{Higgs} > 2m_Z$. It is affectionately referred to as the “golden channel” as it is an incredibly clean final state with little background. It is also a final state of the light Higgs discovered in July of 2012 as well, but since $m_{LightHiggs} < 2m_Z$ one Z must be off-shell and does not fall in the scope of this paper. Other beyond SM processes that couple to this process include a doubly-charged Higgs [6], radion resonances [7] and supersymmetric particles. Anomalous triple gauge

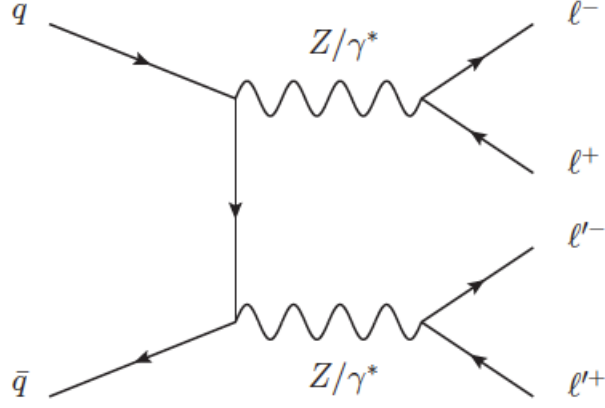


Figure 2.6: Tree level feynman diagram for the process $q\bar{q} \rightarrow Z/\gamma^* Z/\gamma^* \rightarrow l^+l^-l^+l^-$.

couplings, as shown in figure 2.5, are also another possibility where this final state proves to be a sensitive probing mechanism and helps determine limits on the associated couplings.

Currently the predicted cross section for the process $pp \rightarrow ZZ$ at $\sqrt{s} = 8$ TeV with next to leading order corrections and including the gg contribution is $7.23^{+0.30}_{-0.22}$ pb (the cross section is calculated using the CT10 pdf)[8]. The OPAL, ALEPH and DELPHI collaborations at LEP probed Z boson pair production using the process $e^+e^- \rightarrow l^+l^-l^+l^-$. The D0 experiment at the Tevatron collider has also measured the ZZ cross section via the $ZZ \rightarrow l^+l^-l^+l^-$ channel at $\sqrt{s} = 1.96$ TeV using 6.4 fb^{-1} of data to be $1.40^{+0.43}_{-0.37}(\text{stat.}) \pm 0.14(\text{sys.})$ pb. The CDF experiment measured the ZZ cross section to be $1.47^{+0.7}_{-0.6}$ pb (Fig. 2.7) where the quoted errors are the statistical and systematic errors added in quadrature.

2.5 Anomalous Triple Gauge Coupling (aTGC) Theory and Introduction

Figure 2.4 shows the allowed SM ZZ production modes and figure 2.5 shows the forbidden s-channel mode that contains an aTGC vertex. ATLAS is not the first experiment to probe aTGC enhancements. The D0 experiment set limits on anomalous ZZZ and $ZZ\gamma^*$ couplings

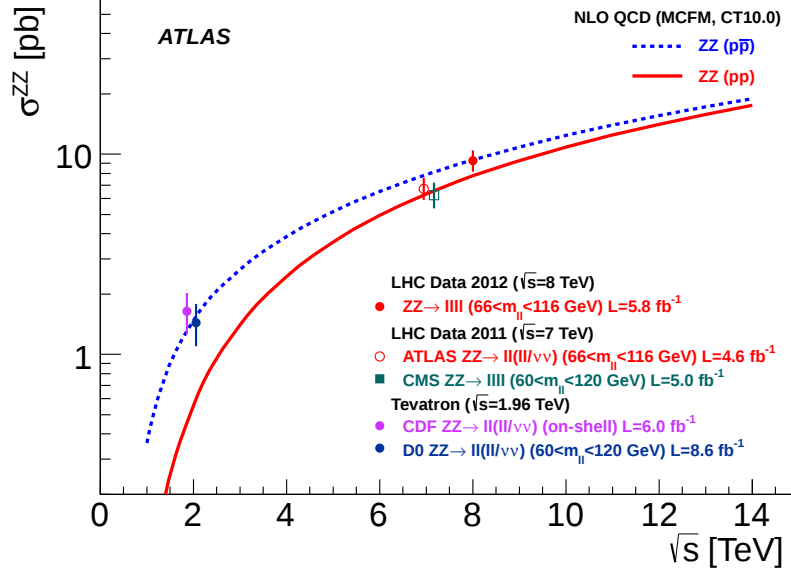


Figure 2.7: Predicted and measured ZZ cross section versus center of mass energy.

using 1.9 fb^{-1} of data [9]. ATLAS [10] and CMS [11] have also set limits on aTGC couplings using 5 fb^{-1} of data at $\sqrt{s} = 7 \text{ TeV}$.

The approach taken here to describe the aTGC enhancement to the SM ZZ cross section is to use an effective Lagrangian. In the case where both Z 's in the final state are on-shell there are four couplings in the effective Lagrangian: two ZZZ couplings and two $ZZ\gamma$ couplings. The aTGC Lagrangian that yields the vertex function in Figure 2.8 is as follows [12]

$$\mathcal{L} = -\frac{e}{M_Z^2} [f_4^V (\partial_\mu V^{\mu\beta}) Z_\alpha (\partial^\alpha Z_\beta) + f_5^V (\partial^\sigma V_{\sigma\mu}) \tilde{Z}^{\mu\beta} Z_\beta] \quad (2.8)$$

where $V = Z, \gamma$, $V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$, Z is the Z boson and $\tilde{Z}^{\mu\beta} = \frac{1}{2} \epsilon_{\mu\beta\rho\sigma} Z^{\rho\sigma}$.

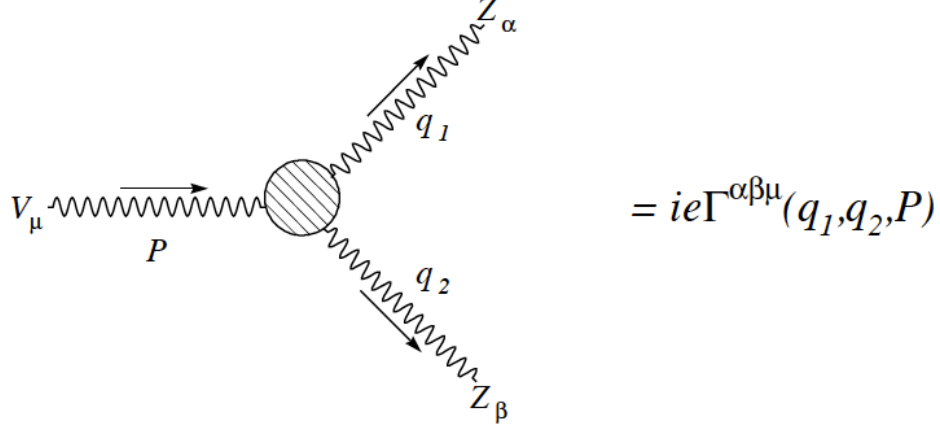


Figure 2.8: The general vertex for anomalous triple gauge boson couplings where the final state contains two Z bosons and internal line V_μ can be either a Z or γ .

The general form of this particular triple gauge vertex (Figure 2.8) is written as [12]

$$g_{ZZV}\Gamma_{ZZV}^{\alpha\beta\mu} = e \frac{P^2 - M_V^2}{M_Z^2} [i f_4^V (P^\alpha g^{\mu\beta} + P^\beta g^{\mu\alpha}) + i f_5^V \epsilon^{\mu\alpha\beta\rho} (q_1 - q_2)_\rho] \quad (2.9)$$

The couplings f_4^V and f_5^V are complex functions of q_1^2 , q_2^2 and P^2 [13] [14] (q_1, q_2 and P are the momenta of the particles in Figure 2.8) and are also dimensionless. The f_4^V couplings are CP violating while the f_5^V couplings are CP conserving. All couplings are C odd.

As $\sqrt{\hat{s}}$ ($\hat{s}$ is the center of mass energy squared) increases, these couplings innately grow. In order to preserve partial wave unitarity a form factor with $\hat{s}$ dependence is introduced to the couplings. The form factor is defined as

$$\frac{1}{(1 + \frac{\hat{s}}{\Lambda_{FF}^2})^n} \quad (2.10)$$

This yields the following expression for the couplings which now have an $\hat{s}$ dependence

$$f_i^V(\hat{s}) = \frac{f_{i0}^V}{(1 + \frac{\hat{s}}{\Lambda_{FF}^2})^n} (i = 4, 5) \quad (2.11)$$

where f_{i0}^V are the values of $f_i^V(M_Z^2, M_Z^2, 0)$ at $\hat{s} = 0$ and Λ_{FF} is the energy scale at which

physics beyond the SM becomes observable. In this analysis $n = 0$.

The presence of non-trivial aTGC couplings has the effect of an enhanced ZZ cross section at high center of mass energy and large scattering angles. Therefore, the spectra of the invariant mass of the diboson system and the transverse momenta of the Z bosons (Fig. 2.9) are most sensitive to the effects the aTGC enhancement.

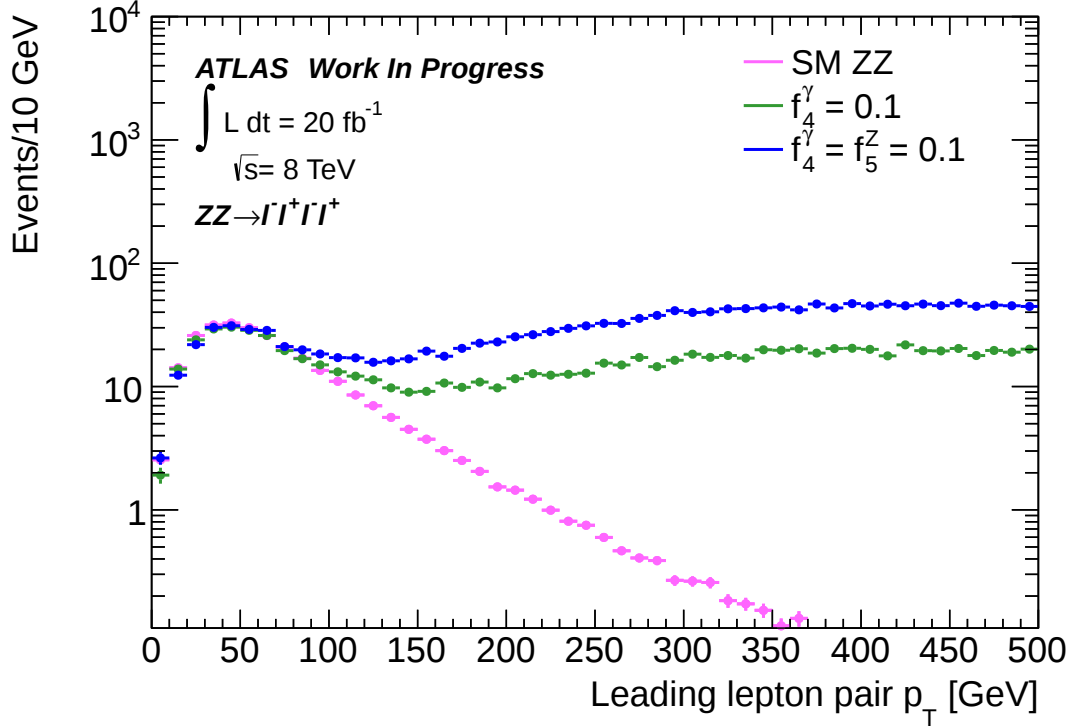


Figure 2.9: The p_T spectrum of the leading Z boson in a signal event for various TGC point values. As is expected there is a significant enhancement in the higher p_T regime.

Chapter 3

THE LHC AND THE ATLAS DETECTOR

ATLAS (A Toroidal LHC ApparatuS) [15] is one of two general purpose detectors on the LHC ring and is designed to survive the extreme conditions provided by the Large Hadron Collider (LHC) caused by the collisions of two counter-rotating proton beams. Designed with a 14 TeV center of mass energy, design luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and a bunch spacing of 25 ns the LHC is the most powerful collider in the world.

The ATLAS detector (as seen in Figure 3.1) contains several sub-systems each designed with a particular purpose to help verify the Standard Model and look for physics extending beyond the Standard Model. Going from interaction point (IP) outwards we have the BCM (Beam Conditions Monitor), BLM (Beam Loss Monitor), pixel detector, Semi-Conductor Tracker (SCT), Transition Radiation Tracker (TRT), electromagnetic calorimeter (EMcal), Liquid Argon (LAr/hadronic) calorimeter and the muon tracking system. All sub-systems provide vital information on particle energy/momentum and direction.

3.1 Definitions of Coordinates

The coordinate system in ATLAS defines the z-axis to be along the beampipe and the x-y plane as the transverse plane. The positive x-axis points toward the center of the ring from the interaction point (IP) and the y-axis points upwards. ϕ (azimuthal angle) is defined to be around the beam axis and θ (polar angle) is measured from the beam axis. The rapidity

is defined as

$$y = \frac{1}{2} \ln \frac{E + p_z c}{E - p_z c} \quad (3.1)$$

and the difference in rapidity (δy), is invariant under boosts. As is common with high energy experiments, η or pseudo-rapidity is used in place of rapidity. It is approximated as $-\ln \tan(\frac{\theta}{2})$. Separation between tracks is often measured in η, ϕ space and is defined as $\Delta R = \sqrt{\delta\eta^2 + \delta\phi^2}$.

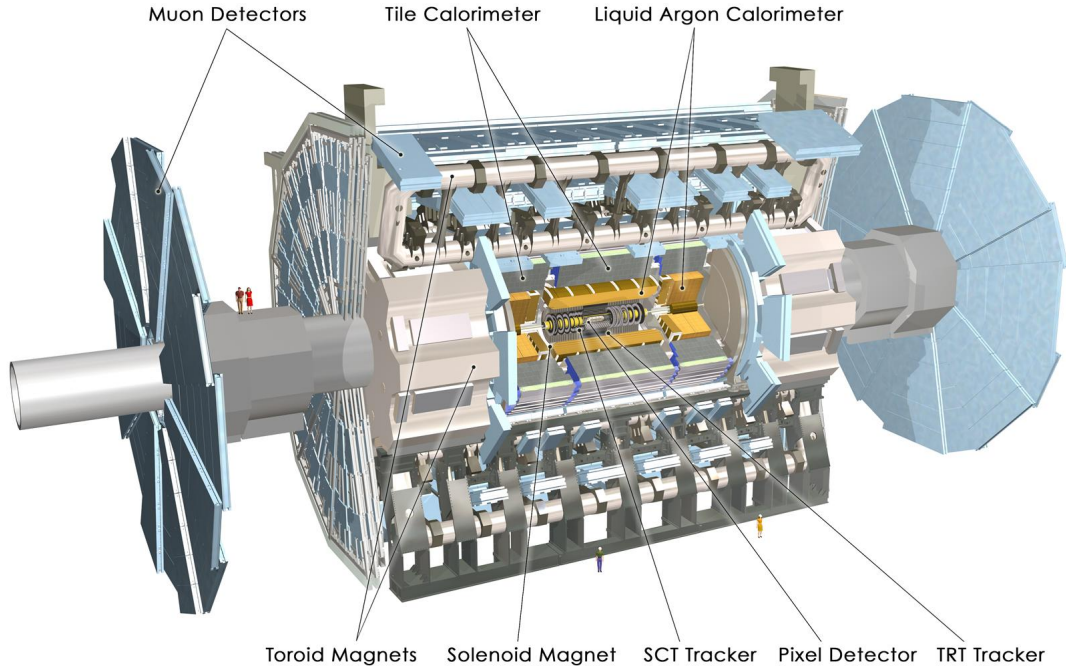


Figure 3.1: The ATLAS detector with all sub-systems listed.

3.2 Design Purpose

The design of ATLAS was motivated by certain physics processes. The Higgs boson decay channel $H \rightarrow \gamma\gamma$ requires a precise and accurate energy measurement whereas the $H \rightarrow ZZ \rightarrow l^+l^-l^+l^-$ decay mode necessitates a precise and accurate momentum measurement.

Very good lepton identification is a necessity for the latter channel as well. In order to effectively identify electrons and photons very efficient electromagnetic calorimetry was essential. Along with that, full-coverage hadronic calorimeter was necessary to accurately measure jets and missing transverse energy. The tracking systems must be able to accurately reconstruct tracks in both the inner detector and in the muon spectrometer from low to high p_T meaning they must provide high-granularity and very precise measurements. To ensure maximum acceptance at large η and nearly full azimuthal coverage is needed.

3.3 Magnet System

3.3.1 Central Solenoid

The entire Inner Detector and BCM sit within the ATLAS central solenoid. It is designed to generate a magnetic field of 2 T (1.998 T at the center of the magnet using the nominal 7.730 kA current) [3]. Since the calorimeters sit outside the solenoid, the thickness of the solenoid was kept at an absolute minimum to reduce energy loss of particles traversing the detector, which led to the solenoid having approximately 0.66 radiation lengths incident along the normal. The single-layer coil is made with a high-strength Al-stabilized NbTi conductor that was specifically designed to achieve the high field needed for particle tracking while simultaneously minimizing the thickness of the magnet. The inner and outer diameters of the solenoid are 2.46 m and 2.56 m respectively and measures 5.8 m in the z direction. It has a weight of approximately 5.4 tonnes and stores 40 MJ of energy. This results in a stored-energy-to-mass ratio of 7.4 kJ/kg [3]. It takes 30 minutes to charge and discharge the solenoid. In the case of a quench the energy is absorbed by the cold mass consequently raising the temperature of the cold mass to a maximum of 120 K (which is still deemed “safe”). It can be re-cooled to 4.5 K in about one day. A summary of the specifications of both the solenoid and the toroids is available in figure 3.2 and the bare solenoid can be seen in figure 3.4.

Property	Feature	Unit	Solenoid	Barrel toroid	End-cap toroids
Size	Inner diameter	m	2.46	9.4	1.65
	Outer diameter	m	2.56	20.1	10.7
	Axial length	m	5.8	25.3	5.0
	Number of coils		1	8	2×8
Mass	Conductor	t	3.8	118	2×20.5
	Cold mass	t	5.4	370	2×140
	Total assembly	t	5.7	830	2×239
Coils	Turns per coil		1154	120	116
	Nominal current	kA	7.73	20.5	20.5
	Magnet stored energy	GJ	0.04	1.08	2×0.25
	Peak field in the windings	T	2.6	3.9	4.1
	Field range in the bore	T	0.9–2.0	0.2–2.5	0.2–3.5
	Overall size	mm ²	30 x 4.25	57 x 12	41 x 12
	Ratio Al:Cu:NbTi		15.6:0.9:1	28:1.3:1	19:1.3:1
	Number of strands (NbTi)		12	38–40	40
Conductor	Strand diameter (NbTi)	mm	1.22	1.3	1.3
	Critical current (at 5 T and 4.2 K)	kA	20.4	58	60
	Operating/critical-current ratio at 4.5 K	%	20	30	30
	Residual resistivity ratio (RRR) for Al		> 500	> 800	> 800
	Temperature margin	K	2.7	1.9	1.9
	Number of units $\times$ length	m	4×2290	$8 \times 4 \times 1730$	$2 \times 8 \times 2 \times 800$
	Total length (produced)	km	10	56	2×13
Heat load	At 4.5 K	W	130	990	330
	At 60–80 K	kW	0.5	7.4	1.7
	Liquid helium mass flow	g/s	7	410	280

Figure 3.2: Specifications of the ATLAS magnet system.

3.3.2 Toroid Magnets

The muon spectrometer utilizes three large superconducting air-core magnets covering the pseudorapidity range $0 \leq |\eta| \leq 2.7$. They have an open structure that minimizes the effects on momentum resolution due to multiple scattering. The barrel toroid (BT) magnets measure 25 m in the z direction, an inner diameter of 9.4 m and outer diameter of 20.1 m. The end cap toroids (ETCs) have a length in the z direction of 5.0 m, inner diameter of 1.65m and outer diameter of 10.7 m.

Each toroidal magnet is made of eight flat coils. They are situated radially and symmetrically about the beam axis. The end cap toroid magnets are situated with an azimuthal offset of 22.5° with respect to the BT which can be seen in figure 3.5. This results in an

overlap between the fields that helps maximize the bending power in the transition region between the barrel and end caps.

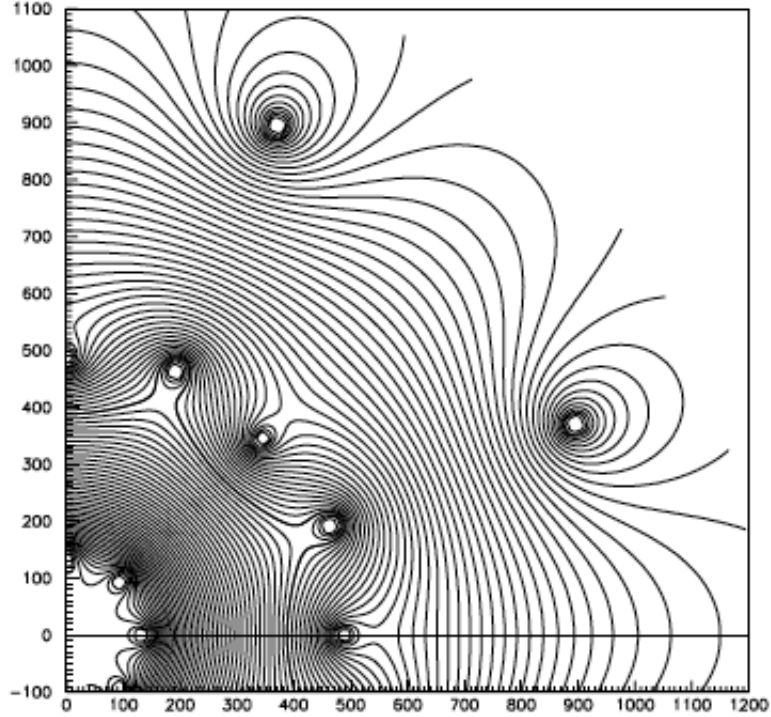


Figure 3.3: Above is a magnetic field map in the transverse plane (x-y plane) in the transition region between the barrel and end cap toroids in the muon spectrometer. The separation between the lines is 0.1 Tm. Also visible are the BT and ECT coils.

3.4 Beam Conditions Monitor

A possible worst case scenario for any experiment at the LHC is when the beams scrape the collimators designed to protect the detectors. When this happens, a large spray of particles comes from the beam-collimator interaction. Although the radiation dose associated with these types of events are within the design limits of the detector (integrated dose), the large instantaneous rate of particle flux could damage one or more of the detector subsystems. The BCM was designed to protect the ATLAS experiment from the aforementioned type



Figure 3.4: The ATLAS solenoid after completion of the coil winding [3].

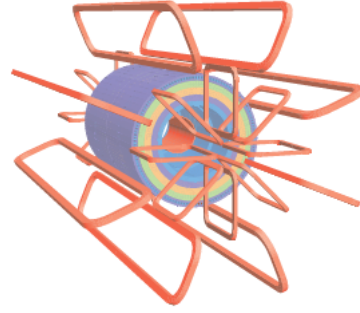


Figure 3.5: The barrel and end-cap coils of the open air toroid can be seen above [3].

of events and also monitor the bunch-by-bunch luminosity delivered by the LHC.

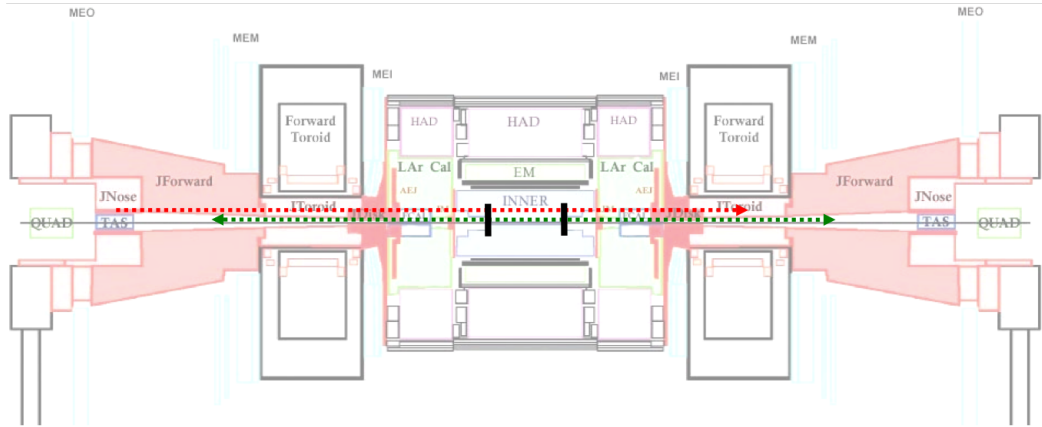


Figure 3.6: The BCM sits closest in the radial direction to the IP in the ATLAS detector. The black bars are the modules situated 1.86 m from the IP on both sides of the detector.

3.4.1 Luminosity Measurement

It is paramount to determine the amount of data collected at the LHC. Without this information it would be impossible to determine if experimental observations are in agreement with the theoretical predictions. At particle colliders this can be determined by counting

the number of particles scattered after a primary collision occurs. The number of scattered particles (N) can be written as:

$$\frac{dN}{d\Omega dt} = L \frac{d\sigma}{d\Omega} \quad (3.2)$$

Where σ is the scattering cross section, $d\Omega$ is the differential solid angle element and L is the luminosity that is most commonly expressed in units of $\text{cm}^{-2}\text{s}^{-1}$. Integrating over $d\Omega$ gives:

$$\frac{dN}{dt} = L\sigma \quad (3.3)$$

$\frac{dN}{dt}$ can be thought of as scattering rate and L is the instantaneous luminosity.

The ATLAS approach to luminosity monitoring is through event counting. The number of detected particles (N_{det}) can be related to the number of particles in a bunch crossing (N_{BC})

$$N_{det} = N_{BC}(1 - e^{-B \cdot L}) \quad (3.4)$$

where B depends on total cross section and the detector efficiency.

Equation 3.3 can be rearranged to represent the luminosity in terms of $\langle\mu\rangle$ (average interactions per bunch crossing) and f_{rev} (the frequency of revolution) as

$$L = \frac{\langle\mu\rangle f_{rev}}{\sigma}. \quad (3.5)$$

There is a problem however. We do not know the true values of $\langle\mu\rangle$ and σ , but we can express 3.5 in terms of their visible or measured values

$$\begin{aligned} \mu_{vis} &= \langle\mu\rangle \epsilon \\ \sigma_{vis} &= \sigma \epsilon \end{aligned} \quad (3.6)$$

where ϵ is the detector efficiency of a single p-p interaction. The BCM is capable of measuring μ_{vis} so the only unknown remaining is the visible cross section.

Van der Meer Scans

In order to measure the visible cross section a calibration constant specific to the BCM must be measured as well. This is done by performing Van der Meer scans [16]. The Van der Meer approach expresses the luminosity in terms of the beam parameters. The luminosity of a single bunch can be written as

$$L = f_{rev} N_1 N_2 \int \rho_1(x, y) \rho_2(x, y) dx dy \quad (3.7)$$

where $\rho_{1,2}(x, y)$ are the particle density functions for beams 1 and 2. Assuming these are independent in x and y, the overlap integrals in x and y can be written as

$$\Omega_x(\rho_1, \rho_2) = \int \rho_1(x) \rho_2(x) dx \quad \Omega_y(\rho_1, \rho_2) = \int \rho_1(y) \rho_2(y) dy. \quad (3.8)$$

The overlap integrals can then be related to a measured rate, $R_x \delta$, as a function of beam separation δ and are shown in Equation 3.9.

$$\Omega_x(\rho_1, \rho_2) = \frac{R_x(0)}{\int R_x(\delta) d\delta} \quad (3.9)$$

The luminosity is often expressed in terms of an effective beam width defined as

$$\Sigma_x(\rho_1, \rho_2) = \frac{1}{\sqrt{2\pi}} \frac{R_x(0)}{\int R_x(\delta) d\delta}. \quad (3.10)$$

The luminosity is then written as

$$L = \frac{f_{rev} N_1 N_2}{2\pi \Sigma_x \Sigma_y}. \quad (3.11)$$

During the scan, one beam is held fixed (at the central point $x=0, y=0$) and the other beam is moved in either the x or y direction only. Measuring the interaction rate as the displacement changes gives the distributions $R_{x,y}(\delta)$. It is also important to note that in this particular case the rates measured by the BCM are actually the average interactions per bunch crossing. Equating Equations 3.5 (using the visible quantities) and 3.11 the visible

cross section is

$$\sigma_{vis} = \frac{2\pi \Sigma_x \Sigma_y \mu_{vis}}{N_1 N_2}. \quad (3.12)$$

Using the visible cross section measurement and μ_{vis} measured by the BCM, Equation 3.5 will yield a measurement of the instantaneous luminosity.

3.4.2 Diamond Modules

The BCM consists of 8 diamond modules (four on each side) approximately 0.6 cm^2 ($0.81 \text{ cm} \times 0.81 \text{ cm}$) in area on both sides of the detector. It is centered at $z = 0$ (along the beampipe) with modules at $z = \pm 1.86 \text{ m}$. Since the BCM is situated in such close proximity (6 cm radially) to the interaction point, a material that can withstand the large radiation dose and fluence associated with that environment must be used. It is for these reasons that diamond was the material chosen to be the active medium.

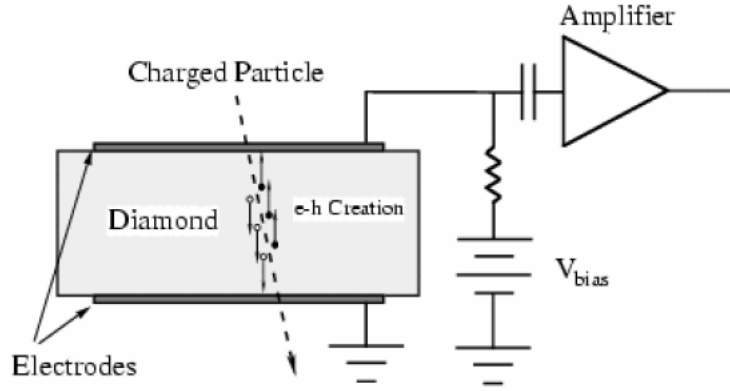


Figure 3.7: A schematic of a diamond sensor in the BCM. A charged particle traverses the diamond and knocks loose electrons which then drift towards the electrode held at positive high voltage.

