

1 MEASUREMENT OF ELECTROWEAK PRODUCTION OF
2 SAME-SIGN W BOSON PAIRS WITH ATLAS

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23 WITH ATLAS

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ABSTRACT

62 MEASUREMENT OF ELECTROWEAK PRODUCTION OF SAME-SIGN W BOSON PAIRS
 63 WITH ATLAS

William Kennedy DiClemente

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66 This thesis presents two studies of electroweak same-sign $W^\pm W^\pm jj$ scattering with the ATLAS
 67 experiment. The first is a measurement of the fiducial cross section at $\sqrt{s} = 13$ TeV using 36.1 fb^{-1}
 68 of data recorded in 2015 and 2016. The electroweak production is observed with a signal significance
 69 of 6.9σ , and the fiducial cross section is measured to be $\sigma_{\text{meas}}^{\text{fid}} = 2.91^{+0.51}_{-0.47}(\text{stat})^{+0.28}_{-0.29}(\text{sys}) \text{ fb}$. The
 70 second is a study on the future prospects for the $W^\pm W^\pm jj$ process at the planned High-Luminosity
 71 LHC, with a projected $\sqrt{s} = 14$ TeV and 3000 fb^{-1} of data. The expected electroweak production
 72 cross section is determined with a total uncertainty of 6%, and the purely longitudinal scattering
 73 component is extracted with an expected significance of 1.8σ . Additionally, some time is taken to
 74 detail the alignment of the ATLAS Inner Detector subsystems, as good alignment performance is
 75 essential for making high-quality physics measurements.

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558 red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is
559 normalized to the same area as the sum of the backgrounds (colored histogram). [135](#)

Preface

561 This thesis presents the major highlights of my work with the ATLAS experiment as a graduate
562 student at the University of Pennsylvania from Fall of 2013 until early Spring of 2019.

563 The first step of working on the experiment is to complete a *qualification task* in order to be
564 included on the author list of ATLAS publications. These tasks are an opportunity to contribute
565 to the experiment as a whole, such as maintaining detector hardware or monitoring physics perfor-
566 mance. For my qualification task, I worked with the Inner Detector Alignment group which works
567 to make sure we have accurate knowledge of the locations of each and every sensor in the tracking
568 detector. My qualification task involved investigating a possible momentum bias in the Monte Carlo
569 (MC) simulated data. The MC is supposed to be reconstructed with a perfect detector geometry
570 which should in principle be free of any momentum biases. Ultimately I determined that the size of
571 the biases were small enough to be negligible compared to what is seen in the real data, and that
572 they could be corrected for if necessary.

573 My work with the alignment group would continue for the duration of my time here at Penn. In
574 early 2015, at the start of the LHC’s second data-taking run (Run 2), I assisted with the validation
575 of the first set of alignment constants using $\sqrt{s} = 13$ TeV proton-proton collision data. At this point
576 I took over the responsibility of alignment of the TRT subdetector. The TRT was aligned to high
577 accuracy in Run 1, and over the course of my time working on alignment, the TRT never required
578 a straw-by-straw alignment; however it did require a module-level alignment at the end of 2015.
579 My final responsibility in the alignment group was monitoring momentum biases using the energy-
580 momentum ratio (E/p) of electrons. For the large data reprocessing, the E/p method served as a
581 cross check to a similar method using Z boson events for monitoring and aligning out momentum
582 biases in the detector. The results from both methods were also used in the uncertainties for the
583 tracking measurements.

584 On the analysis side, I had previous experience in Standard Model (SM) electroweak physics
585 from my time as an undergraduate at Duke University, and it remained a point of interest for
586 me in graduate school. As such, I was happy to work with fellow Penn students on the cross
587 section measurement of SM WZ diboson production with the early $\sqrt{s} = 13$ TeV ATLAS data.
588 My contribution to the analysis was primarily on the software side, as I maintained and updated
589 the analysis framework. While the WZ measurement is not covered by this thesis, it provided me
590 with invaluable analysis experience in electroweak physics, as well as a detailed understanding of a
591 major background to many diboson processes. The results for this analysis can be found published
592 in Physics Letters B in 2016 [1].

593 The final two analyses I worked on involved the scattering of same-sign W bosons, and they make
594 up the majority of this thesis. The first analysis is a measurement of the $W^\pm W^\pm jj$ cross section
595 at $\sqrt{s} = 13$ TeV. This measurement along with that of the CMS collaboration represent the first
596 observation of the $W^\pm W^\pm jj$ scattering process. My primary contribution to the analysis is in the
597 estimation of the fake lepton background, where we implemented a brand new version of the fake-
598 factor method using particle isolation variables. I also did a preliminary study of the interference
599 between electroweak and strong production of $W^\pm W^\pm jj$ events, assisted in the production of data
600 samples for use with the analysis framework, and used my familiarity with the WZ process to
601 optimize the rejection of this background. Ultimately the results of this optimization were not
602 included in the final result; however, it is still covered in the thesis in the hopes that it will be useful
603 for similar analyses in the future. The formal publication for this measurement will likely be coming
604 out within the next few months.

605 The second $W^\pm W^\pm jj$ analysis is a study on the prospects for a measurement of the process at the
606 upgraded High-Luminosity LHC, scheduled to begin operation in 2026. Here my main contribution
607 was an optimization of the event selection using a Random Grid Search algorithm. Through the
608 optimization we expect to take advantage of the higher center of mass energy and greater volume of
609 data and tighten certain selection cuts to increase the strength of the $W^\pm W^\pm jj$ signal. In addition, I
610 once again maintained and updated the analysis framework and produced the group's data samples,
611 and I also developed a truth-based particle isolation criteria in order to reduce contributions from
612 backgrounds involving the top quark. The results of this prospects study will be published as a part
613 of the annual Yellow Report for the High-Luminosity LHC.

614

Will K. DiClemente
Philadelphia, February 2019

CHAPTER 1

Introduction

617 The Large Hadron Collider (LHC) at CERN is the most powerful collider experiment in the world.
 618 At the time of its construction, the largest unanswered question in the Standard Model (SM) was
 619 the mechanism behind electroweak symmetry breaking (EWSB). As a result, one of the primary
 620 goals of the experiment is to learn as much as possible about this mechanism. Thus far, the LHC
 621 has succeeded in discovering a particle consistent with the long-awaited Higgs boson. In addition,
 622 measurements of many SM processes have been performed for the first time or at better precision
 623 than before thanks to the high collision energy and large volume of data collected by the LHC.

624 Processes involving the scattering of two massive electroweak (EWK) gauge bosons are of par-
 625 ticular interest at the LHC for two main reasons. Firstly, they allow for tests of the self-interactions
 626 predicted by the EWK gauge theory through triple and quartic gauge couplings. While the triple
 627 couplings have been studied by previous experiments as well as at the LHC, the quartic couplings
 628 of the massive gauge bosons have not been accessible previously. Thus, processes involving these
 629 couplings can be measured and compared to the SM predictions for the first time. Secondly, the scat-
 630 tering of two massive gauge bosons is sensitive to the underlying EWSB mechanism. The W^\pm and
 631 Z bosons are given non-zero masses—and consequently a longitudinal polarization mode—through
 632 the Higgs mechanism, and thus their interactions serve as a direct probe of the symmetry breaking
 633 sector.

634 This thesis presents two separate analyses dealing with the scattering of two same-sign W^\pm
 635 bosons with the LHC’s ATLAS experiment. The $W^\pm W^\pm jj$ process is one of the most sensitive to the
 636 goals above: it has access to the $WWWW$ quartic gauge coupling, production modes that involve the
 637 exchange of a Higgs boson, and relatively low backgrounds. Evidence of EWK $W^\pm W^\pm jj$ production
 638 was first seen by the ATLAS and CMS experiments at $\sqrt{s} = 8$ TeV, however the data set was too

639 small to claim observation of the process. The first analysis covered here is the follow up to the above
640 ATLAS measurement, measuring the EWK fiducial cross section at $\sqrt{s} = 13$ TeV with a larger data
641 sample. The second analysis explores the prospects for future measurements of the $W^\pm W^\pm jj$ process
642 at the planned High-Luminosity LHC (HL-LHC). A measurement of the production cross section
643 as well as sensitivity to the purely longitudinal component of the $W^\pm W^\pm$ scattering is presented.

644 In addition to the SM measurements, a part of this thesis is devoted to alignment of the detector
645 components making up ATLAS's Inner Detector (ID). Precise knowledge of the locations of detector
646 elements is essential for accurate particle track reconstruction, which in turn results in improved
647 resolutions for physics measurements. The ATLAS alignment algorithm determines the positions
648 of each ID sensor through minimizing the distance between reconstructed particle tracks and the
649 sensor hit position. Special emphasis is given to the monitoring of momentum biases that may exist
650 in the ID even after alignment.

651 This first few chapters of this thesis are intended to provide context for the main topics. Chapter 2
652 gives a brief introduction to the Standard Model with a focus on the mechanism of electroweak
653 symmetry breaking and vector boson scattering. The experimental apparatus—the LHC and the
654 ATLAS detector—are detailed in Chapter 3. The next three chapters present the main body of
655 work. Chapter 4 covers the alignment of the ATLAS Inner Detector. Finally, Chapters 5 and
656 6 detail the ATLAS $\sqrt{s} = 13$ TeV $W^\pm W^\pm jj$ cross section measurement and the $\sqrt{s} = 14$ TeV
657 HL-LHC $W^\pm W^\pm jj$ prospects study, respectively.

CHAPTER 2

Theoretical Framework

660 This chapter outlines the theoretical groundwork for the rest of the thesis. An overview of the Stan-
661 dard Model of particle physics (SM) is given in Section 2.1, followed by the electroweak symmetry
662 breaking mechanism involving the Higgs boson in Section 2.2. Finally, Section 2.3 will go into detail
663 on the interests of electroweak vector boson scattering (VBS).

664 2.1 Introduction to the Standard Model

665 The Standard Model of particle physics serves as a mathematical description of the fundamental
666 particles of the universe and their interactions. It has been developed over the course of the past
667 century, incorporating both predictions from theory and results from experiments. All in all, the
668 SM has proven to be very accurate in describing the particle interactions seen in experiments, as can
669 be seen in the summary plot of ATLAS standard model measurements through 2018 in Figure 2.1.

670 The SM is a quantum field theory (QFT) [3, 4] in which the fundamental particles are represented
671 as excited states of their corresponding fields. The spin- $\frac{1}{2}$ fermionic fields give rise to the quarks
672 and leptons comprising ordinary matter, the spin-1 fields correspond to the electroweak bosons and
673 the gluon which mediate the electroweak and strong forces, respectively, and finally the scalar Higgs
674 field is responsible for electroweak symmetry breaking. The excitations and interactions of the fields
675 are governed by the SM Lagrangian, which is invariant under local transformations of the group
676 $SU(3) \times SU(2) \times U(1)$.

677 The first quantum field theory to be developed was quantum electrodynamics (QED) [5], which
678 describes the electromagnetic interaction. The theory predicts the existence of a $U(1)$ gauge field
679 that interacts with the electrically charged fermions. This field corresponds to the photon. A key

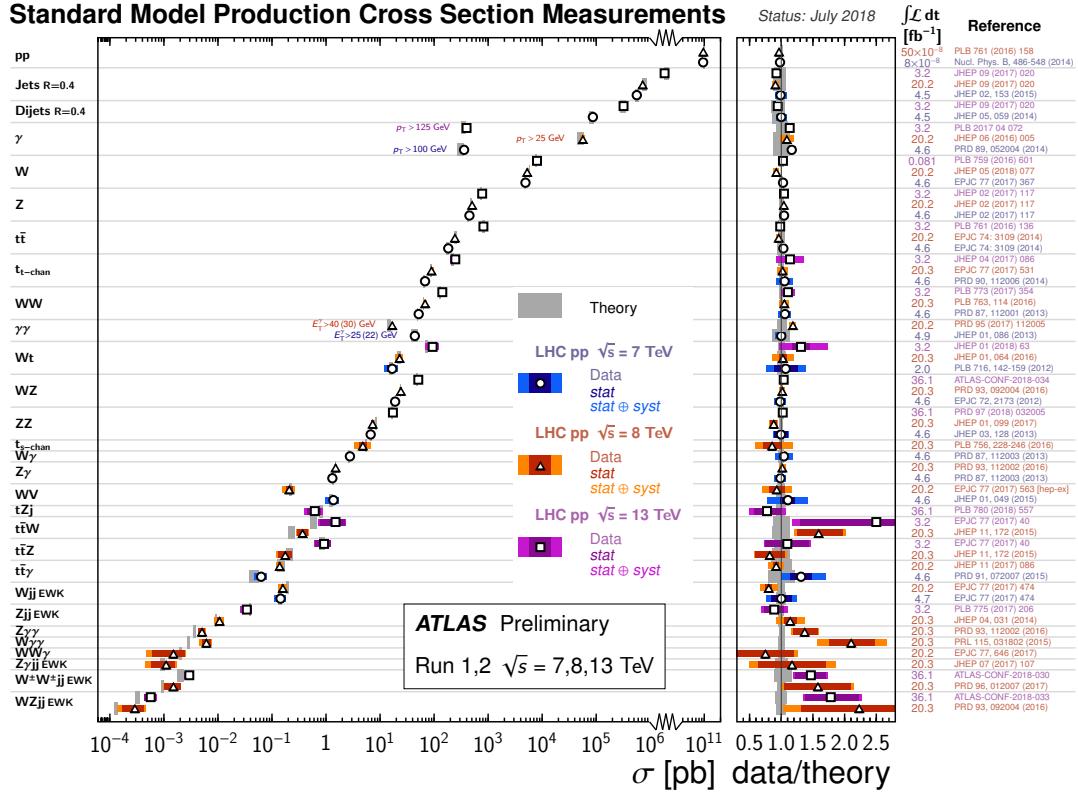


Figure 2.1: Summary of several Standard Model total and fiducial production cross section measurements compared to the corresponding theoretical predictions calculated at NLO or higher. The dark colored error bar represents the statistical uncertainty, and the light colored error bar represents the full uncertainty (including systematic and luminosity uncertainties). The data/theory ratio, luminosity used and reference for each measurement are also shown [2].

aspect of QED is that it is perturbative. The coupling constant $\alpha = e^2/4\pi$ is small, where e is electrical charge of the field, allowing for the use of perturbation theory in calculations. In this case, calculations can be written as a power series in α , where successive higher order terms contribute less to the final result. The accuracy of perturbative calculations is an essential tool for being able to make predictions from the SM.

The strong interaction—the theory of quarks and gluons—has also been described using QFT as quantum chromodynamics (QCD). The symmetry group for QCD is $SU(3)$, and its eight generators correspond to the eight differently charged, massless gluons [6]. Unlike in QED, which has positive and negative charges, the strong force has three “colors”. Color charge combined with the non-Abelian nature of $SU(3)$, which allows the gluons to interact with each other, result in the

most well-known property of QCD: color confinement. In order to increase the separation between two color-charged quarks, the amount of energy required increases until it becomes energetically favorable to pair-produce a new quark-antiquark pair, which then bind to the original quarks. The end result of this is that only color-neutral objects exist in isolation. What this means for the strong coupling constant α_s is that its value at the low energies where confinement occurs is large, on the order of $\alpha_s \sim 1$. The consequence of this is that perturbation theory cannot be used to accurately approximate interactions. While this appears at first to be a critical problem for predictions, fortunately it turns out that α_s “runs”, or decreases in magnitude at higher energy [7, 8]. This so-called “asymptotic freedom” allows QCD to be calculated perturbatively [9] at energies accessible by collider experiments including the LHC.

The last gauge field corresponds to the weak interaction. Ultimately, the weak SU(2) and the electromagnetic U(1) mix to form the $SU(2) \times U(1)$ *electroweak* (EWK) interaction [10, 11]. A more detailed description of the mixing will be discussed in conjunction with electroweak symmetry breaking (EWSB) in Section 2.2; however, a summary of the resulting EWK interaction is presented here, at the risk of some repeated information to follow. There are three weak isospin bosons arising from the SU(2) group (W_μ^1 , W_μ^2 , and W_μ^3) and one weak hypercharge boson from the U(1) group (B_μ). The W_3 and B bosons mix according to the weak mixing angle θ_W to form the Z boson and the photon according to:

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix} \quad (2.1)$$

The value of θ_W is not predicted by the SM; it is one example of an experimental input to the theory, measured to be $\sin^2 \theta_W = 0.23153 \pm 0.00016$ [12]. The charged W^\pm bosons are a mixture of the remaining W_μ^1 and W_μ^2 bosons:

$$W^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2) \quad (2.2)$$

Unlike the photon (and the gluon of QCD), the W^\pm and Z bosons are massive. This means that even though SU(2) is non-Abelian, the range of interaction is short and confinement does not occur. Lastly, the EWK interaction is chiral, only coupling to the left-handed component of the fermion fields.

One final field remains within the SM: the scalar Higgs field. It was originally proposed in the 1960’s to explain the masses of the W^\pm and Z bosons [13, 14, 15] and is the mechanism for the EWSB process. The particle associated with the field is a massive scalar boson, the Higgs boson, which was recently discovered by ATLAS and CMS in 2012 [16, 17] with a mass of 125 GeV.

⁷¹⁹ **2.2 Electroweak symmetry breaking and the Higgs boson**

⁷²⁰ The results of electroweak mixing and the implications of the Higgs field have been introduced
⁷²¹ in the previous section. If the EWK theory were an unbroken symmetry, the associated W^\pm and
⁷²² Z bosons would be massless; however, when observed experimentally, they were found to be quite
⁷²³ heavy [18, 19], at around 80 GeV and 91 GeV, respectively [20]. Here, a more detailed explanation
⁷²⁴ of the Higgs mechanism and how it “spontaneously breaks” the EWK symmetry, resulting in the
⁷²⁵ three massive bosons (W^\pm and Z) and one massless boson (photon), is presented.

⁷²⁶ To see how the Higgs mechanism results in the massive vector bosons and a massless photon,
⁷²⁷ consider the following. Beginning with a complex scalar doublet ϕ defined as:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \sqrt{\frac{1}{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2.3)$$

⁷²⁸ a Lagrangian \mathcal{L} can be written:

$$\mathcal{L} = (\mathcal{D}_\mu \phi)^\dagger (\mathcal{D}^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2 \quad (2.4)$$

⁷²⁹ where $\lambda > 0$ and \mathcal{D}_μ is the covariant derivative defined such that \mathcal{L} is invariant under a local
⁷³⁰ $SU(2) \times U(1)$ gauge transformation:

$$\mathcal{D}_\mu \phi = \left(\partial_\mu + \frac{ig}{2} \tau_a W_\mu^a + \frac{ig'}{2} B_\mu \right) \phi \quad (2.5)$$

⁷³¹ Here W_μ^a ($a = 1, 2, 3$) are the $SU(2)$ fields with generators τ_a and coupling constant g , and B_μ is the
⁷³² $U(1)$ field with coupling constant g' .

⁷³³ Isolating the potential term of the Lagrangian:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 \quad (2.6)$$

⁷³⁴ a choice must be made on the sign of μ^2 , and the case of interest is for $\mu^2 < 0$. This results in
⁷³⁵ the famous “Mexican hat potential” shown in Figure 2.2, which is minimized along the collection of
⁷³⁶ points:

$$\phi^\dagger \phi = \frac{1}{2} (\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{2\lambda} \quad (2.7)$$

⁷³⁷ This means that the minimum of the potential is not at $\phi = 0$ (as it would be in the case where
⁷³⁸ $\mu^2 > 0$), but rather at a value:

$$v \equiv \sqrt{-\frac{\mu^2}{\lambda}} \quad (2.8)$$

With no loss of generality due to the SU(2) symmetry, $\phi_1 = \phi_2 = \phi_4 = 0$ can be imposed on Equation 2.7 leaving $\phi_3^2 = v^2$. Finally, the *vacuum expectation value* (VEV) of the field can be written as:

$$\langle\phi\rangle = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad (2.9)$$

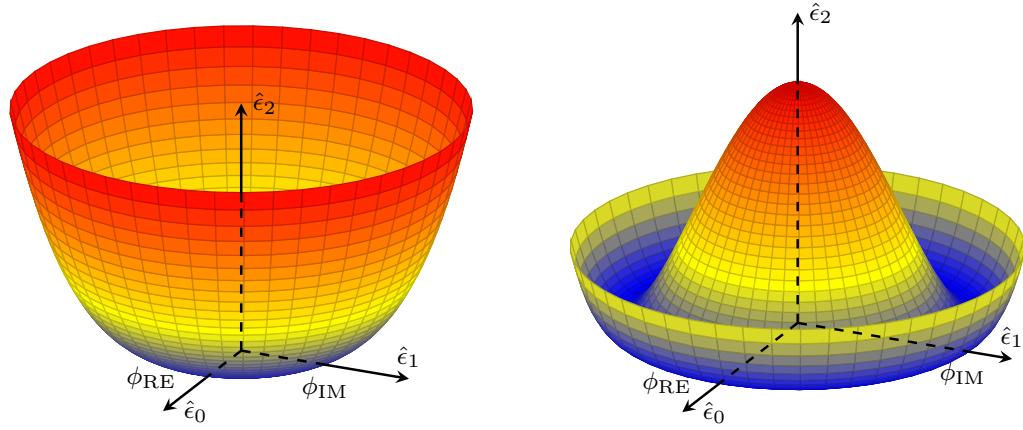


Figure 2.2: An illustration of the potential term $V(\phi)$ in Equation 2.6 for the cases where $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). The right-hand plot shows the Higgs potential, or ‘Mexican hat potential’, with the minimum at $|\phi| = \sqrt{-\frac{\mu^2}{\lambda}}$ rather than at $|\phi| = 0$ as in the left-hand plot.

The VEV can be substituted back into the original Lagrangian in Equation 2.4, and, following quite a bit of math [21], a collection of mass terms can be identified:

$$\mathcal{L} \subset \mathcal{L}_M \equiv \frac{1}{8}v^2g^2 \left[(W_\mu^1)^2 + (W_\mu^2)^2 \right] + \frac{1}{8}v^2 \left[g^2(W_\mu^3)^2 - 2gg'W_\mu^3B^\mu + g'^2(B_\mu)^2 \right] \quad (2.10)$$

Focusing on the first term for the moment, if Equation 2.2 for the physical W^\pm bosons is substituted in, the mass term can be seen clearly:

$$M_W^2 W^+ W^- = \left(\frac{1}{2}vg \right)^2 W^+ W^- \quad (2.11)$$

746

$$M_W = \frac{1}{2}vg \quad (2.12)$$

With a bit of clever forward-thinking, the second term of Equation 2.10 can be rewritten as:

$$\frac{1}{8}v^2 \left[gW_\mu^3 - g'B_\mu \right]^2 + 0 \left[g'W_\mu^3 - gB_\mu \right]^2 = \frac{1}{2}M_Z^2 Z_\mu^2 + \frac{1}{2}M_A^2 A_\mu^2 \quad (2.13)$$

⁷⁴⁸ where Z_μ^2 and A_μ^2 represent the physical Z boson and photon, respectively, and are defined as:

$$Z_\mu = \frac{gW_\mu^3 - g'B_\mu}{\sqrt{g^2 + g'^2}} \quad (2.14)$$

⁷⁴⁹

$$A_\mu = \frac{g'W_\mu^3 - gB_\mu}{\sqrt{g^2 + g'^2}} \quad (2.15)$$

⁷⁵⁰ From this, it can be seen that the photon is massless ($M_A = 0$ in Equation 2.13), and the mass of
⁷⁵¹ the Z boson is identified as:

$$M_Z = \frac{1}{2}v\sqrt{g^2 + g'^2} \quad (2.16)$$

⁷⁵² Lastly, the Higgs field can couple directly to the fermions. Taking the electron as an example,
⁷⁵³ an additional Lagrangian term can be written:

$$\mathcal{L}_e = -G_e[\bar{e}_L\phi e_R + \bar{e}_R\phi^\dagger e_L] \quad (2.17)$$

⁷⁵⁴ where e_L and e_R are the left-handed doublet and right-handed singlet, respectively, and ϕ is as in
⁷⁵⁵ Equation 2.3. The symmetry can be spontaneously broken by a perturbation about the VEV:

$$\phi = \sqrt{\frac{1}{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \quad (2.18)$$

⁷⁵⁶ which, when substituted into \mathcal{L}_e gives:

$$\begin{aligned} \mathcal{L}_e &= -\frac{G_e}{\sqrt{2}}v(\bar{e}_L e_R + \bar{e}_R e_L) - \frac{G_e}{\sqrt{2}}(\bar{e}_L e_R + \bar{e}_R e_L)h \\ &= -m_e \bar{e}e - \frac{m_e}{v} \bar{e}eh \end{aligned} \quad (2.19)$$

⁷⁵⁷ for electron mass $m_e = \frac{G_e v}{\sqrt{2}}$. From the second term, it can be seen that the strength of the Higgs
⁷⁵⁸ coupling to the electron is proportional to the mass of the electron. The rest of the fermion couplings
⁷⁵⁹ follow from this example.

⁷⁶⁰ What is accomplished here is quite remarkable. The weak and electromagnetic interactions have
⁷⁶¹ been unified into a single $SU(2) \times U(1)$ interaction, and the physical bosons observed in nature
⁷⁶² arise as mixtures of the four gauge fields. Three of the four degrees of freedom in the scalar field
⁷⁶³ ϕ of Equation 2.3, are absorbed (or “eaten”) by the W^\pm and Z bosons, and the fourth generates
⁷⁶⁴ the Higgs boson. Additionally, it is shown that the Higgs couples to fermions in proportion to
⁷⁶⁵ their mass. From experimental measurements, the value of the VEV has been determined to be
⁷⁶⁶ $v \approx 246$ GeV [20]. However, it should be noted that the theory does not predict the mass of the
⁷⁶⁷ Higgs boson or of the fermions; these must all be determined from experiment.

768 **2.3 Electroweak vector boson scattering**

769 Due to the non-Abelian nature of the EWK interaction, the associated gauge bosons are allowed
770 to self-interact. This results in triple and quartic couplings of gauge bosons (TGCs and QGCs,
771 respectively). The SM allowed TGCs are the $WW\gamma$ and WWZ vertices, which can be measured
772 experimentally via diboson production or through vector boson fusion (VBF). QGCs predicted by the
773 model include $WWZ\gamma$, $WW\gamma\gamma$, $WWZZ$, and $WWWW$ vertices accessible in triboson production
774 or via vector boson scattering (VBS)¹ [22]. VBS processes are defined by a $VV \rightarrow VV$ signature,
775 where V represents one of the EWK gauge bosons (W^\pm , Z , or γ), as shown in Figure 2.3. The actual
776 interaction between the incoming and outgoing vector bosons can be mediated by the exchange of
777 a virtual V , directly via a QGC (as in Figure 2.4), or by the exchange of a Higgs boson (as in
778 Figure 2.5).

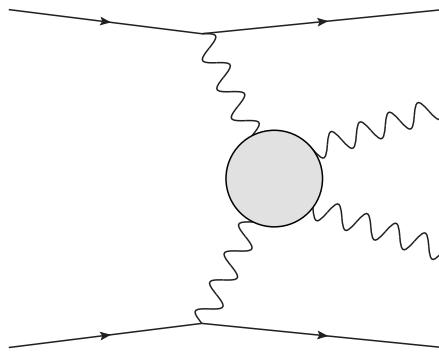


Figure 2.3: Feynman diagram of a generic VBS process. The gray circle represents any interaction with two incoming and two outgoing vector bosons, including any of the diagrams shown in Figures 2.4 and 2.5.

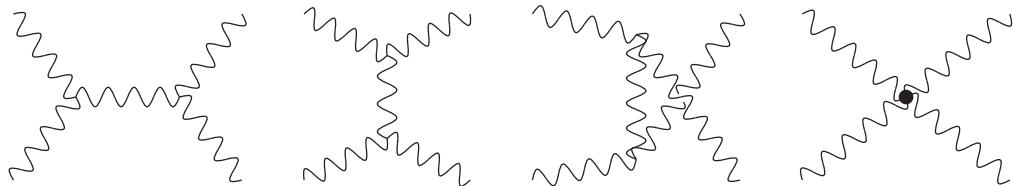


Figure 2.4: Leading order $VV \rightarrow VV$ Feynman diagrams involving EWK bosons. From left to right: s -channel, t -channel, u -channel, and the quartic gauge coupling.

¹Vector boson fusion and scattering typically refer to the s -channel and t -channel exchanges of a vector boson, respectively. Since both deal with a similar $VV \rightarrow VV$ process, for the remainder of this thesis, *vector boson scattering* will refer to both VBF and VBS.

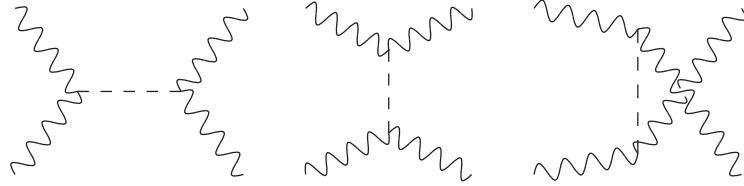


Figure 2.5: Leading order $VV \rightarrow VV$ Feynman diagrams involving the exchange of a Higgs boson. From left to right: s -channel, t -channel, and u -channel.

As detailed in the previous section, the Higgs mechanism produces three Goldstone bosons and a Higgs boson. The Goldstone bosons are then “eaten” by the physical gauge bosons, giving them mass and consequently a longitudinal polarization². In fact, according to the Electroweak Equivalence Theorem, the high-energy interactions of longitudinal gauge bosons can be accurately described by the Goldstone bosons of the EWSB mechanism [23]. Thus, the scattering of the massive gauge bosons are inextricably linked to EWSB.

It turns out that without a light SM Higgs boson, the scattering amplitude of longitudinally polarized vector bosons grows with center-of-mass energy and ultimately violates unitarity above $\sqrt{s} \approx 1.2$ TeV [24, 25]. Writing down the equations for the transverse and longitudinal polarization vectors for a gauge boson of mass M_V [26]:

$$\epsilon_{\pm}^{\mu} = \frac{1}{\sqrt{2}}(0, 0, \pm i, 0) \quad (2.20)$$

where

$$\begin{aligned} \epsilon_L^{\mu} &= \frac{1}{M_V}(|\vec{p}|, 0, 0, E) \\ &= \frac{p^{\mu}}{M_V} + v^{\mu} \end{aligned} \quad (2.21)$$

where v^{μ} is of the order M_V/E and becomes small in the high energy limit, it can be seen that ϵ_L^{μ} grows with the momentum of the boson p^{μ} . Therefore, the dominant contribution to the VBS process at high energy comes from the longitudinally polarized gauge bosons [27].

The high-energy behavior of longitudinally polarized vector boson scattering can be explored in the case of opposite-sign $W^+W^- \rightarrow W^+W^-$ scattering. In the high-energy limit ($s \gg M_W^2, M_H^2$), the amplitude of W^+W^- scattering without considering the Higgs contributions (the relevant diagrams in Figure 2.4) can be written as [25]:

$$\mathcal{M}_{\text{gauge}} = -\frac{g^2}{4M_W^2}u + \mathcal{O}\left(\left[\frac{E}{M_W}\right]^0\right) \quad (2.22)$$

²A massless spin-1 boson can have one of two transverse polarization states, while a massive spin-1 boson can also be longitudinally polarized. As a result, only the massive W^{\pm} and Z bosons, and not the massless photon, are sensitive to EWSB.

where g is the EWK coupling and u is one of the Mandelstam variables (the others being s and t). The $\mathcal{O}(E^4)$ terms cancel out between the TGC and QGC diagrams [27]. What is left is an amplitude proportional to E^2 that diverges as $E/M_W \rightarrow \infty$. However, the amplitude from the diagrams involving the Higgs boson (the relevant diagrams in Figure 2.5) is:

$$\mathcal{M}_{\text{Higgs}} = -\frac{g^2}{4M_W^2} \left[\frac{(s - M_W^2)^2}{s - m_H^2} + \frac{(t - M_W^2)^2}{t - M_H^2} \right] \quad (2.23)$$

which, in the high-energy limit, reduces to:

$$\mathcal{M}_{\text{Higgs}} = \frac{g^2}{4M_W^2} u + \mathcal{O}\left(\left[\frac{E}{M_W}\right]^0\right) \quad (2.24)$$

Adding the two equations together cancels out the E^2 term and leaves only terms constant in energy. Therefore, with a SM Higgs, the scattering amplitude for longitudinally polarized W bosons no longer diverges. Plots of the cross section of several $VV \rightarrow VV$ scattering processes are shown in Figure 2.6 with and without a SM Higgs boson.

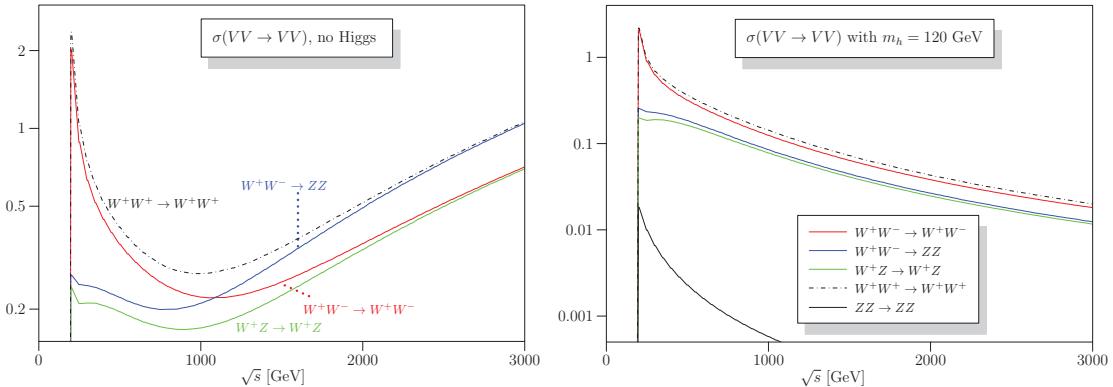


Figure 2.6: Cross sections in nanobarns for five different longitudinally polarized VBS processes as a function of center of mass energy \sqrt{s} . Without a Higgs boson (left), the cross sections grow unbounded with \sqrt{s} . With a 120 GeV Higgs boson (right), the cross sections no longer diverge. Plots taken from [28].

CHAPTER 3

LHC and the ATLAS Detector

808 This chapter covers the experimental apparatus relevant to this thesis: the Large Hadron Collider
 809 (LHC) and the ATLAS detector in Sections 3.1 and 3.2, respectively. Some time is taken to overview
 810 the methods used to identify and measure various particle types within ATLAS in Section 3.2.4.

811 **3.1 The Large Hadron Collider**

812 The Large Hadron Collider (LHC) [29] is the most powerful particle accelerator in the world in
 813 terms of beam energy, colliding two beams of protons at a center of mass energy of $\sqrt{s} = 13$ TeV. It
 814 is operated by the European Organization for Nuclear Research (CERN), and the collider is located
 815 beneath the France–Switzerland border. The LHC itself consists of a 27 km ring in which the
 816 collisions occur, and it is the last piece in a chain of several smaller accelerators that begin boosting
 817 the protons³ to high energies. Collisions occur at each of four detector experiments situated around
 818 the ring: ATLAS [30], ALICE [31], CMS [32], and LHCb [33].

819 Protons are obtained from hydrogen atoms stripped of their electrons by an electric field. A beam
 820 of protons is first accelerated up to 50 MeV in the Linac 2 accelerator, then to 1.4 GeV in the Proton
 821 Synchrotron Booster (PSB), 25 GeV in the Proton Synchrotron (PS), and finally to 450 GeV in the
 822 Super Proton Synchrotron (SPS). The protons are now injected into the LHC ring in two beams
 823 running in opposite directions where they each accelerate up to the collision energy of 6.5 TeV.
 824 The beams consist of bunches containing on the order of 10^{11} protons separated by 25 ns [34]. A
 825 schematic of the CERN accelerator complex, including the chain of accelerators mentioned above,
 826 is shown in Figure 3.1.

³The LHC can also collide beams of heavy ions; however, this thesis focuses exclusively on the proton-proton collisions.

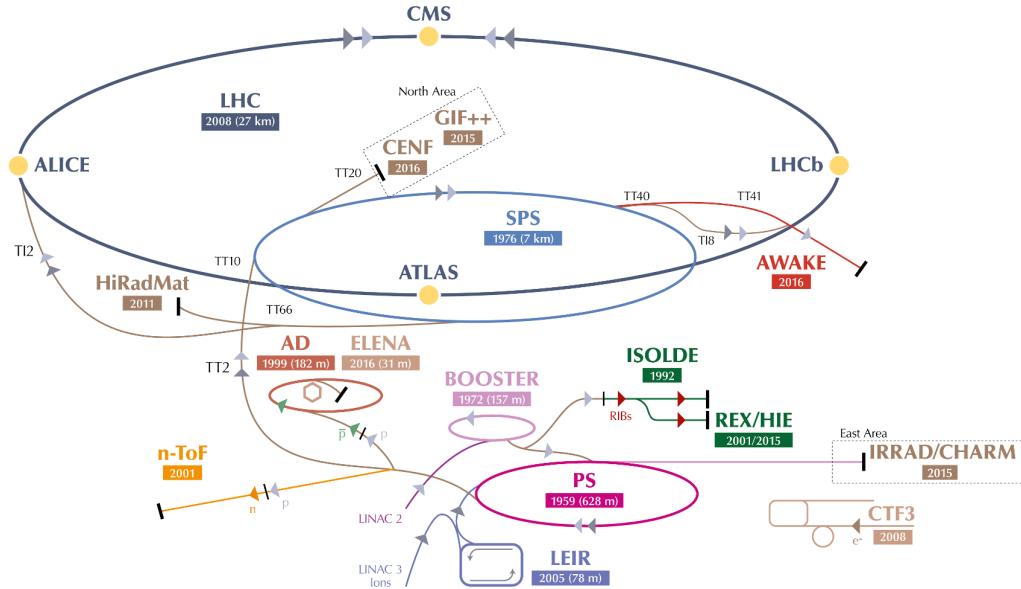


Figure 3.1: The CERN accelerator complex. For LHC collisions, protons are accelerated in the PSB (purple), the PS (magenta), and the SPS (light blue) before entering the LHC ring (dark blue) [35].

827 In addition to a high center of mass energy, the LHC must also deliver enough data to measure
 828 rare processes. The amount of data collected is measured in terms of *luminosity*. The instantaneous
 829 luminosity \mathcal{L} is defined in terms of the number of events per second $\frac{dR}{dt}$ and the production cross
 830 section σ_p :

$$\mathcal{L} = \frac{1}{\sigma_p} \frac{dR}{dt} \quad (3.1)$$

831 The calculation itself can be quite tricky, as it depends on a number of factors including (but not
 832 limited to) the number of particles per bunch, the spread of the beam, and the crossing angle of the
 833 beam [36].

834 The LHC was originally designed to operate at an instantaneous luminosity of $1.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$;
 835 however, this number was exceeded by the end of the 2016 data taking period, with a peak luminosity
 836 of $1.38 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. This number has been more than doubled by the end of Run 2 in December
 837 of 2018 [37]. The instantaneous luminosity of pp collisions as a function of time in 2015 and 2016
 838 are shown in Figure 3.2. The integrated luminosity is then the time integral of the instantaneous
 839 luminosity. By the end of Run 2 (2015-2018), approximately 140 fb^{-1} of 13 TeV data is available
 840 for physics, as shown in Figure 3.3. The 36.1 fb^{-1} collected during the first two years (2015 and
 841 2016) is used for the analysis later in this thesis.

842 Due to the high instantaneous luminosity, more than one pp interaction occurs in a single bunch

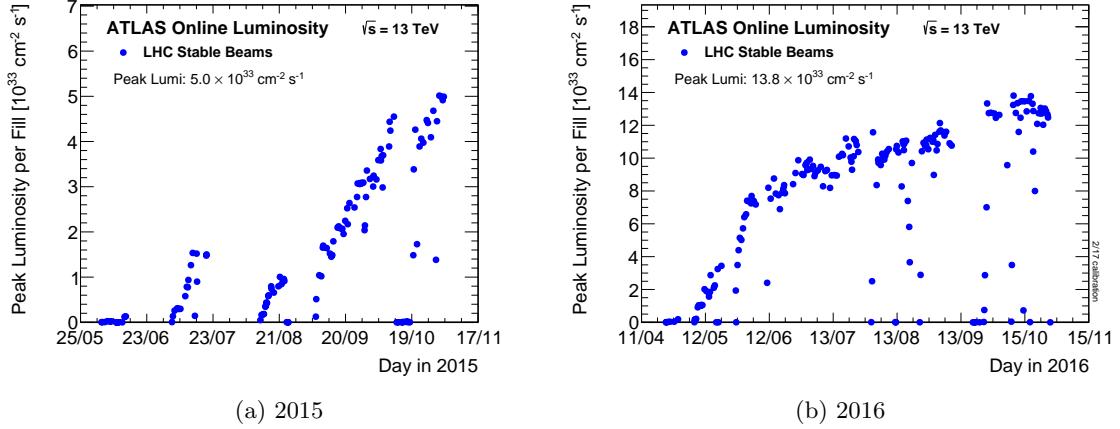


Figure 3.2: Peak instantaneous luminosity delivered to ATLAS during 13 TeV pp data taking as a function of time [37].

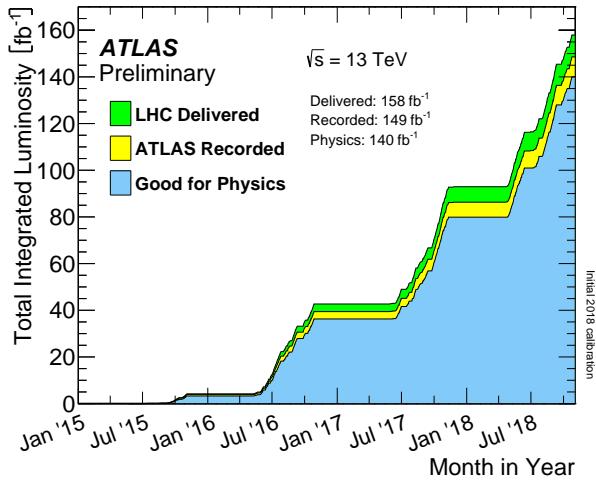


Figure 3.3: Integrated luminosity collected by ATLAS as a function of time at 13 TeV from 2015-2018 [37].

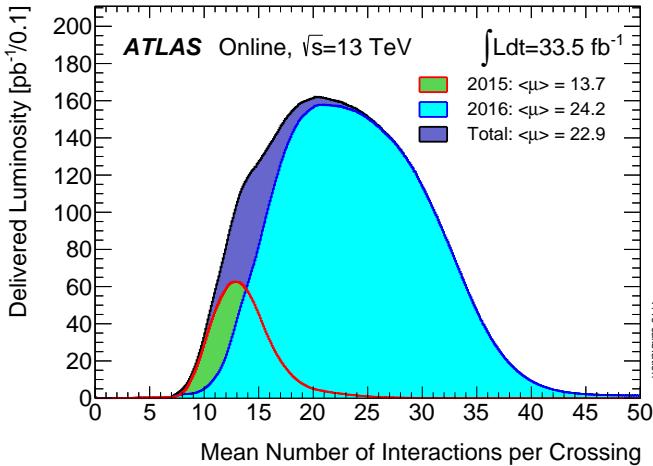


Figure 3.4: Distribution of the mean number of interactions per bunch crossing for the 2015 and 2016 pp collision data at 13 TeV [37].

crossing, referred to as *pileup*. During the 2016 data taking campaign, the average number of interactions per bunch crossing $\langle \mu \rangle$ was approximately 24 but has increased to upwards of 37 in 2017 and 2018 [37]. Figure 3.4 contains the average μ for the 2015–2016 data set used for analysis in this thesis. The high pileup is a challenge for accurately reconstructing an individual collision.

3.2 The ATLAS Detector

ATLAS (A Toroidal LHC ApparatuS) is a general-purpose particle detector. It is made up of several different subdetector systems designed to measure different types of particles. Starting from the beam line and working outwards, the Pixel Detector (PIX), Semiconductor Tracker (SCT), and Transition Radiation Tracker (TRT) make up the Inner Detector (ID) and are responsible for measuring the trajectories and momenta of charged particles. Next are two calorimeters: the Liquid Argon Calorimeter (LAr) stops electromagnetic objects and measures their energies, and the Tile Calorimeter (TileCal) does the same for hadronic objects. Finally, the outermost Muon Spectrometer (MS) measures muon tracks as they leave the detector, as they are not stopped in the calorimeters. The ATLAS detector and its subsystems are shown in Figure 3.5.

ATLAS uses a global, right-handed coordinate system with the origin at the center of the detector (the nominal interaction point). The x -axis points from the origin inwards to the center of the LHC ring, the y -axis points upwards, and the z -axis points along the beam line. Due to the azimuthal symmetry of the detector, it is useful to use cylindrical coordinates (r, ϕ) in the plane transverse

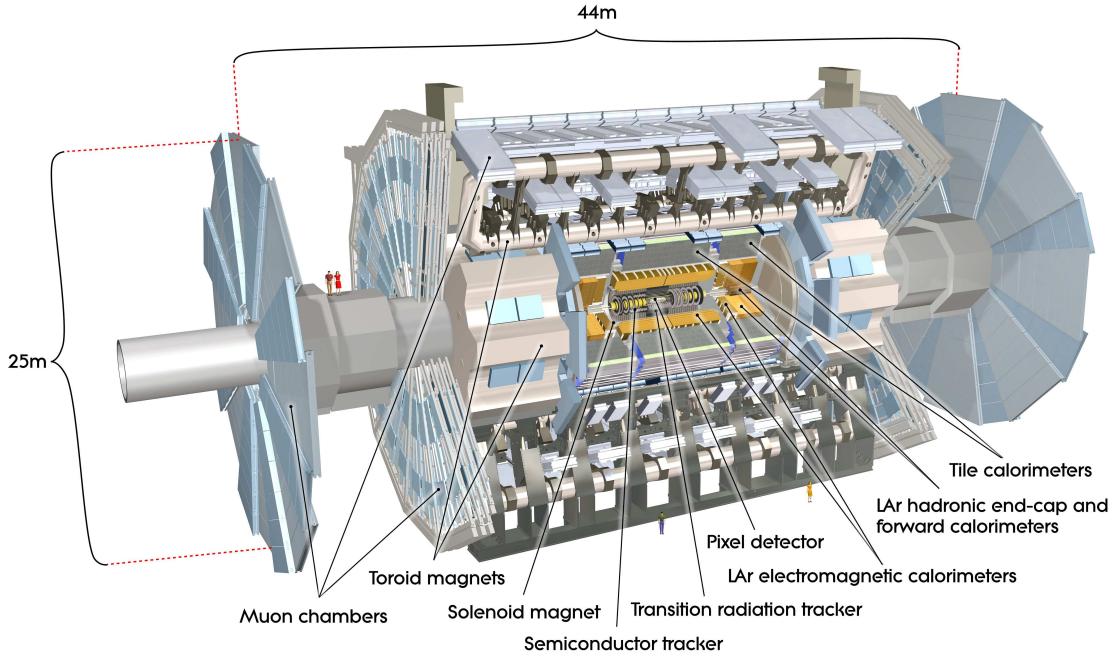


Figure 3.5: Cut-away view of the ATLAS detector [30].