The diamond sensors are designed to tolerate up to 500 kGy doses of radiation and a fluence of 10^{15} charged particles per cm^2 over the lifetime of the BCM (10 years). Two

sensors are arranged back to back (double-decker assembly) in order to achieve twice the signal compared to a single module; the noise is measured to be less than twice that of the single module assembly. The sensors are oriented so that particle incidence is at an angle of 45° with respect to the beam line (z-axis). This increases the particle path length and signal by $\sqrt{2}$.

Each diamond module of the BCM outputs rates to two channels: High Gain (Low Threshold) and Low Gain (High Threshold). The High Gain output is sensitive enough to measure individual minimum ionizing particles (MIPs) which is essential to measuring the luminosity with a very low uncertainty. The Low Gain channels are much less sensitive since their purpose is to measure the much larger rates that are associated with dangerous beam losses. The BCM can also distinguish between “collisions” and “background” using the particle time of flight between sides A and C and the interaction point. The BCM uses an event counting algorithm to measure the luminosity and therefore only “collisions” should be used to determine the luminosity.

3.5 Inner Detector

The ATLAS Inner Detector (ID) was designed to give robust and hermetic charged-particle tracking. Along with providing excellent momentum resolution it also provides primary and secondary vertex measurements up to $|\eta| < 2.5$. Through the use of the Transition Radiation Tracker (TRT), electron identification is provided up to $|\eta| < 2.0$ and in the energy range of 0.5 GeV to 150 GeV. All three of these systems and the BCM sit within the 2 T solenoidal field.

3.5.1 Pixel Detector

The pixel detector is the innermost tracking system consisting of three layers in both the barrel and the endcaps: the B-layer (closest to the interaction point), layer 1 and layer 2. With 1744 pixel modules on board and 47232 pixels on each module, the detector contains approximately 80 million pixels. Approximately 90% of the pixels have a size of

$50 (r - \phi) \times 400(z) \mu\text{m}^2$ while the remaining have a size of $50 (r - \phi) \times 600 \mu\text{m}^2$.

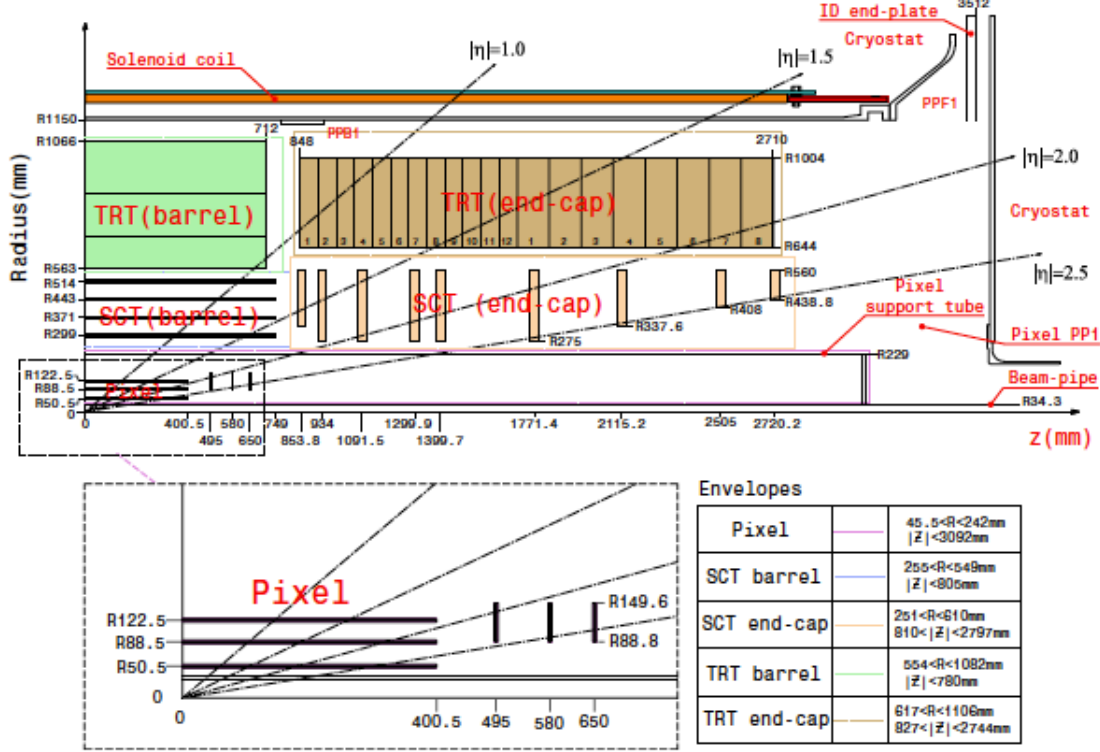


Figure 3.8: A cross sectional view of the pixel detector in the z-y plane. The η coverage is shown along with the location of the three layers within the detector.

The pixel detector provides tracking information up to $|\eta| < 2.5$ which can be seen in Fig. 3.8. The sensors used must be able to perform adequately over the lifetime of the detector which necessitates the ability to function continuously in a high radiation environment. The leakage current of the sensors increases with radiation dose. This combined with the n-type doping becoming primarily p-type doping after a neutron equivalent fluence of approximately $2 \times 10^{13} \text{ cm}^{-2}$ requires the sensors to operate in a temperature range of -5°C to -10°C . The sensors are oxygenated n-type wafers with a thickness of $250 \mu\text{m}$ with the readout pixels located on the n^+ -implanted side of the sensor. The n^+ implants and

oxygenated material help maintain a good charge-collection efficiency after type inversion. The oxygenated material also increases radiation tolerance to charged hadrons. At the beginning of operation, the sensors will operate at 150 V which can increase up to 600 V after an extended amount of time (around 10 years).

3.5.2 Semiconductor Tracker

The semiconductor tracker (SCT) is another silicon tracking detector located just outside the pixel detector. Instead of using silicon pixels, the SCT implements the use of silicon micro-strip sensors arranged in four cylindrical double layers (one axial and one at a stereo angle of 40 mrad). Due to cost and reliability, the SCT sensors employ a classic single p-in-n technology. These sensors are currently operated at a voltage of approximately 150V, but after ten years of high radiation operation, a bias voltage between 250 and 350 V will be necessary to provide adequate charge collection efficiency. In the barrel region, the strips have a size of $17 (r - \phi) \times 580 (z) \mu\text{m}^2$ and in the end cap disks a size of $17 (r - \phi) \times 580 (r) \mu\text{m}^2$. The sensors are situated at a pitch of $80 \mu\text{m}$, however in the end cap disks one set of strips is arranged radially instead of axially. The SCT is also equipped with interferometric monitoring allowing to detect how much the modules have moved over a period of time.

Similar to the pixel sensors the sensors in the SCT must also be functional in the high radiation environment. The same specifications mentioned earlier in the pixel detector subsection apply to the SCT sensors as well.

3.5.3 Transition Radiation Tracker

The Transition Radiation Tracker (TRT) is the outermost subsystem of the Inner Detector. The TRT, like the pixel and SCT detectors, has a barrel region and an endcap region. The TRT barrel uses polyimide drift tubes (straws) oriented axially to provide tracking, whereas the end cap region utilizes the same straws oriented radially to track charged particles. The TRT was designed to be able to track charged particles with $p_T > 5 \text{ GeV}$ and $|\eta| < 2.0$ (the TRT barrel acceptance is $|\eta| < 1.0$, the endcaps extend to 2.0). The gas mixture inside the tubes is comprised of 70% Xe, 27% CO₂ and 3% O₂. The cathodes are operated at

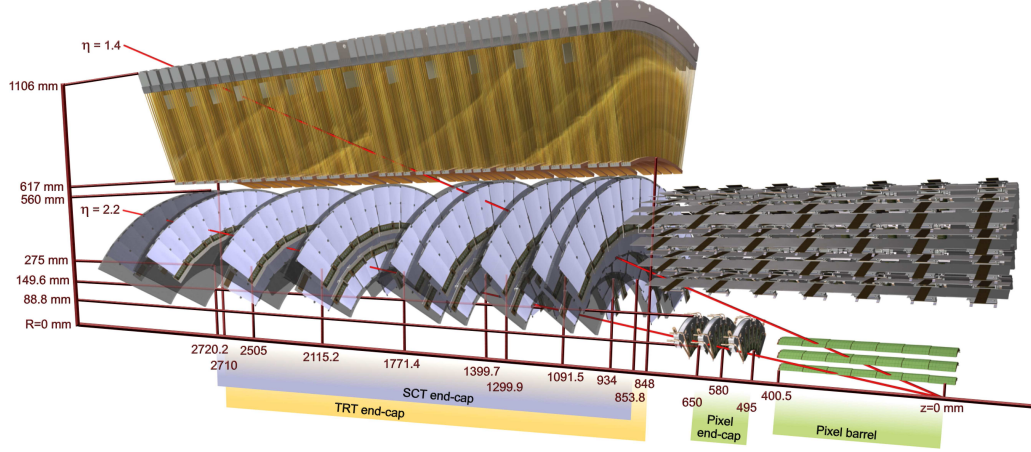


Figure 3.9: Diagram showing two charged tracks traveling through the Inner Detector subsystems. The SCT's four layers and end cap disks are pictured along with the η and R positions.

1530V to give a gain of 2.5×10^4 . Discrimination between electrons and pions is possible since electrons will lose much more energy via transition radiation than pions.

As was mentioned previously, all the sub-systems of the ID play a complimentary role to one another and this can be seen in the overall momentum resolution of the ID (Fig. 3.11 and 3.12). For high-momentum tracks the relative momentum resolution was measured to be $\frac{\sigma_p}{p} = (4.83 \pm 0.16) \times 10^{-4} \text{ GeV}^{-1} \times p_T$ [17].

3.6 Calorimetry

The calorimeters in the ATLAS detector play a hugely important role in the physics program. Among these, some notable processes include the photonic and leptonic final states of Higgs decays, in particular, $H \rightarrow \gamma\gamma$ and $H \rightarrow Z^0 Z^0 \rightarrow e^+ e^- e^+ e^-$. Excellent mass resolution (on the order of 1%) is needed. Accurate energy measurements are absolutely essential for precision electroweak processes such as $Z \rightarrow e^+ e^-$ and $W \rightarrow e^\pm \nu_e$. This requires an accuracy over a large range of p_T (from a few GeV to a few TeV).

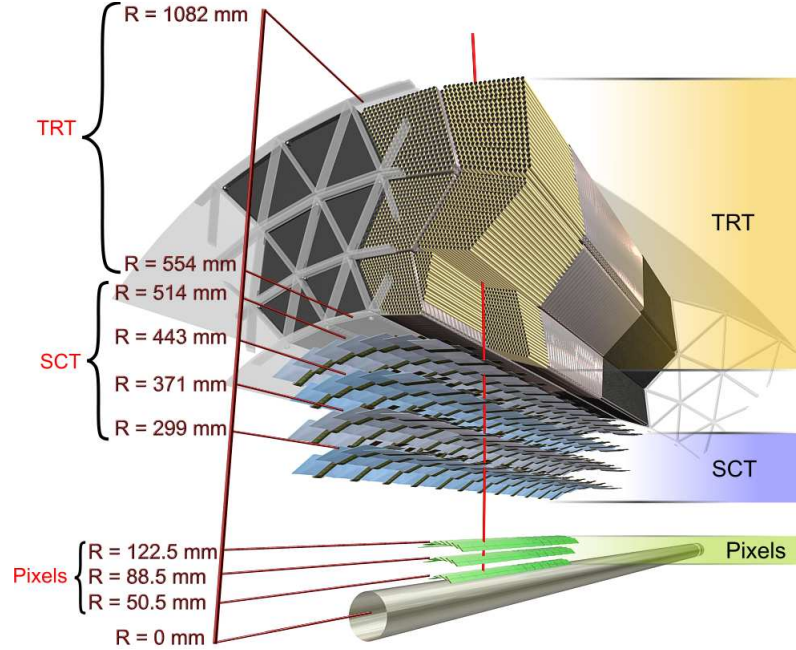


Figure 3.10: The orientation of the TRT drift tubes can be seen here. The barrel orientation of the tubes is parallel with the beam axis (z-axis) whereas the endcap tubes are situated radially.

3.6.1 Electromagnetic Calorimeter

The electromagnetic calorimeter consists of the barrel calorimeter and end cap calorimeters. The barrel calorimeter consists of two half barrels that cover an eta range of $|\eta| < 1.475$, $z = \pm 3.2$ m with inner and outer diameters of 2.8 m and 4.0 m respectively. The material in front of the barrel calorimeter consists of approximately $1.5 X_0$ ¹. It is due to this that a liquid argon presampler detector is situated in front of its inner surface over the full η range. Each half barrel has 1024 accordion absorbers interleaved with the electrode readouts. The drift gap on either side of the electrodes is 2.1 mm corresponding to a drift time of approximately 450 ns at a voltage of 2 kV. There are a total of 32 modules in the barrel (16 per half barrel). The thickness of a module equates to at least $22 X_0$: $22 X_0$ to $30 X_0$ over $|\eta| < 0.8$ and $24 X_0$ to $33 X_0$ over $|\eta| > 0.8$ and $|\eta| < 1.3$.

¹ X_0 is defined as the amount of material an electron needs to traverse until its energy is $\frac{E_0}{e}$ where E_0 is the initial energy of the electron.

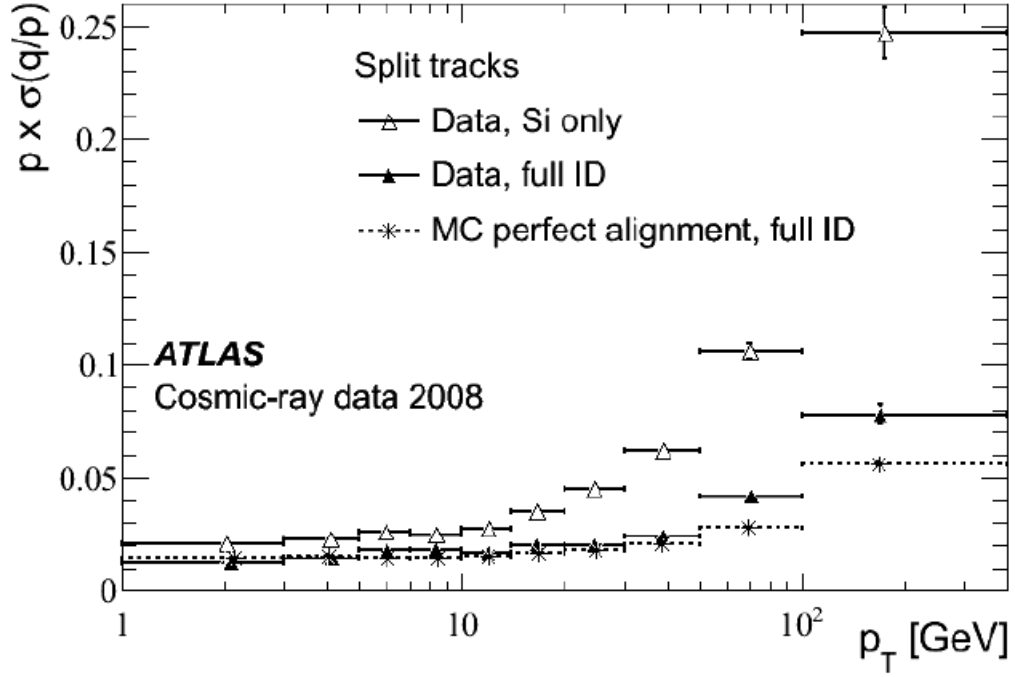


Figure 3.11: The ID momentum resolution as a function of p_T for silicon only tracks, the full set of ID tracks and the full set of simulated (MC) ID tracks.

Each module contains absorbers made of lead plates (1.53 mm for $|\eta| < 0.8$ and 1.13 mm for $|\eta| > 0.8$) that are glued between two 0.2 mm thick stainless steel sheets using resin-impregnated glass fiber fabric. The module's readout electrodes consist of three copper layers separated by insulating polyimide sheets: the two outer layers are held at high voltage while the inner layer is used to read out the signal.

The electromagnetic end-cap calorimeter (EMEC) is a lead-liquid argon sampling calorimeter that uses interleaved accordion-shaped absorbers and electrodes. It covers an η range of $1.375 < |\eta| < 3.2$. The material in front of the end cap calorimeters results in energy loss and requires a liquid argon presampler to be implemented over the η range of $1.5 < |\eta| < 1.8$. For construction reasons, there are two coaxial wheels that make up the end caps with the boundary placed at $\eta = 2.5$ to match the tracking coverage of the Inner Detector. There are a total of 1024 absorbers and readout electrodes in the end cap calorimeters (768 in the outer wheel and 256 in the inner wheel). The lead absorbers are

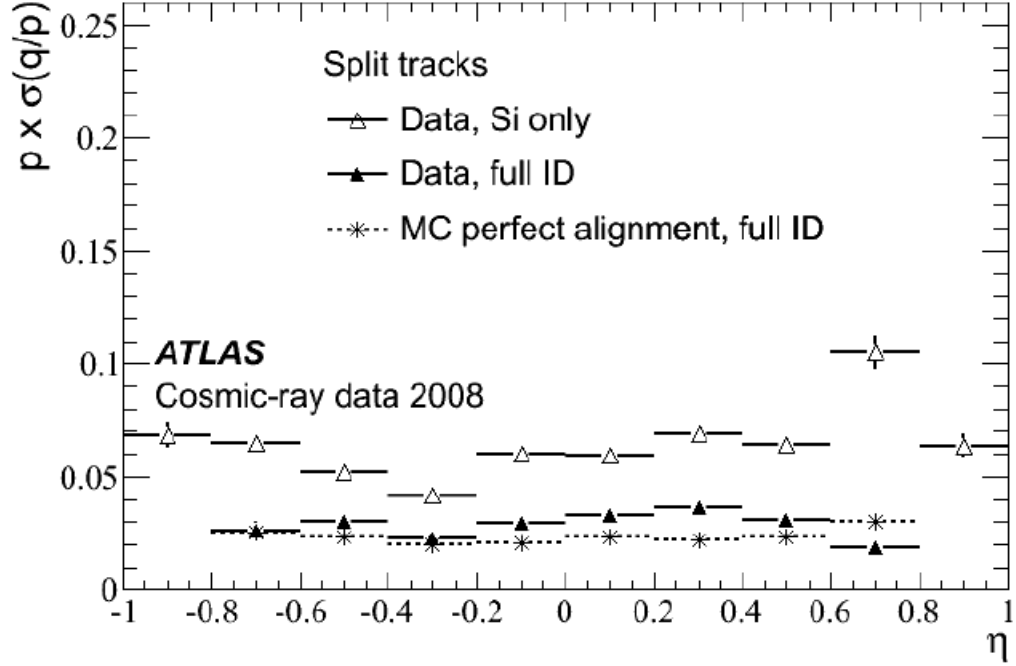


Figure 3.12: The ID momentum resolution as a function of η for silicon only tracks, the full set of ID tracks and the full set of simulated (MC) ID tracks.

sandwiched between 0.2 mm thick stainless steel layers and are 1.7 mm thick in the outer wheel and 2.2 mm thick in the inner wheel. The active thickness of an end cap is larger than $24 X_0$ up to $\eta = 1.475$, $38 X_0$ from 1.475 to 2.5 and $36 X_0$ from 2.5 to 3.2.

Both the barrel and end cap calorimeters are sampling calorimeters and consist of three compartments per module: front, middle and back each with different granularities. The barrel calorimeter has an energy resolution of $\sigma_E = 10\% \cdot \sqrt{E}$ where E is the energy of the particle [18].

3.6.2 Hadronic Calorimeter

Tile Calorimeter (Tile Cal)

Similar to the electromagnetic calorimeters, the hadronic calorimeter consists of a barrel and end cap calorimeter. The central hadronic calorimeter (also known as the Tile Calorimeter) is a sampling calorimeter. It uses steel absorbers and plastic scintillating tiles as the active

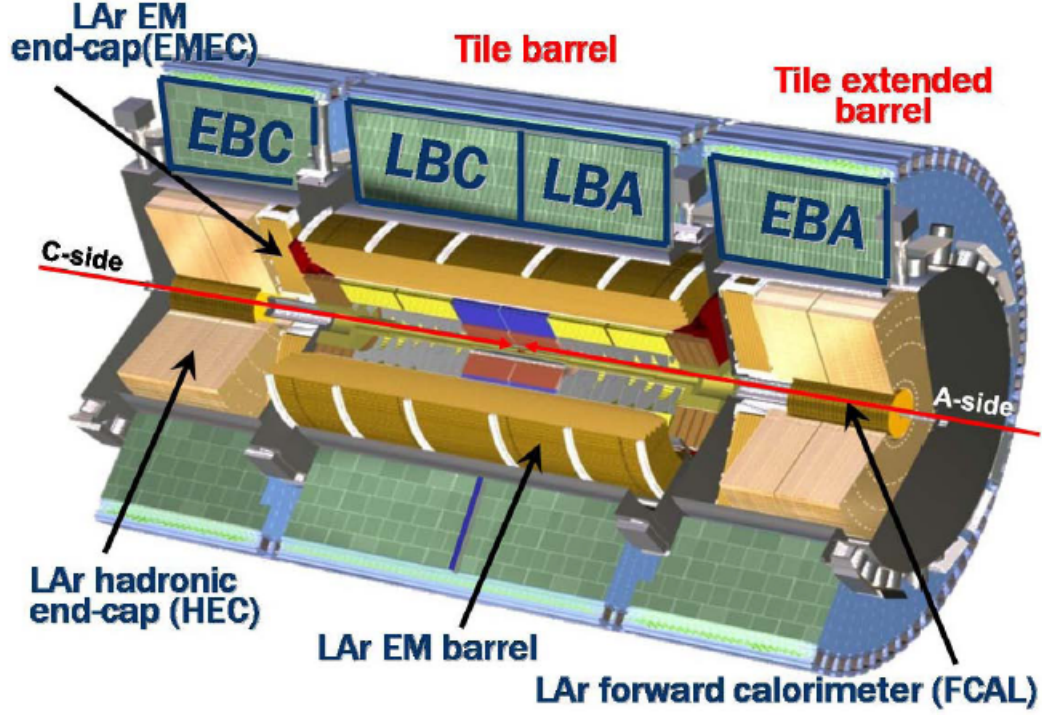


Figure 3.13: The ATLAS calorimetry is shown above. The LAr electromagnetic calorimeter (barrel and endcaps), the hadronic calorimeter (tile calorimeter and end caps) and the LAr forward calorimeter are all shown.

medium. The Tile Calorimeter covers an η range of $|\eta| < 1.7$ and is divided into the long barrel (LB) covering $|\eta| < 1.0$ and the extended barrels (EB) covering $0.8 < |\eta| < 1.7$. The long barrel measures 5640 mm (z) and the extended barrel measures 2910 mm (z), and the inner and outer radii measure 2280 mm and 4230 mm respectively. Both the long and extended barrel regions are divided into 64 wedge modules in ϕ . The innermost cells (A and BC cells seen in Fig. 3.15) have a granularity of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ and $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$ for the outermost layer (D cells). These modules are segmented into three layers with a respective thickness of 1.5, 4.1 and 1.8 λ (where λ is the average interaction length for a proton) in the long barrel and 1.5, 2.6 and 3.3 λ in the extended barrel.

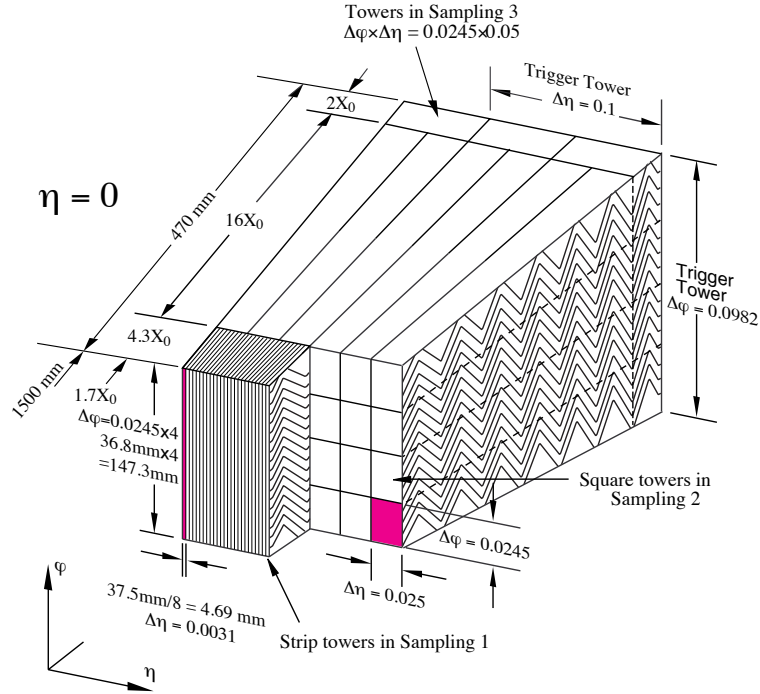


Figure 3.14: A section of the electromagnetic calorimeter is shown above. The lead absorbers assembled in the "accordion" shape can be seen along with the segmented chambers characteristic of a sampling calorimeter.

Hadronic End Cap Calorimeter (HEC)

The hadronic end cap calorimeter (HEC) covers the η range $1.5 < |\eta| < 3.2$, uses copper absorbers and liquid Argon as the active scintillating medium and sits directly behind the electromagnetic end cap calorimeter. The HEC consists of two cylindrical wheels in each ATLAS end-cap cryostat referred to as the front wheel (HEC1) and the rear wheel (HEC2). Each wheel contains 32 wedge modules which can be seen in Fig. 3.16. The HEC1 modules are made of 25 copper plates and the HEC2 modules contain 17 copper plates. The plates in HEC1 (HEC2) are 25 mm (50 mm) thick except for the front plates of the front and rear modules which are half the nominal thickness. The distance between all plates is 8.5 mm.

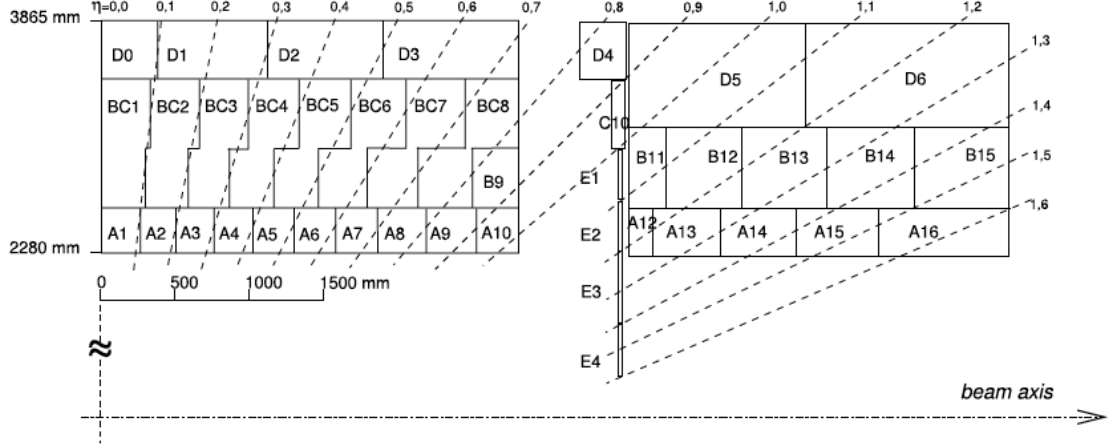


Figure 3.15: A cutaway view of one of the symmetric barrels of the hadronic tile calorimeter. The dashed lines represent incremental η values showing the coverage of the barrel. The three compartment "sampling" structure can also be seen.

Forward Calorimeter

The calorimeters in ATLAS are meant to work in tandem with the tracking systems to provide better and more information about the particles observed. However, since the tracking provided by the Inner Detector only covers up to $|\eta| < 2.5$ and $|\eta| < 2.7$ for the muon spectrometer, calorimetry is needed in this region.

Processes resulting in missing transverse energy (E_T) such as the weak decay of W bosons into a lepton and neutrino will be present in the collisions at the LHC. This missing E_T can be inferred by the large momentum imbalance in the transverse plane and for cases where these final state objects are very forward, calorimetry is the only pragmatic way to get a reliable energy measurement. The Forward Calorimeter (FCal) in ATLAS uses liquid Argon as the active medium and is a sampling calorimeter. It also covers a pseudorapidity range of $3.1 < |\eta| < 4.9$.

As is the case with the other calorimeters, the Forward Calorimeter consists of two halves: FCalA and FCalC. Each of these consists of three modules situated one behind the other. The module located closest to the Interaction Point uses copper as the absorber.

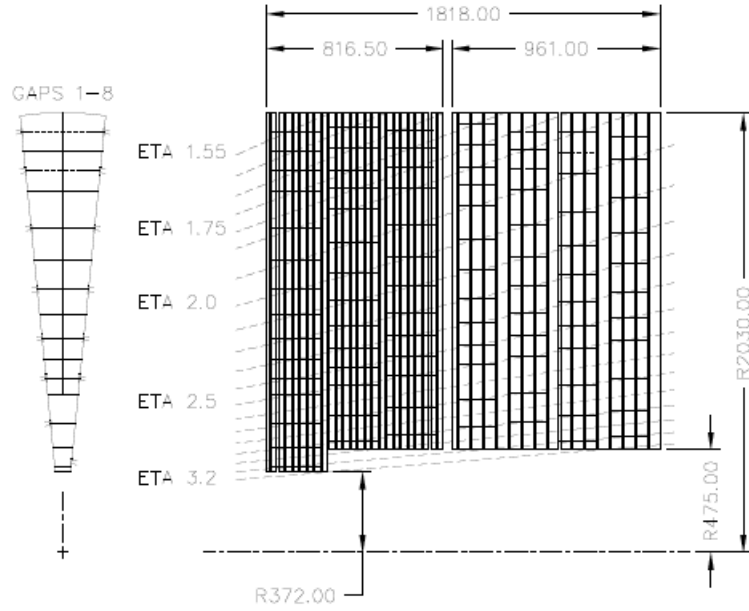


Figure 3.16: The diagram on the right shows the eta coverage of the hadronic end cap calorimeter along with the inner radii for the first 9 plates and the last 16 plates of HEC1 and all plates of HEC2. The image on the left shows the shape of the wedge modules as seen in the $r - \phi$ plane.