861 to the z -axis where ϕ is the azimuthal angle. Instead of using the polar angle θ to describe particle
 862 trajectories, pseudorapidity η is used instead, defined in terms of θ :

$$\eta = -\ln(\tan(\theta/2)) \quad (3.2)$$

863 Pseudorapidity has the useful property that differences in η are invariant under Lorentz boosts along
 864 the z -axis. The separation between two particles p_i and p_j is often expressed in terms of the quantity
 865 ΔR , defined as:

$$\Delta R(p_i, p_j) = \sqrt{(\eta_i - \eta_j)^2 + \min[|\phi_i - \phi_j|, |\phi_j - \phi_i|]^2} \quad (3.3)$$

866 Here, the difference in ϕ is taken in whichever direction results in a value less than π , since $\phi = [0, 2\pi]$
 867 “wraps around” the detector in the azimuthal direction.

868 3.2.1 The Inner Detector

869 The ID is a tracking system that reconstructs the trajectories of charged particles. It spans just over
 870 a meter in radius, with the innermost layer of sensors at 33.25 cm away from the beam line. Charged
 871 particles traveling through the ID leave *hits* in each sensor they pass through, and a track is fit to

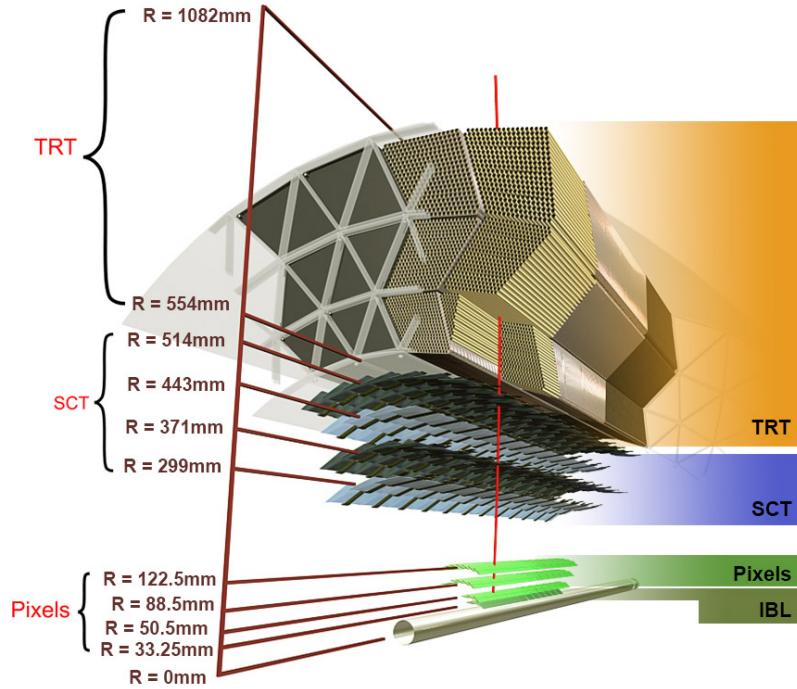


Figure 3.6: The barrel layers of the Pixel, SCT, and TRT detectors making up the Inner Detector.

872 the hits to reconstruct the path of the particle. Tracks are reconstructed within a pseudorapidity
 873 range of $|\eta| < 2.5$. A solenoid magnet outside the ID produces a 2 T magnetic field that bends the
 874 particles, allowing for their momenta transverse to the field to be measured according to:

$$p_T = q \cdot B \cdot r \quad (3.4)$$

875 where q is the charge of the particle (± 1), B is the strength of the magnetic field, and r is the radius
 876 of the track's curvature. The three subdetectors making up the ID are detailed in the following
 877 subsections, and more technical information can be found in [38, 39]. A cut-away view of the barrel
 878 region of the ID is shown in Figure 3.6.

879 3.2.1.1 Pixel Detector

880 The Pixel Detector consists of four cylindrical barrel layers⁴ and three endcap disks on either side. It
 881 is the innermost subdetector of the ID with coverage up to $|\eta| < 2.5$. The individual sensors measure

⁴For now, the outer three barrel layers will be covered in conjunction with the endcaps; the innermost layer will be described separately.

882 50 $\mu\text{m} \times 400 \mu\text{m}$ and are installed on the silicon wafers that make up the layers. All in all, there are
883 1744 wafers with 80 million readout channels. The sensors themselves are silicon semiconducting
884 diodes that provide a signal when a charged particle passes through. The Pixel Detector has the
885 finest resolution of all the ID subdetectors, at 10 μm in the $r\text{-}\phi$ plane and 40 μm in the z direction.

886 During the upgrade period prior to Run 2, a new innermost layer was added to the Pixel detector
887 barrel: the Insertable B-Layer (IBL) [40]. The IBL lies closest to the interaction point, at a radius
888 of 33.25 cm from the beam line, and it is relied upon to provide high-precision measurements close
889 to the interaction point. Its addition allows better precision in detecting displaced vertices from
890 b -jets, for example. It consists of 280 silicon pixel modules arranged on 14 staves that run parallel
891 to the beam line. Each stave consists of 12 two-chip planar modules in the middle ($|\eta| < 2.7$) with
892 four 3D sensors [41] on either side ($2.7 < |\eta| < 3.0$). The IBL's pixel sensors are 50 $\mu\text{m} \times 250 \mu\text{m}$ in
893 size and have a resolution of 10 μm in $r\text{-}\phi$ and 75 μm in z [42].

894 **3.2.1.2 Semiconductor Tracker**

895 The next subdetector of the ID is the SCT, which has four barrel layers and nine endcap disks per
896 side and provides coverage within $|\eta| < 2.5$. The SCT operates on the same principle as the Pixel
897 Detector, but the sensitive elements are larger silicon “strips” placed on the wafers. This shape
898 change assissts in covering the larger surface area required by the increasing detector radius. Each
899 detector layer is actually made up of two layers of wafers, placed back-to-back with an angle of
900 40 mrad between them. The resolution in the $r\text{-}\phi$ plane is very fine at 17 μm , but, due to the strip
901 shape, the resolution along z is rather poor at 580 μm .

902 **3.2.1.3 Transition Radiation Tracker**

903 The outermost component of the ID is the TRT [43, 44, 45], which uses a completely different
904 technology from the Pixel and SCT to identify particle hits. The TRT is unique in that it combines a
905 drift tube tracker with transition radiation detection for electron identification. The TRT's sensitive
906 elements are drift tubes (referred to as “straws”) that are 4 mm in diameter and consists of a
907 cylindrical cathode with an anode wire running through the center. Each straw is filled with a gas
908 mixture including xenon or argon which provide ionizing radiation when high energy particles pass
909 through them. The resulting electrons drift to the anode and register a voltage, indicating a hit in
910 the detector element.

911 Between the straws are polyethelene fibers in the barrel and polypropylene foil in the endcaps

912 in order to encourage particles to emit transition radiation photons. These photons also ionize the
 913 gas within the straws, leading to a higher signal. The TRT takes advantage of the fact that lighter
 914 particles are more likely to emit transition radiation by using a ternary output: zero, low-threshold,
 915 and high-threshold. High-threshold hits are generally caused by electrons due to their low mass,
 916 and this can help in discriminating electrons against backgrounds.

917 There are over 100,000 straws in the barrel of the TRT, and nearly 250,000 in the endcaps. The
 918 TRT provides pseudorapidity coverage up to $|\eta| < 2.0$ with a resolution in the $r\phi$ plane of 130 μm .
 919 Since the drift tubes are insensitive along the direction of the wire, the TRT has no resolution in
 920 the z direction.

921 3.2.2 The Calorimeters

922 ATLAS utilizes two different calorimeters, the Liquid Argon and Tile Calorimeters [46, 47], in order
 923 to measure electromagnetic and hadronic objects. The general principle behind both calorimeters is
 924 the same: an incoming particle showers as it passes through and eventually stops, and the resulting
 925 energy deposits are read out. Both are sampling calorimeters, which consist of alternating layers
 926 of a dense material to induce the showering (absorber) and a second material which measures the
 927 energy (active material). An advantage to this type of calorimeter is that a very dense absorber can
 928 be used in order to produce a shower in a limited space, even if it is unsuitable for measuring the
 929 energy from the shower. However, as some of the energy is deposited in the dense material, and the
 930 total shower energy must be estimated. ATLAS's calorimeter systems are shown in Figure 3.7.

931 Electromagnetic objects, such as electrons and photons, shower via cascades of bremsstrahlung
 932 photons and e^+e^- pairs. The radiation length X_0 is defined as the mean distance over which an
 933 electron's energy is reduced to $1/e$ of its original value, or $E(x) = E_0 e^{-x/X_0}$. The majority of the
 934 shower energy is deposited in the first few radiation lengths. The longitudinal shower depth scales
 935 logarithmically with particle energy, and the transverse shower width is described by the Molière
 936 radius⁵ of the material.

937 Hadronic showers (referred to as *jets*) are the result of quarks or gluons which hadronize and
 938 shower primarily via the strong interaction. Hadronic showers are generally wider than the electro-
 939 magnetic showers described above. The longitudinal depth of the hadronic shower scales with the
 940 nuclear interaction length of the material λ , defined as the mean distance for the number of particles

⁵A cone with a radius equal to the Molière radius (M_R) will contain approximately 90% of the shower energy. At a radius of $2M_R$, 95% of the energy will be contained.

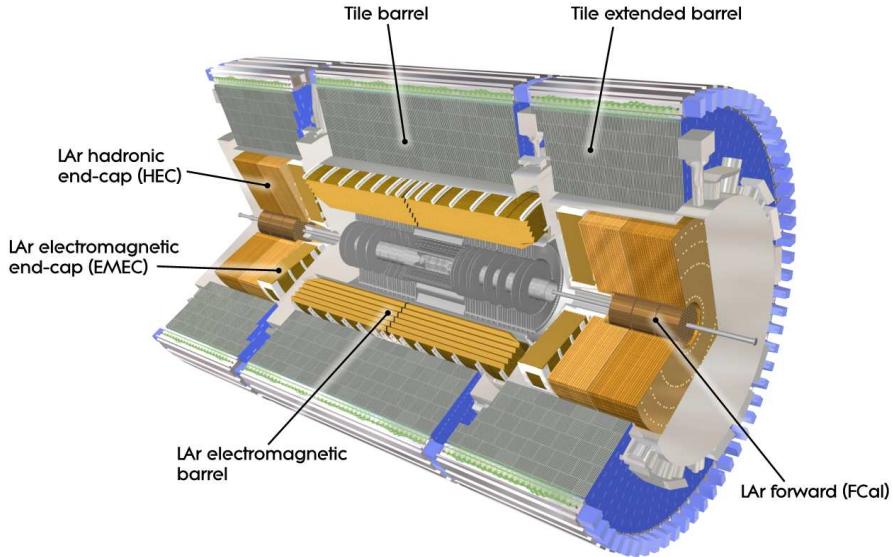


Figure 3.7: Cut-away view of the ATLAS calorimeter systems [48].

941 in a hadronic jet to be reduced to $1/e$ of the initial number. In addition, about $1/3$ of the shower
 942 products are neutral pions π^0 which decay electromagnetically.

943 3.2.2.1 Liquid Argon Calorimeter

944 The LAr Calorimeter contains four individual calorimeters: the electromagnetic barrel (EMB) and
 945 endcaps (EMEC), and the hadronic endcap (HEC) and forward calorimeter (FCal). The calorimeter
 946 is surrounded by a cryostat held at a temperature around 90 K.

947 Focusing on the electromagnetic components first, the EMB covers $|\eta| < 1.475$ and the two
 948 EMECs cover $1.375 < |\eta| < 3.2$. They consist of alternating layers of lead absorber and liquid
 949 argon. The thickness of the lead depends on the location within the detector, but the layers range
 950 from 1.1-2.2 mm. The absorbers are folded into an accordion shape, where the folding angles are
 951 varied in order to keep the thickness of the liquid argon gap constant (about 2.1 mm) across the
 952 barrel. The minimum number of radiation lengths at the end of the electromagnetic calorimeter is
 953 24 X_0 .

954 There are four layers within the EMB and EMEC including an innermost pre-sampler that helps
 955 correct for energy lost before the shower reaches the calorimeter. The next three layers consist of
 956 differently shaped cells successively reducing in granularity. The first layer consists of narrow strips

for fine-grained η resolution, and the majority of the shower energy is deposited in the second layer.
 The accordion shape as well as the sizes of the cells in the EMB are shown in Figure 3.8.

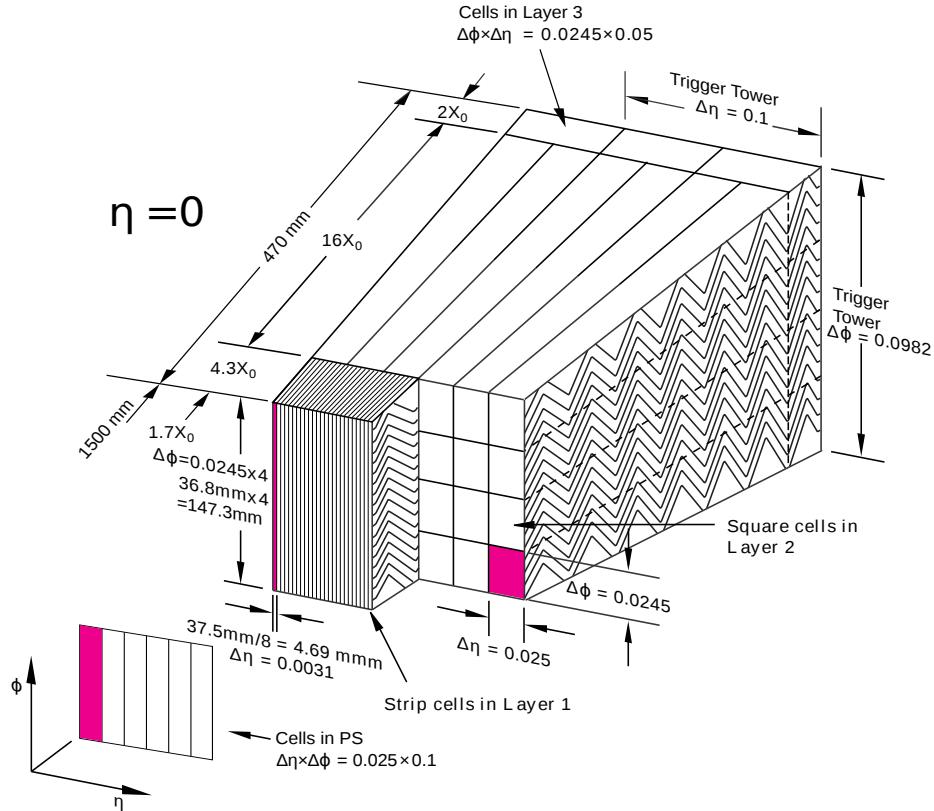


Figure 3.8: Diagram of the cells within the LAr barrel. The accordion structure can be seen in the cut-away view [46].

The HEC is located directly behind the EMEC and covers $1.5 < |\eta| < 3.2$. It uses thick copper plates as the absorber (25 mm in the front wheels and 50 mm in the rear wheels) separated by 8.5 mm gaps filled with liquid argon. Rather than the accordion shape, the HEC cells are rectangular.

The FCal provides coverage for hadronic jets over the range $3.2 < |\eta| < 4.9$. Each FCal endcap consists of three layers. The first is an electromagnetic calorimeter with a copper absorber, while the other two hadronic layers use a tungsten absorber. Due to the high particle flux entering the FCal, the liquid argon gaps are very narrow, and electrodes are embedded into the absorbers parallel to the beam line.

967 **3.2.2.2 Tile Calorimeter**

968 The TileCal consists of a barrel and two “extended barrel” sections which cover the range $|\eta| < 1.7$.
969 It consists of alternating layers of steel plates and polystyrene scintillator tiles as the absorbers and
970 active material, respectively. The total thickness of the TileCal is approximately 9λ . As the shower
971 passes through the scintillators, photons are emitted that are picked up by wavelength shifting fibers
972 and passed to photomultiplier tubes.

973 **3.2.3 The Muon Spectrometer**

974 The outermost subdetector in ATLAS is the Muon Spectrometer [49]. Due to the high mass of muons
975 compared to electrons, they pass through the calorimeters, necessitating their own detector. The
976 MS is a high-resolution spectrometer providing tracking for muon reconstruction within $|\eta| < 2.7$.
977 A set of toroid magnets provide an azimuthal magnetic field that bends the muons for momentum
978 measurements, much like in the ID. Four different technologies are used in the MS:

- 979 ● Monitored Drift Tubes (MDT) are used across the entire η range for precision measurements
980 of the tracks with a per-hit resolution in the range of $60\text{--}80 \mu\text{m}$. These consist of an aluminum
981 tube with an anode wire running through the middle; the tubes are filled with a gas mixture
982 containing argon. When a muon passes through, the gas is ionized, and the electrons are
983 collected on the wire.
- 984 ● Cathode Strip Chambers (CSC) are used for the forward regions of the endcaps ($|\eta| >$
985 2.0). They operate on a similar principle to the MDTs, except they are strips instead of tubes,
986 with a mesh of anode wires running in parallel.
- 987 ● Resistive Plate Chambers (RPC) in the barrel are primarily used to provide input for the muon
988 trigger system. They consist of pairs of plastic resistive plates with a 2 mm gap between them
989 filled with a gas mixture. Electrodes are attached to the plates, and muons passing through
990 ionize the gas and lead to electric discharges which in turn reduce the potential.
- 991 ● Thin Gap Chambers (TGC) are also used for triggering, but for the endcaps. The TGCs are
992 arranged on circular disks consisting of two rings, and are similar in function to the CSCs but
993 with a different gas mixture.

994 **3.2.4 Particle reconstruction**

995 In order to convert the raw detector readouts to information about a given particle, various sets of
996 reconstruction algorithms are run. This includes building particle trajectories in the ID, as well as
997 identifying and measuring electrons and muons. A brief overview of these reconstruction methods
998 follow in order to provide context for when these objects are used later in the thesis.

999 **3.2.4.1 Track reconstruction**

1000 *Track reconstruction* is the process by which a particle’s trajectory is reconstructed from the raw
1001 measurements (also called *hits*) recorded in the ID. The ATLAS track reconstruction algorithm [50]
1002 follows three main steps: clusterization, track finding, and ambiguity solving.

1003 The first step, clusterization, uses hits from the Pixel and SCT detectors. Neighboring pixels and
1004 silicon strips in a sensor are grouped together into clusters using a connected component analysis.
1005 Each cluster represents a *space-point*, or a three-dimensional measurement corresponding to the
1006 point where the particle intersected the sensor. Since the SCT sensors consist of two strip layers on
1007 top of each other (as described in Section 3.2.1.2), clusters from each layer combine to form a single
1008 space-point. It is possible to have overlapping clusters from multiple particles in a single sensor, and
1009 care is taken that these *merged clusters* are identified and handled accordingly.

1010 Next, track seeds are formed using sets of three space-points. This number allows for a first
1011 momentum estimate to be made while still maximizing the number of track combinations as much as
1012 possible. The impact parameters of a track seed—the distance of closest approach to the collision—
1013 are estimated by assuming a perfect helical trajectory in a uniform magnetic field. In order to ensure
1014 the quality of a track seed, criteria on the momentum and impact parameters are imposed as well as
1015 a requirement that at least one additional space-point lies along the preliminary trajectory. Finally,
1016 a combinatorial Kalman filter [51] builds track candidates from the track seeds by incorporating
1017 additional space-points lying along the preliminary trajectory. The filter allows for multiple track
1018 candidates to be fit to the same track seed if more than one set of space-points is compatible.

1019 The final step of the reconstruction process is the ambiguity solving. Each track candidate is
1020 processed individually sorted by their *track score*, a metric for quantifying the likelihood that a given
1021 track candidate correctly represents the particle’s trajectory. The track score is determined by a
1022 number of factors. Each cluster in the track candidate increases the score by an amount weighted
1023 by, for example, the intrinsic resolution of the relevant detector’s sensors. Conversely, if a track
1024 candidate passes through a sensor but there is no associated cluster (called a *hole*), the score is

1025 reduced. The χ^2 of the track fit contributes as well in order to promote tracks with high quality
 1026 fits. Finally, the logarithm of the momentum adds to the score in order to suppress tracks with
 1027 incorrectly assigned clusters which typically have low momenta. A track candidate is rejected by
 1028 the ambiguity solver if its score is too low, or if it fails to meet a basic set of quality criteria. If a
 1029 cluster would be shared by more than one track, at most two tracks are allowed to pass through it.
 1030 In this case, preference is given to tracks already passing through the ambiguity solver, which by
 1031 construction results in the two highest scoring tracks using the shared cluster being kept.

1032 Following this procedure, TRT hits can be incorporated into the track fit through *TRT track*
 1033 *extension* [52]. Compatible sets of TRT measurements are found for tracks found in the silicon
 1034 detectors surviving the ambiguity solving. The algorithm requires that the original silicon-only
 1035 track not be modified by the inclusion of the TRT hits; it is simply an extension of the existing
 1036 track.

1037 What is described above is the *inside-out* reconstruction algorithm; there is also an *outside-in*
 1038 reconstruction that begins in the TRT. This algorithm is not covered in detail here, as much of the
 1039 process is similar to the above. The general workflow begins with finding track segments in the
 1040 TRT, constructing the track candidates including the silicon hits, and finally ambiguity solving.

1041 3.2.4.2 Electron reconstruction

1042 Electron reconstruction [53] uses information from both the ID and the electromagnetic calorimeters.
 1043 The characteristic signature of an electron in ATLAS is a charged particle track in the ID matched
 1044 in $\eta\text{-}\phi$ to localized clusters of energy deposited in the calorimeter.

1045 Calorimeter cluster candidates are seeded from localized energy deposits according to a sliding-
 1046 window algorithm [54]. The clusters are a 3×5 rectangle of calorimeter towers in $\eta \times \phi$ with a
 1047 total transverse energy greater than 2.5 GeV. In the event that two clusters overlap, if the E_T of
 1048 the clusters vary by more than 10%, the highest E_T cluster is kept, otherwise the candidate with
 1049 the highest E_T in the central tower is kept. The ID tracks are those generated using the algorithm
 1050 detailed above in Section 3.2.4.1, and tracks with a nearby calorimeter cluster are re-fit using a
 1051 Gaussian-sum filter [55] designed to take into account bremsstrahlung effects.

1052 To reconstruct the final electron candidate, the refit track and the cluster are subject to the final

1053 matching criteria:

$$\begin{aligned} |\eta_{\text{cluster}} - \eta_{\text{track}}| &< 0.05 \\ \text{and} \\ -0.10 < q \times \Delta\phi_{\text{cluster, track}} &< 0.05 \quad \text{or} \quad -0.10 < q \times \Delta\phi_{\text{res}} < 0.05 \end{aligned} \tag{3.5}$$

1054 where q is the charge of the track and $\Delta\phi_{\text{res}}$ is the azimuthal separation between the cluster position
 1055 and the track after rescaling its momentum to the energy of the cluster. If multiple tracks satisfy the
 1056 above criteria, the primary track is selected by an algorithm that takes into account the center of
 1057 each cluster relative to the parameters of the candidate track. Finally, the clusters are reconstructed
 1058 about the seed cluster using a larger window size, 3×7 in the barrel and 5×5 in the endcaps, and
 1059 the energy is calibrated to the original electron energy using techniques described in [56, 57].