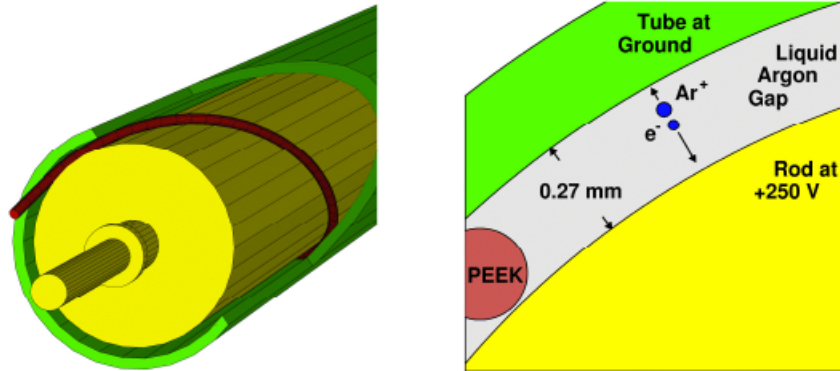


Figure 3.17: An enhanced cross-sectional view of an FCal1 electrode. The liquid Argon gap can be seen, along with the cathode (tube) and anode (rod).

The FCal2 and FCal3 modules are mainly comprised of tungsten in order to suppress the longitudinal and transverse spreading of hadronic showers. The front face of FCal1 is 4.7

m from the Interaction Point and the modules it contains measure 2.7λ in depth. The modules in FCal2 and FCal3 are 3.7λ and 3.6λ deep respectively resulting in a total depth of 10λ .

3.7 Muon Spectrometer

The muon spectrometer has a triggerable volume over the pseudo rapidity region of $|\eta| \leq 2.4$. Resistive Plate Chambers (RPCs) are used in the barrel region and are arranged in three stations. Thin Gap Chambers (TGCs) are used in the end-cap regions. In addition to triggering, the RPCs and TGCs also provide a “second-coordinate” measurement of track coordinates that are orthogonal to the primary precision measurement coordinates. This “second-coordinate” measurement allows for improved and more reliable track reconstruction which indirectly translates into better mass resolution when reconstructing mass resonances from muon tracks.

The Muon Spectrometer measures the momentum of muon tracks by using three superconducting air-core toroid magnets. In the pseudorapidity range $|\eta| \leq 1.0$ the muons are bent by a magnetic field produced a large barrel magnet consisting of eight coils that surround the hadronic calorimeter. In the η range $1.0 \leq |\eta| \leq 1.4$ (transition region), the magnetic field is provided by a combination of the barrel and end-cap magnets. This particular configuration was chosen as it produces a field mostly orthogonal to the trajectories that the muons have when traversing the field. It also minimizes resolution degradation due to multiple scattering.

It is designed in a way such that particles originating from the IP pass through multiple stations of chambers. Most precision measurements are made by Monitored Drift Tubes (MDTs), however at larger η and close to the Interaction Point, Cathode Strip Chambers (CSCs) are used. The CSCs have a higher granularity and are used since they can sustain the high rate environment close to the IP. In the barrel region track measurements are made by three cylindrical layers (stations) of Monitored Drift Tubes surrounding the beam axis (z-axis) at approximate radii of 5, 7.5 and 10 m. The barrel chamber coverage extends to

$|\eta| < 1$. In the end-cap region the chambers are oriented vertically in four discs and cover the pseudorapidity range $1 < |\eta| < 2.7$. The discs are situated at approximately 7, 10, 14 and 21 m from the IP and are concentrically arranged around the beam axis. MDTs are used as the primary tracking detector in the end caps except for the innermost layer ($2.0 < |\eta| < 2.7$), where CSCs are used. The barrel and end caps combine to provide nearly complete coverage over $0 < |\eta| < 2.7$, excluding a very small region at $\eta = 0$ which is used for the passing of cables for other subsystems of the detector.

3.7.1 Momentum Measurement

The muon spectrometer is designed to provide a momentum resolution of $\Delta p_T/p_T < 1.0 \times 10^{-4} \times p/\text{GeV}$ for muons with large transverse momentum ($p_T > 300 \text{ GeV}$). For less energetic muons the resolution is on the order of one percent due to multiple scattering (in the magnets) and energy loss in the calorimeters. To obtain the quoted resolution, each measurement made at the three stations must be measured with an accuracy better than $50 \mu\text{m}$. The precision momentum measurement is made in the r-z plane (bending plane), with the z position measured in the barrel and the radial measurement made in the end cap and transition region.

3.7.2 Monitored Drift Tubes

Monitored Drift tubes, as stated previously, form the majority of the tracking detectors used in the muon spectrometer. The tubes are made of aluminum, 30 mm in diameter and have a wall thickness of $400 \mu\text{m}$. Located at the center of the tube is a gold plated tungsten-rhenium wire $50 \mu\text{m}$ in diameter held at approximately 3100 V. Each tube can vary from 1 m to 6 m in length. The active ionising gas is a mixture of Ar and CO_2 (93% and 7%) pressurized at 3 bars and has a maximal drift time of 700 ns. A single tube spatial resolution of $80 \mu\text{m}$ is achievable with the aforementioned specifications. To improve the resolution beyond the single wire value the chambers implement a stacking structure. Each MDT chamber has two layers of tubes stacked four high in the inner station and two layers by 3 high in the middle and outer stations.

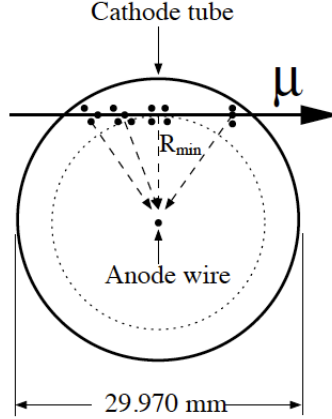


Figure 3.18: A schematic showing the MDT structure in ATLAS. Seen is a muon traversing the tube, ionizing the ArCO₂ gas mixture and the resulting charge collecting at the center wire. The resulting signal is read out at the end of the tube.

The chambers themselves will deform and therefore the deformations must be tracked and accounted for. This is done using the Rasnik, BCam and Saced [19] alignment systems. A CCD or CMOS sensor takes images of the chambers and corrects for the deformation in real time. It is also necessary to know where the chambers are positioned in space and also with respect to one another. This is accomplished by a complicated alignment system that can measure the position of a chamber with respect to the others with a precision of 0.03 mm. The barrel and end cap alignment systems are different, however they both make use of the Rasnik system described earlier.

3.7.3 Cathode Strip Chambers

The Cathode Strip Chambers are multiwire proportional chambers that use an active ionising medium of Ar and CO₂ (80% and 20%). They are present only in the end caps of the muon spectrometer and cover the high eta region ($2.0 < |\eta| < 2.7$). They consist of anode wires to collect the ionized charge in the gas and cathode strips to measure the induced signal giving the position of the hit within the chamber. The CSCs are also segmented using two sets of cathode strips: one set of strips parallel to the anode wires that measures the precision (bending) coordinate and one orthogonal to the anode wires that measures

the transverse coordinate.

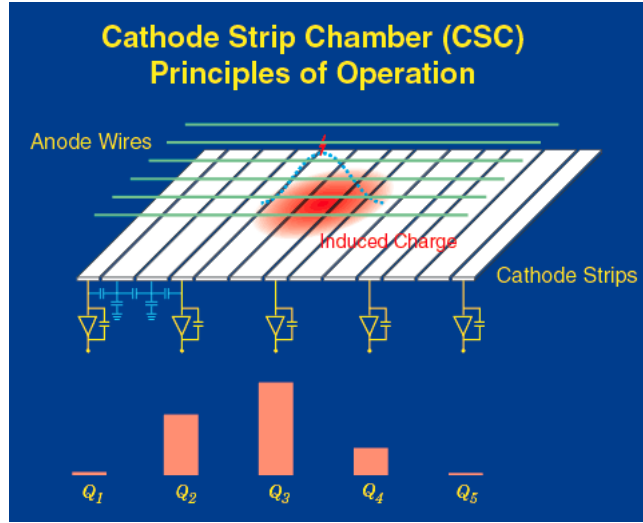


Figure 3.19: A general schematic of the Cathode Strip Chambers used in the ATLAS muon spectrometer. The muons traversing the chambers ionize the ArCO_2 gas causing an avalanche to occur on the various anode wires. This induces a charge distribution on the cathode strips which gives the location of the hit.

The CSCs also experience forces due to the toroidal magnetic field and therefore must be monitored as well. The same alignment system used to monitor the MDTs in the end caps is also used to monitor the CSCs.

3.7.4 Trigger Detectors

There are two types of trigger chambers used in the muon spectrometer: Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs). The barrel region exclusively uses RPCs whereas TGCs are used in the high rate environment of the end cap regions.

Resistive Plate Chambers

Resistive Plate Chambers are gaseous detectors that measure particle interaction via the ionization of the gas contained within the detector. The RPCs used in ATLAS have 2 mm

thick plates, a plate separation of 2 mm and a gas mixture comprised of $\text{C}_2\text{H}_2\text{F}_4$ - C_4H_{10} - SF_6 (97%, 5%, 0.3%). The potential between the plates is approximately 9.8 kV resulting in a very large electric field (4.9 kV/mm). This high electric field facilitates the avalanche of ionization caused by the initial ionization by the incident charged particle. Each chamber has two sets of 30 mm readout strips: one in η and ϕ .

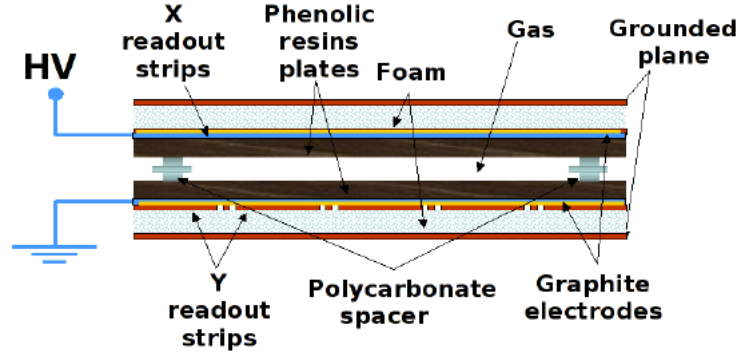


Figure 3.20: A schematic of a resistive plate chamber used in ATLAS.

Thin Gap Chambers

The second type of trigger detector used in ATLAS is a Thin Gap Chamber. The TGCs have two main purposes: provide triggering capability in the end cap regions and to measure the azimuthal coordinate of incident charged particle tracks. The anode wires in Fig. 3.21 are held at a positive high voltage. The ionization charges caused by the incident particle collect at the anode wires and provide a measurement of the bending coordinate. A charge distribution is induced on radial read out strips providing an azimuthal coordinate measurement. The active gas is a mixture of 55% CO_2 and 45% n-pentane ($\text{n-C}_5\text{H}_{12}$).

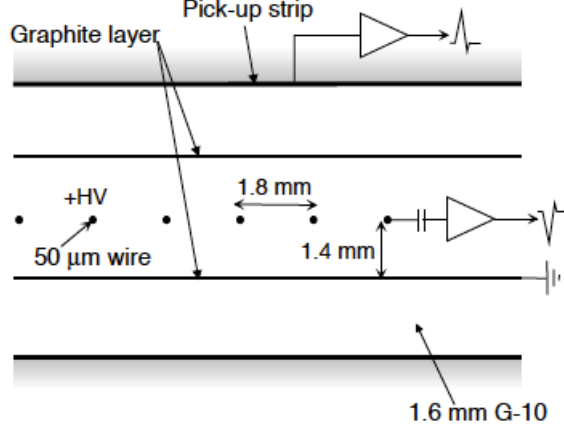


Figure 3.21: A schematic of a thin gap chamber used in ATLAS.

3.8 Level 1 Trigger System

The ATLAS trigger system is designed to operate at the nominal rate of 40 MHz ($\frac{1}{25\mu s}$) at the LHC. It is a three tiered system consisting of the Level-1 (L1), Level-2 (L2) and event filter (EF) event selection systems. The L1 trigger utilizes hardware (specifically designed electronics), and the L2 and EF triggers (collectively known as the High-Level Trigger (HLT)) are software level triggers.

The L1 trigger looks for large p_T muon, electron/photon, jet and hadronic τ decay signatures. It also can trigger on events that have associated large missing transverse energy (E_T^{miss}) and/or large transverse energy (E_T) signatures. It uses reduced-granularity information from the RPCs and TGCs to trigger on high p_T muons and the calorimeter systems to trigger on events associated with large calorimeter signatures. The maximum L1 accept rate is 75 kHz which can be upgraded to 100 kHz [3] and the L1 decision has to reach the front-end electronics within $2.5 \mu s$ after the associated bunch-crossing. A flow diagram of the L1 system is seen in Fig. 3.22.

The L2 trigger uses information from Regions-of-Interest (RoI's) to further filter the event rate. RoI's are regions where the L1 trigger has identified possible trigger objects of a particular event. The information includes but is not limited to the coordinates and

energy of the trigger object. The L2 trigger reduces the event rate to below 3.5 kHz with a processing time around 40 ms [3].

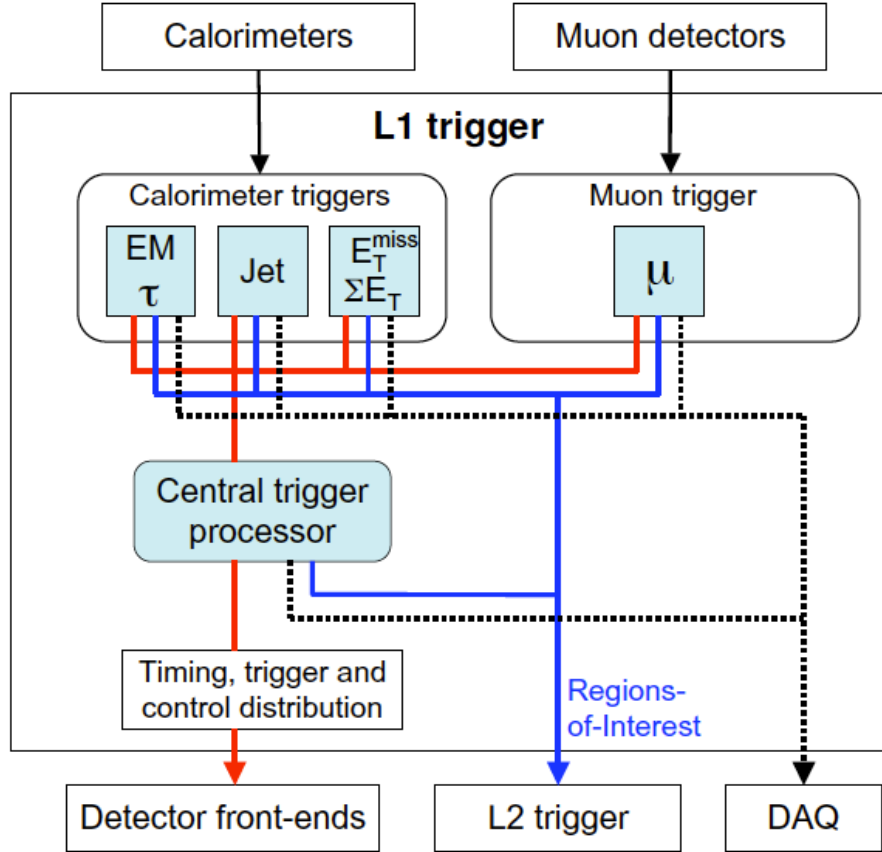


Figure 3.22: Flowchart showing the trigger process in ATLAS.

Chapter 4

MEASUREMENT OF THE ZZ CROSS SECTION AND ATGC LIMITS

4.1 Monte Carlo Signal and Data Samples

The $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ process and associated decays are modelled using the CT10 PDF [20] (parton density function) set and the PowhegBox (NLO)²[21] [22] [23] and gg2zz (LO) [24] generators. The gg2zz samples simulate the $gg \rightarrow ZZ$ process at LO which is a NNLO correction to the total cross section. It contributes approximately 5.93% of the total cross section. The gauge boson decays into electrons, muons and τ leptons with all τ leptons decaying inclusively.

The signal MC samples used in this analysis are listed in Table 4.1. The k-factor (σ_{LO}/σ_{NLO}) listed in Table 4.1 is needed to correct to the full NLO prediction. The PowhegBox and gg2zz samples have a filter applied at the generator level that requires at least 3 leptons (e, μ flavor) that have $p_T > 5$ GeV and $|\eta| < 10$. This filter mainly serves to reject events with τ leptons. Approximately 0.05% of $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ events are rejected when requiring that both Z bosons have masses in the range of 66-116 GeV (on-shell fiducial region). The gg2zz samples have a generator level filter that requires each Z to have a $p_T > 7$ GeV.

²Next to Leading Order (NLO), Leading Order (LO) and NNLO (Next to Next to Leading Order).

MCID	Process	Generator	Events	k-factor	ϵ_{filter}	cross section [pb]
126937	$ZZ \rightarrow e^+e^-e^+e^-$	PowhegBox	1099997	1.04	0.91	0.077
126938	$ZZ \rightarrow e^+e^-\mu^+\mu^-$	PowhegBox	1599696	1.04	0.83	0.176
126939	$ZZ \rightarrow e^+e^-\tau^+\tau^-$	PowhegBox	1099897	1.04	0.58	0.175
126940	$ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$	PowhegBox	1099798	1.04	0.91	0.077
126941	$ZZ \rightarrow \mu^+\mu^-\tau^+\tau^-$	PowhegBox	1098999	1.04	0.59	0.175
126942	$ZZ \rightarrow \tau^+\tau^-\tau^+\tau^-$	PowhegBox	300000	1.04	0.11	0.077
116601	$ZZ \rightarrow e^+e^-e^+e^-$	gg2zz	90000	1.0	1.0	0.000627
116602	$ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$	gg2zz	89699	1.0	1.0	0.000627
116603	$ZZ \rightarrow e^+e^-\mu^+\mu^-$	gg2zz	89899	0.935	1.0	0.00134

Table 4.1: All MC samples simulating the $pp \rightarrow ZZ X \rightarrow l^+l^-l^+l^-$ process along with number of events, cross section, filter efficiencies, k-factor, MC ID run number and generator used.

4.2 Event Triggers

A description of the ATLAS trigger system is given in section 3.8 and therefore will not be discussed here. Every $ZZ \rightarrow l^+l^-l^+l^-$ event must pass the event level trigger preselection. The triggers used are the lowest p_T un-prescaled triggers spanning the entire 2012 data taking period. The electron trigger requirement is an OR of the **EF_e24vhi_medium1** and **EF_e60_medium1** triggers. The muon trigger requirement is an OR statement of the **EF_mu24i_tight** and **EF_mu36_tight** triggers. The **EF_e60_medium1** and **EF_mu36_tight** triggers are necessary to maintain high efficiency at higher lepton p_T . The $e^+e^-e^+e^-$ final state must satisfy the electron trigger, the $\mu^+\mu^-\mu^+\mu^-$ final state must satisfy the muon trigger and the $e^+e^-\mu^+\mu^-$ can satisfy either or both triggers. In the case of both triggers the threshold p_T is 24 GeV. The sum of the p_T of the tracks in a cone of $\Delta R < 0.2$ surrounding the lepton must be less than $0.10 p_T$ for electrons and $0.12 p_T$ for muons.

Each event must contain a trigger-matched lepton. This is defined to be an electron within a cone of $\Delta R < 0.15$ of the electron that fired the trigger and a muon within a cone of $\Delta R < 0.1$ of the muon that fired the trigger. The trigger-matched object must have a p_T at least 1 GeV above the trigger threshold, meaning in our case an electron must have a $p_T > 25$ GeV.

4.3 Muons

Muon Object Selection	Cut
<u>Central Muons:</u>	
1. μ : type	“loose” STACO muons, either Combined or Segment Tagged
2. μ : p_T	$p_T > 7 \text{ GeV}$
3. μ : η	$ \eta < 2.5$
4. μ : ID hits	MCP recommendation
5. μ : $z_0 * \sin(\theta)$	$ z_0 * \sin(\theta) < 0.5 \text{ mm}$
6. μ : d_0	$d_0/\sigma_{d_0} < 3.0$
7. μ : track isolation	$\Sigma p_T(\Delta R < 0.2)/p_T < .15$
<u>Forward Muons:</u>	
1. μ : p_T	$p_T > 10 \text{ GeV}$
2. μ : $2.5 < \eta < 2.7$	
3. μ : ID hits	MCP recommendation
4. μ : $z_0 * \sin(\theta)$	$ z_0 * \sin(\theta) < 0.5 \text{ mm}$
5. μ : d_0	$d_0/\sigma_{d_0} < 3.0$
6. μ : calo isolation	$\Sigma E_T(\Delta R < 0.2)/E_T < .15$
<u>Calo Muons:</u>	
1. μ : type	Calorimeter tagged muon
2. μ : p_T	$p_T > 20 \text{ GeV}$
3. μ : η	$ \eta < 0.1$
4. μ : ID hits	MCP recommendation
5. μ : $z_0 * \sin(\theta)$	$ z_0 * \sin(\theta) < 0.5 \text{ mm}$
6. μ : d_0	$d_0/\sigma_{d_0} < 3.0$
7. μ : track isolation	$\Sigma p_T(\Delta R < 0.2)/p_T < .15$
8. μ : Quality Cuts	$\text{CaloMuonIDTag} > 10 \parallel \text{CaloLRLikelihood} > 0.9$
9. μ : Overlap Removal	Removed if within $\Delta R < 0.1$ of standard muon

Table 4.2: Muon object selection requirements for the specific categories of muons.

The two muon reconstruction algorithms used in this analysis are the STACO and CaloTrkMuID algorithms. STACO muons are reconstructed using information from a muon track in the ID and a muon track in the MS. The energy loss between the ID and MS is taken into account. There are three categories of STACO muons: *Combined*, *Segment Tagged* and *Stand Alone*. Combined muons are reconstructed using a full ID track and a full MS track whereas Segment Tagged muons use information from a full ID track and MS

track segment. Stand Alone muons have no ID track and are therefore reconstructed from an MS track only. Central and forward muons are required to pass the “loose” identification requirement.

Muons in the $|\eta| < 2.5$ region are referred to as “central muons”, muons with $2.5 < |\eta| < 2.7$ are referred to as “forward muons” and muons with $|\eta| < 0.1$ are “calo muons.” Central muons are required to be either *Combined* or *Segment Tagged* muons and have a $p_T > 7$ GeV. As per the MCP recommendation, every central muon track must have at least 1 hit in at least 1 Pixel layer, 4 hits in the SCT and less than 3 holes (no hit in a layer that is traversed by the track) over all silicon layers [25]. Each track must also satisfy TRT hit requirements that depend on the η region the track lies in. If the track is in the $0.1 < |\eta| < 1.9$ region, then $(\text{nTRT hits} + \text{nTRT outliers}) > 5$ and $\text{nTRT outliers} < 0.9 \times (\text{nTRT hits} + \text{nTRT outliers})$. If the track $|\eta| \leq 0.1$ or $|\eta| \geq 1.9$ and the $\text{nTRT hits} > 5$ then the $\text{nTRT outliers} < 0.9 \times (\text{nTRT hits} + \text{nTRT outliers})$. A TRT outlier is defined as a TRT straw that shows a signal yet was not crossed by the nearby track or as a set of TRT measurements that did not form a smooth trajectory with the measurements made by the Pixel and SCT [26].

Forward muons must have a $p_T > 10$ GeV and be either *Combined* or *Segment Tagged* muons. Each forward muon track must register a hit across all three stations in the muon spectrometer (inner, middle and outer). The hit requirements for forward muons are slightly relaxed in comparison to central muons. Each forward muon must have at least 1 hit in all Pixel layers, 3 SCT hits and less than 3 holes over all silicon layers.

The CaloTrkMuID algorithm tags certain tracks in the inner detector as muons in an attempt to regain efficiency around $\eta = 0$ (specifically $|\eta| < 0.1$). It does so by matching the aforementioned ID tracks with signals in the calorimeters that are inconsistent with electrons, photons or hadrons. Low p_T hadrons will deposit nearly all their energy in the first cell of the hadronic calorimeters while high p_T hadrons will deposit more in the proceeding layers. However, muons will leave very little energy in the calorimeters. Using this information one can tag calo muons. They are by definition “loose” muons and must have a $p_T > 20$ GeV as their identification algorithm is optimized for isolated muons with

$p_T > 20$ GeV [25]. Every calo muon must satisfy the same ID hit requirements as central muons. No TRT hits are required, but if there are more than 5 then nTRT outliers $< 0.9 \times (\text{nTRT hits} + \text{nTRT outliers})$. To reduce the amount of particles faking muons each calo muon must have a CaloMuonIDTag value greater than 10 or a CaloLRLikelihood value greater than 0.9. More detail about these algorithms can be found in [27].

We expect $pp \rightarrow ZZ X \rightarrow l^+ l^- l^+ l^-$ events to come from hard processes and therefore the final state muons should come from the primary vertex (defined as the vertex with the highest Σp_T^2 of associated tracks). Requiring the magnitude of the distance of closest approach to the primary vertex, $|z_0 \sin(\theta)|$ to be less than 0.5 mm and the transverse impact parameter significance ($|d_0|/(\sigma_{d_0})$) to be less than 3.0 ensures that this is the case. This is only required for *Combined* and *Segment Tagged* muons, since *Stand Alone* muons do not have an inner detector track.

In order to discriminate between prompt muons originating from Z bosons and secondary muons coming from hadronic jets the muons are required to be isolated. For central and calo muons the scalar sum of the transverse momenta of tracks surrounding the muon in a cone of $\Delta R = 0.2$ is required to be less than $0.15 \times p_T$ of the muon.

4.4 Electrons

Electrons with $|\eta| < 2.47$ are referred to as “central” and are the only type considered in this analysis. They must satisfy the “Loose++” identification criteria and have an “author” value of 1 or 3. An author value of 1 means that only the cluster based algorithm has identified the electron object. An author value of 3 means that the object has been identified by the cluster and track-based algorithms. The cluster based algorithm is used primarily to reconstruct isolated electrons while the track based algorithm is used to reconstruct soft (low p_T) electrons.

In order to avoid energy measurements made in problematic regions of the LAr calorimeter, electrons must pass the object quality check (OQ AND 1446 = 0). The number “1446” is a bitmask indicating that the electron’s cluster is affected by one of the following prob-

Electron Object Selection	Cut
<u>Central Electrons:</u>	
1. e : type	author = 1 or 3
2. e : quality	(OQ AND 1446 == 0)
3. e : ID cut	“Loose++”
4. e : E_T	$E_T > 7$ GeV
5. e : η	$ \eta < 2.47$ includes crack region: $1.37 < \eta_{cluster} < 1.52$
6. e : $z_0 * \sin(\theta)$	$ z_0 * \sin(\theta) < 0.5$ mm
7. e : d_0	$d_0/\sigma_{d_0} < 6.0$
8. e : track isolation	$\Sigma p_T(\Delta R < 0.2)/p_T < .15$
9. e : Overlap Removal	a) remove if $\Delta R < 0.1$ to a selected muon.
	b) remove lowest E_T if $\Delta R < 0.1$ of another electron

Table 4.3: Electron object selection requirements.

lems: the existence of a dead front-end board in the first or second sampling layer, the existence of a dead region affecting all three sampling layers, or an associated cell core that is masked.

Impact parameter cuts requiring $|z_0 * \sin(\theta)| < 0.5$ mm and $d_0/\sigma_{d_0} < 6.0$ ensure that the electrons come from the primary vertex.

The electron energy measurement is always made from the EM calorimeter cluster information, however if the electron has four or more silicon hits (Pixel + SCT) the η and ϕ measurements are made from the track information. If the number of silicon hits is less than 4, they are taken from the cluster information. In the case of overlap removal and the η requirement, the cluster information is used. Each electron must have $E_T > 7$ GeV.

As is the case with selected muons, each electron must be isolated from other surrounding tracks by requiring the sum of the transverse momenta of tracks surrounding the electron in a cone of $\Delta R = 0.2$ must be less than $0.15 \times p_T$ of the electron. If a selected electron track overlaps with a selected muon in a cone of $\Delta R = 0.1$ it is removed. If a selected electron overlaps with another selected electron within a cone of $\Delta R = 0.1$, the lower E_T electron is removed.

4.5 Event Selection

A certain set of conditions must be satisfied by each event for it to be considered a valid event in which to search for four isolated leptons originating from two Z bosons.

1. **Good Runs List** : The event must exist in the Good Runs List.
2. **Triggers** : Each event must fire at least one of the triggers mentioned in Sec. 4.2.
3. **Primary Vertex** : Each event must have a primary vertex with at least three associated tracks.
4. **Event Cleaning** : Each event should not have a LAr error value greater than 1.
5. **Data Corruption** : Each event should be free of data corruption in the tile calorimeter ($\text{tileError}==2$) and have no coreFlags error ($\text{coreFlags}\&0x400000!=0$).

4.5.1 $\ell^+\ell^-\ell'^+\ell'^-$ Selection

The $e^+e^-e^+e^-$, $\mu^+\mu^-\mu^+\mu^-$ and $e^+e^-\mu^+\mu^-$ final states represent all final state signatures considered in this analysis. Before continuing it will be helpful to describe the nomenclature and specific requirements of the aforementioned final states.

The Z boson candidates reconstructed from di-lepton pairs are classified in two ways:

- The difference of each Z candidate mass to the Z pole (PDG Z mass). The Z candidate with invariant mass closest to the Z pole is the **primary** Z and the remaining is the **secondary** Z.
- The Z candidate with the higher p_T is referred to as the **leading** Z and the remaining is the **subleading** Z.

Each event is required to satisfy the following conditions:

- **Four Leptons** : Each event must have four and only four leptons in the final state. Each lepton must satisfy the selection criterion described in Sec. 4.3 and 4.4.

- **Trigger Matching** : At least one lepton must be trigger matched. If the trigger matched lepton is an electron it must have a $p_T > 25$ GeV and pass the Medium++ identification requirement. If the trigger matched lepton is a muon it must have a $p_T > 25$ GeV, be a Combined muon and have $|\eta| < 2.4$.
- **Quadruplet Formation** : Each pair of leptons must be opposite sign and same flavor (OSSF). In general, there are multiple ways to pair the leptons in the final state. The pairing combination that minimizes the sum of the magnitude of the distances to the Z pole for each lepton pair is chosen as the proper combination. In other words the pair minimizing $|m_{12} - m_Z^{PDG}| + |m_{34} - m_Z^{PDG}|$ is chosen where '1','2','3' and '4' are the final state leptons and m_Z^{PDG} is the Z mass.
- **Primary Z mass** : The primary Z mass must fall in the window $66 < m_Z^{primary} < 116$ GeV.
- **Secondary Z mass** : The secondary Z mass must fall in the window $66 < m_Z^{secondary} < 116$ GeV.
- **Lepton Separation** : The leptons must have a ΔR separation greater than 0.2 ($\Delta R(l, l) > 0.2$).
- **Extension Lepton Limit** : Each event is limited to at most two extension leptons (calorimeter and forward muons) and one of each type. Each extension lepton must be paired with one central lepton.
- **J/ ψ Veto** : If any OSSF pair combination results in an invariant mass below 5 GeV the event is vetoed.

4.6 Event Weights

4.6.1 Pileup Reweighting

As was mentioned in Sec. 3.4.1, μ is a measurement of the number of proton-proton collisions per event. Ranging from a few to many, a collision is considered a reconstructed vertex in

an event. The number of reconstructed vertices increases as the beam luminosity increases. The μ value is not the same in every data period (since the luminosity is not always the same) and must be measured. Using the measured μ distribution per Bunch Crossing ID (BCID) in data one can compare that to the distribution produced in Monte Carlo and calculate a weight. This weight, referred to as the pileup reweight, is applied on an event level basis to Monte Carlo.

4.6.2 Muons

Multiple scale factors are applied to the selected muon objects falling within our final state definition. As was mentioned in Sec. 4.3, an identification selection is imposed on muons. This selection has an efficiency that differs between data and Monte Carlo and must therefore be corrected. This is done by comparing the efficiency measured in data with that measured in Monte Carlo using a “tag and probe” method described in detail in [28]. In this method $Z \rightarrow \mu^+ \mu^-$ decays are selected by looking for two oppositely charged, isolated muon tracks with an invariant mass near the Z mass. One track must be a Combined muon (“tag”) and the other track (“probe”) must either be a Stand Alone muon if the ID efficiency needs to be measured or an ID track if the MS efficiency is to be measured. The ID efficiency is the fraction of Stand Alone “probes” that can be associated to an ID track. The MS efficiency is the fraction of ID “probes” that can be associated to a Combined or Segment Tagged track. A Stand Alone “probe” is matched to an ID track if $\Delta R \leq 0.05$ and an ID “probe” is matched if $\Delta R \leq 0.01$. The overall muon ID scale factor for $\ell^+ \ell^- \ell'^+ \ell'^-$ events is 99.3%. The tool used in this analysis is **MuonEfficiencyCorrections-02-01-12**.

In the forward region the sum of the transverse energy in a cone of $\Delta R = 0.2$ around the muon must be less than 0.15 of the muon p_T . The energy within the cone is corrected for contributions from pile-up events by using the number of reconstructed vertices in the event (**MuonIsolationCorrection-01-01**).

4.6.3 Electrons

The efficiency corrections applied to electrons are of two specific types: ID (Loose++, Medium++ and Tight++) efficiency and reconstruction efficiency. Both efficiencies are measured in data and Monte Carlo using a Z tag and probe method where the invariant mass of the di-electron system (M_{ee}) must be between 80 and 100 GeV. More details on this method can be found in Ref [29]. The tools used to apply these scale factors in this analysis are **egammaAnalysisUtils-00-04-17** and **ElectronEfficiencyCorrection-00-00-09**.

4.7 Momentum Smearing For Monte Carlo Events

The p_T distributions of both electrons and muons differ slightly in data and Monte Carlo. In order to accurately simulate data these distributions must be corrected or “smeared” in Monte Carlo.

The muon p_T in Monte Carlo needs to be corrected to match the data distribution. This is done by looking at muons in events with Z bosons, reconstructing the di-muon mass and comparing the experimental and simulated distributions. Using these corrections the muon p_T is “smeared” while keeping the direction unchanged (**MuonMomentumCorrections-00-08-05**).

Electrons not only have the p_T smeared in Monte Carlo but an energy scale correction must also be applied to data. This is done using **egammaAnalysisUtils-00-04-17**.

4.8 Fiducial Region Definition

In order to measure the ZZ cross section it is necessary to define a fiducial region. This region defines the kinematic space that events must exist in in order to be considered valid candidate events and helps separate “signal” processes from “background” processes.

The $ZZ \rightarrow l^+l^-l^+l^-$ signal region is defined as:

- $ZZ \rightarrow l^+l^-l^+l^-$ where $l = e, \mu$ and each Z must decay to an opposite sign and same flavor lepton pair (ie. $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$).

- $66 < m_{12} < 116$ GeV. m_{12} is the mass of the Z that is reconstructed from the first and second leptons.
- $66 < m_{34} < 116$ GeV. m_{34} is the mass of the Z that is reconstructed from the third and fourth leptons.
- The pair of reconstructed Z 's that minimizes $|m_{12} - m_Z^{PDG}| + |m_{34} - m_Z^{PDG}|$ is chosen.
- $p_T^l > 7$ GeV.
- $|\eta| < 2.7$.
- Each lepton must have a ΔR separation of at least 0.2 between the other three leptons in the event ($\min(\Delta R(l, l)) > .2$).

4.9 Background to $pp \rightarrow ZZ X \rightarrow l^+ l^- l^+ l^-$

There are many sources of background for this particular final state. The main contributions come from $Z + jet$, $Zb\bar{b}$, $Z + \gamma + jet$, and decays involving top quarks such as $t\bar{t}$ and single top where a jet from a heavy flavor decay is misidentified as an isolated lepton or a lepton from a heavy flavor decay passes the lepton isolation requirement (see sec. 4.4 for electrons and 4.3 for muons). The $Z + jet$ sources have two prompt leptons originating from a Z , whereas the $t\bar{t}$ source has the two prompt leptons coming from the $W^\pm$ bosons. The remaining two leptons can be “fake” leptons (charged hadrons such as pions misidentified as leptons), real leptons originating from heavy flavor (b or c quark) decays, muons decaying in-flight from pions or kaons or electrons coming directly from photons. Additional sources of background are $WZ + jet$ and $WW + jet$ that have three (two) real, prompt leptons and one (two) “fake” leptons and irreducible backgrounds coming from $t\bar{t}Z$ and ZZZ/WWZ processes (not aTGC processes).

In the case of a $WZ + jet$ ($WW + jet$) event where the bosons decay leptonically, there are 3 (2) prompt leptons from the vector boson decays present. Combine that with a fourth (third and fourth) lepton originating from the various aforementioned sources and a 4 lepton event not originating from a ZZ initial state could pass the selection criteria.

It is appropriate to note that even though the majority of leptons in a jet would fail the object level isolation cuts, the tails of the distribution contain leptons that could pass the isolation and identification requirements of selected leptons. It is therefore very important to estimate the contribution from these particular events. Since it is likely that the MC may not model the tails of the jet distributions well a data-driven method is used to estimate the contribution from this type of background.

4.9.1 Data-driven Method

In order to estimate the background from the aforementioned sources, the identification of events very near to the “signal region” is defined. This is done by inverting one or two of the lepton requirements (sec. 4.3 and 4.4) while all others remain the same. A “fake factor” is used to extrapolate these events near the “signal region” into the signal region. This “fake factor”, referred to as FF, is measured in a separate sample that consists mostly of jets and does not contain real leptons.

The calculation of the fake factors begins by defining “pre-selected” leptons as leptons satisfying some of the requirements listed in sections 4.4 and 4.3. These requirements depend on flavor and will be discussed later in subsequent sections. The leptons are then categorized as “L” objects (selected leptons) that pass all selection requirements, or “J” objects (lepton-like jets) that pass all but specific requirements. The fake factor is defined as

$$FF = \frac{L}{J}. \quad (4.1)$$

and is calculated from a sample of events that consists mostly of $Z + jet$ events. It is therefore assumed that any “L” object is a jet that satisfies the “L” selection requirements and is not a real lepton.

4.9.2 Electron Selection

As was mentioned earlier, we must define what the L and J definitions are for both electrons and muons. For central electrons the sample made of L and J objects satisfy all electron selection requirements up to before the track isolation and electron identification cuts. The pre-selected electrons are categorized as L objects if they pass the aforementioned electron selection requirements and satisfy the track isolation and electron ID requirements. The pre-selected electrons that fail either the track isolation or electron ID requirement but pass all other requirements are categorized as J objects. Pre-selected electrons that fail both the track isolation and ID requirements are discarded (fall outside either category) since they represent an area too far from our selected (“good”) electrons. Additionally, studies have shown that these electrons are not well modeled in Monte Carlo which is yet another reason to discard them.

The specific definition for selected electrons (L) and electron-like jets (J) are summarized in Table 4.4.

Flavor	Selected (L)	Lepton-like Jets (J)
<u>Muons:</u>	Track isolation < 0.15 and d_0 significance < 3.0	(d_0 significance > 3.0 and Track iso < 0.15) or (d_0 significance < 3.0 and Track iso > 0.15)
<u>Electrons:</u>	Track isolation < 0.15 and Loose++	(!Loose++ and Track iso < 0.15) or (Loose++ and Track iso > 0.15)

Table 4.4: Muon and electron L and J definitions.

To extrapolate to region A, a fake factor must be calculated. The fake factor for electrons is defined as

$$FF_e = \frac{N_{\text{selected electrons}}^{\text{data}} - N_{\text{selected electrons}}^{\text{MC } WZ, ZZ}}{N_{\text{electron-like jets}}^{\text{data}} - N_{\text{electron-like jets}}^{\text{MC } WZ, ZZ}}. \quad (4.2)$$

When selecting the leptons used to measure the fake factor, we pull from a sample

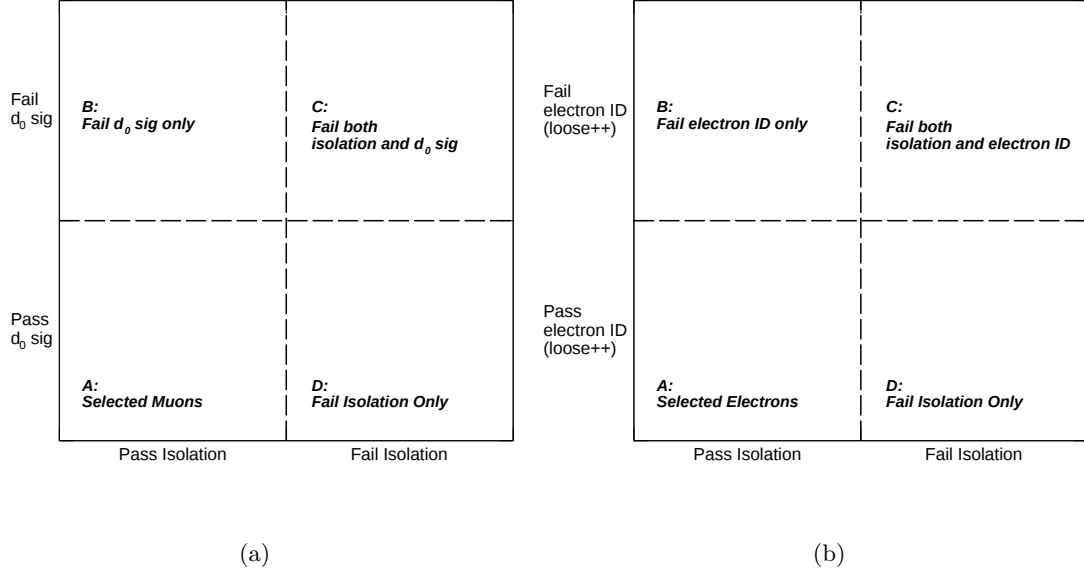


Figure 4.1: The definition of selected leptons and lepton-like jets for muons (a) and electrons (b). Objects in region A are leptons used in our analysis that can form candidate Z bosons. Muons in regions B and D are categorized as muon-like jets (J). Electrons in regions B and D are categorized as electron-like jets (J). Objects in region C lie too far from the selected region and are discarded. The fake factor is used to extrapolate from regions B and D to region A in both cases of lepton flavor.

of events with a reconstructed Z boson and search for additional leptons in those events. Events that are associated with a reconstructed Z boson are referred to as “Z-tagged” events. Requiring a tagged Z to be present in each event ensures that the sample of events from which the fake factor is calculated consists largely of $Z + jet$ events. The “Z-tagged” requirements are listed in Table 4.5.

The fake leptons can come from various sources, with the majority originating from $Z + jet$ events. However, real leptons from WZ and ZZ events can also contribute fake leptons. It is because of this that they must be removed from the L and J populations via the $N_{\text{selected electrons}}^{\text{MC } WZ, ZZ}$ and $N_{\text{electron-like jets}}^{\text{MC } WZ, ZZ}$ terms in eq. 4.2. Histograms of the p_T and η of selected leptons and lepton-like jets are created for data, WZ and ZZ Monte Carlo. The WZ and ZZ histograms are then subtracted from the data histograms to eliminate their contribution to the fake factor calculation. The fake factor is then calculated by dividing the

Criteria	Selection Requirements
Leptons	2 selected muons or 2 selected electrons
Z-reconstruction	lepton pair must be oppositely charged and same flavor
	1 lepton must be trigger matched to event
	$ M_{ll} - M_Z < 20 \text{ GeV}$
E_T^{miss}	$E_T^{miss} < 25 \text{ GeV}$

Table 4.5: Reconstructed Z requirements for “Z-tagged” events.

selected lepton histogram by the lepton-like jet histogram. This effectively parameterizes the fake factor in p_T and η and the distributions are seen in Fig. 4.2 and 4.3.

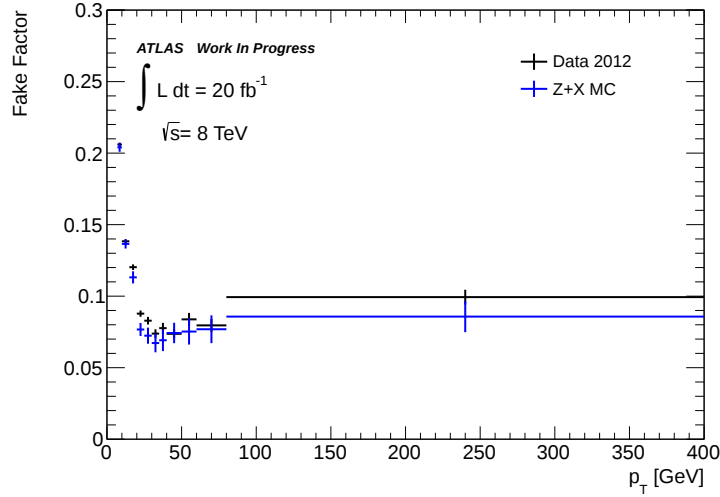


Figure 4.2: Fake factor distribution parameterized in p_T for electrons.

When applying the fake factors to extrapolate to the signal region, there is assumed to be no correlation between the fake factors parameterized in p_T and η . Assuming this the fake factor that is applied is defined as

$$FF_e(p_T, \eta) = \frac{FF^e(p_T) \cdot FF^e(\eta)}{\langle FF_e(p_T, \eta) \rangle} \quad (4.3)$$

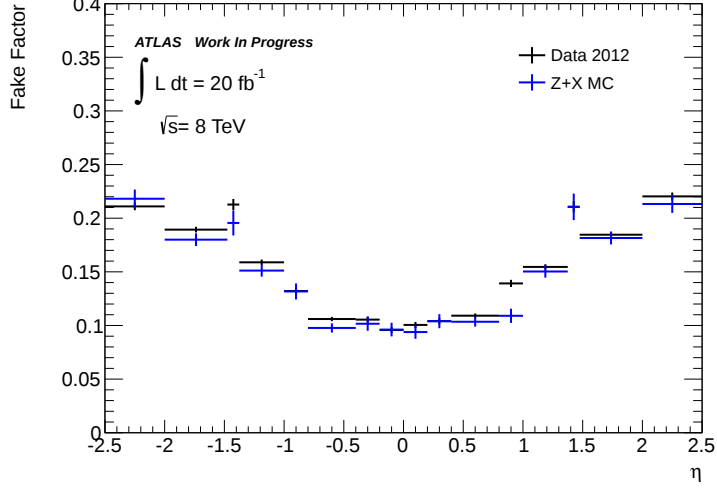


Figure 4.3: Fake factor distribution parameterized in η for electrons.

where $\langle FF_e(p_T, \eta) \rangle$ is the average fake factor defined as the total number of selected electrons (L) divided by the total number of electron-like jets (J).

4.9.3 Muon Selection

Sources of fake muons include heavy flavor decays (b or c quarks that hadronize), K/π decays or hadrons that punch through all other sub-systems into the muon spectrometer. Muon-like jets are defined as objects with d_0 significance > 3.0 or with track isolation > 0.15 . As is the case with electrons, muons that fail both the d_0 significance and isolation (track isolation for central and calo muons and calorimeter isolation for forward muons) requirements are discarded from the analysis as they are too far from our signal region (regions shown in Fig. 4.1). The muon fake factor is defined as

$$FF_\mu = \frac{N_{\text{selected muons}}^{\text{data}} - N_{\text{selected muons}}^{\text{MC } WZ, ZZ}}{N_{\text{muon-like jets}}^{\text{data}} - N_{\text{muon-like jets}}^{\text{MC } WZ, ZZ}}. \quad (4.4)$$

The sample of muons used to calculate the fake factor come from events that contain a reconstructed Z boson (“Z-tagged”), the selection of which is summarized in Table 4.5. Any muons found in addition to the Z are categorized as selected muons or muon-like jets.

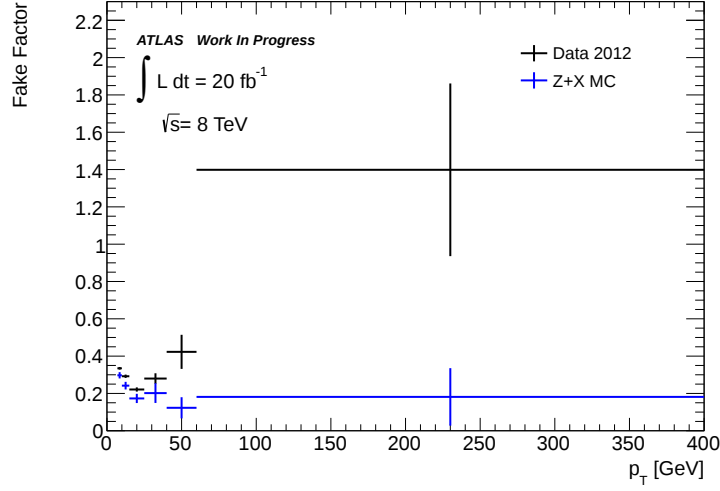


Figure 4.4: Central muon fake factor parameterized in p_T . The poor agreement from 50 GeV to 400 GeV is further justification for using this data driven method to estimate the background.

The real leptons from WZ and ZZ contributions are removed via the $N_{\text{selected muons}}^{\text{MC } WZ, ZZ}$ and $N_{\text{muon-like jets}}^{\text{MC } WZ, ZZ}$ terms in Eq. 4.4.

Unique to muons, there are three separate fake factors calculated and applied to events with fake muons. As was mentioned in section 4.3, there are three types of muons: central, forward and calo. Since these muons are in three unique areas of the detector, the respective probabilities of being faked are not assumed to be the same. Therefore, their fake factors must be measured individually.

All muon fake factors are parameterized in p_T and η . The distributions are shown in Fig. 4.4 and 4.6.

The fake factor applied to extrapolate to the signal region is defined as

$$FF_{\mu}(p_T, \eta) = \frac{FF_{\mu}(p_T) \cdot FF_{\mu}(\eta)}{\langle FF_{\mu}(p_T, \eta) \rangle} \quad (4.5)$$

where $\langle FF_{\mu}(p_T, \eta) \rangle$ is the average fake factor defined as the total number of selected muons (L) divided by the total number of muon-like jets (J).

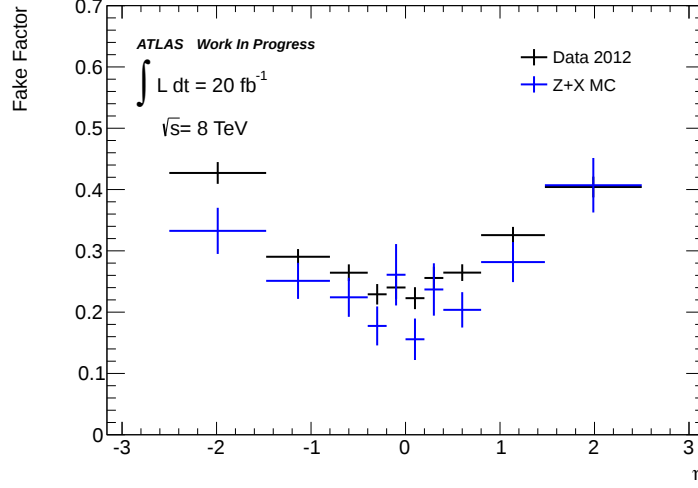


Figure 4.5: Central muon fake factor parameterized in η .

4.9.4 Calculation of Fake Lepton Background

The event content of the fake lepton background consists mainly of events with two fake leptons (F) and two true leptons (T) and events with one fake lepton and three true leptons. For this reason the number of fake 4 lepton events is described as

$$N_{4l}^{\text{fake}} = N_{TTTF} \times f + N_{TTFF} \times f^2. \quad (4.6)$$

where f is the probability of a fake lepton being reconstructed as a selected lepton (L). Events with three true leptons and one fake lepton can arise from $WZ + jet$ events, whereas events with two true and fake leptons can come from $Z + jet$ (multiple jets), $t\bar{t}$, $tW + jet$ and $t + jets$. However, since in data it is impossible to know what is truly a lepton and what is truly a fake, we must relate N_{4l}^{fake} to events with selected leptons and lepton-like jets. The probability (f) in Eq. 4.6 is expressed as

$$f = \frac{L}{L + J}. \quad (4.7)$$

where L is the number of jets that pass the lepton (L) selection requirements.

Using Eq. 4.1, FF and f can then be expressed as

$$FF = \frac{f}{1-f} \text{ and } f = \frac{FF}{1+FF}. \quad (4.8)$$

The number of events with two true leptons and two fake leptons can be related to events with two selected leptons and two lepton-like jets via:

$$N_{LLJJ} = N_{TTFF} \times (1-f)^2 \quad (4.9)$$

The number of events with three true leptons and one fake lepton can be related to events with three selected leptons and one lepton-like jet via:

$$N_{LLLJ} = N_{TTTF} \times (1-f) + N_{TTFF} \times 2f(1-f) \quad (4.10)$$

where the factor of 2 arises from combinatorics. When combining Eq. 4.10 and 4.9 the background estimate is written as

$$N_{4l}^{\text{fake}} = (N_{TTTF} \times f + N_{TTFF} \times 2f^2) - N_{TTFF} \times f^2 = N_{LLLJ} \times FF - N_{LLJJ} \times FF^2 \quad (4.11)$$

A correction for the contamination from ZZ events is applied and the final expression for the background estimate is

$$N_{4l}^{\text{fake}} = (N_{LLLJ} - N_{LLLJ}^{ZZ}) \times FF - (N_{LLJJ} - N_{LLJJ}^{ZZ}) \times FF^2. \quad (4.12)$$

where N_{LLLJ} (N_{LLJJ}) is the number of events with 3 (2) objects that satisfy the “L” selection and 1 (2) objects that satisfy the “J” selection. It is important to mention that in this estimate events containing zero “true” leptons and one “true” lepton are neglected and therefore so are their respective terms in Equation 4.12.

4.9.5 Uncertainties

The statistical uncertainty on the background estimate is calculated by adding the relative statistical error associated with the fake factors in quadrature with the relative statistical error on the number of events found in the data, both per channel and total. The systematic uncertainty is defined as the difference between the nominal background estimate and the estimate using average fake factors per lepton flavor (all fake factors applied are parameterized in p_T and η).

4.9.6 Data-driven Estimates

Event Type	$eeee$	$\mu\mu\mu\mu$	$ee\mu\mu$	$llll$
N_{LLLJ}	164	8	113	285
ZZ_{LLLJ}	11.31	3.99	16.56	31.86
N_{LLJJ}	645	11	443	1096
ZZ_{LLJJ}	1.78	0.07	1.00	2.85

Table 4.6: Number of $LLLJ$ and $LLJJ$ events per channel and combined over all channels.

The number of N_{LLLJ} , N_{LLJJ} , ZZ_{LLLJ} , ZZ_{LLJJ} events is summarized in Table 4.6. The number of $LJJJ$ events in data totals 264.

A summary of the fake estimates are shown in Table 4.7 for ZZ events falling within our fiducial region. The total data-driven background estimate summed over all three channels ($eeee, \mu\mu\mu\mu$ and $ee\mu\mu$) is

The total data driven fake estimate for on-shell ZZ events is

$$17.73 \pm 4.21(\text{stat}) \pm 4.00(\text{syst}) \quad (4.13)$$

where the systematic uncertainty is defined as the difference in the data driven estimate using parameterized fake factors and average fake factors. The statistical uncertainty is calculated by adding N_{LLLJ} , ZZ_{LLLJ} , N_{LLJJ} and ZZ_{LLJJ} statistical errors in quadrature.

Event Type	$eeee$	$\mu\mu\mu\mu$	$ee\mu\mu$	$llll$
(+) $N_{LLLL} \times FF$	22.05 ± 1.93	3.82 ± 1.63	19.19 ± 2.80	45.06 ± 3.77
(-) $ZZ_{LLLL} \times FF$	1.02 ± 0.02	1.81 ± 0.06	3.09 ± 0.08	5.92 ± 0.10
(-) $N_{LLJJ} \times FF^2$	11.38 ± 0.57	1.38 ± 0.45	8.72 ± 0.66	21.47 ± 0.98
(+) $ZZ_{LLJJ} \times FF^2$	0.02 ± 0.001	0.02 ± 0.005	0.03 ± 0.003	0.07 ± 0.006
N_{4l}^{fake}	9.67 ± 3.11 (stat.) ± 1.34 (syst.)	0.65 ± 0.81 (stat.) ± 0.28 (syst.)	7.41 ± 2.72 (stat.) ± 2.38 (syst.)	17.73 ± 4.21 (stat.) ± 4.00 (syst.)

Table 4.7: Summary of data-driven background estimate per channel and combined over all channels. N_{LLLL} and N_{LLJJ} are events observed in data and ZZ_{LLLL} and ZZ_{LLJJ} are events in Monte Carlo.

Combining the MC background prediction from irreducible sources gives the total number of fake 4 lepton events in Eq. 4.14

$$19.70 \pm 4.21(\text{stat.}) \pm 4.00(\text{syst.}). \quad (4.14)$$

4.9.7 Monte Carlo Background Estimation

Due to the fact that the Monte Carlo predictions are limited by statistics and heavily rely on proper modelling of leptons in jets, the event yield of multiple background processes modelled by Monte Carlo is used as a rough cross-check on the data driven background estimation (within an order of magnitude). The background processes used are Z + jets, WZ/WW , $t\bar{t}$ and single top and all MC yields are normalized to 20 fb^{-1} . All scale factors mentioned in Sections 4.6.2 and 4.6.3 and corrections (smearing) are applied as well.

The dominant background source over all channels is Z +jets (Table 4.8) with a predicted yield of 2.66 ± 2.62 on-shell ZZ events. The total MC background prediction is 7.43 ± 2.81 events satisfying the combined ZZ selection requirements which is to be compared to the data driven background estimation of $17.73 \pm 4.21(\text{stat}) \pm 4.00(\text{syst})$. A consequence of the limited statistics associated with the MC background prediction and the large luminosity scaling factor of the Z + jets samples (≈ 3) is that the channel predictions which are found to be zero could have a fluctuation upward of a single event resulting in an increase of the MC background prediction of several events.

Source	$eeee$	$\mu\mu\mu\mu$	$ee\mu\mu$	$llll$
$Z + \text{jets}$	2.66 ± 2.62	0.00 ± 0.00	0.00 ± 0.00	2.66 ± 2.62
WW/WZ	0.42 ± 0.15	0.05 ± 0.04	0.67 ± 0.18	1.14 ± 0.24
$t/t\bar{t}$	0.88 ± 0.64	0.00 ± 0.00	0.77 ± 0.75	1.66 ± 0.98
$t\bar{t} + V$	0.40 ± 0.06	0.41 ± 0.06	0.60 ± 0.07	1.41 ± 0.11
$ZZZ/ZWW \rightarrow 2l2\nu$	0.12 ± 0.01	0.18 ± 0.01	0.26 ± 0.01	0.56 ± 0.02
Total	4.48 ± 2.70	$0.64 \pm 0.07 \pm 0.28$	2.30 ± 0.78	7.43 ± 2.81

Table 4.8: Summary of Monte Carlo background predictions for various sources. The $t\bar{t} + V$ and ZZZ/ZWW values are the irreducible background predictions.

The background estimate due to the irreducible sources $t\bar{t}Z$, ZZZ and ZWW broken down per channel can be seen in Table 4.8. A summary of the data driven background estimate and irreducible background estimate per channel is provided in Table 4.9.