1060 **Electron identification** To determine whether an electron candidate is a signal electron or back-
 1061 ground object, an identification criteria (ID) is implemented, covered in more detail in [53, 58]. Elec-
 1062 tron ID is performed using a multivariate likelihood technique (LH) that simultaneously evaluates
 1063 a list of measurements of an electron candidate, including both tracking and calorimeter clustering
 1064 information. To cover the different requirements of various physics and performance studies, four
 1065 different likelihood working points are constructed corresponding to increasing thresholds for the
 1066 LH discriminant: `VeryLooseLH`, `LooseLH`, `MediumLH`, and `TightLH`. Each successive working point is
 1067 a subset of its predecessors. The efficiencies of the `LooseLH`, `MediumLH`, and `TightLH` working points
 1068 as a function of electron E_T are shown in Figure 3.9.

1069 **Electron isolation** Signal electrons, such as those from the decay of a W boson, tend to have
 1070 little detector activity nearby in both the ID and the calorimeters. Background electrons, such as
 1071 those from photon conversions or jets, are often produced in association with other particles. To
 1072 take advantage of this, variables are constructed to quantify the amount of activity within a cone of
 1073 a specified radius in ΔR about an electron—one track-based and a second calorimeter-based.

1074 The track-based isolation consists of the sum of the transverse momentum of tracks within a cone
 1075 of a specified radius about an electron (not including the electron itself). The tracks are required to
 1076 have $p_T > 1$ GeV, that satisfy basic quality requirements, and be associated with the vertex from
 1077 which the electron originated. Additionally, particles from bremsstrahlung radiation are considered
 1078 part of the original electron and are subtracted from the isolation cone. A variable cone radius
 1079 dependent on the p_T of the electron is used in order to compensate for busy detector environments:

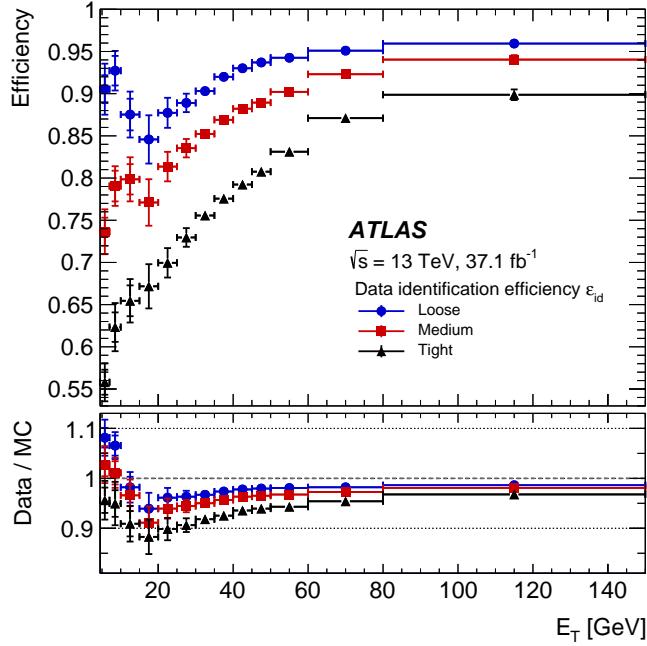


Figure 3.9: Measured LH electron ID efficiencies in $Z \rightarrow ee$ events for the `LooseLH` (blue), `MediumLH` (red), and `TightLH` (black) working points as a function of electron E_T . The bottom plot shows data-to-simulation ratios. Plot taken from [53].

$$\Delta R = \min \left(\frac{10 \text{ GeV}}{p_T}, R_{\max} \right) \quad (3.6)$$

where R_{\max} is the largest allowed cone size, typically set at 0.2 for electrons.

Calorimeter isolation is a bit more difficult, due to the size of the energy deposits relative to the cone size, as parts of an energy cluster can lie outside of the cone. As such, topological clusters [59] (topo clusters) are seeded by calorimeter cells with deposited energy greater than four times the expected noise-level of that cell. The cluster is then expanded incorporating electromagnetic and hadronic cells with an energy greater than two times the noise-level until no adjacent clusters remain satisfying the requirement. The isolation cone is then the sum of the E_T of all positive-energy topo clusters whose barycenters fall within a cone of radius $\Delta R < 0.2$. The electron's energy is subtracted by removing the cells within a rectangle around the electron.

The isolation selection uses the *relative isolation*, defined as the ratio of the track- or calorimeter-based isolation variable divided by the electron p_T . Four isolation working points are defined targeting specific values of efficiency. `Loose` and `LooseTrackOnly` target a fixed efficiency value across the p_T and η spectrum of the electrons, with the latter not applying a cut on calorimeter isolation.

1094 Gradient and GradientLoose target a p_T -dependent fixed efficiency that is uniform in η . The effi-
 1095 ciencies for these working points as a function of electron E_T are shown in Figure 3.10. Additional
 1096 working points are provided that instead use fixed values for the relative track and calorimeter
 1097 isolation cuts.

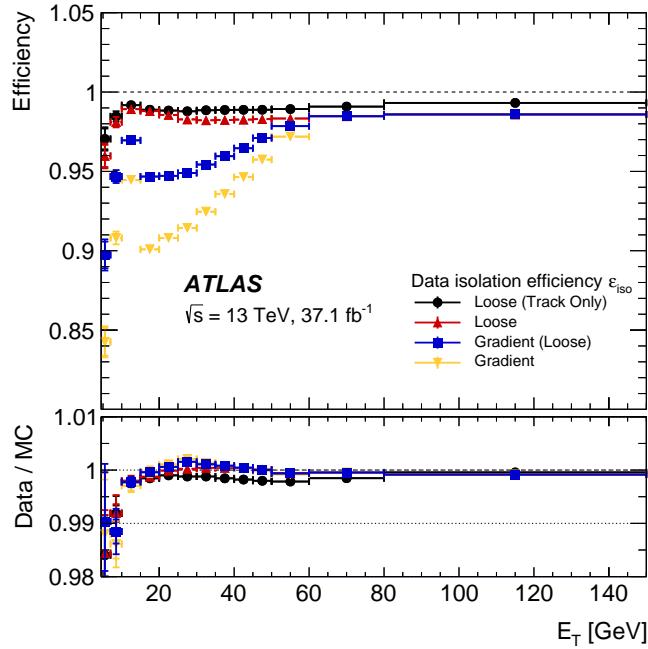


Figure 3.10: Measured isolation efficiencies for the LooseTrackOnly (black), Loose (red), GradientLoose (blue), and Gradient (yellow) working points as a function of electron E_T . The bottom panel shows data-to-simulation ratios. Plot taken from [53].

1098 3.2.4.3 Muon reconstruction

1099 Muon reconstruction [60, 61] occurs independently in the ID and the MS, and then the informa-
 1100 tion from both is combined to form the final muon tracks used in analysis. Muons in the ID are
 1101 reconstructed as a charged particle track following the standard procedure detailed in Section 3.2.4.1.

1102 In the MS, hits within each muon chamber are collected into segments, with separate algorithms
 1103 for each of the four different detector components (see Section 3.2.3). Muon track candidates are
 1104 then built by fitting together segments using a combinatorial search seeded by segments in the
 1105 middle layers first, and then expanding to the outer and inner layers. A track must contain at least
 1106 two matching segments, except in the transition region between the barrel and endcap where a single
 1107 segment can be used. In the event that a segment is shared by multiple tracks, an overlap removal

1108 algorithm decides which track should keep the segment, or if it should remain shared. Finally, the
 1109 hits within each track candidate are fitted using a global χ^2 fit, and the track is accepted if the χ^2
 1110 satisfies a set of selection criteria.

1111 The ID and MS tracks are then combined according to several different reconstruction criteria
 1112 determined by the available information from the ID, MS, and calorimeters. This results in four
 1113 different muon “types”:

- 1114 • Combined (CB): Independent tracks in the ID and MS are combined with a global track refit
 1115 using both sets of hits. MS hits may be added or removed if it improves the quality of the
 1116 track fit. Muons are typically reconstructed outside-in, matching a MS track to one in the ID;
 1117 however, an inside-out matching is also used as a complementary approach.
- 1118 • Segment-tagged (ST): An ID track is classified as a muon if it can be extrapolated to at least
 1119 one track segment in the MDT or CSC chambers. These are used when a muon only crosses
 1120 one layer of the MS, either due to low p_T or falling in a region of reduced acceptance.
- 1121 • Calorimeter-tagged (CT): An ID track is classified as a muon if it can be matched to a calorimeter
 1122 energy deposit compatible with a minimum ionizing particle. These muons are generally
 1123 lower in purity than the other types, but they are useful for recovering acceptance in the region
 1124 $|\eta| < 0.1$ where the MS is only partially instrumented.
- 1125 • Extrapolated (ME): The muon is reconstructed using a MS track that is loosely compatible
 1126 with having originated from the interaction point. The MS track must transverse at least
 1127 two layers of the MS in the central region and three in the forward region. These muons are
 1128 generally used to extend the acceptance of muon reconstruction in the forward regions not
 1129 covered by the ID ($2.5 < |\eta| < 2.7$).

1130 **Muon identification** Muon identification serves to select signal muons with a high quality mo-
 1131 mentum measurement from backgrounds (mainly from pions and kaons). For CB muons, three
 1132 variables are used:

- 1133 • q/p significance: The absolute value of the difference the q/p of the muons (where q is the
 1134 muon’s charge) as measured by the ID and the MS divided by the corresponding uncertainties
 1135 added in quadrature.
- 1136 • ρ' : The absolute value of the difference between the p_T measurements in the ID and the MS
 1137 divided by the p_T of the combined track.

- 1138 • The normalized χ^2 of the combined track fit.
- 1139 Additional requirements are imposed on the number of hits within the ID to ensure the tracks'
- 1140 momenta are well measured.
- 1141 There are three primary muon identification working points⁶ of increasing background rejection:
- 1142 **Loose**, **Medium**, and **Tight**. **Loose** muons include all four types listed above, but CT and ST muons
- 1143 are restricted to the region $|\eta| < 0.1$. The default recommendation for analysis are **Medium** muons,
- 1144 which only include CB and ME tracks. Finally, **Tight** muons are made up of CB muons with hits in
- 1145 at least two components of the MS and that pass the **Medium** requirements. Each successive working
- 1146 point is a subset of the previous one, and the cuts on the three variables listed above are tightened
- 1147 in each step. The muon reconstruction efficiency for each of these three working points in $Z \rightarrow \mu\mu$
- 1148 events is shown in Figure 3.11.

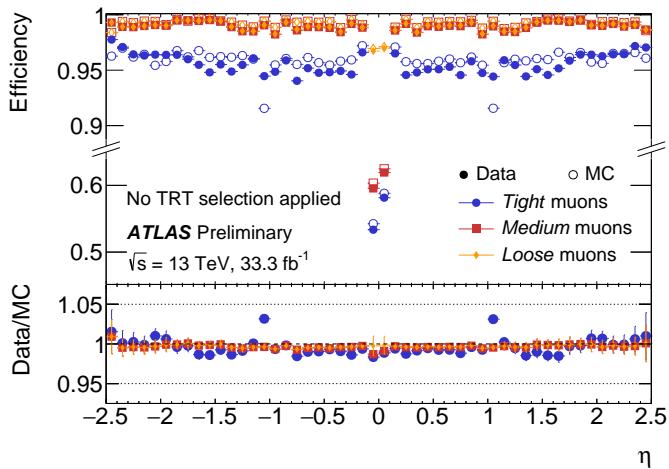


Figure 3.11: Muon reconstruction efficiencies in $Z \rightarrow \mu\mu$ events for the **Loose** (yellow), **Medium** (red), and **Tight** (blue) ID working points as a function of muon η . Collision data (solid points) is compared to simulation (open points) and the ratio is in the lower panel. Plot taken from [62].

- 1149 **Muon isolation** Isolation for muons is handled in much the same way as for electrons (see Sec-
- 1150 tion 3.2.4.2). A track-based variable is computed by summing the transverse momenta of tracks with
- 1151 $p_T > 1$ GeV within a cone of variable radius as in Equation 3.6 with $R_{\max} = 0.3$. The calorimeter-
- 1152 based isolation again uses topo clusters of radius $\Delta R < 0.2$ with the energy deposit corresponding
- 1153 to the muon removed. Similar isolation working points are constructed using the same criteria as

⁶A fourth working point, **High p_T** , is optimized for high mass searches, such as W' and Z' resonances, and is not covered here.

for electrons, and the efficiency of the `Loose` and `GradientLoose` working points as a function of muon p_T are shown in Figure 3.12.

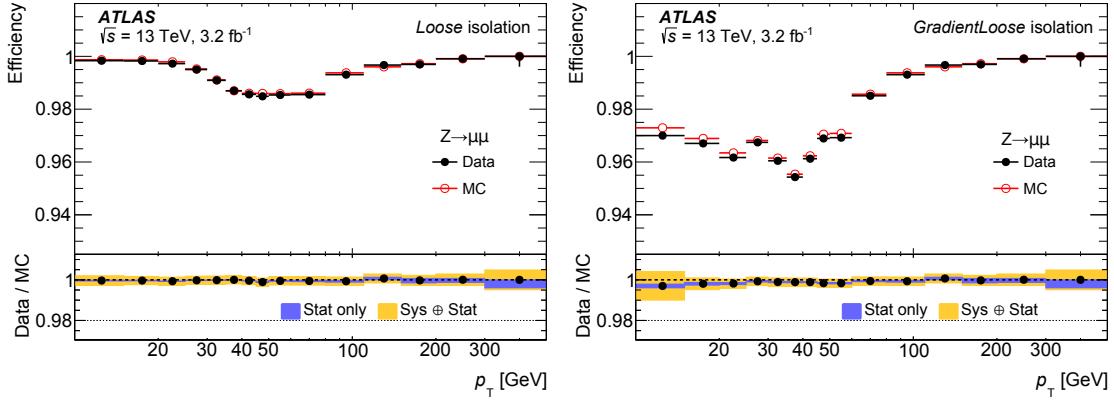


Figure 3.12: Muon isolation efficiencies in $Z \rightarrow \mu\mu$ events for the `Loose` (left) and `GradientLoose` (right) working points as a function of muon p_T . Collision data (black) is compared to simulation (red) and the ratio is in the lower panel. Plots taken from [61].

CHAPTER 4

Alignment of the ATLAS Inner Detector

When a charged particle passes through the ATLAS ID, it leaves hits in the sensors along its path. In order to accurately measure the track of the particle, it is necessary to know where these hits occurred as precisely as possible, which in turn requires knowledge of the physical location of the sensor that registered the hit. If one of these sensors is displaced relative to its expected position in the known detector geometry, or *misaligned*, the assumed location of the corresponding hit will not match its actual location, resulting in an incorrect track fit. These misalignments can occur for any number of reasons, including but not limited to elements shifting during maintenance periods or cycles in ATLAS's magnetic field, or small movements during normal detector operations. The effect of a misaligned detector element on the track reconstruction is shown in Figure 4.1.

In order to correct the misalignments, the ID alignment procedure is applied to accurately determine the physical position and orientation of each detector element. The baseline accuracy of the alignment is required to be such that the track parameter resolutions are not degraded by more than 20% with respect to those derived from a perfect detector geometry⁷. This corresponds to a precision of better than $10\mu\text{m}$ in the positioning of the elements of the silicon detectors [63].

This chapter outlines the ID alignment procedure, the alignment of the detector during the 2015 data taking period, and the steps taken to measure momentum biases in the alignment.

⁷The so-called *perfect geometry* refers to the description of the ATLAS detector in which every sensor precisely matches its design specifications. The perfect geometry contains no misalignments, and the position of each sensor is known exactly.

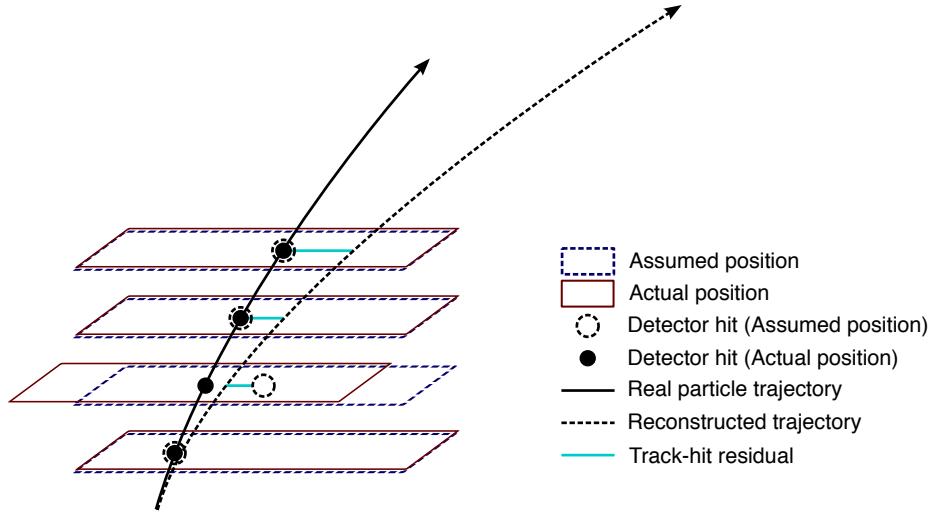


Figure 4.1: Graphical representation of the effect of a misaligned detector element. The reconstructed particle track (dashed arrow) differs from the actual trajectory of the particle (solid arrow) due to the shift in one of the detector elements. The cyan lines represent the track-to-hit residuals.

1174 4.1 The alignment method

1175 The alignment procedure uses a track-based algorithm that updates the locations of detector ele-
 1176 ments in order to minimize the set of track-hit *residuals*. These residuals are defined as the distance
 1177 between the fitted track position in a given detector element to the position of the hit recorded by
 1178 the same element, and are shown by the cyan lines in Figure 4.1.

1179 Tracks in ATLAS are parameterized as five-dimensional vectors [64]:

$$\vec{\tau} = (d_0, z_0, \phi_0, \theta, q/p) \quad (4.1)$$

1180 where d_0 and z_0 are the transverse and longitudinal impact parameters with respect to the origin,
 1181 ϕ_0 is the azimuthal angle of the track at the point of closest approach to the origin, θ is the polar
 1182 angle, and q/p is the charge of the track divided by its momentum. The residual for the i^{th} hit of a
 1183 given track can then be written in terms of the track parameters $\vec{\tau}$ and a set of alignment parameters
 1184 \vec{a} that describe the hit location [65]:

$$r_i(\vec{\tau}, \vec{a}) = (\vec{m}_i - \vec{e}_i(\vec{\tau}, \vec{a})) \cdot \hat{k} \quad (4.2)$$

1185 where \vec{e}_i is the intersection point of the extrapolated track with the sensor, \vec{m}_i is the position of the
 1186 associated hit within the sensor, and \hat{k} is the unit vector defining the direction of the measurement
 1187 within the sensor. \vec{r} then represents the vector of residuals for the given track.

1188 A χ^2 function can be built from the residuals of all collected tracks:

$$\chi^2 = \sum_{\text{tracks}} \vec{r}^T V^{-1} \vec{r} \quad (4.3)$$

1189 where V is the covariance matrix of the hit measurements. The χ^2 function is then minimized with
 1190 respect to the alignment parameters \vec{a} , which contain all degrees of freedom being aligned. The
 1191 minimization condition with respect to \vec{a} is:

$$\frac{d\chi^2}{d\vec{a}} = 0 \rightarrow 2 \sum_{\text{tracks}} \left(\frac{d\vec{r}}{d\vec{a}} \right)^T V^{-1} \vec{r} = 0 \quad (4.4)$$

1192 This equation can be difficult to solve exactly, so the residual is rewritten as a first order Taylor
 1193 expansion:

$$\vec{r} = \vec{r}_0 + \frac{d\vec{r}}{d\vec{a}} \delta\vec{a} \quad (4.5)$$

1194 where \vec{r}_0 is dependent on an initial set of track and alignment parameters \vec{r}_0 and \vec{a}_0 , respectively;
 1195 the track parameter dependence has also been folded into the total derivative $\frac{d\vec{r}}{d\vec{a}}$. Equation 4.5 can
 1196 then be inserted into the minimization condition from Equation 4.4 to give:

$$\left[\sum_{\text{tracks}} \left(\frac{d\vec{r}}{d\vec{a}} \right)^T V^{-1} \left(\frac{d\vec{r}}{d\vec{a}} \right) \right] \delta\vec{a} + \sum_{\text{tracks}} \left(\frac{d\vec{r}}{d\vec{a}} \right)^T V^{-1} \vec{r}_0 = 0 \quad (4.6)$$

1197 From this equation, the alignment matrix \mathcal{M}_a and alignment vector $\vec{\nu}_a$ can be defined:

$$\mathcal{M}_a = \sum_{\text{tracks}} \left(\frac{d\vec{r}}{d\vec{a}} \right)^T V^{-1} \left(\frac{d\vec{r}}{d\vec{a}} \right) \quad (4.7)$$

1198

$$\vec{\nu}_a = \sum_{\text{tracks}} \left(\frac{d\vec{r}}{d\vec{a}} \right)^T V^{-1} \vec{r}_0 \quad (4.8)$$

1199 Finally, the alignment corrections $\delta\vec{a}$ can be solved for by inverting the alignment matrix:

$$\delta\vec{a} = -\mathcal{M}_a^{-1} \vec{\nu}_a \quad (4.9)$$

1200 which is a linear system of equations with a number of equations equal to the number of alignment
 1201 degrees of freedom [66].

1202 Inverting the full matrix and solving the resulting system of equations is referred to as *Global*
 1203 χ^2 alignment [65]. This can be useful, as \mathcal{M}_a contains all the correlations between the alignable
 1204 structures. However, inverting the matrix is difficult when the number of degrees of freedom becomes
 1205 large—as the number of alignable structures increases, so too does the size of the matrix \mathcal{M}_a .
 1206 Eventually inverting the matrix becomes too computationally intensive to be practical.

1207 This problem is solved by the *Local* χ^2 algorithm [67]. In this case, the alignment matrix is
 1208 constructed to be block-diagonal, allowing for it to be inverted even for large numbers of degrees of
 1209 freedom. This is achieved by replacing the full derivative in Equation 4.6 with the partial derivative
 1210 $\frac{\partial \vec{r}}{\partial \vec{a}}$. The new alignment matrix \mathcal{M}'_a and alignment vector $\vec{\nu}'_a$ become:

$$\mathcal{M}_a = \sum_{\text{tracks}} \left(\frac{\partial \vec{r}}{\partial \vec{a}} \right)^T V^{-1} \left(\frac{\partial \vec{r}}{\partial \vec{a}} \right) \quad (4.10)$$

$$\vec{\nu}_a = \sum_{\text{tracks}} \left(\frac{\partial \vec{r}}{\partial \vec{a}} \right)^T V^{-1} \vec{r}_0 \quad (4.11)$$

1211 1212 Inverting \mathcal{M}'_a is considerably faster and less memory intensive even for large numbers of degrees of
 1213 freedom; however, the correlations between the alignable structures is lost.

1214 Due to the Taylor expansion used in Equation 4.6, several iterations of the alignment algorithm
 1215 may be necessary to converge on a final set of alignment constants. The Local χ^2 alignment typically
 1216 requires more iterations due to the loss of the correlation information [68]. In practice, the ATLAS
 1217 reconstruction is run over a set of events, and the resulting tracks are fed to the alignment algorithm.
 1218 The residuals are calculated, the alignment matrix is built and inverted, and a new set of alignment
 1219 constants is obtained. The convergence is checked in two ways:

1220 1. Measuring the $\Delta\chi^2$ with respect to the previous iteration. If it is near zero, then the χ^2 is
 1221 approaching its minimum.

1222 2. Looking at the residual distributions for different alignable structures. A well aligned detector
 1223 will have a mean residual of zero with a width approximating the intrinsic resolution of the
 1224 detector.

1225 If the above checks are satisfied, the process is finished and the final alignment constants are read
 1226 out; if not, another iteration is performed. A visual representation of the alignment chain is shown
 1227 in Figure 4.2.