Backgrounds	$eeee$	$\mu\mu\mu\mu$	$ee\mu\mu$	$llll$
Data Driven	$9.67 \pm 3.11 \pm 1.34$	0.65 ± 0.81	$7.41 \pm 2.72 \pm 2.38$	$17.73 \pm 4.21 \pm 4.00$
Irreducible	0.52 ± 0.06	0.59 ± 0.06	0.86 ± 0.07	1.97 ± 0.11
Total Background	$10.19 \pm 3.11 \pm 1.34$	$1.24 \pm 1.10 \pm 0.28$	$8.27 \pm 1.98 \pm 2.38$	$19.70 \pm 4.21 \pm 4.00$

Table 4.9: Summary of total ZZ background consisting of the data driven background estimate combined with the MC prediction from irreducible backgrounds. The first set of errors is statistical and the second set (if provided) are systematic errors.

4.9.8 Systematic Uncertainties on Monte Carlo Estimates

Muons

There are three types of systematic uncertainties associated with muon corrections:

1. **Reconstruction Efficiency:** The muon efficiency scale factors (4.6.2) have 1σ variations in both directions that give the associated systematic uncertainty.
2. **p_T Smearing and Scale:** The muon momentum scale correction is determined as

described in section 4.7. Associated with this correction that smears the muon p_T distribution in MC to match the data distribution, are 1σ variations (up and down) that allow the calculation of a systematic uncertainty associated with the smearing correction. For muons, the uncertainty is calculated separately for ID parameter variation and MS parameter variation and then subsequently added in quadrature to give the total smearing systematic uncertainty. The scale correction is varied up and down within 1σ and the resulting event difference between the nominal and varied yield is the associated scale systematic uncertainty.

3. **Isolation and IP Scale Factors:** The isolation and IP scale factors and the uncertainties are calculated using a Z tag and probe method with the probe muons satisfying the nominal muon selection.

All muon systematics are summarized in Table 4.10.

4.9.9 Electrons

There are multiple types of systematic uncertainties associated with electron corrections:

1. **Reconstruction and Identification efficiency:** As mentioned in Section 4.6.3, there are scale factors applied to electrons to match the reconstruction and identification efficiencies measured in Monte Carlo to data. The identification and reconstruction efficiency scale factors and the associated uncertainties are dependent on η , p_T and electron identification algorithm (Loose++, Medium++, Tight++, etc.). The η and p_T uncertainties are added in quadrature to give the total identification and reconstruction efficiency scale factor uncertainties. These scale factors are varied 1σ in both directions and the resulting event yield difference is taken as the systematic uncertainty.
2. **Energy Scale:** The electron energy scale correction factors are varied up and down within 1σ of the nominal values to obtain the systematic uncertainty on the predicted yield.

3. **Energy Reconstruction:** A smearing correction is applied to the electrons in Monte Carlo to match the energy resolution measured in data. The smearing corrections are varied within the measured 1σ and the resulting predicted yield difference gives the systematic uncertainty associated with the MC signal expectation.
4. **Isolation and IP scale factors:** The isolation and IP scale factors and the uncertainties are calculated using a Z tag and probe method with the probe electrons satisfying the nominal electron selection.

All electron systematics are summarized in Table 4.10.

4.10 Comparison of Observed and Expected Events

Using 20.04 fb^{-1} of 2012 data collected at $\sqrt{s} = 8 \text{ TeV}$, a total of 305 candidate $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ events falling within the fiducial region were observed. The predicted $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ event yield within the same fiducial region using Monte Carlo modelling is $293.55 \pm 0.85 \text{ (stat.)} \pm 11.07 \text{ (syst.)}$ and the background expectation is $19.70 \pm 4.21 \text{ (stat.)} \pm 4.00 \text{ (syst.)}$. A summary of these results broken down per channel can be seen in Table 4.11.

4.11 Cross Section Extraction

4.11.1 Cross Section Definition

The fiducial cross section for $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ is defined as

$$\sigma_{pp \rightarrow ZZX}^{\text{fid}} \cdot BR(Z \rightarrow \ell^+ \ell^-)^2 = \frac{N_{\ell^+ \ell^- \ell'^+ \ell'^-}^{\text{obs}} - N_{\ell^+ \ell^- \ell'^+ \ell'^-}^{\text{bkg}}}{\mathcal{L} \times C_{ZZ}} \quad (4.15)$$

where $N_{\ell^+ \ell^- \ell'^+ \ell'^-}^{\text{obs}}$ is the number of events observed in data, $N_{\ell^+ \ell^- \ell'^+ \ell'^-}^{\text{bkg}}$ is the data-driven estimate in Eq. 4.14, $\mathcal{L}$ is the integrated luminosity represented by the data and C_{ZZ} is the reconstruction correction factor defined in Equation 4.18. The branching ratio for each Z decaying into electrons and/or muons used in Equation 4.15 is defined as

Source (%)	$eeee$	$\mu\mu\mu\mu$	$ee\mu\mu$	$llll$
Reconstruction Uncertainties				
e momentum smearing	0.42	0.27	0.16	0.25
e energy scale	0.00	0.00	0.04	0.02
e identification efficiency	5.33	0.0	2.58	2.34
e reconstruction	3.07	0.00	1.51	1.36
e isolation z_0 d_0 sig	1.77	0.00	0.82	0.76
μ momentum smearing	0.42	0.27	0.16	0.25
μ energy scale	0.00	0.05	0.03	0.02
μ reconstruction	0.00	1.02	0.52	0.58
μ isolation z_0 d_0 sig	0.00	3.44	1.73	1.90
Trigger SF	0.03	0.20	0.09	0.11
Total Reconstruction Uncertainty (C_{ZZ})	6.43	3.61	3.60	3.46
Theoretical Uncertainties				
MC Generator Difference (C_{ZZ})	1.7	0.9	1.8	1.5
Scale (C_{ZZ})	0.1	0.1	0.01	0.03
PDF (C_{ZZ})	0.02	0.02	0.002	0.002
PDF and Scale (A_{ZZ})	0.95			
MC Generator Difference (A_{ZZ})	0.78			
Total (A_{ZZ})	1.3			
Total (C_{ZZ})	6.65	3.72	4.02	3.77
Luminosity	2.8			

Table 4.10: Summary of the systematic uncertainties per channel and combined over all channels used in the $pp \rightarrow ZZX \rightarrow l^+l^-l^+l^-$ cross section calculation. The $4l$ systematics are the weighted average of all the individual channel systematics.

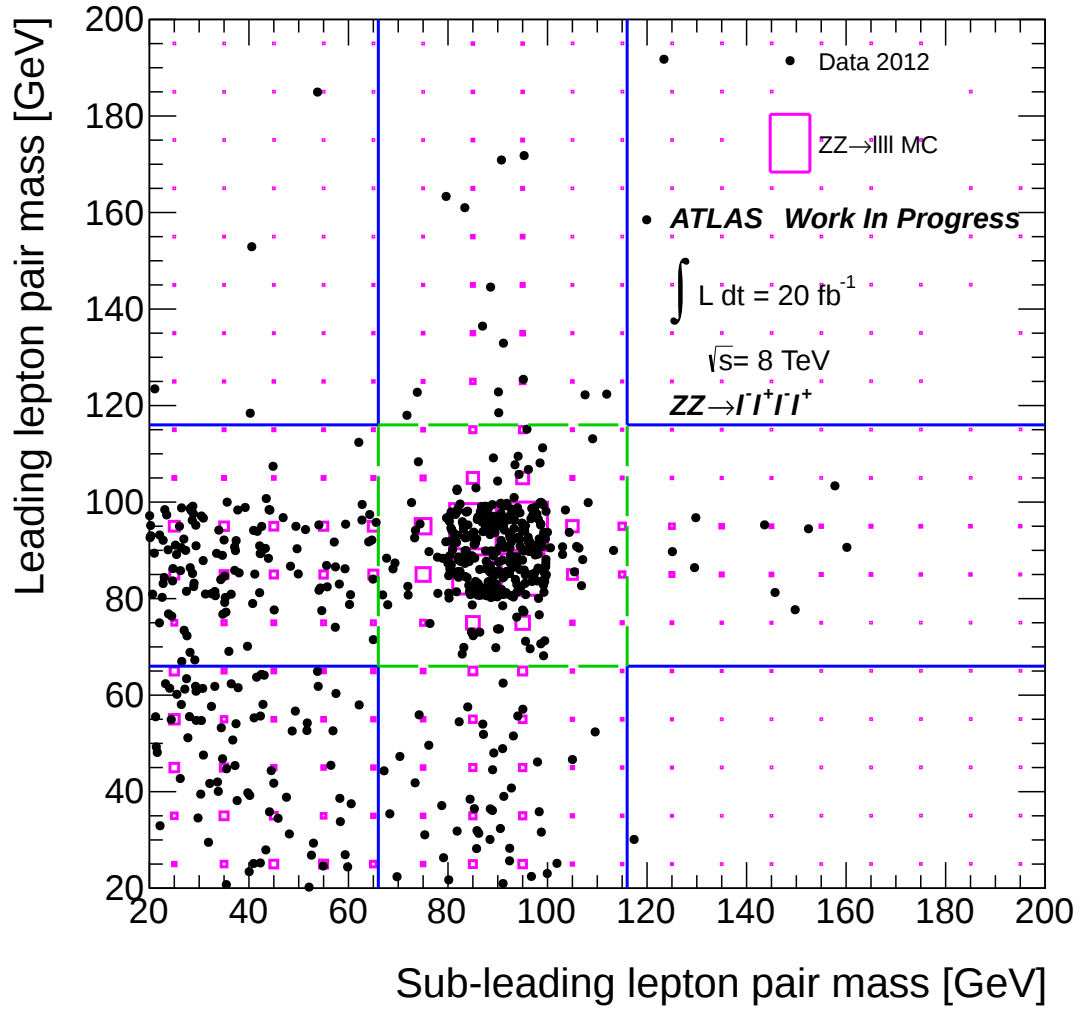


Figure 4.6: Subleading Z mass plotted versus leading Z mass. The blue lines represent the Z mass window each Z must satisfy and the dashed green box represents the fiducial region in which every ZZ candidate event must fall.

	$eeee$	$\mu\mu\mu\mu$	$ee\mu\mu$	$\ell^+\ell^-\ell^+\ell^-$
Observed	62	85	158	305
Total Expected MC	70.1 $\pm$ 2.1 $\pm$ 4.2	92.1 $\pm$ 1.2 $\pm$ 3.4	151.1 $\pm$ 2.1 $\pm$ 6.2	313.3 $\pm$ 4.3 $\pm$ 11.8
Expected Sig MC	59.9 $\pm$ 0.3 $\pm$ 4.0	90.9 $\pm$ 0.4 $\pm$ 3.4	142.8 $\pm$ 0.6 $\pm$ 5.7	293.6 $\pm$ 0.9 $\pm$ 11.06
Expected Bkg	10.2 $\pm$ 3.1 $\pm$ 1.3	1.2 $\pm$ 1.10 $\pm$ 0.28	8.3 $\pm$ 2.0 $\pm$ 2.4	19.7 $\pm$ 4.2 $\pm$ 4.0

Table 4.11: Summary of candidate events observed in data and expected events predicted from Monte Carlo in the 3 sub-channels and combined $\ell^+\ell^-\ell^+\ell^-$ channel. Also shown is the expected background contribution which consists of the data-driven estimation combined with the irreducible sources modelled by Monte Carlo.

$BR(Z \rightarrow \ell^+\ell^-) = BR(Z \rightarrow e^+e^-) + BR(Z \rightarrow \mu^+\mu^-)$ where $BR(Z \rightarrow e^+e^-) = 0.0363 \pm 0.00004$, $BR(Z \rightarrow \mu^+\mu^-) = 0.0366 \pm 0.00007$.

The total cross section over the entire phase space is defined as

$$\sigma_{pp \rightarrow ZZ}^{\text{tot}} = \frac{N_{\ell^+\ell^-\ell^+\ell^-}^{\text{obs}} - N_{\ell^+\ell^-\ell^+\ell^-}^{\text{bkg}}}{\mathcal{L} \times C_{ZZ} \times A_{ZZ} \times BR(Z \rightarrow \ell^+\ell^-)^2} \quad (4.16)$$

An extrapolation from the measurement done with detector acceptance is needed to extract the total $pp \rightarrow ZZ$ cross section. There are theoretical uncertainties associated with this extrapolation and it is because of this that a fiducial cross section is calculated free of the aforementioned uncertainties.

A quantity is defined

$$C_{ZZ} = \epsilon_{\text{trig}} \times \epsilon_{\text{event}} \times \epsilon_{\text{lep}} \times \epsilon_{\alpha} \quad (4.17)$$

where ϵ_{trig} is the trigger efficiency, ϵ_{event} is the efficiency of the event level selection (primary vertex, etc.), $\epsilon_{\text{lep}} = \epsilon_{\text{lep1}}\epsilon_{\text{lep2}}\epsilon_{\text{lep3}}\epsilon_{\text{lep4}}$ is the product of the individual lepton efficiencies for all four leptons that pass the object selection requirements and ϵ_{α} is the reconstruction to generator-level fiducial region correction that includes the smearing and resolution corrections. C_{ZZ} is calculated for each channel and is defined as the ratio of number of events which pass all selection requirements in MC to the number of events that fall within the fiducial region at the generator level as seen in Eq. 4.18. MC events that satisfy all selection requirements also have the necessary corrections (efficiency scale factors and smearing, etc)

applied.

$$C_{ZZ} = \frac{N_{\text{Reconstructed ZZ}}^{\text{MC Pass All Cuts}} \times \text{SF}}{N_{\text{Generated ZZ}}^{\text{MC Fiducial Volume}}} \quad (4.18)$$

The scale factor applied to MC events corrects for efficiency discrepancies between data and MC and is defined as

$$\text{SF} = \frac{\epsilon_{\text{trig}}^{\text{data}} \epsilon_{\text{reco}}^{\text{data}}}{\epsilon_{\text{trig}}^{\text{MC}} \epsilon_{\text{reco}}^{\text{MC}}} \quad (4.19)$$

where $\epsilon_{\text{reco}} = \epsilon_{\text{lep}} \cdot \epsilon_{\text{event}}$. C_{ZZ} extrapolates the reconstructed fiducial region to the truth fiducial region of each channel, however the branching ratios unique to each channel are necessary to be able to obtain a total cross section measurement.

The primary purpose of C_{ZZ} is to correct the measured reconstructed fiducial cross section to a truth-level fiducial cross section defined by the volume in which the measurement is made. Correcting to the fiducial volume keeps the measurement free of theoretical systematic uncertainties such as those associated with the PDF set used. This correction factor is essentially the probability that an event is reconstructed within the defined fiducial volume given that at truth-level this event and all associated objects passed all selection and event requirements.

Another correction factor is needed since the selection cuts for electrons and muons are different, thus resulting in the three sub-channels ($eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$) having different geometric acceptances. Therefore a common geometric volume of acceptance is defined to which each sub-channel measurement is extrapolated using this correction factor. The common geometric region is defined in Section 4.8. This factor, A_{ZZ} , corrects the reconstruction-level cross section to the full phase space describing the possible truth-level qualities and is defined as

$$A_{ZZ} = \frac{N_{\text{Generated ZZ}}^{\text{MC Fiducial Volume}}}{N_{\text{Generated ZZ}}^{\text{MC All}}}. \quad (4.20)$$

The uncertainties associated with this correction factor come from the PDF set, varying the PDF set, varying the factorization and renormalization scales and the weighted

difference of the calculation of this factor using a $gg \rightarrow ZZ$ generator.

The factorization and renormalization scales are varied up and down by a factor of two and the resulting difference in A_{ZZ} is taken as an uncertainty.

A_{ZZ} is calculated using version 6.3 of the MCFM generator. The total cross section extrapolated to is the scenario where both Z bosons have invariant masses between 66 and 116 GeV. Version 6.3 of MCFM includes the gluon-gluon production contribution and amounts to 5.93% of the total NLO cross section.

Using the CT10 PDF set with the renormalization and factorization scales ($\mu_R = \mu_F$) set to $0.5 \cdot m_{ZZ}$ the cross section for on-shell ZZ production at NLO is $7.23^{+0.30}_{-0.22}$ pb.

The cross section results using a zero-width approximation for the Z mass are shown in Table 4.12.

	σ (fb)	Shift (%)	
	CT10	CT10 error set	Scale Variation
$e^+e^-\mu^+\mu^-$	10.54 ± 0.01	$+2.0$ -2.3	$+3.63$ -2.58
$l^+l^-l^+l^-$	21.08 ± 0.02	$+2.0$ -2.3	$+3.63$ -2.58

Table 4.12: NLO cross sections calculated using MCFM (version 6.3) in QCD using the on-shell approximation. The errors on the central values of the cross sections are due to MC statistics. The cross sections shown are for the $ee\mu\mu$ final state; the 4ℓ final state is twice that value. The “CT10 error set” values are derived using the 52 CT10 error sets and the difference in central values between CT10 and MSTW2008NLO. The “scale variation” values are the differences between varying the default value of m_{ZZ} up and down by a factor of two.

The values of A_{ZZ} and C_{ZZ} are summarized in Table 4.13 for all channels. The values of C_{ZZ} for different generators are presented in Table 4.14.

4.11.2 Cross Section Calculation

The number of observed events in data and expected (MC prediction) number of events along with an estimate on the number of background events is needed to calculate the total

Correction	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
Powheg	0.536 ± 0.008	0.815 ± 0.007	0.663 ± 0.006	0.670 ± 0.004
gg2zz	0.564 ± 0.009	0.815 ± 0.008	0.672 ± 0.009	0.680 ± 0.005
Powheg+gg2zz	0.538 ± 0.007	0.815 ± 0.006	0.663 ± 0.006	0.671 ± 0.004

Table 4.13: The fiducial reconstruction correction factors for different generators. The errors quoted are statistical only. The differences are taken as a systematic error on C_{ZZ} .

Factor	$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
A_{ZZ}	$0.644\pm 0.001\pm 0.008$	$0.644\pm 0.001\pm 0.008$	$0.644\pm 0.001\pm 0.008$	$0.644\pm 0.001\pm 0.008$
C_{ZZ}	$0.538\pm 0.007\pm 0.036$	$0.815\pm 0.006\pm 0.030$	$0.663\pm 0.006\pm 0.027$	$0.671\pm 0.004\pm 0.026$

Table 4.14: The fiducial reconstruction and total geometric acceptance correction factors per channel and combined over all channels is presented above. For C_{ZZ} the first uncertainty is statistical and the second systematic. The A_{ZZ} uncertainty is comprised of the PDF and scale systematics.

and fiducial cross sections. The number of expected events can be written as

$$N_{exp} = N_{sig} + N_{bkg} \quad (4.21)$$

where N_{sig} is the number of signal events predicted by the MC samples listed in Table 4.1 and N_{bkg} is the data-driven background estimate in Eq. 4.14. The number of signal events can be written as a function of the total cross section as in Eq. 4.22.

$$N_{sig}(\sigma_{pp \rightarrow ZZ X}^{tot}) = \sigma_{pp \rightarrow ZZ X}^{tot} \times BR(Z \rightarrow \ell^+ \ell^-)^2 \times \mathcal{L} \times A_{ZZ} \times C_{ZZ} \quad (4.22)$$

where BR is the branching ratio representing both Z bosons decaying to $\ell^+ \ell^-$ (where $\ell = e, \mu$). Eq. 4.22 can be expressed in terms of the fiducial cross section by substituting $\sigma_{pp \rightarrow ZZ X}^{tot}$ for $\sigma_{pp \rightarrow ZZ X}^{fid}$ and removing A_{ZZ} and BR . The systematic uncertainties must be taken into account resulting in the addition of a sum of terms to Eq. 4.22

$$N_{sig}(\sigma_{pp \rightarrow ZZX}^{\text{tot}}, \{x\}) = \sigma_{pp \rightarrow ZZX}^{\text{tot}} \times BR(Z \rightarrow \ell^+ \ell^-)^2 \times \mathcal{L} \times A_{ZZ} \times C_{ZZ} \times \left(1 + x_{A_{ZZ}} \frac{\sigma_{A_{ZZ}}}{A_{ZZ}} + x_{C_{ZZ}} \frac{\sigma_{C_{ZZ}}}{C_{ZZ}} + x_{lumi} \frac{\sigma_{lumi}}{\mathcal{L}}\right) \quad (4.23)$$

and

$$N_{bkg}(\{x\}) = N_{bkg} \times \left(1 + x_{bkg} \frac{\sigma_{bkg}}{N_{bkg}}\right) \quad (4.24)$$

In Eq. 4.23 and 4.24, each x is assumed to be normally distributed with a mean of 0 and a variance of 1. The parameters $\sigma_{A_{ZZ}}, \sigma_{C_{ZZ}}, \sigma_{lumi}, \sigma_{bkg}$ are the standard deviations for each corresponding systematic source.

A minimum log-likelihood technique is used to calculate the cross section (both fiducial and total). Using the information above a likelihood function is defined as

$$L(\sigma, \{x\}) = \prod_{k=1}^m P(N_{data}, \mu(\sigma, \{x_k\})) \times \frac{1}{(\sqrt{2\pi})^m} e^{-\frac{1}{2}(\{x_k\}^2)} \quad (4.25)$$

where each x_k is a source of systematic error represented by the x terms in Equation 4.23 and Equation 4.24. Additionally,

$$\mu(\sigma, \{x_k\}) = N_{sig}(\sigma, \{x_k\}) + N_{bkg}(\{x_k\}). \quad (4.26)$$

The value of m in Equation 4.25 is 4 and accounts for the four sources of systematic uncertainty, C_{ZZ} , A_{ZZ} , background estimation and luminosity. The total systematic uncertainties associated with the correction factors are listed in Table 4.10.

The expression $P(N_{data}, \mu(\sigma, \{x_k\}))$, in Eq. 4.25 represents the Poisson probability that the number of signal plus background events ($N_{sig}(\sigma, \{x_k\}) + N_{bkg}(\{x_k\})$) will yield the number of events observed in data. The negative log of Eq. 4.25 is minimized with respect to σ and x_k using RooFit. The values of the floating parameters are seen in Figure 4.7.

The fiducial cross section is determined to be:

$$\sigma_{pp \rightarrow ZZX}^{\text{fid}} \cdot BR(Z \rightarrow \ell^+ \ell^-)^2 = 20.84_{-1.25}^{+1.30} (\text{stat.})_{-0.82}^{+0.91} (\text{syst.})_{-0.55}^{+0.62} (\text{lumi.}) \text{ fb} \quad (4.27)$$

```

Floating Parameter    FinalValue +/-   Error
-----
          Azz      6.4397e-01 +/-  8.10e-03
          Czz      6.7093e-01 +/-  3.82e-02
          NBg      1.9703e+01 +/-  5.78e+00
           cx      7.1938e+03 +/-  6.57e+02
          lumi     2.0398e+01 +/-  5.70e-01

RooArgList:: = (Azz,Czz,NBg,cx,lumi)

5x5 matrix is as follows

      |      0      |      1      |      2      |      3      |      4      |
-----
0 |      1      |  9.8e-06  |  1.625e-06  | -0.1377  |  5.237e-06  |
1 |  9.8e-06  |      1      |  1.277e-05  | -0.6233  |  2.294e-05  |
2 |  1.625e-06  |  1.277e-05  |      1      | -0.2229  |  4.971e-06  |
3 | -0.1377  | -0.6233  | -0.2229  |      1      | -0.3065  |
4 |  5.237e-06  |  2.294e-05  |  4.971e-06  | -0.3065  |      1      |

5x5 matrix is as follows

      |      0      |      1      |      2      |      3      |      4      |
-----
0 |  6.562e-05  |  3.033e-09  |  7.646e-08  | -0.7331  |  2.423e-08  |
1 |  3.033e-09  |  0.001459  |  2.834e-06  | -15.65  |  5.007e-07  |
2 |  7.646e-08  |  2.834e-06  |      33.75  | -851.1  |  1.65e-05  |
3 | -0.7331  | -15.65  | -851.1  |  4.32e+05  | -115.1  |
4 |  2.423e-08  |  5.007e-07  |  1.65e-05  | -115.1  |  0.3263  |

```

Figure 4.7: Shown in this figure are the parameter values that minimize the negative log of the likelihood function. Also shown are the correlation and covariance matrices resulting from the fit.

and after extrapolating to the total phase space the total ZZ cross section is:

$$\sigma_{pp \rightarrow ZZ}^{\text{tot}} = 7.19_{-0.43}^{+0.45} (\text{stat.})_{-0.31}^{+0.35} (\text{syst.})_{-0.19}^{+0.21} (\text{lumi.}) \text{ pb.} \quad (4.28)$$

4.12 Anomalous Triple Gauge Coupling Limits

4.12.1 Matrix Element Reweighting

A matrix element reweighting method is used to facilitate the limit extraction of the aTGC couplings. The elements describing the effects of the aTGCs are calculated at NLO using the BHO MC generator and Baur-Rainwater MC generator described in detail in [30] [31] [32]. The magnitude of the effect is calculated using the four vectors and PDG ID codes of the colliding partons and outgoing particles originating from the hard scattering [33].

This reweighting scheme allows an on-the-fly reweighting of existing MC events and is applicable to any ZZ MC sample as long as there is information present regarding the hard process and the colliding partons.

As was stated earlier, there are four unique anomalous couplings present in ZZ production (f_4^V and f_5^V where $V = \gamma, Z$). As shown in Eq. 2.8, each coupling appears linearly in the effective Lagrangian. This means that the scattering amplitude and indirectly the cross section will contain linear and quadratic coupling terms. The cross section including the aTGC enhancement can be written as

$$\begin{aligned} \sigma_{SM+TGC} = & F_{00} + f_4^\gamma F_{01} + f_4^Z F_{02} + f_5^\gamma F_{03} + f_5^Z F_{04} \\ & + (f_4^\gamma)^2 F_{11} + f_4^\gamma f_4^Z F_{12} + f_4^\gamma f_5^\gamma F_{13} + f_4^\gamma f_5^Z F_{14} \\ & + (f_4^Z)^2 F_{22} + f_4^Z f_5^\gamma F_{23} + f_4^Z f_5^Z F_{24} \\ & + (f_5^\gamma)^2 F_{33} + f_5^\gamma f_5^Z F_{34} \\ & + (f_5^Z)^2 F_{44} \end{aligned} \quad (4.29)$$

where F_{kl} are coefficients describing individual contributions to the total cross section. F_{00} represents the Standard Model contribution and the rest represent the contributions due to the anomalous triple gauge couplings. From equation 4.29, one can subsequently reweight any event from a sample with trivial couplings to an event representing a particular non-

trivial aTGC point. The weight is defined as

$$\text{Weight}_{event} = \frac{\sigma_{SM+TGC}}{\sigma_{SM}} \quad (4.30)$$

The F_{kl} coefficients are entirely governed by the interacting particles specific to the samples being used meaning that they do not change with respect to the anomalous couplings and therefore only needed to be determined once. If we consider a Standard Model coupling, then in principal there are 5 couplings in total. This means that there are 25 coefficients resulting from the calculation of the scattering amplitude, but due to symmetry ($F_{kl} = F_{lk}$) this reduces the number to 15 unique coefficients. These coefficients can be determined by considering 15 different cases of coupling values and then solving the linear system of equations.

To clarify a simple example is presented. Consider a case where only a single coupling is present. This reduces equation 4.29 to

$$\sigma_{SM+TGC} = F_0 + fF_1 + f^2F_2 \quad (4.31)$$

Now let's consider three different coupling values for f : 0,1,-1. This now yields three independent linear equations that may be written in matrix form.

$$\begin{bmatrix} \sigma_a \\ \sigma_b \\ \sigma_c \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 1 \\ 1 & -1 & 1 \end{bmatrix} \begin{bmatrix} F_0 \\ F_1 \\ F_2 \end{bmatrix} \quad (4.32)$$

Here F_0 is the Standard Model contribution. The 3×3 matrix from here on will be referred to as $\hat{A}$ and contains the coupling values for each case. To determine $\vec{F}$ one simply inverts equation 4.32. Extrapolating this simple example to the case where there are four distinct couplings, $\hat{A}$ is a 15×15 matrix and $\vec{\sigma}$ and $\vec{F}$ is a 15-dimensional vector.

Using the coefficients derived above extraction of the yield coefficients is now possible.

The yield coefficient is defined as

$$Y_{kl} = \frac{F_{kl}}{F_{00}} \cdot N_{expected}. \quad (4.33)$$

where $N_{expected}$ is the number of signal events predicted by Monte Carlo and $F_{00} = 250.19$.

Every yield coefficient is determined with all corrections to MC taken into account as this is necessary to achieve an accurate prediction of the number of events expected. The yield coefficients for two scenarios are summarized in Table 4.16 and Tables 4.17, 4.18.

Y_{SM}	$Y_{f_4^\gamma}$	$Y_{f_4^Z}$	$Y_{f_5^\gamma}$	$Y_{f_5^Z}$
1.0	0.003 ± 0.009	-0.038 ± 0.019	0.047 ± 0.010	-0.026 ± 0.023
	$Y_{f_4^\gamma f_4^\gamma}$	$Y_{f_4^\gamma f_4^Z}$	$Y_{f_4^\gamma f_5^\gamma}$	$Y_{f_4^\gamma f_5^Z}$
	507.50 ± 6.84	454.4 ± 6.33	-0.272 ± 0.625	-0.257 ± 0.349
	$Y_{f_4^Z f_4^Z}$	$Y_{f_4^Z f_5^\gamma}$	$Y_{f_4^Z f_5^Z}$	
	686.3 ± 9.85	-0.258 ± 0.349	-0.729 ± 1.12	
	$Y_{f_5^\gamma f_5^\gamma}$	$Y_{f_5^\gamma f_5^Z}$		
	496.2 ± 6.73	443.3 ± 6.22		
	$Y_{f_5^Z f_5^Z}$			
	669.0 ± 9.69			

Table 4.15: Each term in the above table represents the enhancement in terms of the Standard Model (no aTGC enhancement) yield for each coupling. They are determined for a 1 bin leading Z p_T distribution.

The yield coefficients were calculated using a TGC sample with $f_4^\gamma = 0.1$, $f_4^Z = 0.0$, $f_5^\gamma = 0.0$, $f_5^Z = 0.0$. To check the validity of the event weights produced by the matrix element method, the aforementioned TGC sample was reweighted to the Standard Model expectation. The results are seen in Figs. 4.8 and 4.9.

4.12.2 Limit Procedure and Method

All limits on anomalous couplings are set at the 95% confidence level using a frequentist method and are determined by minimizing a negative log likelihood function. The system-

Y_{SM}	$Y_{f_4^\gamma}$	$Y_{f_4^Z}$	$Y_{f_5^\gamma}$	$Y_{f_5^Z}$
293.55	0.776 ± 2.58	-11.02 ± 5.57	13.83 ± 2.90	-7.59 ± 6.63
	$Y_{f_4^\gamma f_4^\gamma}$	$Y_{f_4^\gamma f_4^Z}$	$Y_{f_4^\gamma f_5^\gamma}$	$Y_{f_4^\gamma f_5^Z}$
	148976 ± 5742.2	133380 ± 5162.4	-79.85 ± 183.6	-75.46 ± 102.37
	$Y_{f_4^Z f_4^Z}$	$Y_{f_4^Z f_5^\gamma}$	$Y_{f_4^Z f_5^Z}$	
	201466 ± 7828.2	-75.77 ± 102.37	-214.11 ± 328.89	
	$Y_{f_5^\gamma f_5^\gamma}$	$Y_{f_5^\gamma f_5^Z}$		
	145657 ± 5618.3	130125 ± 5041.4		
	$Y_{f_5^Z f_5^Z}$			
	196395 ± 7640.6			

Table 4.16: The yield coefficients and their respective errors are seen above which are determined for a 1 bin leading Z p_T distribution. The coefficients give the total number of expected events when multiplying by their respective couplings: ie. if $f_4^\gamma = 0.1$ and $f_4^Z, f_5^\gamma, f_5^Z = 0.0$ then the total yield would be $Y_{SM} + Y_{f_4^\gamma} f_4^\gamma + Y_{f_4^\gamma} Y_{f_4^\gamma} (f_4^\gamma)^2$. Note that $Y_{SM} = 293.55$ events which is the Standard Model predicted yield.

atic uncertainties associated with the MC prediction of expected events are introduced as Gaussian nuisance parameters in the likelihood function.

The likelihood function used to determine the TGC coupling values is the product of a Poisson probability distribution (P) which describes the data and MC measurements and Gaussian terms representing the systematics (nuisance parameters). The nuisance parameters are referred to as x_{jk} and σ_{jk} are the standard deviations representing the k^{th} systematic in the j^{th} bin. The systematic uncertainty per bin can be expressed as

$$\frac{\text{true } N_{sig}}{N_{sig}} = \left(1 + x_{A_{ZZ}} \frac{\sigma_{A_{ZZ}}}{A_{ZZ}} + x_{C_{ZZ}} \frac{\sigma_{C_{ZZ}}}{C_{ZZ}} + x_{lumi} \frac{\sigma_{lumi}}{\mathcal{L}} \right) \quad (4.34)$$

$$\frac{\text{true } N_{bkg}}{N_{bkg}} = \left(1 + x_{bkg} \frac{\sigma_{bkg}}{N_{bkg}} \right) \quad (4.35)$$

$0 < p_{\mathbf{T}}^Z < 60$				
Y_{SM}	$Y_{f_4^\gamma}$	$Y_{f_4^Z}$	$Y_{f_5^\gamma}$	$Y_{f_5^Z}$
145.2	0.199 ± 0.078	-0.681 ± 0.151	1.02 ± 0.190	10.8 ± 0.98
	$Y_{f_4^\gamma f_4^\gamma}$	$Y_{f_4^\gamma f_4^Z}$	$Y_{f_4^\gamma f_5^\gamma}$	$Y_{f_4^\gamma f_5^Z}$
	278.6 ± 20.9	288.7 ± 21.7	0.678 ± 0.150	-0.892 ± 0.176
	$Y_{f_4^Z f_4^Z}$	$Y_{f_4^Z f_5^\gamma}$	$Y_{f_4^Z f_5^Z}$	
	466.5 ± 34.90	-0.886 ± 0.175	-2.38 ± 0.319	
	$Y_{f_5^\gamma f_5^\gamma}$	$Y_{f_5^\gamma f_5^Z}$		
	192.6 ± 14.53	200.6 ± 15.12		
	$Y_{f_5^Z f_5^Z}$			
	326.4 ± 24.48			
$60 < p_{\mathbf{T}}^Z < 100$				
Y_{SM}	$Y_{f_4^\gamma}$	$Y_{f_4^Z}$	$Y_{f_5^\gamma}$	$Y_{f_5^Z}$
83.68	-1.42 ± 0.272	-2.39 ± 0.403	1.28 ± 0.252	-4.97 ± 0.739
	$Y_{f_4^\gamma f_4^\gamma}$	$Y_{f_4^\gamma f_4^Z}$	$Y_{f_4^\gamma f_5^\gamma}$	$Y_{f_4^\gamma f_5^Z}$
	828.9 ± 109.4	853.9 ± 109.4	-4.14 ± 0.633	-0.013 ± 0.020
	$Y_{f_4^Z f_4^Z}$	$Y_{f_4^Z f_5^\gamma}$	$Y_{f_4^Z f_5^Z}$	
	1366.2 ± 175.0	-0.011 ± 0.018	0.928 ± 0.202	
	$Y_{f_5^\gamma f_5^\gamma}$	$Y_{f_5^\gamma f_5^Z}$		
	643.2 ± 82.45	667.9 ± 85.62		
	$Y_{f_5^Z f_5^Z}$			
	1063.1 ± 136.2			

Table 4.17: The yield coefficients and their respective errors are seen above for two of the four bins in leading Z $p_{\mathbf{T}}$.

The entire likelihood function is as follows:

$$L(f^V, \{x_{jk}\}) = \prod_{k=1}^m \prod_{j=1}^n P(N_{data}^j, \mu^{jk}(f^V, \{x_{jk}\})) \times \frac{1}{(\sqrt{2\pi})^{(n+m)}} e^{-\frac{1}{2}(\{x_{jk}\}^2)}, \quad (4.36)$$

where $m = 4$ due to the sources of systematic uncertainty (C_{ZZ} , A_{ZZ} , lumi and N_{bkg}) and n is the number of bins in the $p_{\mathbf{T}}$ distribution of the leading Z.

$$\mu^{jk}(f, \{x_{jk}\}) = N_{sig}^{jk}(f^V, \{x_{jk}\}) + N_{bkg}^{jk}(\{x_{jk}\}) \quad (4.37)$$

$100 < p_{\mathbf{T}}^Z < 200$				
Y_{SM}	$Y_{f_4^\gamma}$	$Y_{f_4^Z}$	$Y_{f_5^\gamma}$	$Y_{f_5^Z}$
54.24	-3.30 ± 0.719	-12.06 ± 2.45	5.97 ± 1.25	-11.04 ± 2.25
	$Y_{f_4^\gamma f_4^\gamma}$	$Y_{f_4^\gamma f_4^Z}$	$Y_{f_4^\gamma f_5^\gamma}$	$Y_{f_4^\gamma f_5^Z}$
	7135.2 ± 1404.3	6869.7 ± 1352.0	-7.25 ± 1.50	-0.318 ± 0.115
	$Y_{f_4^Z f_4^Z}$	$Y_{f_4^Z f_5^\gamma}$	$Y_{f_4^Z f_5^Z}$	
	10725.3 ± 2110.8	-0.462 ± 0.147	30.13 ± 6.00	
	$Y_{f_5^\gamma f_5^\gamma}$	$Y_{f_5^\gamma f_5^Z}$		
	6335.2 ± 1246.8	6076.3 ± 1195.9		
	$Y_{f_5^Z f_5^Z}$			
	9497.2 ± 1869.1			
$200 < p_{\mathbf{T}}^Z$				
Y_{SM}	$Y_{f_4^\gamma}$	$Y_{f_4^Z}$	$Y_{f_5^\gamma}$	$Y_{f_5^Z}$
10.22	3.71 ± 3.87	-2.11 ± 2.21	5.93 ± 6.17	-4.70 ± 4.89
	$Y_{f_4^\gamma f_4^\gamma}$	$Y_{f_4^\gamma f_4^Z}$	$Y_{f_4^\gamma f_5^\gamma}$	$Y_{f_4^\gamma f_5^Z}$
	145740 ± 151366	130209 ± 135236	-87.58 ± 90.97	-61.87 ± 64.27
	$Y_{f_4^Z f_4^Z}$	$Y_{f_4^Z f_5^\gamma}$	$Y_{f_4^Z f_5^Z}$	
	196464 ± 204048	-61.74 ± 64.13	-200.4 ± 208.1	
	$Y_{f_5^\gamma f_5^\gamma}$	$Y_{f_5^\gamma f_5^Z}$		
	143508 ± 149048	128140 ± 133086		
	$Y_{f_5^Z f_5^Z}$			
	193290 ± 200752			

Table 4.18: The yield coefficients and their respective errors are seen above for each of the four bins in leading Z $p_{\mathbf{T}}$. The large errors in the highest $p_{\mathbf{T}}$ bin are due to the small number of events present in the high $p_{\mathbf{T}}$ regime in the SM Monte Carlo.

where f^V can be any of the triple gauge couplings $(f_4^\gamma, f_4^Z, f_5^\gamma, f_5^Z)$ and

$$N_{sig} = (Y_{SM} + Y_{f^V} \cdot f^V + Y_{f^V f^V} \cdot (f^V)^2) \cdot \mathcal{L} \cdot C_{ZZ}. \quad (4.38)$$

As was mentioned in Section 4.12.1, the number of signal events (N_{sig}) is expressed as a function quadratic in triple gauge coupling. For example, if $f_4^\gamma = 0.1$ and all other couplings are set to their SM values of 0, the number of signal events can be expressed as:

$$N_{sig} = Y_{SM} + Y_{f_4^\gamma} f_4^\gamma + Y_{f_4^\gamma f_4^\gamma} f_4^\gamma f_4^\gamma. \quad (4.39)$$

This equation is plotted in Figure 4.12.

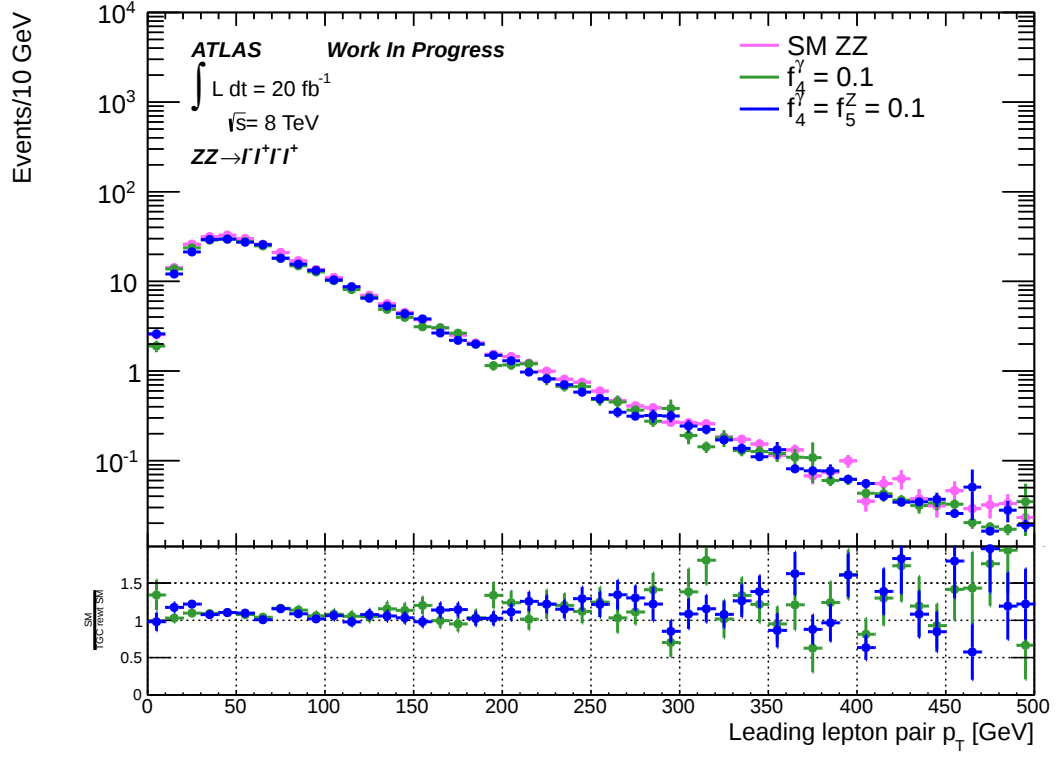


Figure 4.8: Leading Z transverse momentum spectrum of a TGC sample with $f_4^\gamma = 0.1$ reweighted to the Standard Model.

The negative log likelihood of the function in Equation 4.36 is minimized with respect to f^V (coupling) with one particular coupling solely responsible for the enhancement to the SM cross section. The value of coupling that minimizes the aforementioned function is then used to calculate a profile likelihood test statistic defined as:

$$q(f^V) = \frac{-\ln(L(f^V, \hat{x}_{jk}^V))}{-\ln(L(\hat{f}^V, \hat{x}_{jk}^V))} \quad (4.40)$$

where $\hat{x}_{jk}^V$ is the value of x_{jk} that minimizes the numerator for a fixed coupling value and $\hat{f}^V$ and $\hat{x}_{jk}^V$ are the values of f^V and x_{jk} that minimize the denominator. A test statistic value, $q_{\text{obs}}(f^V)$, is determined using the number of events observed in data for each coupling. To determine how often an outcome at least as unlikely as the actual observation is expected to occur, 10,000 pseudo-experiments are performed for each value of f^V . The test statistics

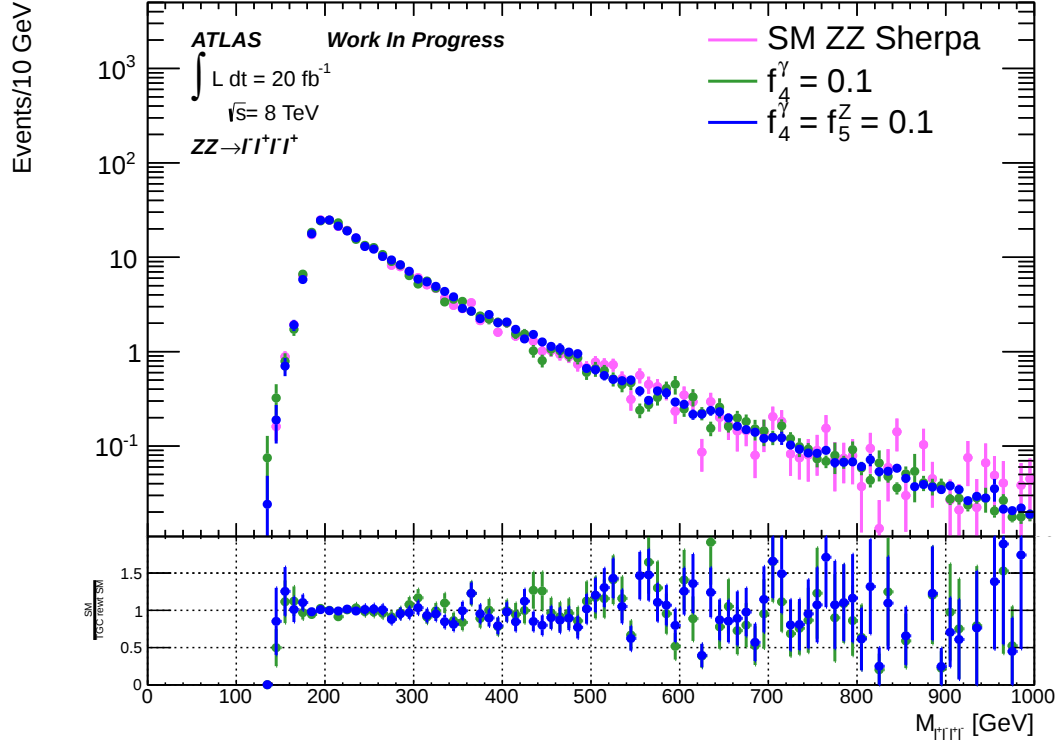


Figure 4.9: Invariant mass spectrum of the 4 lepton system of a TGC sample with $f_4^\gamma = 0.1$ reweighted to the Standard Model.

$q_{\text{pseudo}}(f^V)$ are then compared with $q_{\text{obs}}(f^V)$. In each pseudo experiment, the systematic nuisance parameters are fluctuated according to a Gaussian distribution around the mean value of $\hat{x}_{jk}$ for a fixed coupling value. The number of “observed” events, N_{pe} is drawn randomly from a Poisson distribution with mean equal to the number of events computed using the corresponding coupling (f^V) and systematic values.

The p-value, defined for each value of f^V , is defined as the fraction of pseudo experiments whose test statistic, q_{pe} , is smaller than the observed test statistic, $q_{\text{obs}}(f^V)$. By scanning through many values of f^V , all values of the coupling for which $p(f^V) \geq 5\%$ can be calculated to define the 95% confidence interval of f^V calculated using data. If the coupling value that minimizes the negative log likelihood function falls within this interval, it is said to be set at the 95% confidence level (CL).

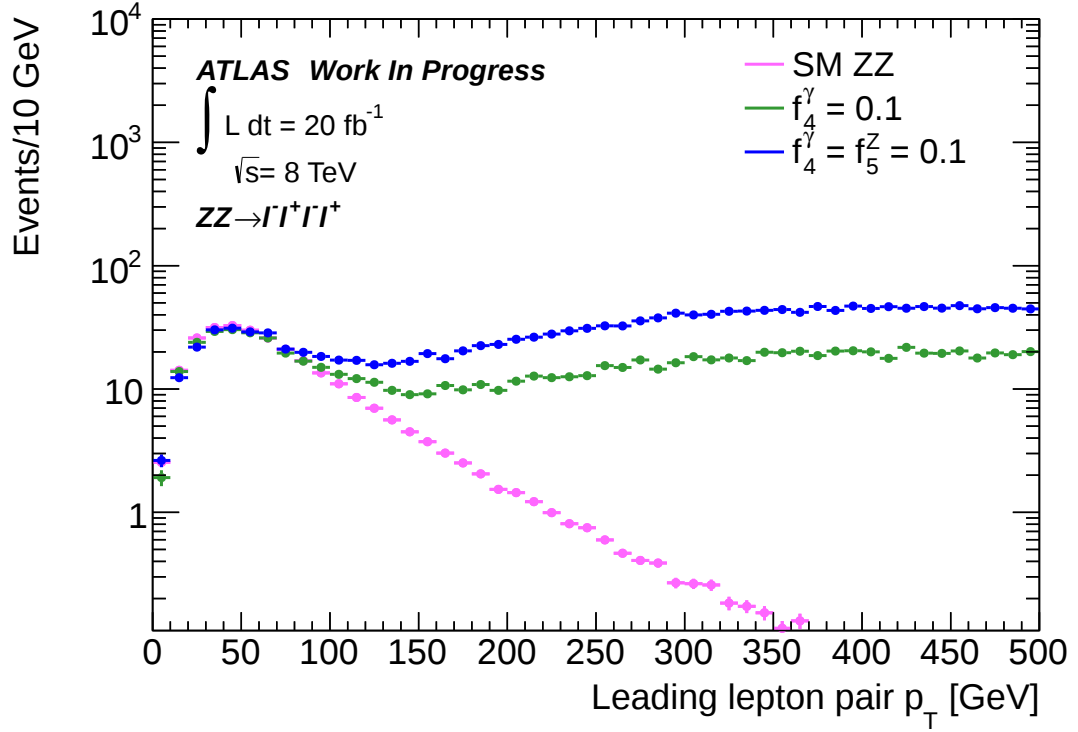


Figure 4.10: The p_T spectrum of the leading Z boson in a signal event for various TGC point values. If coupling value is not specified in legend, it is set to 0. As is expected there is a significant enhancement in the higher p_T regime for non zero aTGCs.

To determine what the expected limits should be using the SM predicted yield (signal plus background) a large number (5,000) pseudo experiments are performed using the SM predicted yield as n_{obs} . The systematics are treated as Gaussian nuisance parameters and the number of “observed” events are sampled from a Poisson distribution with the mean set the SM predicted yield.

4.12.3 Observed and Expected Limits

Two sets of limits are presented using the 20.04 fb^{-1} data set collected at $\sqrt{s} = 8 \text{ TeV}$ with ATLAS. The limits are determined from event yields in the leading Z p_T distribution. The limits for 1 bin in leading Z p_T are presented in Table Table 4.19 and 4 bins in leading Z

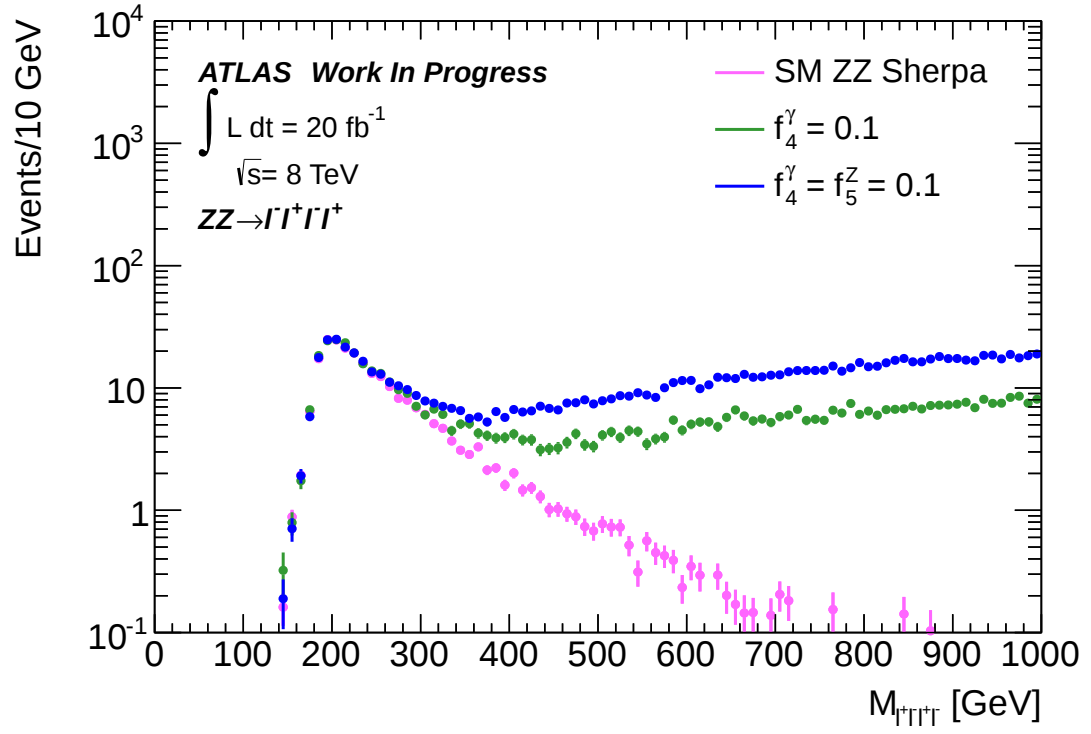


Figure 4.11: Invariant mass spectrum of the 4 lepton system in a signal event for various TGC point values. If coupling value is not specified in legend, it is set to 0. As is expected there is a significant enhancement in the higher mass regime.

p_T are presented in Table 4.20.

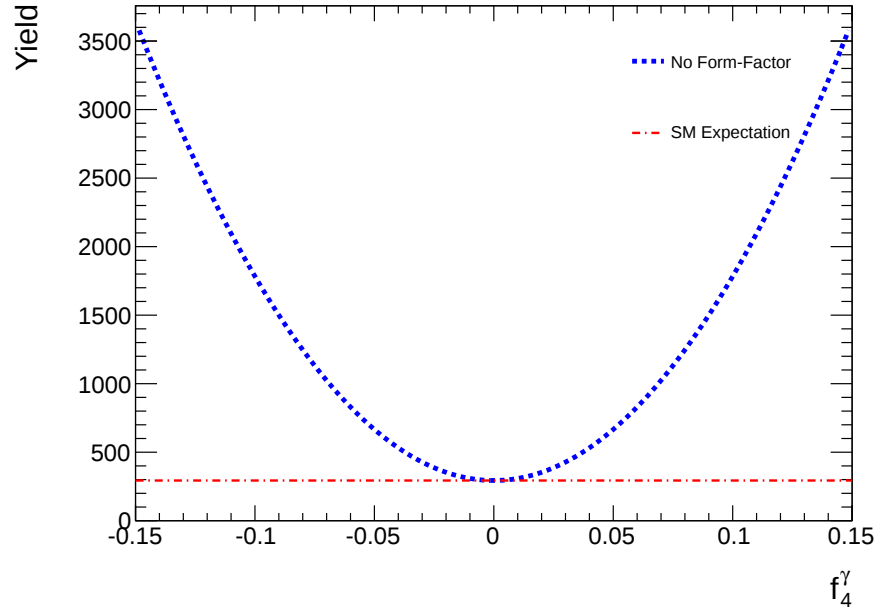


Figure 4.12: Event yield as a function of f_4^γ .

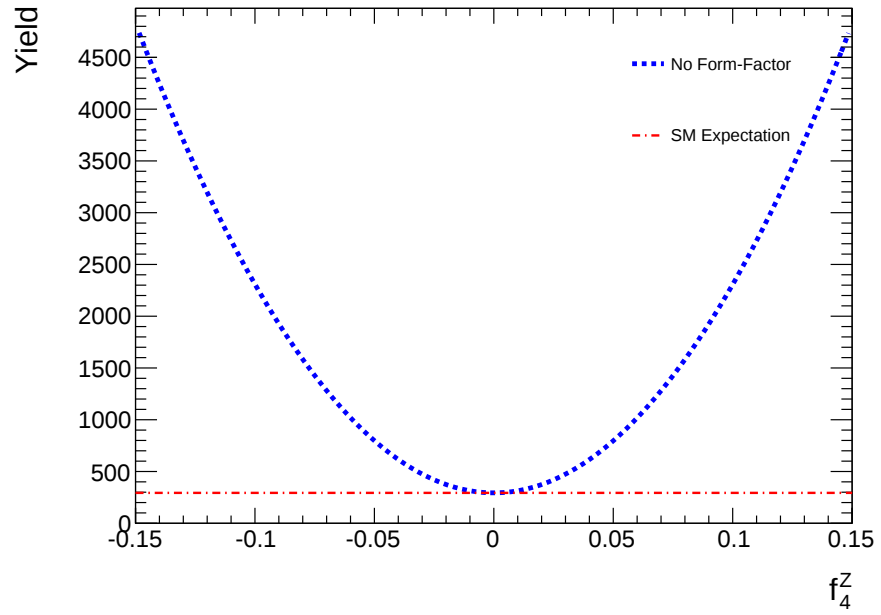


Figure 4.13: Event yield as a function of f_4^Z .

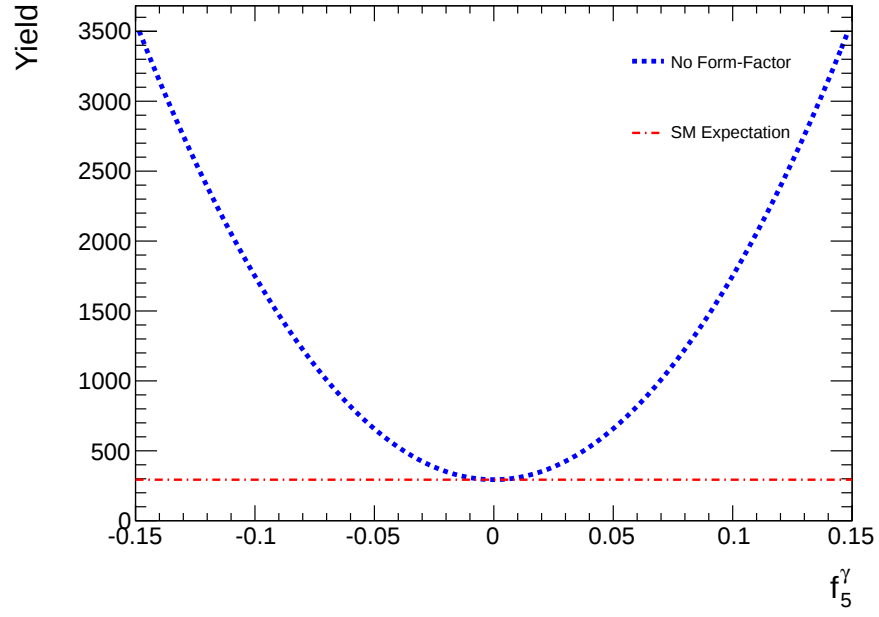


Figure 4.14: Event yield as a function of f_5^γ .

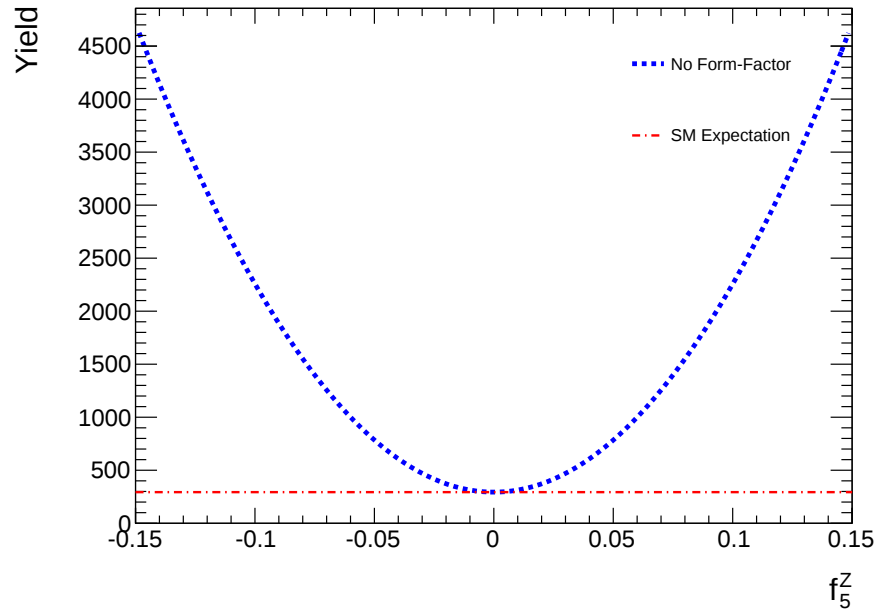


Figure 4.15: Event yield as a function of f_5^Z .