1228 Since a χ^2 minimization is used to align the detector, if there is a systematic misalignments in
 1229 the detector that does not adversely affect the χ^2 , the algorithm will be insensitive to it. These
 1230 misalignments are referred to as *weak modes*, and special care is taken to remove them [69]. One
 1231 potential impact of weak modes is a bias in the track momentum of reconstructed particles. This
 1232 particular effect is the subject of Section 4.4.

1233 The detector is aligned both in “real-time” as data is collected and during dedicated offline
 1234 alignment campaigns. The real-time alignment is run in ATLAS’s *calibration loop*, which comprises

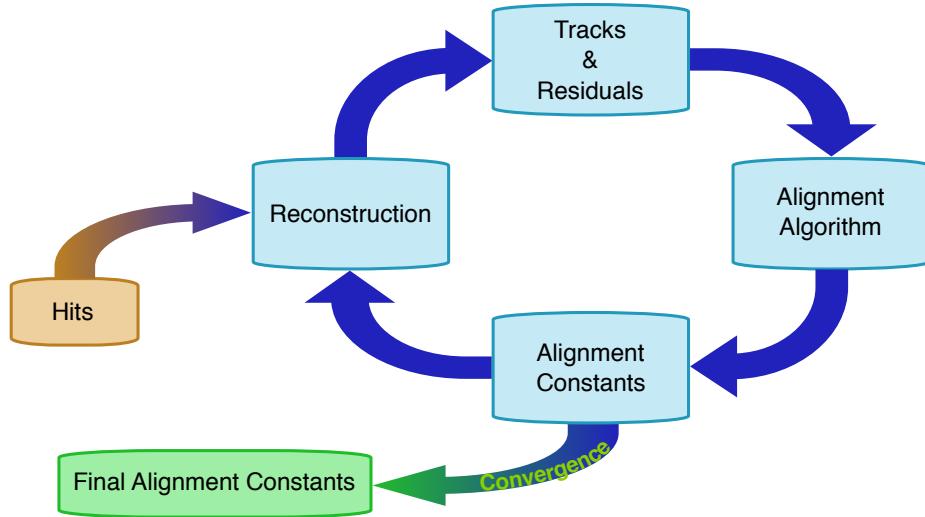


Figure 4.2: Graphical representation of the ID alignment chain.

1235 the first stage in the preparation of data for physics analysis. The calibration loop requires the
 1236 alignment—as well as various other detector calibrations—to be available within 48 hours for initial
 1237 data processing. A fast, coarse-grained alignment⁸ is run on a subset of the available data containing
 1238 full tracking information, and the results are propagated to the reconstruction of that particular
 1239 run [70]. Due to the time constraints of the calibration loop, a full sensor-by-sensor alignment is not
 1240 possible.

1241 The more thorough and finely tuned alignments are reserved for the dedicated alignment cam-
 1242 paigns. These generally occur early in data taking campaigns, typically once a sufficient amount
 1243 of data is collected after a detector shutdown, in order to obtain a good baseline alignment for
 1244 use in the remainder of the data collection period. One such alignment campaign, the initial offline
 1245 alignment of the ATLAS detector at the beginning of Run 2, is the subject of Section 4.2. Once data
 1246 taking is complete, another set of alignment constants is derived for the full set of available data,
 1247 and it is typically divided into several “blocks” to account for potential run-by-run misalignments.
 1248 The data is then reprocessed using the newly derived detector geometry.

1249 4.1.1 Alignment levels

1250 The alignment of the detector is performed at several levels of increasing granularity. This adds
 1251 flexibility in being able to align only as finely as needed, and it also allows for global, detector-level

⁸The calibration loop runs up to a Level 2 alignment in the silicon detectors, which involves treating each layer of sensors as a single object. The alignment levels are defined in greater detail in Table 4.1.

misalignments to be corrected first before dealing with finer adjustments.

- Level 1 (L1) alignment involves moving entire subdetector components as a single unit, such as the entire Pixel detector, or the SCT barrel. These often have the largest misalignments, but they are easily corrected and do not require large volumes of data to do so.
- Level 2 (L2) alignment treats individual layers in the silicon detectors (modules in the TRT) and end cap disks as individual alignable objects.
- Level 2.7 (L27) alignment was introduced with the addition of the IBL to the ID in Run 2. It involves the stave-by-stave alignment of the IBL and Pixel barrel⁹.
- Level 3 (L3) alignment treats each sensor in the silicon detectors and each straw in the TRT as an individual alignable object. It is the finest grained alignment available but also the most computationally intensive due to the large number of degrees of freedom. The large number of individual detector sensors being aligned also requires the largest amount of statistics.

The different alignment levels are listed in more detail in Table 4.1, including the number of alignable structures and associated degrees of freedom for each detector component.

The implementation of the alignment algorithm in the software is flexible enough to allow each subsystem to be aligned individually at a specified level. Each alignable structure has six degrees of freedom: 3 translations (T_x, T_y, T_z) and 3 rotations (R_x, R_y, R_z)¹⁰; however individual degrees of freedom may be turned on and off as required. In a typical alignment job, L1 and L2 contain few enough degrees of freedom that the Global χ^2 algorithm can be used, but L3 alignments (which can contain over 36,000 degrees of freedom in the silicon detectors alone) require the Local χ^2 algorithm.

4.1.2 Alignment coordinate systems

The global coordinate system (x, y, z) used by the ID alignment matches that of the ATLAS detector in general. The positions and orientations of individual detector modules of the ID are defined by a right-handed local coordinate system (x', y', z') where the origin is defined as the geometrical center of the module. The x' -axis for each silicon module is defined to point along the most sensitive direction of the module, the y' -axis is oriented along the long side of the module, and the z' -axis is

⁹For the purposes of this Chapter, the term “Pixel” will refer to the original three layers of the Pixel detector, and the IBL will be referenced separately.

¹⁰The TRT is an exception, as the subdetector does not have any resolution along the length of the straw. Therefore, for the barrel, T_z is omitted. Similarly for the straws themselves, only two parameters are defined: translation with respect to the radial direction (T_ϕ) and rotation with respect to the radial axis (R_r for the barrel and R_z for the end-caps) [71].

Level	Description of alignable structure	Structures	DoF
1	IBL detector	1	6
	Whole Pixel detector	1	6
	SCT barrel and 2 end-caps	3	18
	TRT barrel and 2 end-caps (T_z fixed)	3	17
Total:		8	47
2	IBL detector	1	6
	Pixel barrel layers	3	18
	Pixel end-cap disks	2×3	36
	SCT barrel layers	4	24
	SCT end-cap disks	2×9	108
	TRT barrel 32 modules (T_z fixed)	3×32	480
	TRT end-cap wheels	2×40	480
Total:		208	792
2.7	IBL staves	14	84
	Pixel barrel staves	$22+38+52$	672
	Pixel end-cap disks	2×3	18
	Total:		132
3	IBL modules	280	1,680
	Pixel modules	1,744	10,464
	SCT modules	4,088	24,528
	TRT barrel wires (T_ϕ, R_r only)	105,088	210,176
	TRT end-cap wires (T_ϕ, R_Z only)	245,760	491,520
	Total silicon sensors:		6,112
	Total TRT wires:		350,848
36,672		701,696	

Table 4.1: The four alignment levels for each of the detector subsystems. The total number of alignable structures and degrees of freedom (DoF) to be aligned are given for each level.

1278 orthogonal to the (x', y') plane. For the TRT straws, the x' -axis is perpendicular to both the wire
 1279 and the radial direction, defined from the origin of the global frame to the straw center, the y' -axis
 1280 points along the straw, and once again the z' -axis is orthogonal to the (x', y') plane. A depiction of
 1281 the global and local coordinate systems for the ID is shown in Figure 4.3.

1282 When considering the alignment degrees of freedom listed earlier in Section 4.1.1, grouped collections
 1283 of modules, layers, or entire subdetectors use the global coordinate system; individual modules
 1284 use their respective local coordinate systems. The translations T_i are with respect to the origin of
 1285 the given reference frame, and the rotations R_i are taken about the Cartesian axes.

1286 4.2 Early 2015 alignment of the ATLAS detector

1287 At the end of Run 1, the LHC was shut down for upgrades and maintenance. During this time,
 1288 a number of upgrades were performed on the ATLAS detector, including the installation of a new

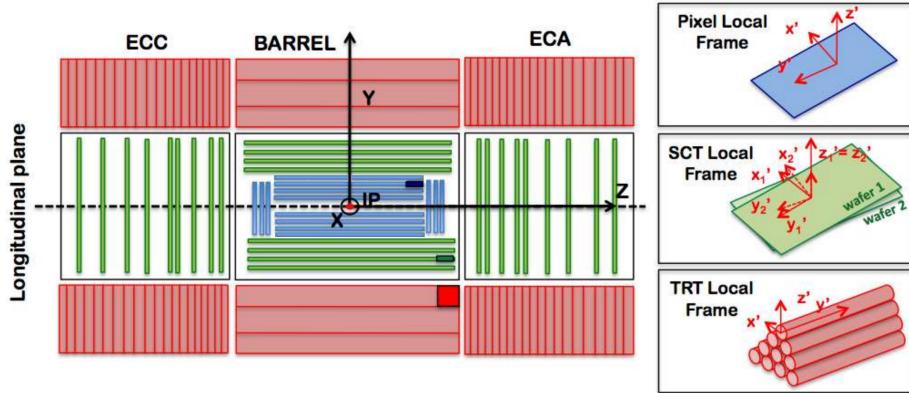


Figure 4.3: A schematic representation of the Inner Detector in the longitudinal plane with the global coordinate system overlaid on top. The Pixel detector and IBL are shown in blue, the SCT in green, and the TRT in red. The local coordinates for each subdetector module are inset on the right. Image taken from [72].

1289 innermost layer of the Pixel detector, the Insertable B-Layer (IBL). These changes to the ID required
 1290 some detector components to be removed temporarily, and many elements shifted relative to each
 1291 other over the course of the maintenance process. In order to correct for these large detector
 1292 movements prior to $\sqrt{s} = 13$ TeV collision data taking, an alignment was performed using cosmic
 1293 ray data collected in early 2015 [72]. This alignment was able to correct for the majority of the large
 1294 detector-wide misalignments as well as determine the global position of the IBL at the micron level.

1295 In June of 2015, shortly after the data taking period began, the first track-based alignment of
 1296 the refurbished ID was performed using the initial 7.9 pb^{-1} of $\sqrt{s} = 13$ TeV pp collision data [73].
 1297 Starting from the geometry determined by the cosmic ray alignment, referred to hereafter as the
 1298 *March alignment*, an improved set of alignment constants (the *June alignment*) was derived from
 1299 a data set of approximately 1.4 million selected tracks. For comparison, a MC sample containing
 1300 approximately 2.7 million tracks was constructed from dijet events simulated using a perfect detector
 1301 geometry; the MC events are reweighted to match the η and p_T distributions found in the data.
 1302 Additional validation of the alignment results uses a set of cosmic ray data collected by the detector
 1303 during the LHC collisions.

1304 4.2.1 June alignment procedure

1305 The data set used as the input for the alignment contains a subset of physics events used for prompt
 1306 reconstruction recorded at a rate of 10 Hz. To ensure that only high quality tracks are used for the

1307 alignment, each track is required to have transverse momentum $p_T > 3$ GeV, contain at least one
1308 hit in the Pixel detector, at least seven hits in the combined silicon detectors, and at least 25 hits
1309 in the TRT.

1310 A full L3 alignment of the IBL was included in the March alignment; however, a realignment was
1311 still necessary. Since cosmic rays used in the March alignment pass through the detector top-down,
1312 the staves on the sides of the IBL recorded fewer hits and thus could not be aligned as precisely
1313 as those on the top and bottom. Additionally, the IBL was operating at a temperature of -20°C
1314 during the cosmic data taking, and it was set to -10°C for collision data taking. This proved to be
1315 significant, as it was observed that the IBL staves experience a temperature-dependent, parabolic
1316 bowing in the local x' -direction of approximately $-10\mu\text{m}/\text{K}$ [74]. As a result, a full L3 alignment
1317 of the IBL was essential in order to correct for the bowing. Due to it being a brand new element of
1318 the detector as well as its importance in vertexing and b jet tagging, aligning the IBL sensors with
1319 a high degree of precision was one of the main goals of the June alignment.

1320 The June alignment was performed in two stages, with the first pass focusing on relative move-
1321 ments of the big structures and correcting for the bowing of the IBL. The March alignment corrected
1322 for these larger movements as well; however, it was observed during Run 1 that these sort of mis-
1323 alignments are introduced by changing conditions in the detector [69], such as in the cooling system
1324 or magnet power cycling, which may have occurred between the early cosmic data taking and the
1325 first $\sqrt{s} = 13$ TeV collisions. The silicon detectors were aligned at several different levels and the
1326 IBL was aligned at the module level; the TRT detector was kept fixed to act as a global reference
1327 frame. The full alignment chain for the first pass consisted of the following steps:

- 1328 1. The IBL, Pixel, and SCT detectors were aligned at L1. The SCT barrel was not aligned in
1329 T_z in order to constrain global displacements along the z -axis, as the TRT is not sensitive to
1330 that degree of freedom.
- 1331 2. The IBL, and Pixel barrel and end-caps, and SCT barrel were aligned at L2. The SCT end-caps
1332 were aligned at L1.
- 1333 3. The IBL and pixel barrel were aligned at L27, using all six degrees of freedom. The Pixel
1334 end-cap disks were only aligned in the plane (T_x , T_y , and R_z). The SCT was treated the same
1335 as in the previous step.
- 1336 4. The IBL was aligned at L3 using all six degrees of freedom for each module.

1337 The primary goal for the second pass was to remove a bias in the transverse impact parameter
 1338 d_0 found in the March alignment. In addition to the bias, the resolution of d_0 was also poorer
 1339 than expected. In order to correct for this, an additional constraint was passed to the alignment
 1340 which added the impact parameter with respect to the beam spot as a pseudo-measurement [75].
 1341 With this setup, when the alignment algorithm minimizes the χ^2 , it will take care of the impact
 1342 parameter minimization as well. Only the IBL and Pixel detectors were aligned in the second pass.
 1343 The different alignment stages are listed below, with the beam spot constraint being used in each:

- 1344 1. The IBL and Pixel detectors were aligned at L2 with the SCT fixed.
 1345 2. The IBL was aligned at L27
 1346 3. The IBL and Pixel barrel and end-caps were aligned at L3.

1347 The set of alignment constants obtained at the end of the second pass represents the June alignment.
 1348 The highest level of alignment each subdetector received over the course of the two passes is listed
 1349 in Table 4.2.

Detector	Highest level of alignment
IBL	L3
Pixel	Barrel
	End-caps
SCT	Barrel
	End-caps
TRT	None

Table 4.2: Summary of the highest level of alignment applied to each ID subsystem when deriving the June alignment.

1350 4.2.2 Alignment results

1351 Alignment quality is primarily assessed by looking at the track-hit residual distributions. If the
 1352 detector is well aligned, the residuals will be Gaussian-distributed with a mean of zero and a width
 1353 approximating the detector's resolution. The residual distributions are constructed from the same
 1354 selection of tracks that were used to perform the alignment, and are the focus of Section 4.2.2.1.
 1355 A second check on the alignment involves observables sensitive to the track parameter resolution.
 1356 In this case, cosmic rays are used, making use of a “split track” technique that takes advantage of
 1357 the top-to-bottom cosmic ray trajectory (compared to the center-out trajectory of collision tracks).
 1358 This method and the corresponding tests of the alignment are detailed in Section 4.2.2.2

1359 Additionally, the effect of the beam spot constrained alignment on the impact parameter d_0
 1360 needs to be checked. The d_0 distributions for both the March and June alignments are compared to
 1361 the MC simulation using a perfect geometry in Figure 4.4. In the March alignment, there is a bias
 1362 of $18 \mu\text{m}$ in the mean of the distribution and the width is nearly twice that of the perfect geometry.
 1363 After the second pass of the June alignment, the mean has shifted to $1 \mu\text{m}$ and the distribution has
 1364 narrowed considerably. From this, it appears that the constrained alignment successfully removed
 1365 the d_0 bias.

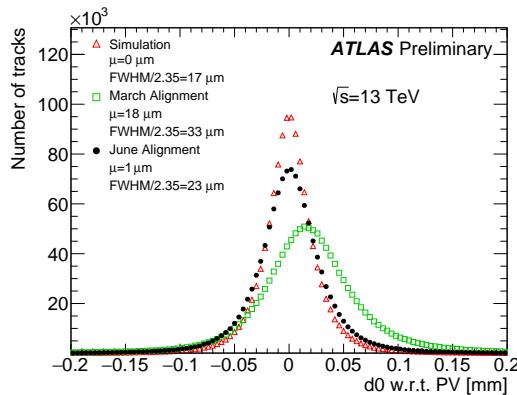


Figure 4.4: The d_0 distributions with respect to the reconstructed primary vertex using the $\sqrt{s} = 13 \text{ TeV}$ collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.

1366 4.2.2.1 Residual distributions from collisions

1367 As mentioned previously, the primary focus of the June alignment campaign was on the IBL and the
 1368 Pixel detectors. These subdetectors are the closest to the beam line and have the finest resolutions
 1369 within the ID. The residual distributions in local x and y of the IBL planar sensors¹¹ are shown in
 1370 Figure 4.5. These and subsequent figures in this section compare the June and March alignments
 1371 to the perfectly-aligned MC simulation. Noticeable improvement in the distribution widths can be
 1372 seen in both the local x - and y -directions, nearly matching the simulation in local x , which is the
 1373 most sensitive direction.

1374 Due to the temperature-dependent bowing of the IBL, it is also interesting to look at the means of
 1375 the residual distributions for each ring of IBL sensors along the beam line, as shown in Figure 4.6. A

¹¹The IBL contains 12 planar sensors in the center of a stave, with four 3D sensors on either end. Only the planar sensors are shown here due to low statistics in the 3D sensors as well as poor MC modeling of these sensors.

deformation is clearly visible in the March alignment in both measurement directions, and the shape in the local x -direction is consistent with an average stave bowing due to the different operating temperature of the IBL during the March alignment and the 13 TeV collisions. This feature was nearly eliminated in both directions through the L3 alignment of the IBL sensors.

The local x and y residual distributions for the Pixel detector barrel and end-caps are shown in Figures 4.7 and 4.8. Even though the IBL is not included in the plots of the barrel, some of the noticeable improvement in the more sensitive local x direction is an effect of the improved IBL alignment. Similarly, the relatively broad local y residual distribution in the barrel likely indicates that further refinement of the IBL alignment was needed along that direction. Even so, the June alignment outperforms the March alignment and rivals the simulation in most of the plots.

Similar distributions for the SCT and TRT barrel and end-caps are shown in Figures 4.9 and 4.10, respectively. Much like with the Pixel residuals, there is a reduction in the width of the TRT residuals between the March and June alignments due to the alignment of the other subdetectors improving the quality of the track fit. Even though neither subdetector was aligned at module-level, the residuals indicate that the previous L3 alignment performed in Run 1 did not degrade significantly during the upgrade and maintenance period.

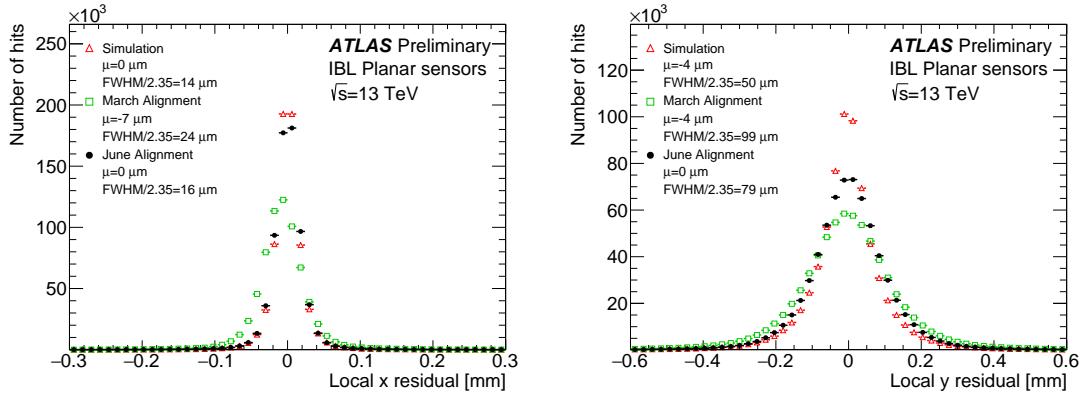


Figure 4.5: Local x (left) and local y (right) residual distributions of the IBL planar sensors using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.

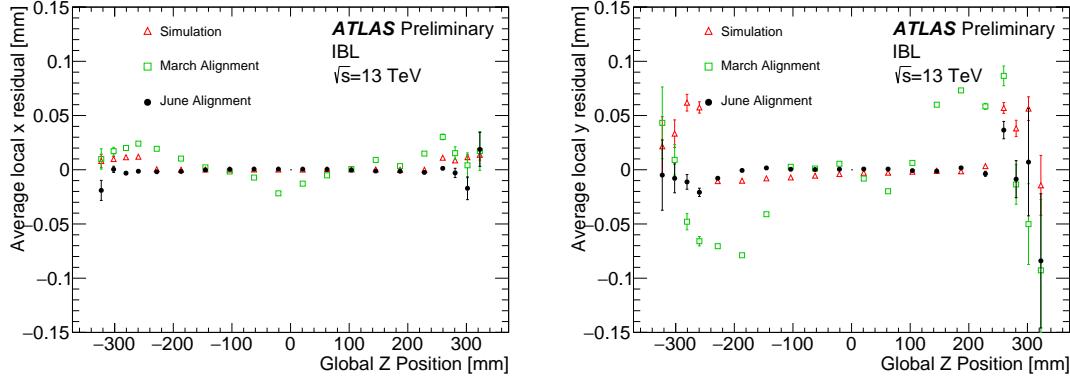


Figure 4.6: The mean of the local x (left) and local y (right) residual distributions as a function of the global z position of each IBL module using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red).

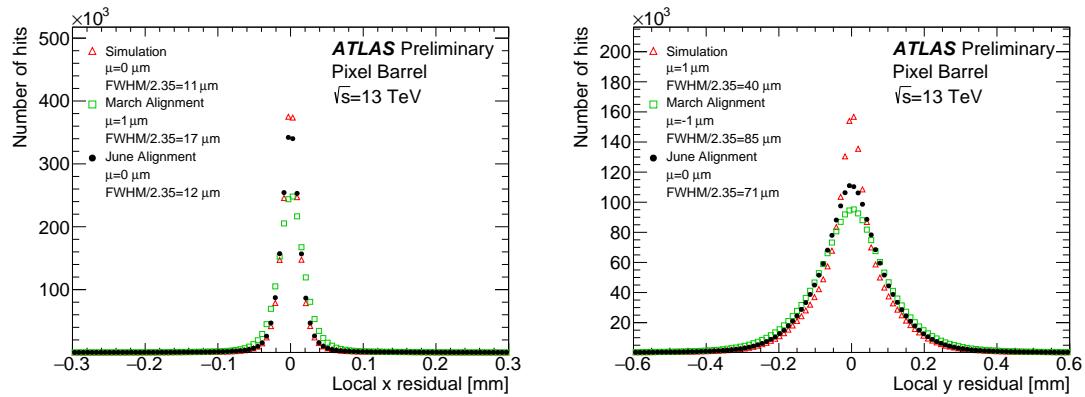


Figure 4.7: Local x (left) and local y (right) residual distributions for the Pixel barrel (excluding the IBL) using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.