1 bin limits		
Coupling	Expected Limit	Observed Limit
No Form Factor		
f_4^γ	$[-0.018, 0.018] \pm 0.003$	$[-0.016, 0.016]$
f_4^Z	$[-0.016, 0.016] \pm 0.003$	$[-0.014, 0.014]$
f_5^γ	$[-0.018, 0.018] \pm 0.003$	$[-0.016, 0.016]$
f_5^Z	$[-0.016, 0.016] \pm 0.003$	$[-0.014, 0.014]$

Table 4.19: Anomalous Triple Gauge Coupling limits for a 1 bin leading Z p_T distribution.

4 bin limits		
Coupling	Expected Limit	Observed Limit
No Form Factor		
f_4^γ	$[-0.007, 0.007] \pm 0.002$	$[-0.004, 0.004]$
f_4^Z	$[-0.006, 0.006] \pm 0.002$	$[-0.003, 0.003]$
f_5^γ	$[-0.007, 0.007] \pm 0.002$	$[-0.004, 0.004]$
f_5^Z	$[-0.006, 0.006] \pm 0.002$	$[-0.003, 0.003]$

Table 4.20: Anomalous Triple Gauge Coupling limits for a 4 bin leading Z p_T distribution.

Chapter 5

CONCLUSIONS

With 20.04 fb^{-1} of data collected at $\sqrt{s} = 8 \text{ TeV}$ by the ATLAS detector, there is a unique opportunity to not only precisely measure electroweak processes, and more specifically, the $pp \rightarrow ZZX$ cross section, but also search for anomalous triple gauge couplings. In the aforementioned data, 305 $ZZ \rightarrow \ell\ell'\ell'$ events were observed (summary of events per channel in Table 4.11). The Standard Model expected yield including the signal and background expectations is $313.3 \pm 4.1(\text{stat.}) \pm 11.8(\text{syst.})$. The $pp \rightarrow ZZX$ fiducial cross section is measured to be:

$$\sigma_{pp \rightarrow ZZX}^{\text{fid}} \cdot BR(Z \rightarrow \ell^+ \ell^-)^2 = 20.84_{-1.25}^{+1.30} (\text{stat.})_{-0.82}^{+0.91} (\text{syst.})_{-0.55}^{+0.62} (\text{lumi.}) \text{ fb.} \quad (5.1)$$

Extrapolating to the total phase space, the total $pp \rightarrow ZZX$ cross section is measured to be:

$$\sigma_{pp \rightarrow ZZX}^{\text{tot}} = 7.19_{-0.43}^{+0.45} (\text{stat.})_{-0.31}^{+0.35} (\text{syst.})_{-0.19}^{+0.21} (\text{lumi.}) \text{ pb} \quad (5.2)$$

which is found to be in good agreement with the SM predicted total cross section of $\sigma_{SM} = 7.23_{-0.22}^{+0.30} \text{ pb}$.

The 1 bin limits set on the $f_4^\gamma, f_4^Z, f_5^\gamma, f_5^Z$ anomalous triple gauge couplings are roughly 3 times tighter and the 4 bin limits are approximately 5 times tighter than the respective limits previously set in the 4.7 fb^{-1} analysis [10].

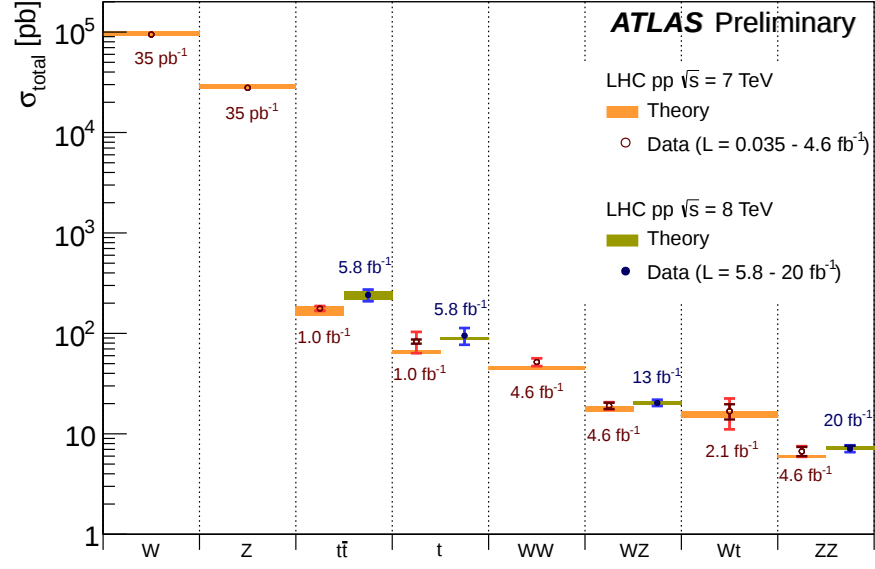


Figure 5.1: Summary of cross sections for various electroweak processes.

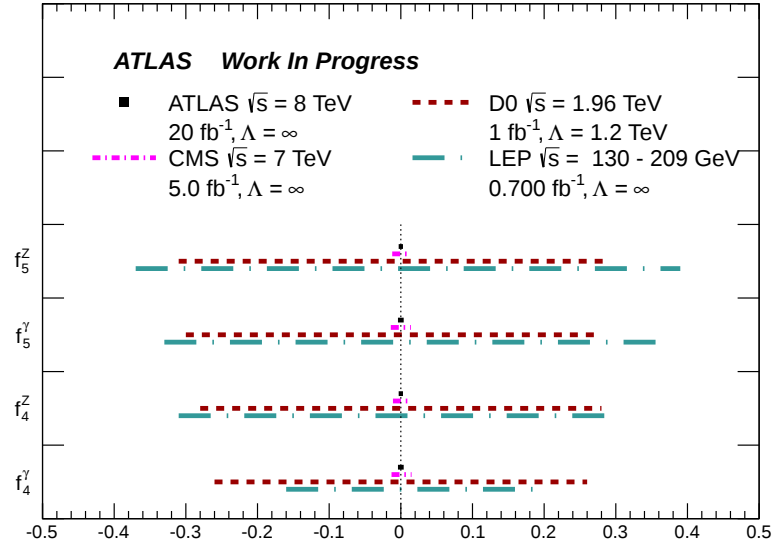


Figure 5.2: Limits on anomalous triple gauge couplings measured by multiple experiments including limits set in this analysis.

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Appendix A

THE HIGGS MECHANISM

Starting with a simple example one can gain an understanding of the Higgs mechanism. Assume a Lagrangian defined as

$$\mathcal{L} = (\partial^\mu \phi^*)(\partial_\mu \phi) - m^2 \phi^* \phi - \lambda (\phi^* \phi)^2 = (\partial_\mu \phi)(\partial^\mu \phi^*) - V(\phi, \phi^*) \quad (\text{A.1})$$

where the λ term represents self-interaction between the scalar field ϕ . To obtain the ground state, one must minimize the potential $V(\phi, \phi^*)$ giving

$$\frac{\partial V}{\partial \phi} = m^2 \phi^* + 2\lambda \phi^* (\phi^* \phi). \quad (\text{A.2})$$

Assuming $\lambda > 0$, if $m^2 > 0$ the minimum occurs when $\phi = \phi^* = 0$, however if $m^2 < 0$ a local maximum exists when $\phi = 0$ and the minimum exists when

$$|\phi|^2 = -\frac{m^2}{2\lambda}. \quad (\text{A.3})$$

If a global transformation such as the one described in Eq. [A.4](#) is applied to the scalar field

$$\phi \rightarrow e^{i\theta} \phi \quad (\text{A.4})$$

one can see that the Lagrangian and the resulting ground state are unchanged when compared to the original Lagrangian (Eq. [A.1](#)) and ground state (Eq. [A.3](#)). This means the Lagrangian is invariant under that global transformation and the ground state is degenerate in θ .

If we then define ϕ as

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2) \quad (\text{A.5})$$

and minimize V with respect to ϕ_1 we find that if $m^2 < 0$ the vacuum expectation value (vev) is

$$(\phi_1^2 + \phi_2^2) = \frac{-m^2}{2\lambda} = a^2. \quad (\text{A.6})$$

If we choose $\langle \phi_1 \rangle_0 = a$, then it follows that $\langle \phi_2 \rangle_0 = 0$. As this choice is made, the symmetry is spontaneously broken. We can expand ϕ around a so that it is now defined as

$$\phi = a + \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2). \quad (\text{A.7})$$

The Lagrangian now becomes

$$\mathcal{L} = \frac{1}{2}(\partial^\mu \phi_1)(\partial_\mu \phi_1) + \frac{1}{2}(\partial^\mu \phi_2)(\partial_\mu \phi_2) - 2\lambda a^2 \phi_1^2 - \sqrt{2}\phi_1(\phi_1^2 + \phi_2^2) - \frac{\lambda}{4}(\phi_1^2 + \phi_2^2)^2. \quad (\text{A.8})$$

As one can see, there is no ϕ_2^2 term, meaning that ϕ_2 is a massless field, however there is a ϕ_1^2 term. Spontaneously breaking the symmetry of the Lagrangian has resulted in one massive field and one massless field.

Consider a Lagrangian that is invariant under the local transformation

$$\phi \rightarrow e^{i\Lambda(x)}\phi. \quad (\text{A.9})$$

In order for the aforementioned Lagrangian to be invariant the covariant derivative is introduced and has the form

$$D_\mu = (\partial_\mu + ieA_\mu) \quad (\text{A.10})$$

resulting in

$$\mathcal{L} = (\partial_\mu + ieA_\mu)\phi(\partial^\mu + ieA^\mu)\phi^* - m^2(\phi^*\phi) - \lambda((\phi^*\phi))^2 - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}. \quad (\text{A.11})$$

Using the scalar field definition in Eq. A.7, Eq. A.11 becomes

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + e^2a^2A^\mu A_\mu + \frac{1}{2}(\partial_\mu\phi_1)^2 + \frac{1}{2}(\partial_\mu\phi_2)^2 - 2\lambda a^2\phi_1^2 + \sqrt{2}eaA^\mu\partial_\mu\phi_2 + H.O. \quad (\text{A.12})$$

The two massive fields in this case are the photon (A_μ) and ϕ_1 and the massless field is ϕ_2 . However, there is also a mixed term in A_μ and ϕ_2 indicating that a photon can change into a scalar field which does not make much sense. In fact, ϕ_2 can be eliminated entirely by a gauge transformation. For infinitesimal Λ the components of ϕ transform like

$$\begin{aligned} \phi_1' &= \phi_1 - \Lambda\phi_2 \\ \phi_2' &= \phi_2 + \Lambda\phi_1 + \sqrt{2}\Lambda a \end{aligned} \quad (\text{A.13})$$

A particular value of Λ may be chosen so that $\phi_2 = 0$ resulting in the Lagrangian having only two fields (Eq. A.14), both of which are massive.

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + e^2a^2A^\mu A_\mu + \frac{1}{2}(\partial_\mu\phi_1)^2 - 2\lambda a^2\phi_1^2 + \text{coupling terms} \quad (\text{A.14})$$

This method, when applied to the electroweak Lagrangian, gives rise to three massive vector bosons ($W^\pm, Z$), one massless boson (photon) and one massive scalar field called the Higgs boson.

Appendix B

ADDITIONAL KINEMATIC PLOTS

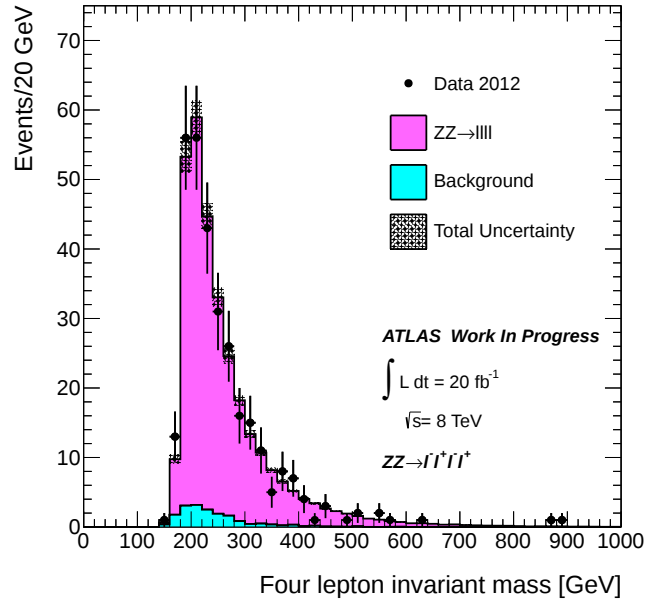


Figure B.1: $\ell^+\ell^-\ell'^+\ell'^-$ invariant mass distribution.

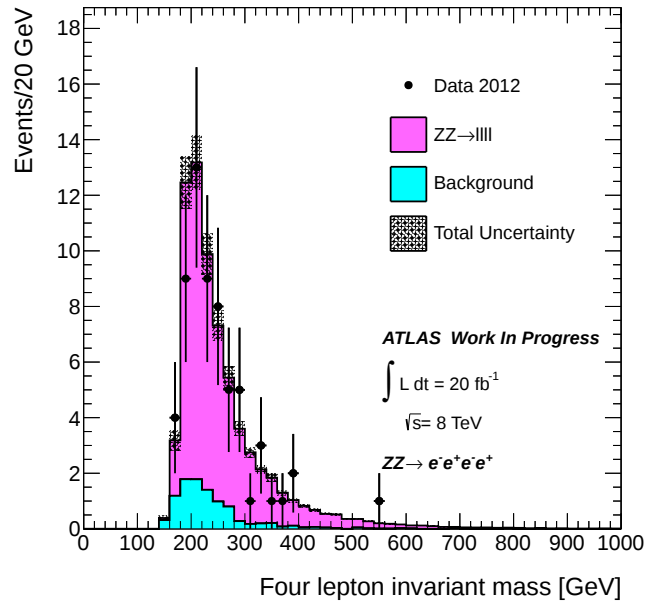


Figure B.2: $e^+e^-e^+e^-$ invariant mass distribution.

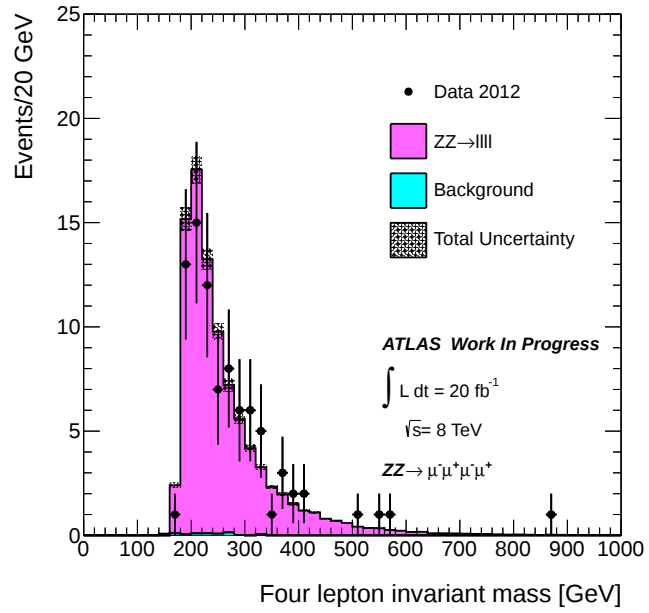


Figure B.3: $\mu^+\mu^-\mu^+\mu^-$ invariant mass distribution.

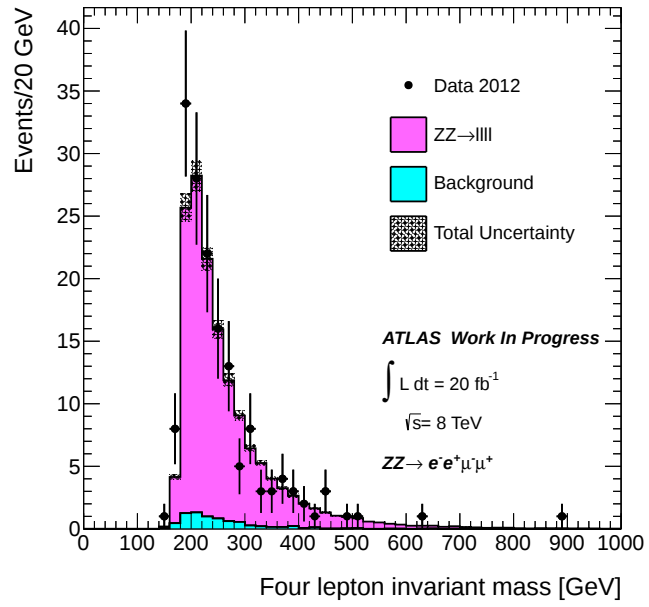


Figure B.4: $e^+e^-\mu^+\mu^-$ invariant mass distribution.

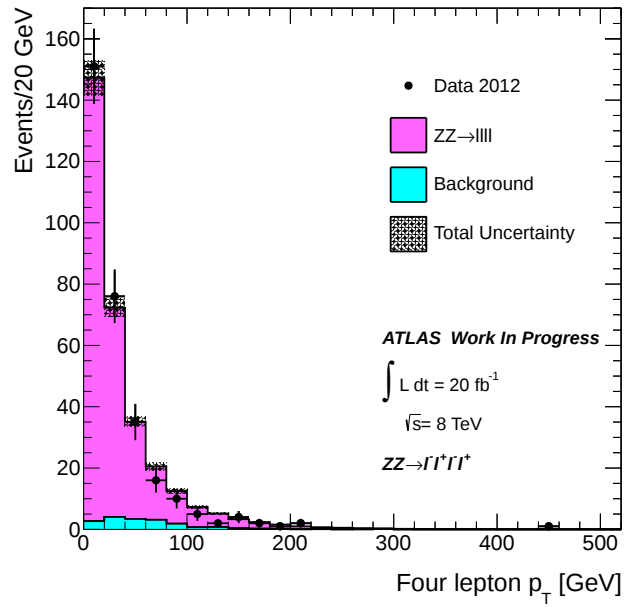


Figure B.5: $\ell^+\ell^-\ell'^+\ell'^-$ p_T distribution

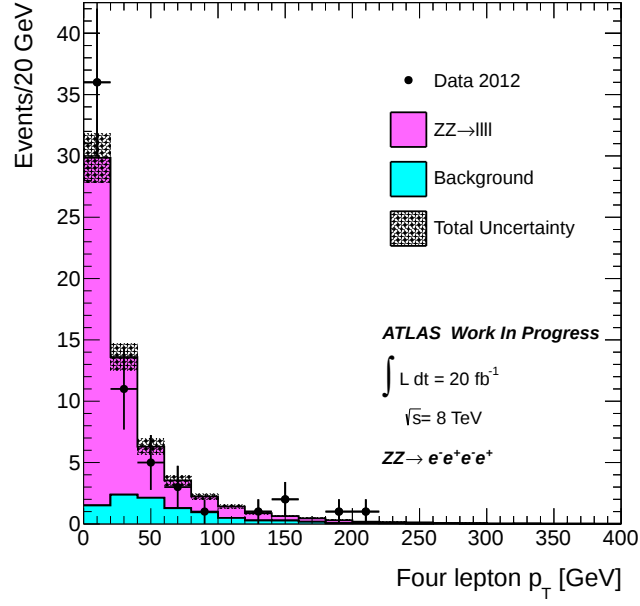


Figure B.6: $e^+e^-e^+e^-$ p_T distribution

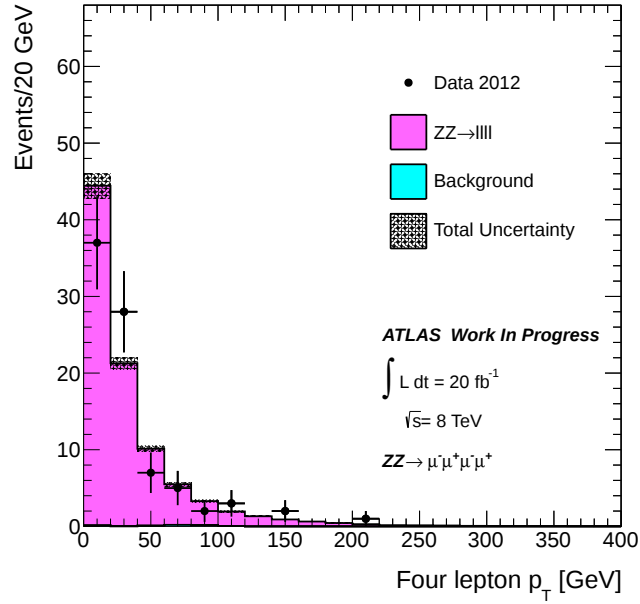


Figure B.7: $\mu^+\mu^-\mu^+\mu^-$ p_T distribution

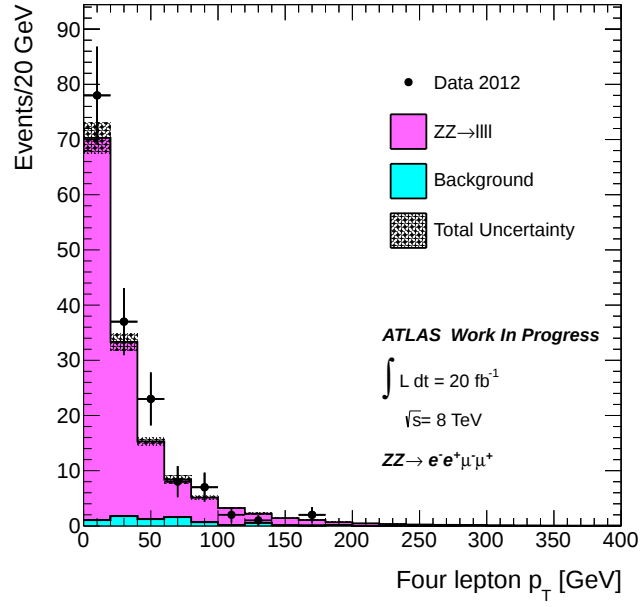


Figure B.8: $e^+e^-\mu^+\mu^-p_T$ distribution

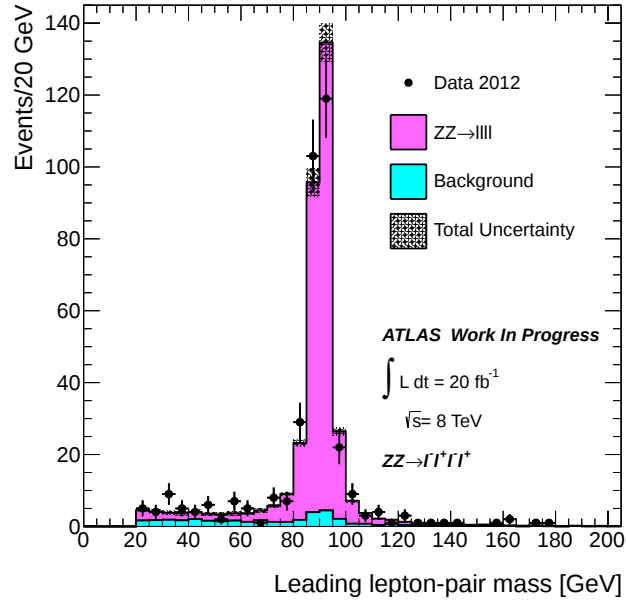


Figure B.9: $\ell^+\ell^-\ell'^+\ell'^-$ leading lepton pair mass distribution. Sub-leading lepton pair has a mass between 66 and 116 GeV.

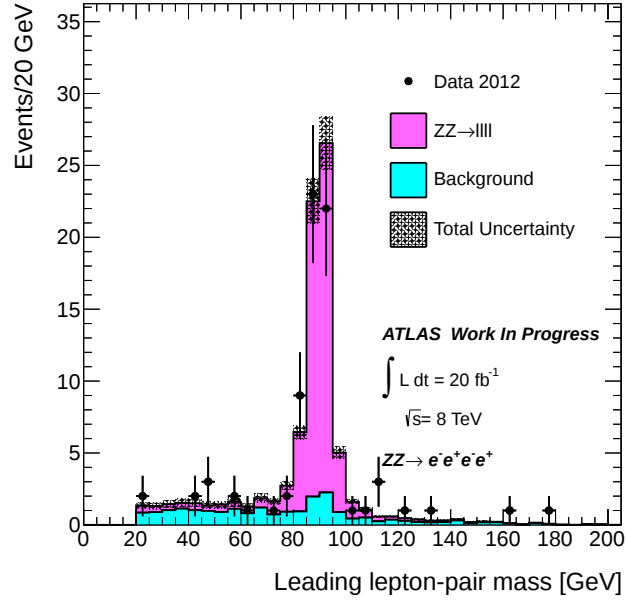


Figure B.10: $e^+e^-e^+e^-$ leading lepton pair mass distribution. Sub-leading lepton pair has a mass between 66 and 116 GeV.

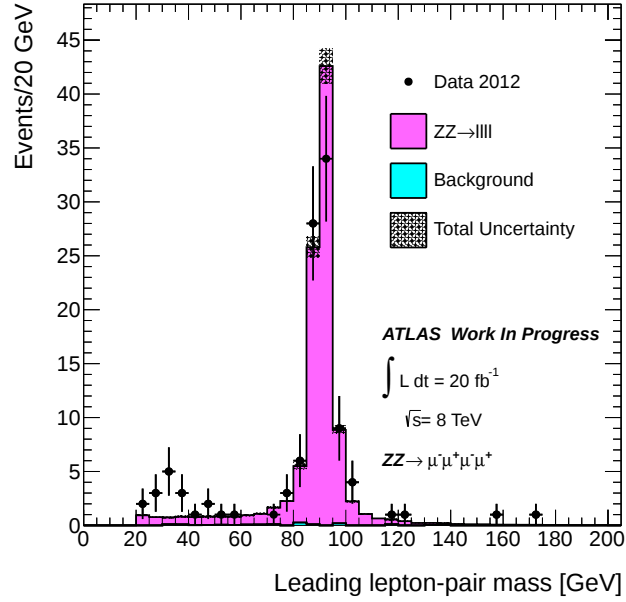


Figure B.11: $\mu^+\mu^-\mu^+\mu^-$ leading lepton pair mass distribution. Sub-leading lepton pair has a mass between 66 and 116 GeV.

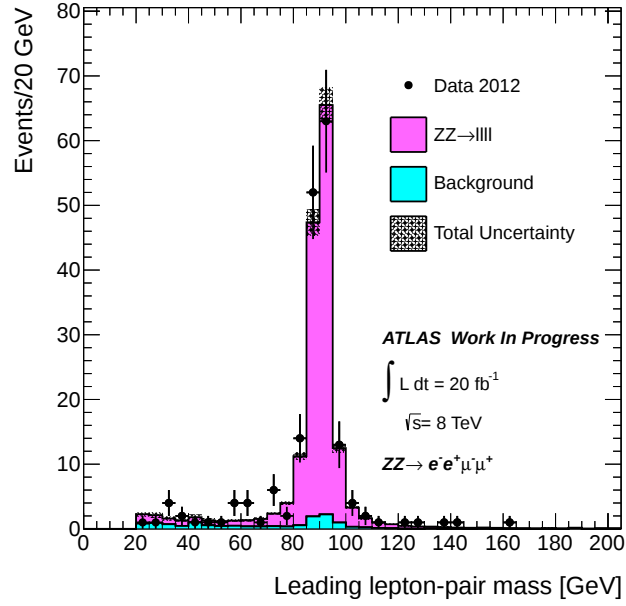


Figure B.12: $e^+e^-\mu^+\mu^-$ leading lepton pair mass distribution. Sub-leading lepton pair has a mass between 66 and 116 GeV.

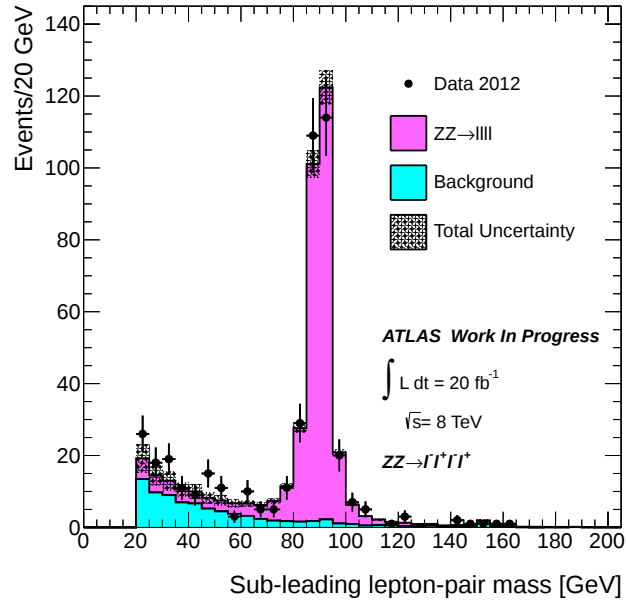


Figure B.13: $\ell^+\ell^-\ell'^+\ell'^-$ sub-leading lepton pair mass distribution. Leading lepton pair has a mass between 66 and 116 GeV.

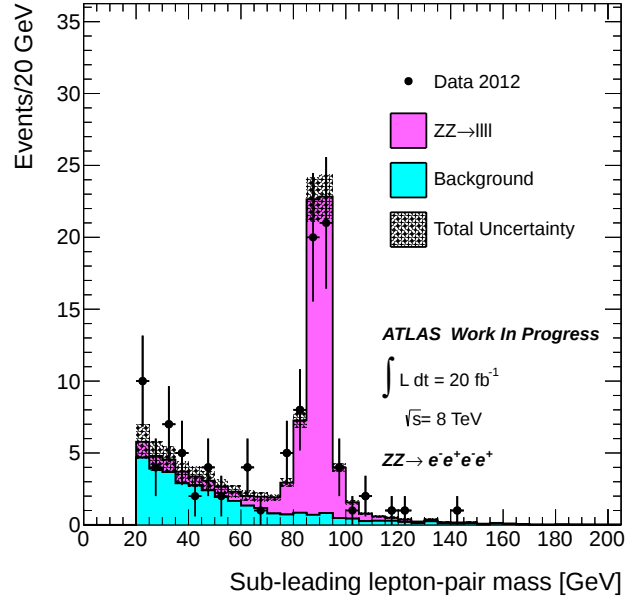


Figure B.14: $e^+e^-e^+e^-$ sub-leading lepton pair mass distribution. Leading lepton pair has a mass between 66 and 116 GeV.

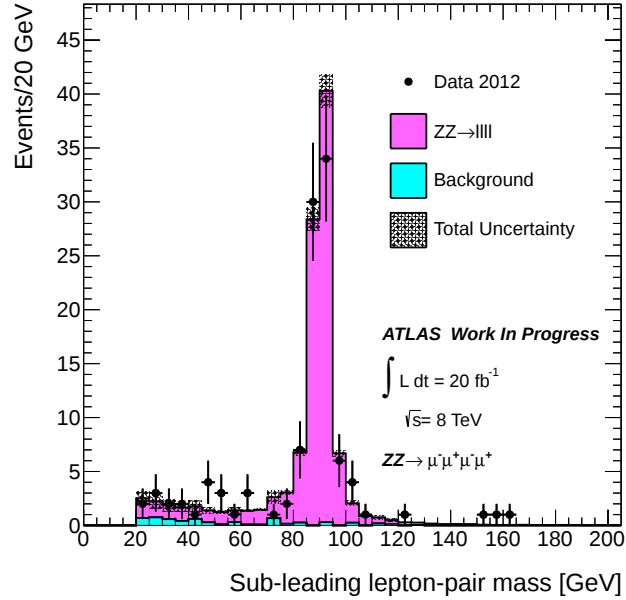


Figure B.15: $\mu^+\mu^-\mu^+\mu^-$ sub-leading lepton pair mass distribution. Leading lepton pair has a mass between 66 and 116 GeV.

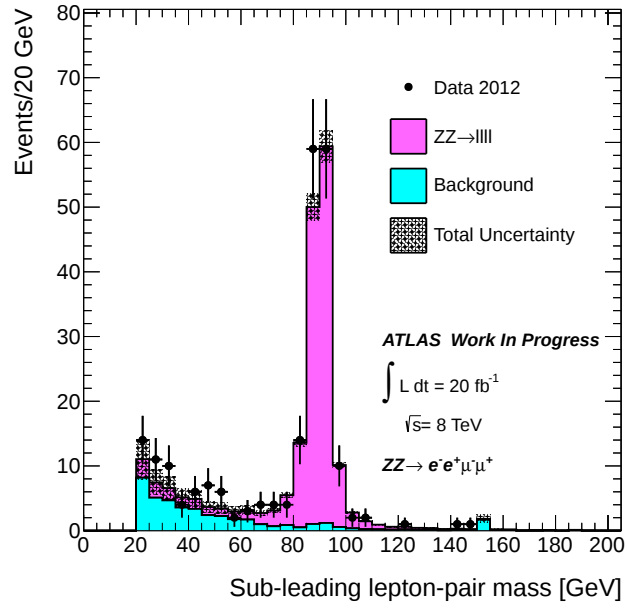


Figure B.16: $e^+e^-\mu^+\mu^-$ sub-leading lepton pair mass distribution. Leading lepton pair has a mass between 66 and 116 GeV.

Appendix C

FAKE FACTOR AND SELECTED AND LEPTON-LIKE JET DISTRIBUTIONS

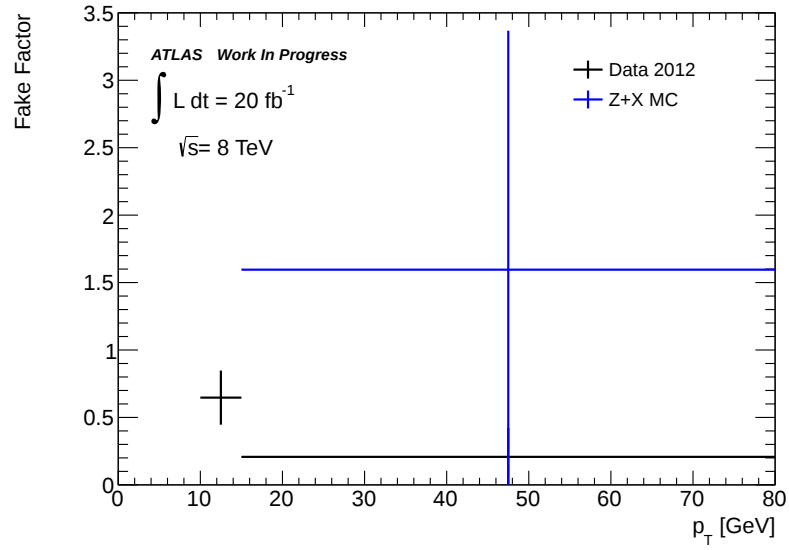


Figure C.1: Forward muon fake factor parameterized in p_T .

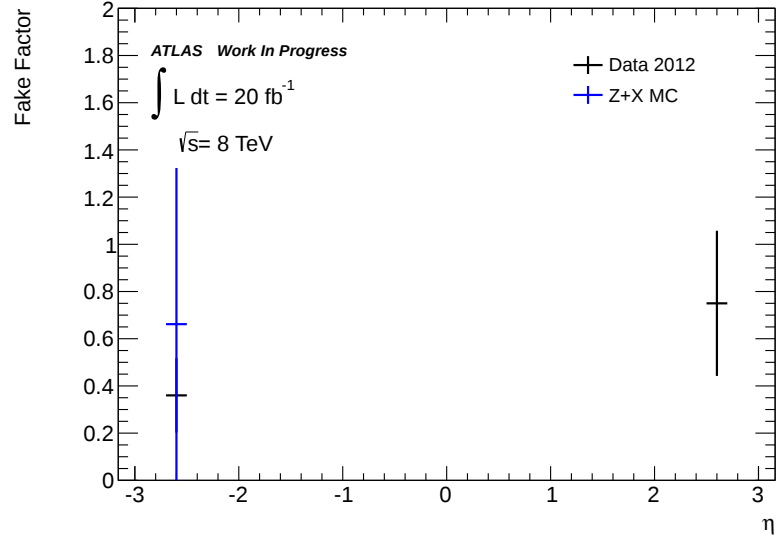


Figure C.2: Forward muon fake factor parameterized in η .

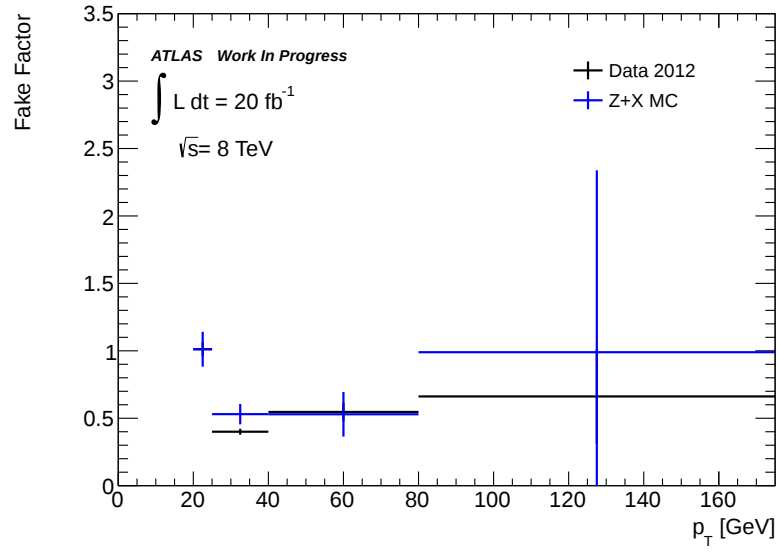


Figure C.3: Calo muon fake factor parameterized in p_T .

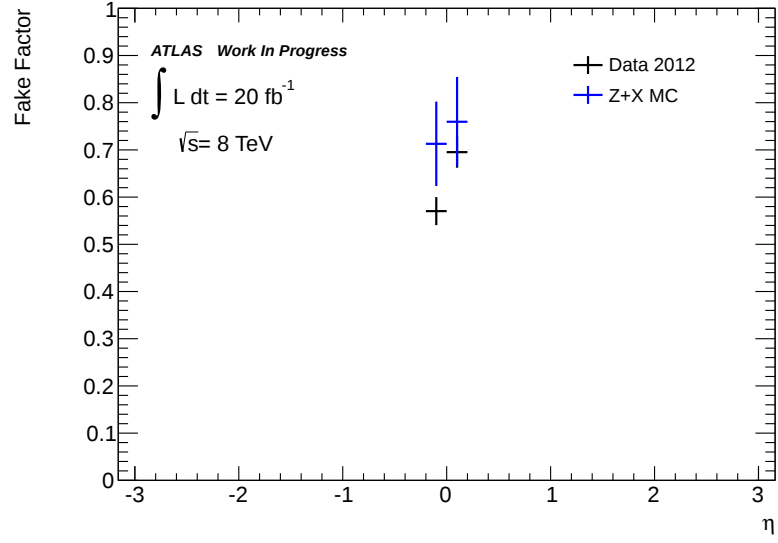


Figure C.4: Calo muon fake factor parameterized in η .

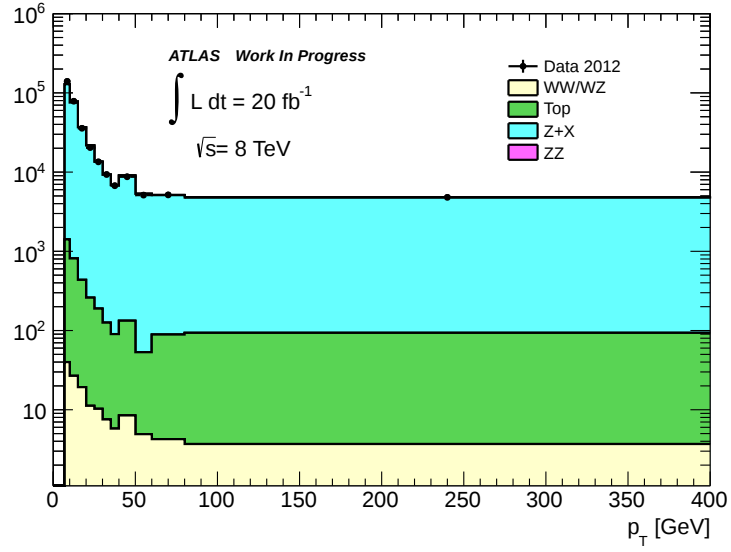


Figure C.5: Electron-like jet p_T distribution.

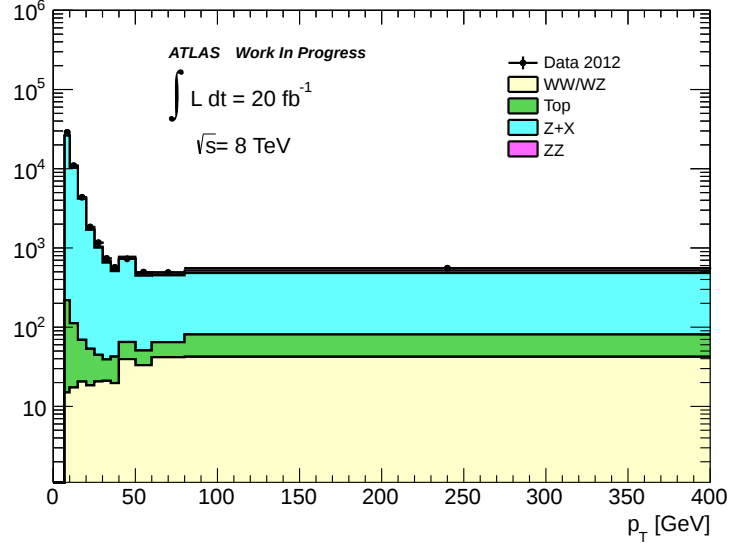


Figure C.6: Selected electron p_T distribution.

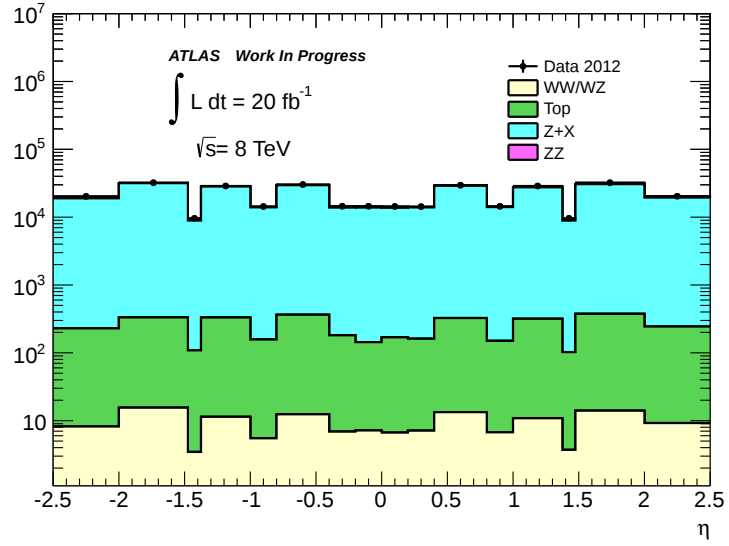


Figure C.7: Electron-like jet η distribution.

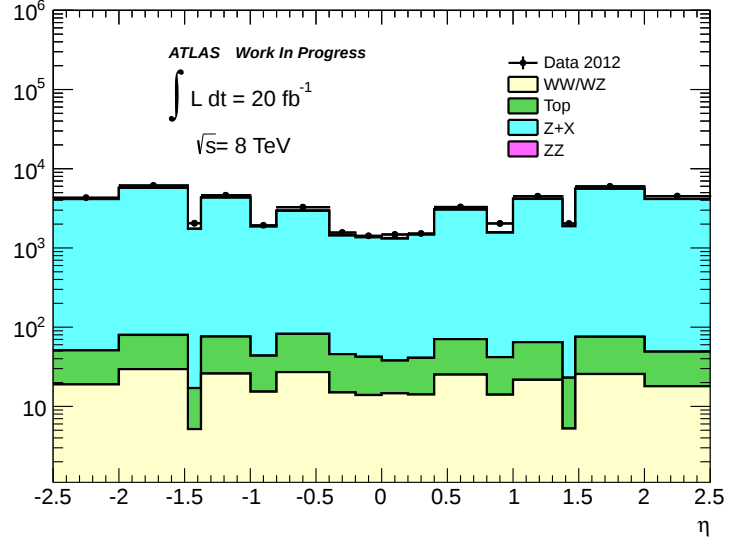


Figure C.8: Selected electron η distribution.

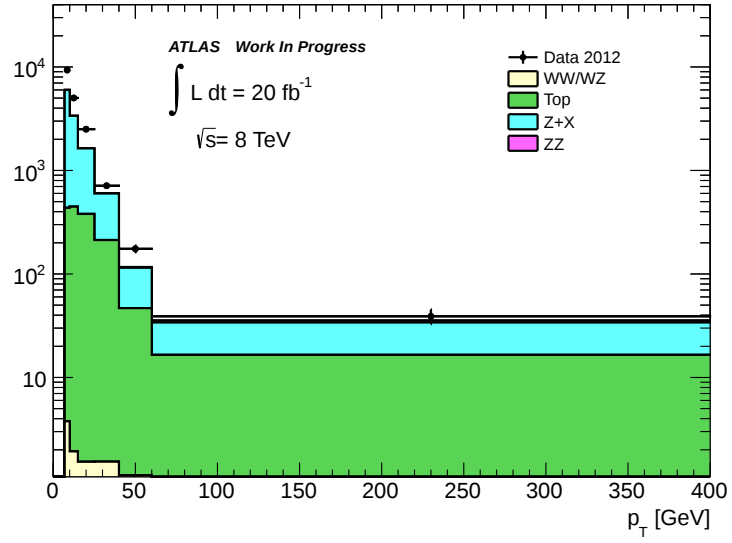


Figure C.9: Muon-like jet p_T distribution.

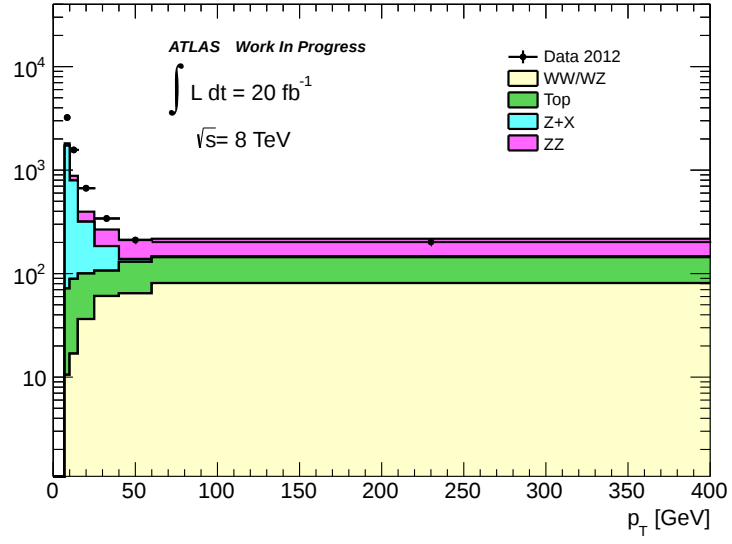


Figure C.10: Selected muon p_T distribution.

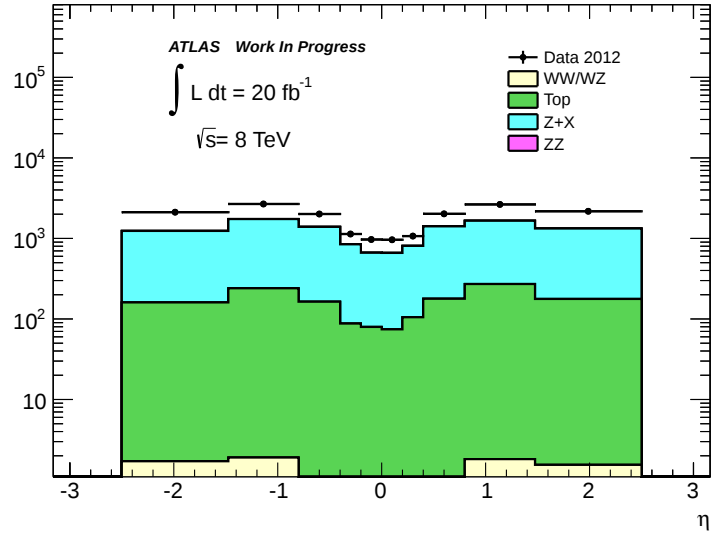


Figure C.11: Muon-like jet η distribution.

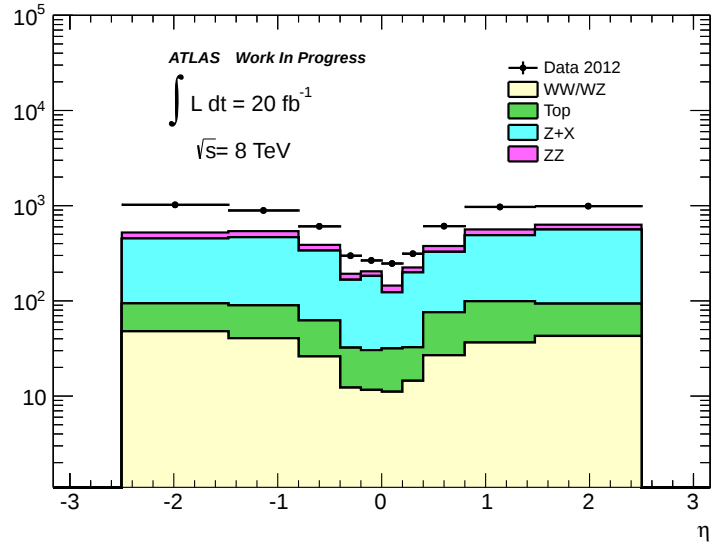


Figure C.12: Selected muon η distribution.

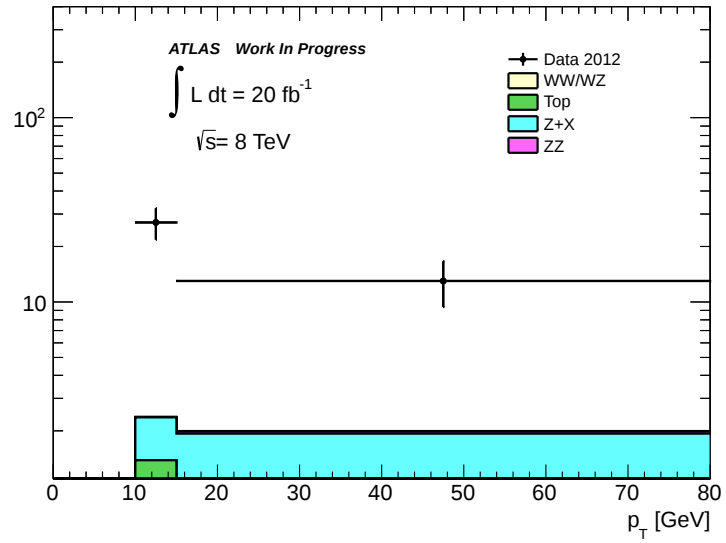


Figure C.13: Forward muon-like jet p_T distribution.

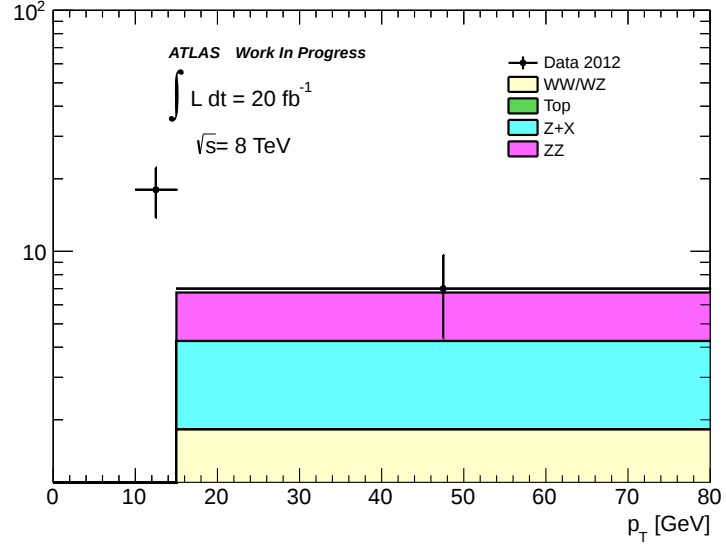


Figure C.14: Selected forward muon p_T distribution.

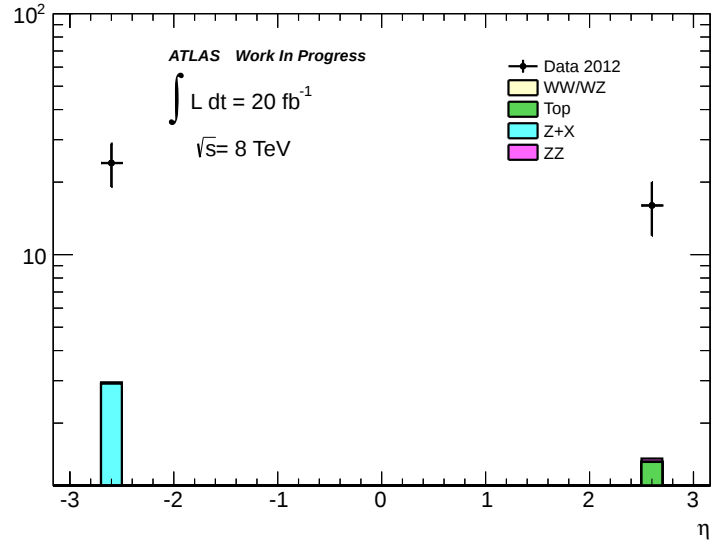


Figure C.15: Forward muon-like jet η distribution.

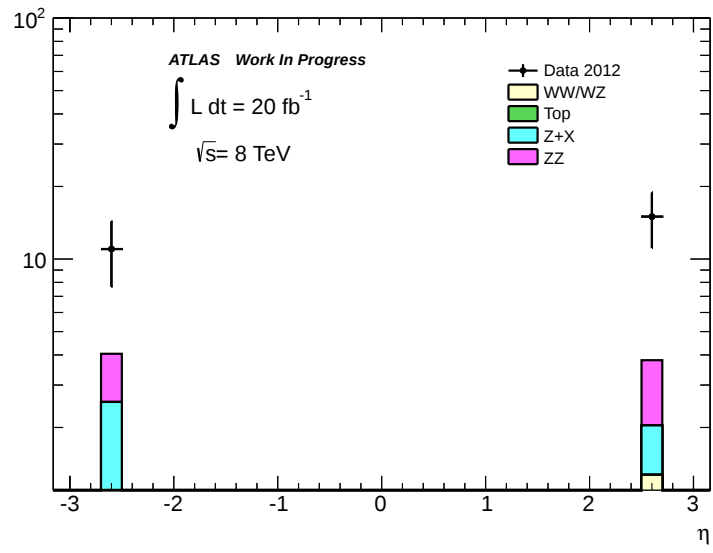


Figure C.16: Selected forward muon η distribution.

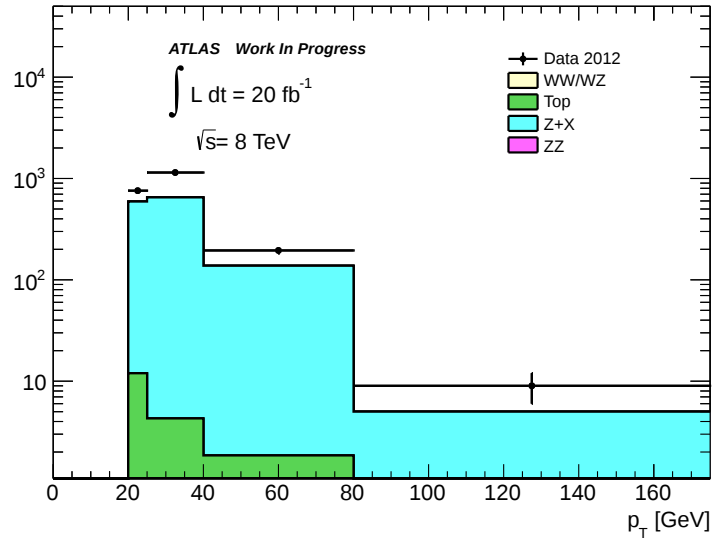


Figure C.17: Calo muon-like jet p_T distribution.

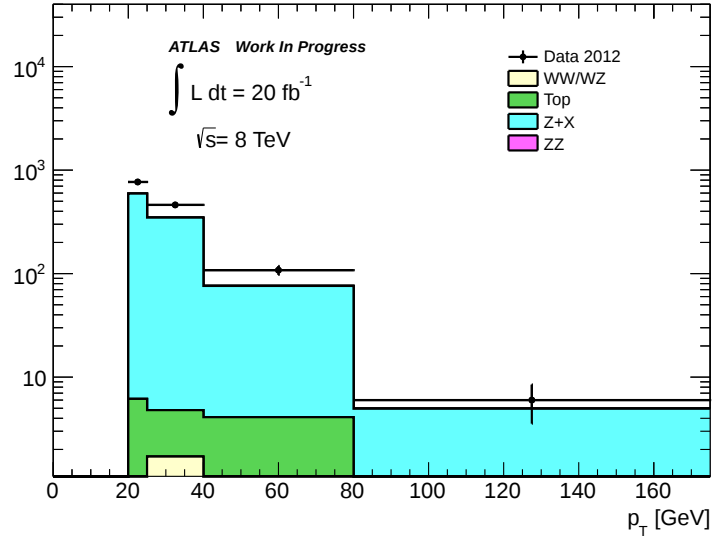


Figure C.18: Selected calo muon p_T distribution.

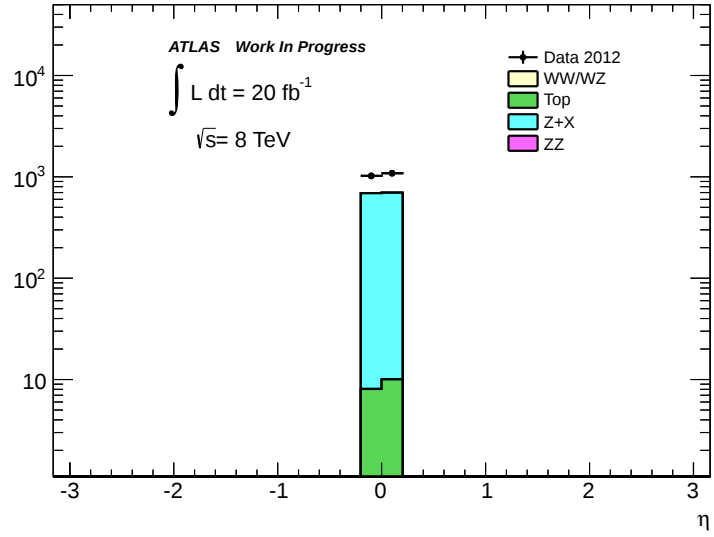


Figure C.19: Calo muon-like jet η distribution.

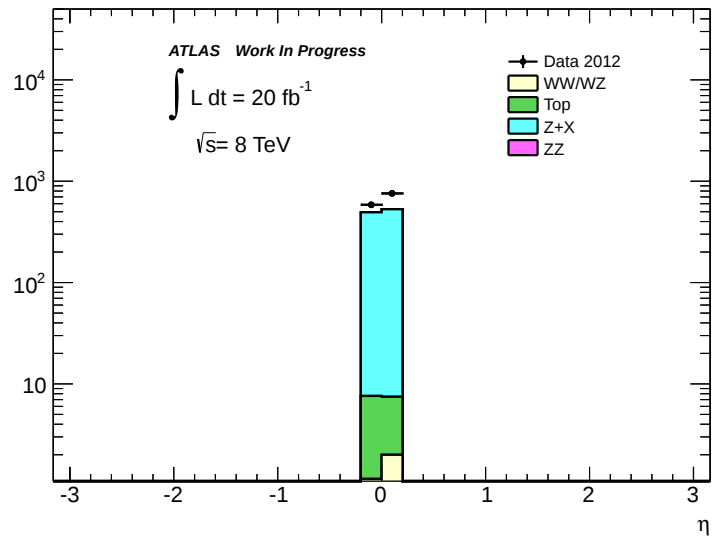


Figure C.20: Selected calo muon η distribution.