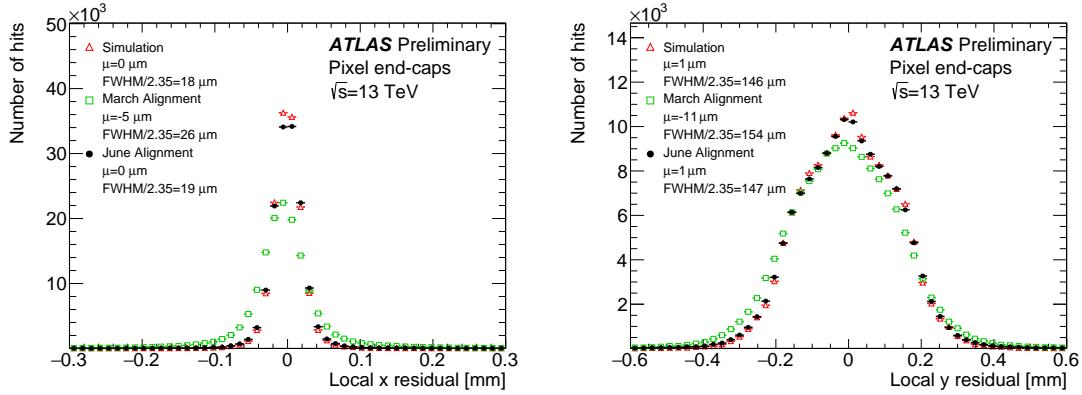


Figure 4.8: Local x (left) and local y (right) residual distributions for the Pixel end-caps using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.

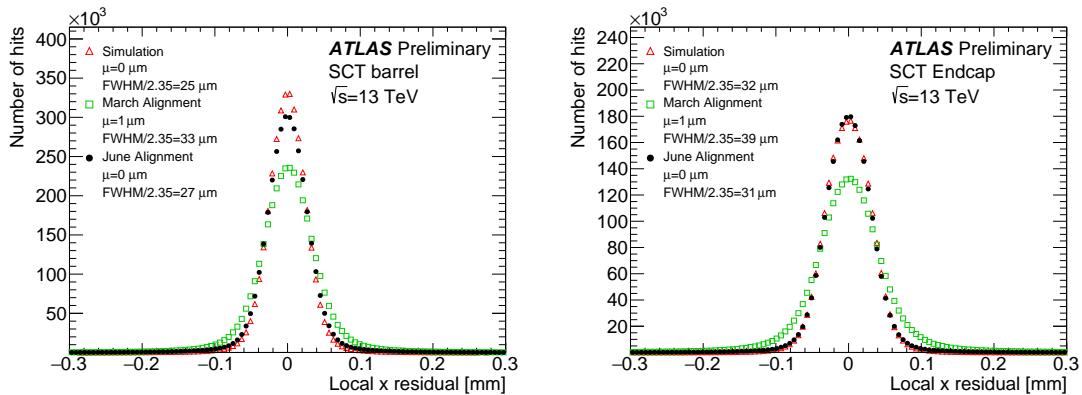


Figure 4.9: Local x residual distributions for the SCT barrel (left) and end-caps (right) using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.

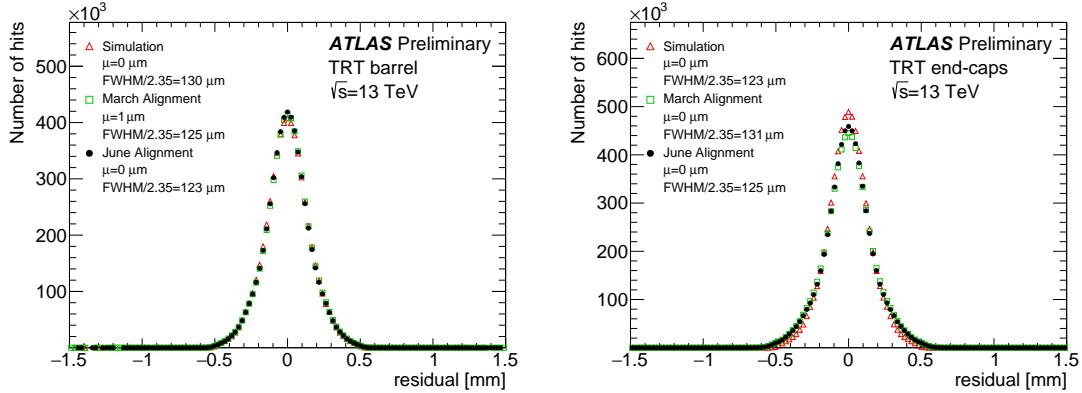


Figure 4.10: Residual distributions for the TRT barrel (left) and end-caps (right) using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.

1392 4.2.2.2 Track parameter resolution from cosmic rays

1393 Cosmic ray data is very useful as an independent check on the alignment in the barrel of the
 1394 detector. While tracks from $p\bar{p}$ collisions originate within the detector and travel outwards, a cosmic
 1395 ray that passes through the center of the detector leaves a track in both halves of the detector.
 1396 If the cosmic ray is split in half, as in Figure 4.11, then it can be treated as two separate tracks
 1397 each with nearly identical track parameters (some differences arise due to energy loss as the particle
 1398 passes through the detector). The distribution of the difference in a given track parameter $\Delta\tau$ is
 1399 approximately Gaussian with a variance $\sigma^2(\Delta\tau)$. Since both tracks come from the same particle,
 1400 each track individually has a variance equal to $\sigma^2(\Delta\tau)/2$. The resolution of the track parameter is
 1401 then given by the root mean square of the distribution divided by $\sqrt{2}$.

1402 Cosmic rays whose split tracks each had transverse momentum $p_T > 2$ GeV and at least one,
 1403 eight, and 25 hits in the barrels of the Pixel, SCT, and TRT detectors, respectively, were selected to
 1404 measure a collection of track parameters. Figure 4.12 shows the difference in the impact parameter
 1405 Δd_0 and the charge divided by the transverse momentum $\Delta q/p_T$ of the selected split-track cosmic
 1406 rays for both the March and June alignments. Both distributions show a reduction in width in the
 1407 June alignment, corresponding to an improvement in the resolution of each track parameter. The
 1408 Δd_0 plot shows a significant improvement in the June alignment, further validating the removal of
 1409 the bias in the impact parameter.

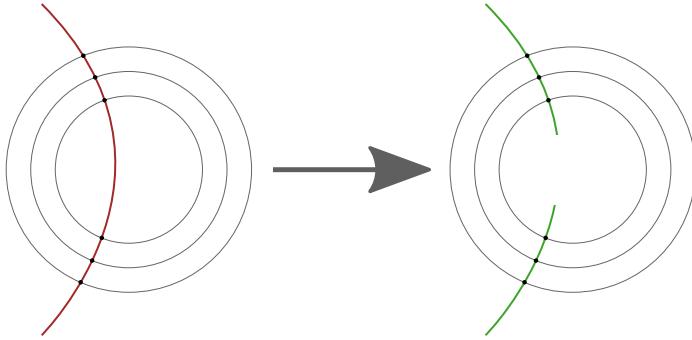


Figure 4.11: Representation of splitting a single cosmic ray track passing through the entire detector (left) into two separate tracks (right).

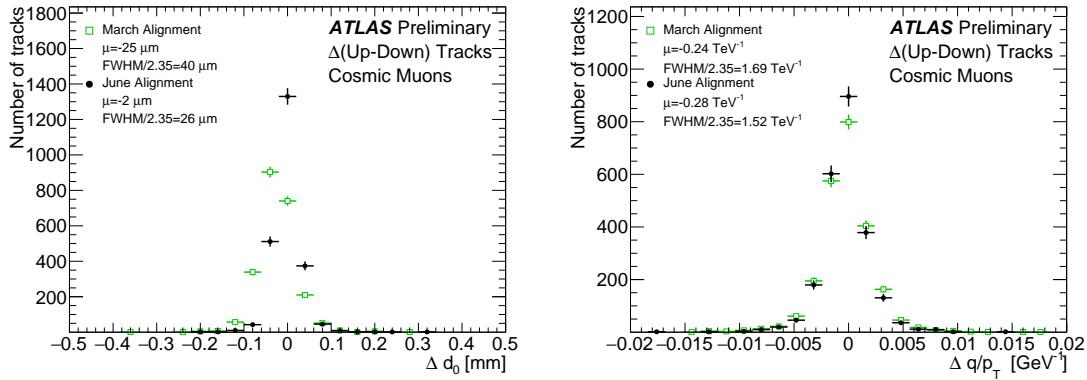


Figure 4.12: Distribution of the difference in the impact parameter Δd_0 (left) and charge over transverse momentum $\Delta q/p_T$ (right) between the two cosmic ray split tracks. The June (black) and March (green) alignments are compared. The distributions are normalized to the same number of entries.

1410 4.2.3 Error scaling

1411 The final step in preparing the new set of June alignment constants deals with the adjustment of
1412 the hit errors, or *error scaling*. Knowledge of the exact position of a hit measurement on a track
1413 is limited by the accuracy with which the sensors' positions are known. Let σ represent the hit
1414 uncertainty used in track fitting, and σ_0 be the detector's intrinsic uncertainty. If $\sigma = \sigma_0$, the pull
1415 of the track-hit residual distributions should form a Gaussian distribution centered at zero with unit
1416 width [66]. In the case of residual misalignment, the pull distributions' standard deviations will
1417 stray from unity. The hit uncertainty can be written as:

$$\sigma = a \cdot \sigma_0 \oplus b \quad (4.12)$$

where a is a scaling factor, and b is a constant term which can be interpreted as a measure of any remaining misalignment of the detector elements. In the June alignment campaign, the value of a was fixed at $a = 1$, and b was evaluated from the residual pull distributions for each subdetector in its sensitive directions.

Once the value of b is determined, pull distributions derived from the new value of σ should have unit width. The error scaling values for each subdetector are listed in Table 4.3, and the pull distributions for the IBL after error scaling are shown in Figure 4.13

Detector	Coordinate	$b(\mu\text{m})$
IBL	x	6.4
	y	43.6
Pixel	x	5.2
	y	28.6
End-caps	x	7.5
	y	0
SCT	Barrel	10.8
	End-caps	8.6
TRT	Barrel	0
	End-caps	0

Table 4.3: Estimated value of the error scaling term b for each subdetector component with the June alignment.

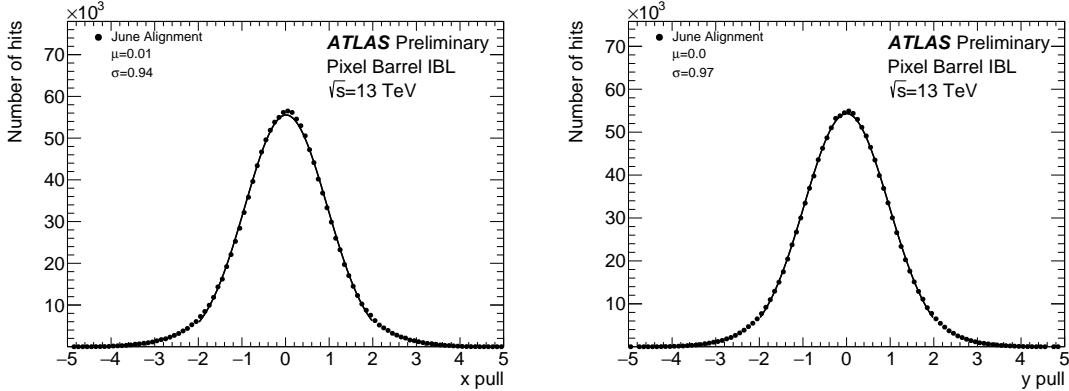


Figure 4.13: Pull distributions in local x (left) and y (right) for the IBL using the $\sqrt{s} = 13 \text{ TeV}$ collision data sample after applying the error scaling.

1425 **4.3 Level 2 alignment of the TRT**

1426 During validation of the final end-of-year reprocessing of the 2015 data, a misalignment was found in
 1427 the barrel of the TRT detector, as several modules (triangular clusters of straws) showed rotations
 1428 in the local y coordinate. The then-best available constants included a full L3 alignment of the
 1429 silicon detectors and a separate L2 alignment of the TRT. However, not all degrees of freedom were
 1430 enabled when the TRT was aligned. To correct for these tilts, an additional four iterations of L2
 1431 alignment was performed on the TRT enabling all available degrees of freedom (T_x , T_y , R_x , R_y , and
 1432 R_z in the barrel, and T_x , T_y , and R_z for the endcaps). Plots of the residual means from barrel ϕ
 1433 sectors containing modules affected by the tilt misalignment are shown in Figure 4.14 before and
 1434 after the L2 alignment.

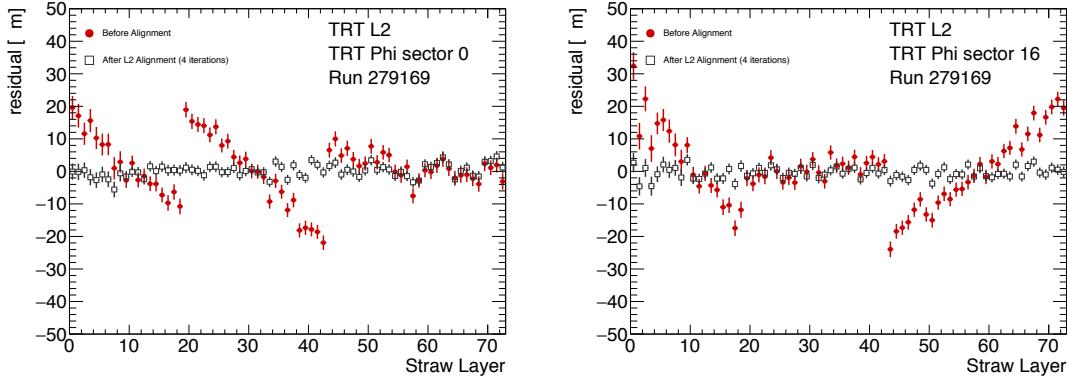


Figure 4.14: Residual means by straw layer in two TRT ϕ -sectors affected by a tilt misalignment. The tilts in each of the three modules are clearly visible in the red points representing the reconstructed data prior to alignment. After four iterations of L2 alignment, the residual means in the gray points are flat.

1435 Following the L2 alignment, some additional time was taken to determine if a full wire-by-wire
 1436 L3 alignment of the TRT was necessary. The TRT was last aligned at L3 during Run 1, but initial
 1437 alignment campaigns in Run 2 did not show signs of misalignment, as can be seen from the residual
 1438 distributions in Figure 4.10. In order to assess the alignment more carefully, two dimensional residual
 1439 maps in ϕ and z were constructed for each layer in the TRT barrel and endcaps using the current
 1440 alignment. These maps were compared to a similar set using the L3 alignment from 2010, from which
 1441 it was determined that the straw-level alignment indeed hadn't degraded and a new L3 alignment
 1442 was not needed. The maps for the first layer of the TRT barrel are shown in Figure 4.15 for both
 1443 sets of alignment constants.

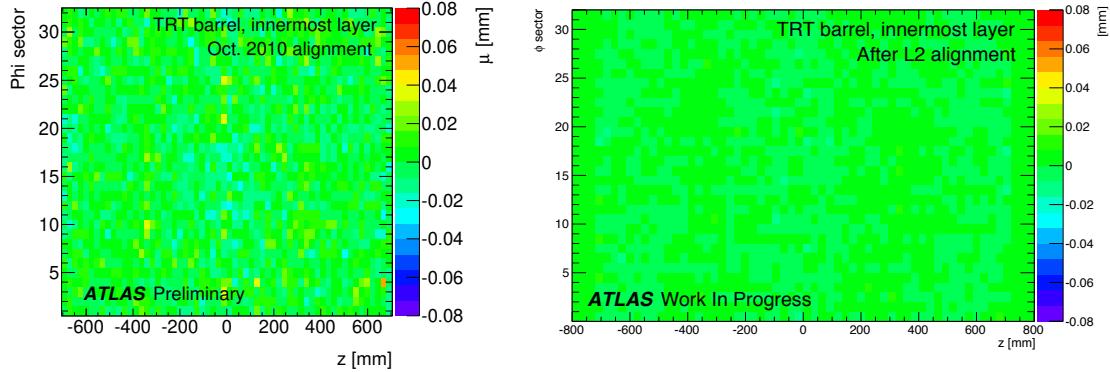


Figure 4.15: Two dimensional map of residuals in the first layer of the TRT barrel vs z and ϕ . Each bin represents the mean of a Gaussian fit to the TRT residuals in that bin. The map on the left is after the L3 (wire-by-wire) alignment of the TRT performed in 2010, and the map on the right is after the L2 alignment at the end of 2015. The z -axis for both plots use the same scale. Left figure taken from [66].

1444 4.4 Momentum bias from sagitta deformations

1445 A variety of weak mode deformations can exist in the detector even after alignment. As mentioned
 1446 previously, these weak modes consist of misalignments which don't affect the χ^2 of the residuals
 1447 and thus are not handled by the basic alignment algorithm. In the presence of a weak mode,
 1448 the description of the detector geometry can still provide efficient and high quality track fits, but
 1449 there may also be systematic biases in one or more track parameters. Several weak modes, their
 1450 impacts on the reconstruction, and the steps taken to eliminate them are detailed in [69, 76]. This
 1451 section focuses specifically on *sagitta* deformations that result in a bias in the reconstructed track
 1452 momentum.

1453 These sagitta distortions consist of detector movements orthogonal to the trajectory of the outgoing
 1454 particle. The effect on the reconstructed track curvature is different for positively and negatively
 1455 charged particles, resulting in a charge-antisymmetric bias. This effect is illustrated in the curl
 1456 deformation shown in Figure 4.16.

1457 In the plane transverse to ATLAS's magnetic field, outgoing particle tracks form circular arcs.
 1458 The sagitta is defined as the distance from the center of this arc to the center of its base, as shown in
 1459 Figure 4.17, and it represents the "amount of bending" in the track. In the case where the sagitta s
 1460 is considerably smaller than the detector radius R_0 , which is a valid assumption when working with

1461 high momentum tracks, the transverse momentum of a particle of charge q can be written as [77]:

$$p_T \propto qB \frac{R_0^2}{8s} \quad (4.13)$$

1462 where B is the strength of the detector's magnetic field. If a sagitta bias is present, the track's
1463 transverse momentum shifts by [76]:

$$q/p_T \rightarrow q/p_T + \delta_s \quad \text{or} \quad p_T \rightarrow p_T \cdot (1 + qp_T\delta_s)^{-1} \quad (4.14)$$

1464 where δ_s is a universal bias parameter that uniquely defines the deformation. Finally, since the
1465 reconstructed polar angle does not change under a sagitta deformation, the longitudinal component
1466 of the momentum scales along with the transverse component, and an equivalent equation can be
1467 written for the total momentum:

$$p \rightarrow p \cdot (1 + qp_T\delta_s)^{-1} \quad (4.15)$$

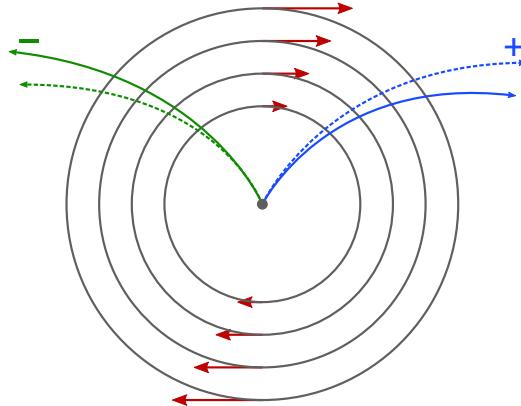


Figure 4.16: Representation of a curl distortion in the detector. The image shows a cutaway in the transverse plane. The deformation is represented by the red arrows, and the impact on the reconstructed positive (blue) and negative (green) tracks are shown. The dashed lines represent the true particle trajectories, and the solid lines represent the reconstructed trajectories.

1468 4.4.1 Sagitta bias monitoring with electron E/p

1469 Since a sagitta bias results in changes in the momentum of particles' tracks as measured by the ID,
1470 they can be identified using independent measurements from other systems in the detector. One
1471 such method involves using the energy-momentum ratio of electrons (E/p). Since the electron's
1472 energy is measured in ATLAS's calorimeter systems, it is not sensitive to any sagitta bias that may
1473 exist in the ID and the corresponding measurement of the track momentum. Under the assumption

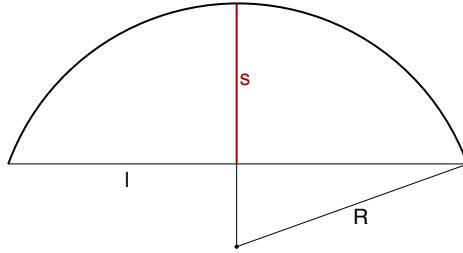


Figure 4.17: Geometric definition of the sagitta s in relation to the length of the chord l and the radius r of a circular arc.

that the calorimeter response is independent of the charge of incoming particles, a charge-dependent momentum bias in the ID will manifest as a difference in the E/p ratio for electrons and positrons.

In the presence of a sagitta bias, the momentum will change according to Equation 4.15 and the average measured $\langle E/p \rangle$ can be written as:

$$\langle E/p \rangle^\pm \rightarrow \langle E/p \rangle^\pm \pm \langle E_T \rangle \delta_s \quad (4.16)$$

where the approximation $p_T \approx E_T$ is used. Assuming that $\langle E/p \rangle^+ = \langle E/p \rangle^-$ in the absence of a bias, the sagitta bias parameter can be written as:

$$\delta_s = \frac{\langle E/p \rangle^+ - \langle E/p \rangle^-}{2\langle E_T \rangle} \quad (4.17)$$

If the kinematic selections for electrons and positrons are identical, the energy scale of the calorimeter will not factor into the $\langle E/p \rangle$ difference; however, it will affect $\langle E_T \rangle$ which would scale the measured δ_s . This is expected to be a small effect, as the energy scale for electrons has been measured at $\sqrt{s} = 13$ TeV with uncertainties on the per-mil level across the entire detector [78].

4.4.1.1 Measuring $\langle E/p \rangle$

The E/p ratio is measured using electrons and positrons from $Z \rightarrow e^\pm e^\mp$ events in order to obtain a high purity sample of candidate particles. They are required to pass a basic selection criteria to ensure they are well measured in both the ID and the calorimeters:

• $E_T > 25$ GeV

• $|\eta| < 2.47$, excluding the calorimeter's barrel-to-endcap transition region in $1.37 < |\eta| < 1.52$

• Pass MediumLH identification working point detailed in Section 3.2.4.2

- 1491 ● Pass a selection of quality cuts, including a requirement that the electron be identified using
 1492 cluster information in the calorimeter

 1493 ● The associated track must have at least one hit in the IBL, three in the Pixel detector, and
 1494 five in the SCT detector.

1495 Events with exactly two opposite-charge electrons passing this selection with a dielectron invariant
 1496 mass within 30 GeV of the Z boson mass are then used for the E/p calculation.

1497 Since the size of the sagitta bias δ_s is not expected to be constant across the entire detector,
 1498 a two-dimensional rectangular grid binned in detector η and ϕ is constructed. From the selected
 1499 events, separate distributions of E/p are made for electrons and positrons lying in each bin. Each
 1500 distribution is fit with Crystal Ball function¹², and the peak of the distribution is taken as the value
 1501 of $\langle E/p \rangle$. If there is no bias on the track momentum in the bin, the peaks for electrons and positrons
 1502 should agree. Example E/p distributions including the Crystal Ball fits are shown in Figure 4.18.

1503 It is important to emphasize that deviations from one in the *ratio* of $\langle E/p \rangle$ for electrons and
 1504 positrons indicates that a momentum bias may be present. The value of $\langle E/p \rangle$ itself is not expected
 1505 to equal one exactly, as the track momentum on average tends to be slightly lower than the energy
 1506 measurement in the calorimeter. This is due to the fact that if the electron were to radiate a photon,
 1507 its momentum would change slightly, while it is likely that both the electron and the emitted photon
 1508 would leave energy deposits near each other in the calorimeter and be reconstructed into the same
 1509 object.

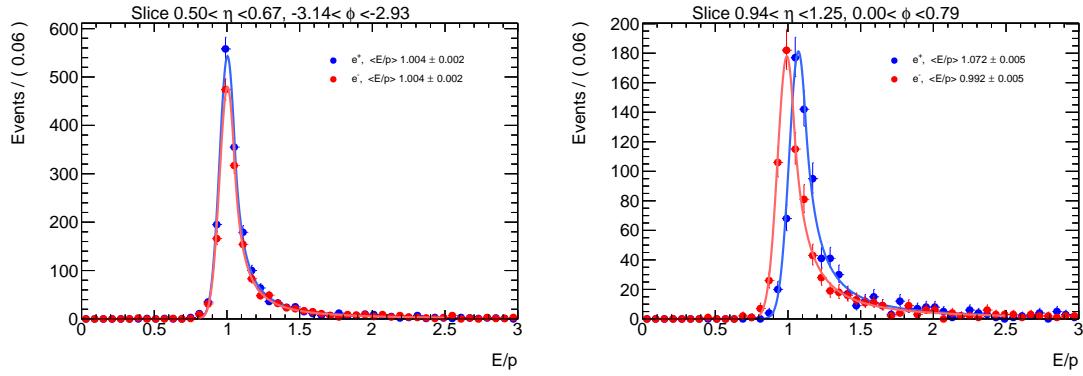


Figure 4.18: E/p distributions of electrons and positrons in two different $\eta\phi$ bins of the detector. The left hand plot is taken from a region with no momentum bias where $\langle E/p \rangle^+ = \langle E/p \rangle^-$, while the right hand plot shows an 8% disagreement in $\langle E/p \rangle$ between electrons and positrons.

¹²The Crystal Ball function is a probability density function consisting of a Gaussian core and a power-law tail.

1510 Once the $\langle E/p \rangle^\pm$ distributions in each $\eta\text{-}\phi$ bin have been extracted from the fits, a two dimensional map of δ_s can be constructed using Equation 4.17. The map gives an overview of sagitta
 1511 biases that may be present in the detector, and can be used by the alignment algorithm to reduce
 1512 the bias in the next iteration. In this case, the tracks fed to the alignment have their momenta
 1513 corrected according to [76]:

$$q/p_{\text{corr}} = q/p_{\text{reco}}(1 - qp_T\delta_s) \quad (4.18)$$

1515 where p_{reco} is the reconstructed momentum of the track. The corrected momentum is then constrained in the alignment.
 1516

1517 4.4.1.2 Results in 13 TeV data

1518 The E/p method has been used to monitor sagitta biases in the detector several times over the
 1519 course of Run 2. During this time, it has primarily served as an independent cross-check to a
 1520 second method using $Z \rightarrow \mu^\pm\mu^\mp$ events [76]. The $Z \rightarrow \mu^\pm\mu^\mp$ method identifies individual track
 1521 momentum biases through shifts in the reconstructed Z mass, which leaves it relatively insensitive
 1522 to global sagitta biases. For this reason, the sagitta bias maps produced using this technique are
 1523 normalized to those from the E/p method before being used to constrain the alignment. The results
 1524 of two implementations of the E/p method are presented here.

1525 1. The first follows the end-of-year reprocessing of the entire ATLAS 2016 data set. Two sets of
 1526 alignment constants are compared: the *prompt* alignment, which was derived shortly after each
 1527 run was recorded, and the *reprocessed* alignment. The maps of the sagitta bias comparing the
 1528 two alignments calculated using the E/p method are shown in Figure 4.19, and the comparison
 1529 of the η projection of each map is shown in Figure 4.20.

1530 2. The second uses the 2017 data after reprocessing, and compares the effects of multiple it-
 1531 erations of the method. In each iteration, the momenta of the electrons and positrons are
 1532 corrected based on Equation 4.15 using the value of δ_s computed in the previous iteration,
 1533 and a new sagitta bias map is calculated. If the method is indeed characterizing the sagitta
 1534 biases correctly, the corrections should converge quickly. The initial sagitta bias map is com-
 1535 pared to the map after two such iterations in Figure 4.21, and the sagitta bias projected along
 1536 η for each iteration is shown in Figure 4.22. Indeed, after just two iterations, δ_s is consistent
 1537 with zero in nearly all bins.

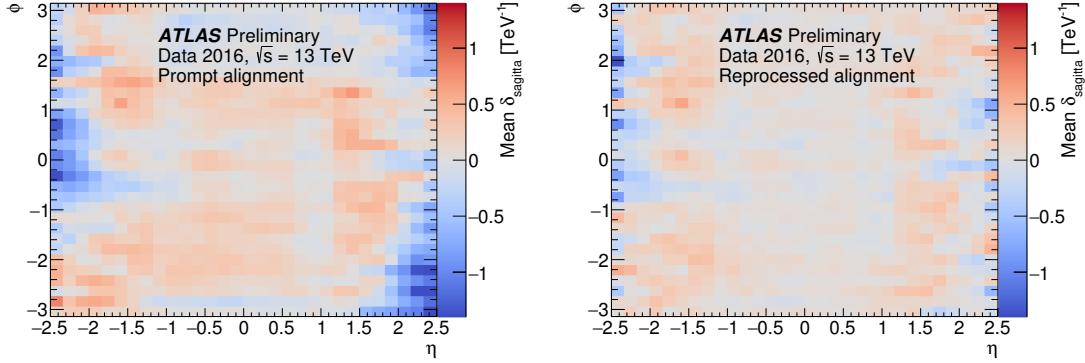


Figure 4.19: Sagitta bias in the $\sqrt{s} = 13$ TeV data collected by ATLAS in 2016 as a function of η and ϕ for the prompt (left) and reprocessed (right) alignments using the E/p method.

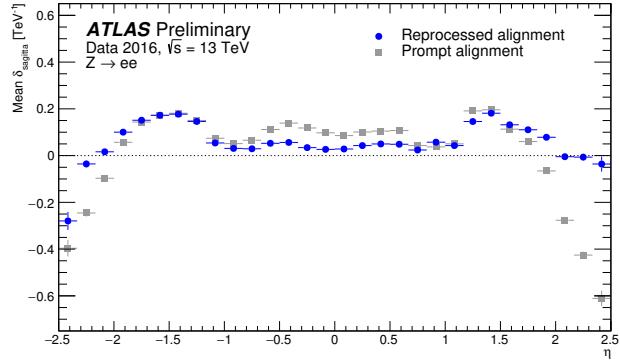


Figure 4.20: Sagitta bias in the $\sqrt{s} = 13$ TeV data collected by ATLAS in 2016 projected along η for the prompt (gray) and reprocessed (blue) alignments using the E/p method.

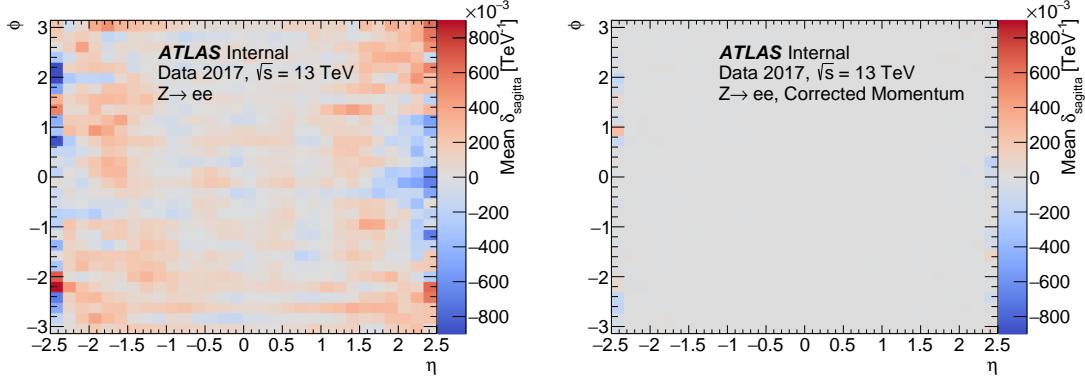


Figure 4.21: Sagitta bias in the $\sqrt{s} = 13$ TeV data collected by ATLAS in 2017 as a function of η and ϕ in reconstructed electrons (left) and after two iterations of momentum corrections (right) from the E/p method.

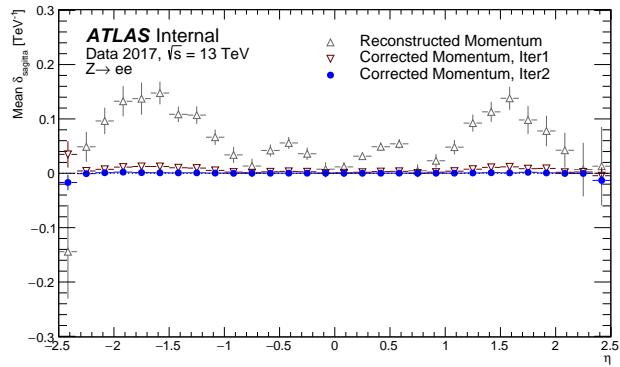


Figure 4.22: Sagitta bias in the $\sqrt{s} = 13 \text{ TeV}$ data collected by ATLAS in 2017 projected along η in reconstructed electrons (gray) and after one (red) and two (blue) iterations of momentum corrections from the E/p method.

CHAPTER 5

Measurement of same-sign WW production at $\sqrt{s} = 13$ TeV with ATLAS

1541 Production of same-sign W boson pairs is a particularly interesting SM process. When produced
 1542 via vector boson scattering (VBS), $W^\pm W^\pm jj$ is sensitive to the electroweak symmetry breaking
 1543 (EWSB) mechanism as well as potential Beyond the Standard Model (BSM) physics processes.
 1544 $W^\pm W^\pm jj$ events can be produced via electroweak-mediated (EWK) diagrams, of which VBS is a
 1545 subset, or QCD-mediated diagrams. The biggest advantage of same-sign $W^\pm W^\pm jj$ over other VBS
 1546 processes lies in its ratio of electroweak (EWK) to QCD production cross sections. Despite the
 1547 opposite-sign $W^\pm W^\mp$ having a larger total cross section, its EWK-mediated diagrams are much
 1548 smaller than its QCD-mediated diagrams, while for same-sign $W^\pm W^\pm$ the EWK production is
 1549 considerably larger. This makes $W^\pm W^\pm jj$ one of the premier channels for studying VBS at the
 1550 LHC.

1551 The first evidence of electroweak (EWK) $W^\pm W^\pm jj$ production was seen by the ATLAS and CMS
 1552 experiments at $\sqrt{s} = 8$ TeV with excesses of 3.6σ [79] and 2.0σ [80] over backgrounds, respectively.
 1553 More recently, ATLAS and CMS have both observed the EWK process at $\sqrt{s} = 13$ TeV with
 1554 significances of 6.9σ [81] and 5.5σ [82], respectively. The ATLAS $\sqrt{s} = 13$ TeV observation and
 1555 cross section measurement of EWK-produced $W^\pm W^\pm jj$ is presented in this chapter [81, 83].

1556 **5.0.1 Experimental overview of vector boson scattering**

1557 VBS processes are very important to understand due to their sensitivity to the EWSB mechanism.
 1558 As explained in Section 2.3, in the absence of a light SM Higgs boson, the scattering amplitude of
 1559 longitudinally polarized vector bosons grows with center-of-mass energy. However, once the Higgs

1560 is introduced, the divergences cancel and the cross section no longer grows unbounded.

1561 With the discovery of the Higgs boson in 2012 [16, 17], the EWSB mechanism can now be directly
 1562 studied. Due to the potential exchange of a Higgs boson in the VBS diagrams ($W^\pm W^\pm jj$ itself does
 1563 not contain an s -channel Higgs exchange), VBS processes are directly sensitive to properties of the
 1564 Higgs. For example, the high-mass tail in the VV scattering system allows an approximation of the
 1565 effective coupling strength of the Higgs to vector bosons that is independent of any assumptions
 1566 on the Higgs width [84]. Additionally, the center of mass energy dependence of the VV scattering
 1567 can reveal whether the Higgs boson unitarizes the longitudinal scattering amplitude fully or only
 1568 partially [85].

1569 VBS events are characterized by two quarks from the colliding protons each radiating a vector
 1570 boson which then scatter and decay in the detector. The incoming quarks carry a large amount of
 1571 momentum and only deflect a small amount upon emitting the vector boson; as a result, they often
 1572 enter the calorimeters very close to the beam line. Ignoring the decay products of the scattered
 1573 bosons for now, these VBS events result in a final state of two vector bosons (V) and two jets (j)
 1574 at high pseudorapidities (called *forward jets* or *tag jets*) from the outgoing quarks. The shorthand
 1575 $VVjj$ is used to represent this final state.

1576 $VVjj$ events can be produced via two different physical processes. The first involves purely
 1577 electroweak interactions in the tree-level diagrams, of order $\mathcal{O}(\alpha_{\text{EWK}}) = 6$ in the electroweak coupling
 1578 constant, and will be referred to as *EWK production*. This can be further broken down into VBS
 1579 and non-VBS events. In the VBS EWK production, the scattering occurs via triple or quartic gauge
 1580 couplings, as well as the exchange of a Higgs boson. The non-VBS EWK production contains the
 1581 same final state of two vector bosons and two outgoing quarks, but the bosons do not scatter. Due to
 1582 gauge invariance, it is not possible to separate the VBS from the non-VBS productions [86]; therefore,
 1583 both are included in the signal generation and are indistinguishable from one another. The second
 1584 process involves a mix of the EWK and strong interactions, of order $\mathcal{O}(\alpha_s) = 2 \otimes \mathcal{O}(\alpha_{\text{EWK}}) = 4$, and
 1585 will be referred to as *QCD production*. The tree-level Feynman diagrams for VBS EWK, non-VBS
 1586 EWK, and QCD $VVjj$ production are found in Figures 5.1, 5.2, and 5.3, respectively.

1587 5.0.2 Same-sign $W^\pm W^\pm$ scattering

1588 Same-sign $W^\pm W^\pm jj$ scattering is considered to be one of the best channels for studying VBS at the
 1589 LHC due to its favorable ratio of EWK to QCD production [84]. Since the VBS diagrams (which are
 1590 a subset of the total EWK production) are the primary source of interest for an analysis, the QCD

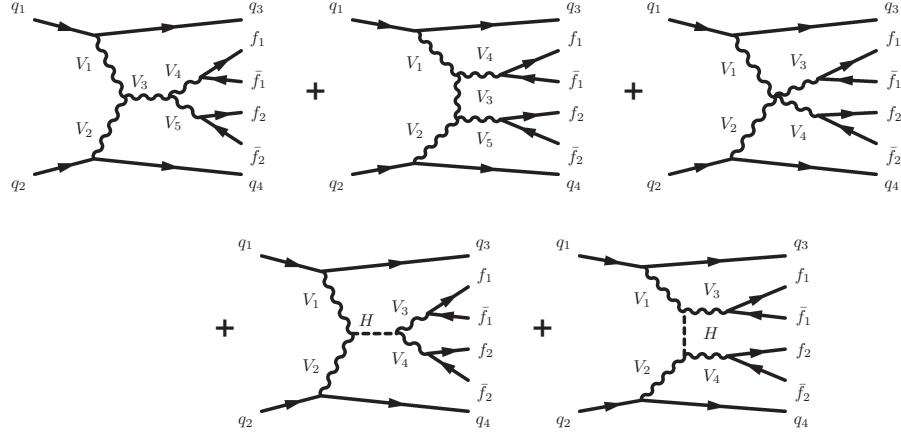


Figure 5.1: Tree-level Feynman diagrams for VBS EWK $VVjj$ production including triple gauge couplings involving W and/or Z bosons (top left and top middle), quartic gauge coupling (top right), or the exchange of a Higgs boson (s -channel bottom left and t -channel bottom right). The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).

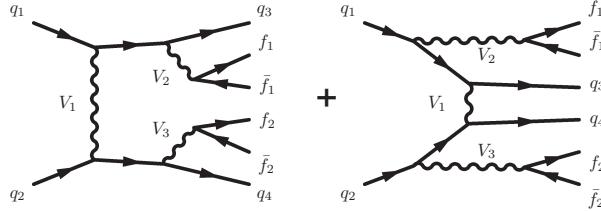


Figure 5.2: Tree-level Feynman diagrams for non-VBS EWK $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).

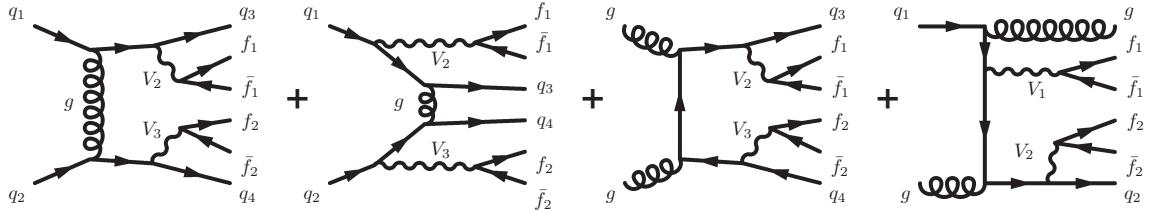


Figure 5.3: Tree-level Feynman diagrams for QCD $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).

1591 production would be considered a background in an analysis. Therefore a higher EWK-to-QCD
 1592 ratio results in increased sensitivity to VBS. EWK and QCD cross sections at $\sqrt{s} = 13$ TeV for
 1593 six leptonic $VVjj$ final states were calculated using the **SHERPA** MC generator in a VBS-enriched
 1594 fiducial phase space in [87]. Despite its relatively low total cross section compared to some other
 1595 $VVjj$ processes, the EWK-to-QCD ratio for $W^\pm W^\pm jj$ is 10-20 times higher than for other processes
 1596 after applying VBS-enhancing selection criteria.

Final state	Process	σ_{EWK} [fb]	σ_{QCD} [fb]	$\sigma_{\text{EWK}}/\sigma_{\text{QCD}}$
$l^\pm l^\mp l^\pm l^\mp jj$	ZZ	0.098	0.100	0.98
$l^\pm l^\pm l^\mp \nu jj$	$W^\pm Z$	2.34	4.38	0.53
$l^\pm l^\mp \nu \nu jj$	$W^\pm W^\mp, ZZ$	12.3	21.8	0.56
$l^\pm l^\pm \nu \nu jj$	$W^\pm W^\pm$	3.97	0.346	11.47
$l^\pm \nu \nu \nu jj$	$W^\pm Z$	7.64	15.5	0.49
$\nu \nu \nu \nu jj$	ZZ	1.68	1.38	1.22

Table 5.1: Predicted cross sections for EQK and QCD production of diboson processes relevant to VBS at $\sqrt{s} = 13$ TeV using the **SHERPA** MC generator. The numbers for the $W^\pm W^\pm jj$ process are bolded. Leptons are required to have $p_T \geq 25$ GeV and lie within $|\eta| \leq 2.5$ with $m_l > 20$ GeV, and at least two jets are required with $p_T \geq 30$ GeV and $|\eta| < 4.5$. The VBS contributions are enhanced by requiring the dijet invariant mass $m_{jj} > 500$ GeV and dijet separation $\Delta y_{jj} > 2.4$. Numbers taken from [87].

1597 This analysis studies $W^\pm W^\pm jj$ scattering where both W bosons decay leptonically to $e\nu$ or $\mu\nu$ ¹³.
 1598 The $W^\pm W^\pm jj$ VBS final state consists of two leptons with the same electric charge, two neutrinos,
 1599 and two high energy forward jets with a large invariant mass. Tree-level Feynman diagrams of VBS
 1600 $W^\pm W^\pm jj$ production can be found in Figure 5.4 and a visual representation of the VBS topology
 1601 can be found in Figure 5.5.

1602 The two tag jets in the characteristic VBS signature also serve as a powerful tool to suppress
 1603 the QCD production mode. In EWK events, the two jets tend to have much higher separation and
 1604 a larger combined invariant mass than the two leading jets in a QCD event. The two plots shown
 1605 in Figure 5.6 highlight the differences in these dijet quantities between the two production modes.
 1606 Finally, an ATLAS event display of a real $W^\pm W^\pm jj$ candidate event is shown in Figure 5.7.

1607 5.0.3 Overview of backgrounds

1608 In addition to QCD production of $W^\pm W^\pm jj$ events, there are several other processes with a final
 1609 state of two same-sign leptons, two neutrinos, and two jets. However, due to the ± 2 final state charge,

¹³Throughout the rest of this chapter, unless stated otherwise, l denotes either electrons (e) or muons (μ), and ν denotes a neutrino. Additionally, e , μ , and ν with no charge or anti-particle designation refer interchangeably to either the particle or anti-particle.

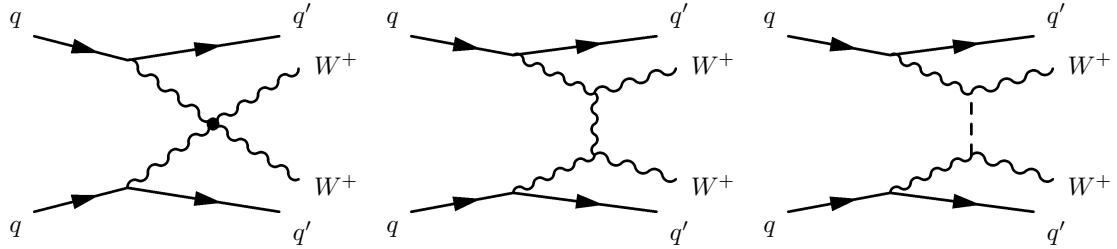


Figure 5.4: Leading order Feynman diagrams for VBS EWK production of $W^\pm W^\pm jj$ events. The leftmost diagram contains a quartic gauge coupling vertex, and the rightmost diagram contains an exchange of a Higgs boson.

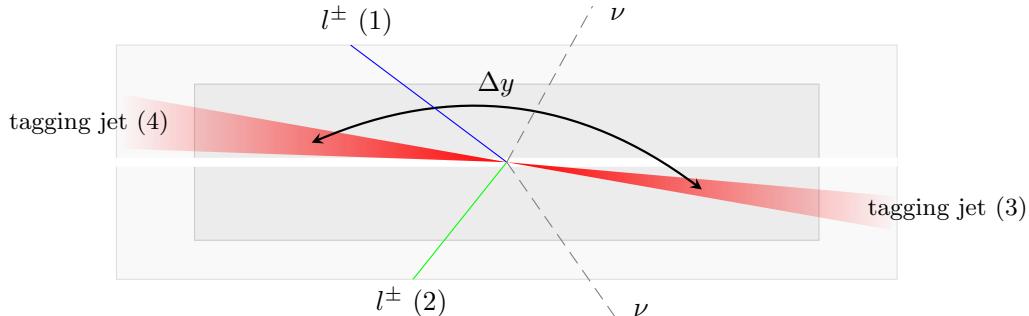


Figure 5.5: $W^\pm W^\pm jj$ VBS event topology containing two leptons (1 and 2) with the same electric charge, two neutrinos, and two forward tagging jets (3 and 4) with large rapidity separation Δy .

1610 there is a considerable reduction in SM backgrounds (such as Z boson events) when compared to
 1611 an analysis like opposite-sign $W^\pm W^\mp jj$.

1612 One of the largest sources of background involves processes with prompt leptons¹⁴. These are
 1613 events that contain two leptons with the same electric charge and one or more additional leptons that
 1614 are “lost”, either by failing the selection criteria or falling outside of the detector’s acceptance. The
 1615 number of processes that can contribute is limited by the requirement of same-sign leptons, and as a
 1616 result this background is dominated by multi-boson processes, with the largest contribution coming
 1617 from WZ events and smaller contributions from ZZ and $t\bar{t} + V$ events. Triboson events where one
 1618 boson decays hadronically also contribute to this background; however, the jets are generally softer
 1619 and more central than in a typical VBS event, and the cuts applied on the forward jets suppress
 1620 these contributions.

¹⁴Prompt leptons are those that are produced in the primary collision and are a direct decay product of the process of interest. Non-prompt leptons originate from some secondary process, such as a b -hadron decay, or are jets that get mis-reconstructed as a lepton.

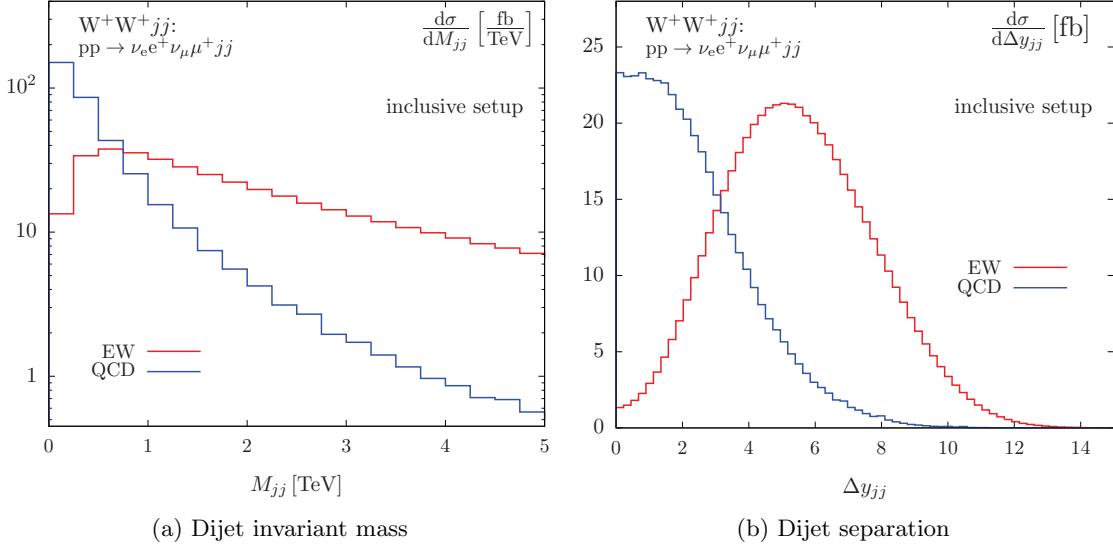


Figure 5.6: Generator level comparisons at $\sqrt{s} = 7$ TeV of dijet invariant mass (M_{jj} , left) and dijet rapidity (Δy_{jj} , right) in EWK (red) and QCD (blue) $W^{\pm}W^{\pm}jj$ events with no selection cuts applied. Plots taken from [88].

1621 The other dominant background comes from non-prompt, or “fake”, leptons. Here one or more
 1622 leptons originate from the decay of another particle unrelated to the signal process, such as a heavy-
 1623 flavor decay or photon conversion, or come from a jet that is misidentified as a lepton. This back-
 1624 ground is mostly made up of events from $t\bar{t}$ and $W+jets$ processes, with a much smaller contribution
 1625 from conversions in $V\gamma$ events.

1626 Finally, opposite-sign lepton pairs can enter the signal region if one of the leptons is reconstructed
 1627 with the wrong charge (called *charge misidentification*¹⁵). In practice, this only affects events with
 1628 electrons, as the charge misidentification rate for muons is negligible [89]. This is a major background
 1629 in events with two electrons, but it is a much smaller contribution for events with one electron and
 1630 one muon.

1631 5.1 Data and Monte Carlo samples

1632 This analysis uses 36.1 fb^{-1} of $\sqrt{s} = 13$ TeV proton-proton collisions recorded by ATLAS during
 1633 the 2015 and 2016 data taking periods. The uncertainty in the combined integrated luminosity is
 1634 2.1%. It is derived following a methodology similar to that detailed in [90] and using the LUCID-2

¹⁵Charge misidentification is also referred to interchangeably as *charge mis-ID* and *charge flip*.

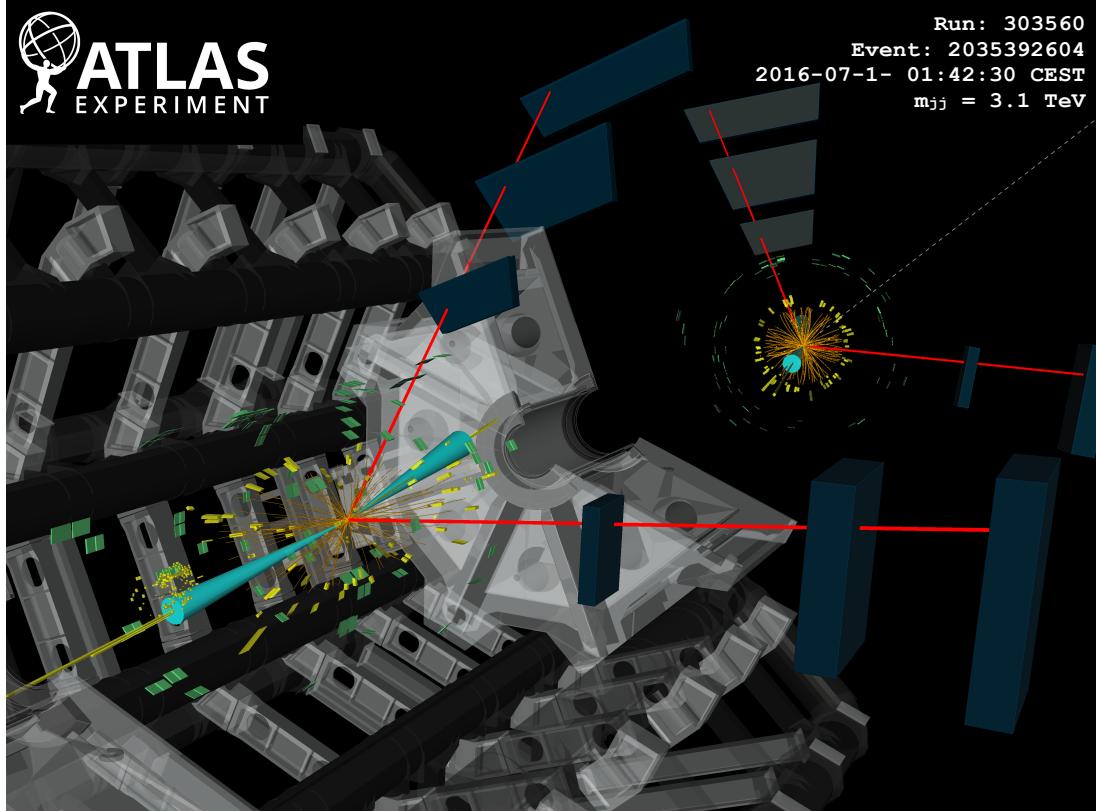


Figure 5.7: ATLAS event display of a $pp \rightarrow W^+W^+ \rightarrow \mu^+\nu_\mu\mu^+\nu_\mu jj$ event. The muons are represented by the red lines travelling from the ID through the MS, and the forward jets are represented by the blue cones with yellow energy deposits in the calorimeters. The direction of the E_T^{miss} in the transverse plane is indicated by the gray dashed line in the inset image. Event display taken from [81].

1635 detector for the baseline luminosity measurements [91] from calibration of the luminosity scale using
 1636 x - y beam-separation scans.

1637 5.1.1 Monte Carlo samples

1638 A number of Monte Carlo (MC) simulations are employed to model signal and background processes.
 1639 In order to model the real collision data as closely as possible, each MC sample has been passed
 1640 through a full simulation of the ATLAS detector in GEANT4 [92, 93], and events have been recon-
 1641 structed using the same algorithms as the data. The simulation reproduces as closely as possible
 1642 the momentum resolutions and calorimeter responses of the detector, and also includes the effects
 1643 of pileup by including soft QCD interactions using PYTHIA v8.1 [94]. The MC samples used in this

Process	Generator	Comments
$W^\pm W^\pm jj$ (EWK)	SHERPA v2.2.2	Signal sample
$W^\pm W^\pm jj$ (EWK)	POWHEG-BOX v2	Systematics sample
$W^\pm W^\pm jj$ (QCD)	SHERPA v2.2.2	
Diboson	SHERPA v2.2.2	Both bosons decay leptonically ($llll$, $ll\nu\nu$, $l\nu\nu\nu$)
	SHERPA v2.2.1	One boson decays leptonically, the other hadronically
Triboson	SHERPA v2.1.1	
$W+jets$	SHERPA v2.2.1	
$Z+jets$	Madgraph5_aMC@NLO	
$V\gamma$	SHERPA v2.1.1	
$V\gamma jj$ (EWK)	SHERPA v2.2.4	
$t\bar{t}V$	Madgraph5_aMC@NLO	
$t\bar{t}$	POWHEG-BOX v2	
Single top	POWHEG-BOX v1	EWK t -, s -, & Wt -channels

Table 5.2: Summary of MC samples used in the analysis.

analysis are detailed in this section and summarized in Table 5.2.

The $W^\pm W^\pm jj$ samples are modeled using SHERPA v2.2.2 [95, 96, 97] with the NNPDF3.0 PDF set [98]. The EWK signal samples were generated by fixing the electroweak coupling constant to $\mathcal{O}(\alpha_W) = 6$, and a QCD background sample was also generated with $\mathcal{O}(\alpha_W) = 4$. SHERPA includes up to one parton at next-to-leading order (NLO) and up to three at leading order (LO) in the strong coupling constant α_s . A second $W^\pm W^\pm jj$ EWK sample was generated using POWHEG-BOX v2 [99] with the NNPDF3.0 PDF set and at NLO accuracy. This sample is only used for systematic studies, as POWHEG-BOX does not include resonant triboson contributions in its matrix element, which are non-negligible at NLO [100].

Diboson processes (VV where $V = W, Z$) are simulated with SHERPA v2.2.2 for mixed hadronic and leptonic decays and SHERPA v2.2.1 for fully leptonic decays of the bosons. Similarly, triboson (VVV) and $V\gamma$ processes are simulated using SHERPA v2.1.1 with up to one parton at NLO and up to three at LO. $W+jets$ processes are simulated with SHERPA v2.2.1 with up to two partons at NLO and four at LO. All the above SHERPA samples use the NNPDF3.0 PDF set and SHERPA's own parton showering. The $Z+jets$ events are generated with Madgraph5_aMC@NLO [101] at LO and interfaced with PYTHIA v8.1 for parton showering.

$t\bar{t}$ events are generated using POWHEG-BOX v2 with the CT10 PDF set [102]. $t\bar{t}V$ samples are generated at NLO with Madgraph5_aMC@NLO and the NNPDF3.0 PDF set interfaced with PYTHIA v8 for parton showering. Finally, single top events are generated with POWHEG-BOX v1 and the CT10f4 PDF set interfaced with PYTHIA v6 [103] for parton showering.

1664 **5.2 Object and event selection**

1665 This section details the selection criteria for objects used in the analysis as well as the selection for
1666 signal events.

1667 **5.2.1 Object selection**

1668 Muons, electrons, and jets all must pass strict selection requirements to ensure that only high quality,
1669 well measured objects are used. For leptons, a baseline selection is defined (called the *preselection*),
1670 which all leptons must pass in order to be considered for the analysis. This preselection is an
1671 intentionally loose set of criteria designed to have high acceptance in order to reject backgrounds
1672 with additional leptons (i.e. $WZ \rightarrow 3l\nu jj$). Signal leptons are then required to satisfy a much
1673 tighter *signal selection* aimed at suppressing backgrounds from non-prompt or fake leptons. A third
1674 set of lepton selection criteria, the *loose selection*, defines a sample enriched in non-prompt leptons,
1675 and it is used in the fake-factor method for estimating the non-prompt background, discussed in
1676 detail in Section 5.3.4. Jets are only required to pass one set of selection criteria. These selections
1677 are detailed in the following sections and summarized in Table 5.3 for muons, Table 5.4 for electrons,
1678 and Table 5.5 for jets.

1679 **5.2.1.1 Muon candidate selection**

1680 Cuts on muon p_T serve to reject low momentum leptons from background processes and additional
1681 collisions from pileup events. Preselected muons must have transverse momentum $p_T > 6$ GeV, and
1682 the signal muons must pass $p_T > 27$ GeV. The p_T requirement for loose muons is lower than for
1683 signal muons, at $p_T > 15$ GeV, for reasons that are discussed in Section 5.3.4.3. Muons are required
1684 to fall within the detector's η acceptance: $|\eta| < 2.7$ for preselected muons, which is tightened to
1685 $|\eta| < 2.5$ for the signal muons.

1686 Cuts on the transverse and longitudinal impact parameters are applied to ensure that the can-
1687 didate muon originated from the primary particle interaction and not some other source, such as a
1688 heavy flavor decay. The preselection and the loose selection both have relaxed requirements on the
1689 transverse impact parameter significance (d_0/σ_{d_0}) than the signal selection; all three have the same
1690 requirement on the transverse impact parameter ($|z_0 \times \sin \theta|$).

1691 Finally, the muon candidates are required to pass a particle identification and an isolation criteria
1692 as defined in [61]. The methods used in constructing the identification and isolation working points
1693 are described in more detail in Section 3.2.4.3. The muon identification serves to select prompt

1694 muons with high efficiency and well measured momenta. This analysis uses two different working
 1695 points: **Loose** for preselected muons and **Medium** for loose and signal muons, where **Medium** muons
 1696 are a tighter subset of those that pass the **Loose** requirement. Muon isolation is a measurement
 1697 of detector activity around the muon candidate, and it is measured with both track-based and
 1698 calorimeter-based variables. The isolation working point used for the signal muons, **Gradient**, is
 1699 defined such that there is 90% or better background rejection efficiency for 25 GeV muons, and 99%
 1700 efficiency at 60 GeV. There is no minimum isolation requirement for preselected or loose muons.
 1701 Loose muons are additionally required to fail one or both of the signal transverse impact parameter
 1702 cut and signal isolation requirement.

Muon preselection	
Momentum cut	$p_T > 6$ GeV
Angular acceptance	$ \eta < 2.7$
Longitudinal impact parameter	$ z_0 \times \sin \theta < 0.5$ mm
Transverse impact parameter	$d_0/\sigma_{d_0} < 10$
Particle identification	Loose

Muon signal selection	
Momentum cut	$p_T > 27$ GeV
Angular acceptance	$ \eta < 2.5$
Longitudinal impact parameter	$ z_0 \times \sin \theta < 0.5$ mm
Transverse impact parameter	$d_0/\sigma_{d_0} < 3$
Particle identification	Medium
Particle isolation	Gradient

Muon loose selection	
Momentum cut	$p_T > 15$ GeV
Angular acceptance	$ \eta < 2.5$
Longitudinal impact parameter	$ z_0 \times \sin \theta < 0.5$ mm
Transverse impact parameter	$d_0/\sigma_{d_0} < 10$
Particle identification	Medium
Fail signal transverse impact parameter and/or isolation cuts	

Table 5.3: Muon selection criteria. All muons are required to pass the preselection (top), and then either the signal (middle) or loose (bottom) criteria is applied to the preselected electrons.

1703 5.2.1.2 Electron candidate selection

1704 The electron candidate selections are very similar to those for muons. The p_T cut starts at $p_T >$
 1705 6 GeV for the preselection, increases to $p_T > 20$ GeV for loose electrons, and finally to $p_T > 27$ GeV

for signal electrons. The $|\eta|$ cut for electrons requires $|\eta| < 2.47$ for all electrons, with the region $1.37 \leq |\eta| \leq 1.52$ removed from loose and signal electrons. This is where the electromagnetic calorimeter transitions from the barrel to the endcaps and is not fully instrumented. Both the transverse and longitudinal impact parameter cuts are the same for all electron selections.

The electron particle identification uses a multivariate likelihood technique (LH) detailed in Section 3.2.4.2. Preselected electrons must pass the `LooseLH` working point with an additional requirement that there be a reconstructed track hit in the first layer of the pixel detector (a so-called B -layer hit). The LH requirement for the loose and signal electrons increases in tightness using `MediumLH` and `TightLH` electrons, respectively. As for isolation, the `Gradient` working point is required for signal electrons only. The loose electrons must fail one or both of the signal identification and isolation requirements.

Electron preselection	
Momentum cut	$p_T > 6$ GeV
Angular acceptance	$ \eta < 2.47$
Longitudinal impact parameter	$ z_0 \times \sin \theta < 0.5$ mm
Transverse impact parameter	$d_0/\sigma_{d_0} < 5$
Particle identification	<code>LooseLH</code> + B -layer hit

Electron signal selection	
Momentum cut	$p_T > 27$ GeV
Angular acceptance	$ \eta < 2.47$, excluding $1.37 \leq \eta \leq 1.52$
Longitudinal impact parameter	$ z_0 \times \sin \theta < 0.5$ mm
Transverse impact parameter	$d_0/\sigma_{d_0} < 5$
Particle identification	<code>TightLH</code>
Particle isolation	<code>Gradient</code>

Electron loose selection	
Momentum cut	$p_T > 20$ GeV
Angular acceptance	$ \eta < 2.47$, excluding $1.37 \leq \eta \leq 1.52$
Longitudinal impact parameter	$ z_0 \times \sin \theta < 0.5$ mm
Transverse impact parameter	$d_0/\sigma_{d_0} < 5$
Particle identification	<code>MediumLH</code>
Fail signal identification and/or isolation cuts	

Table 5.4: Electron selection criteria. All electrons are required to pass the preselection (top), and then either the signal (middle) or loose (bottom) criteria is applied to the preselected electrons.

1717 **5.2.1.3 Jet candidate selection**

1718 The final objects that need to pass selection are jets. Jets are clustered using the anti- k_t algo-
1719 rithm [104] within a radius of $\Delta R = 0.4$. The jets are then calibrated using E_T - and η -dependent
1720 correction factors that are trained using MC simulations [105]. The calibrated jets are required
1721 to have $p_T > 30$ GeV if they lie in the forward regions of the detector ($2.4 < |\eta| < 4.5$) and
1722 $p_T > 25$ GeV in the central region ($|\eta| \leq 2.4$). In order to suppress pileup jets, the so-called jet-
1723 vertex-tagger (JVT) discriminant associates a jet with the primary interaction vertex [106]; central
1724 jets with $p_T > 60$ GeV are required to pass the **Medium** JVT working point, which corresponds to
1725 an average efficiency of over 92%. Finally, the jets are required to be separated from the selected
1726 leptons by at least $\Delta R(j, l) > 0.3$.

Jet selection	
Momentum cut	$p_T > 30$ GeV for $2.4 < \eta < 4.5$ $p_T > 60$ GeV for $ \eta < 2.4$
JVT cut	Medium
Jet-lepton separation	$\Delta R(j, l) > 0.3$

Table 5.5: Jet selection criteria. All jets are required to pass the above selection in order to be used in the analysis.

1727 **5.2.1.4 Treatment of overlapping objects**

1728 In the event that one or more objects are reconstructed very close to each other, there is the possibility
1729 for double-counting if both originated from the same object. The procedure by which this ambiguity
1730 is resolved is called *overlap removal* (OR). The standard ATLAS recommendation for OR [107, 108]
1731 is implemented in this analysis and is summarized in Table 5.6.

1732 Since electrons leave a shower in the EM calorimeter, every electron has a jet associated with
1733 it. Therefore, any jets close to an electron (within $\Delta R(e, j) < 0.2$) are rejected due to the high
1734 probability that they are the same object. On the other hand, when jets and electrons overlap
1735 within a larger radius of $0.2 < \Delta R(e, j) < 0.4$, it is likely that the electron and jet both are part of
1736 a heavy-flavor decay, and the electron is rejected.

1737 High energy muons can produce photons via bremsstrahlung radiation or collinear final state
1738 radiation which result in nearby energy deposits in the calorimeters. Non-prompt muons from
1739 hadronic decays produce a similar signature; however, in this case the jet has a higher track multi-
1740 plicity in the ID. It is possible to address both cases simultaneously by rejecting the jet when the ID

1741 track multiplicity is less than three—and otherwise rejecting the muon—for jets and muons within
 1742 $\Delta R(\mu, j) < 0.4$.

1743 In addition to the case above where muon bremsstrahlung results in a nearby reconstructed jet,
 1744 the ID track from the muon and the calorimeter energy deposit can lead to it being reconstructed
 1745 as an electron. In this case, if both a muon and an electron share a track in the ID, the muon is
 1746 kept and the electron is rejected, unless the muon is calorimeter-tagged¹⁶, in which case the muon
 1747 is removed in favor of the electron.

Overlap	Check	Result (remove → keep)
Electron & Jet	$\Delta R(e, j) < 0.2$	Jet → Electron
	$0.2 < \Delta R(e, j) < 0.4$	Electron → Jet
Muon & Jet	$\Delta R(\mu, j) < 0.4$ and Jet N_{ID} tracks < 3	Jet → Muon
	$\Delta R(\mu, j) < 0.4$ and Jet N_{ID} tracks ≥ 3	Muon → Jet
Electron & Muon	Shared ID track	Electron → Muon
	Shared ID track & muon is calo-tagged	Muon → Electron

Table 5.6: Summary of the overlap removal procedure used in the analysis. If the criteria in the “check” column is met, in the “result” column, the object on the left of the arrow is removed in favor of the object on the right.

1748 5.2.2 Signal event selection

1749 After the objects have been selected, cuts are applied on a per-event level to select $W^\pm W^\pm jj$ signal
 1750 events. The event selection is summarized in Table 5.8.

1751 The initial event selection chooses events that pass one or more of the trigger requirements listed
 1752 in Table 5.7. At least one signal lepton is “matched” to a passed trigger in order to ensure that
 1753 it was indeed a signal lepton that fired the trigger. A collection of *event cleaning* cuts must also
 1754 be passed in order to remove events collected during periods in which one or more components of
 1755 the detector was not operating optimally. Finally, the events are required to contain at least one
 1756 interaction vertex. An event can have multiple reconstructed vertices from additional proton-proton
 1757 collisions that occurred in the same bunch crossing. In this case, the *primary vertex* is determined
 1758 by choosing the vertex with the largest sum of the p_T^2 of its associated tracks.

1759 Events are then required to contain exactly two signal leptons with the same electric charge.
 1760 The dilepton pair must have a combined invariant mass of $m_{ll} \geq 20$ GeV in order to suppress low
 1761 mass Drell-Yan backgrounds. Two additional selections are applied to events in the ee-channel:

¹⁶A calorimeter-tagged (CT) muon is a muon that is identified by matching an ID track to a calorimeter energy deposit. CT muons have relatively low reconstruction efficiency compared to those measured by the MS, but can be used to recover acceptance in regions of the detector where the MS does not have full coverage [61].

	2015 data	2016 data
Electrons	$p_T > 24$ GeV and Medium ID	$p_T > 26$ GeV and Tight ID and Loose isolation
	$p_T > 60$ GeV and Medium ID	$p_T > 60$ GeV and Medium ID
	$p_T > 120$ GeV and Loose ID	$p_T > 140$ GeV and Loose ID
Muons	$p_T > 20$ GeV and Loose isolation $p_T > 50$ GeV	$p_T > 26$ GeV and Medium isolation $p_T > 50$ GeV

Table 5.7: Summary of trigger requirements for electrons and muons for $\sqrt{s} = 13$ TeV data collected in 2015 and 2016. At least one of the triggers must be satisfied.

1762 both electrons are required to have $|\eta| < 1.37$ with an invariant mass at least 15 GeV away from
 1763 the Z -boson mass to reduce events where one electron is reconstructed with the wrong charge (this
 1764 background will be discussed in more detail in Section 5.3.3). To suppress backgrounds from final
 1765 states with more than two leptons, such as WZ or ZZ , events with more than two leptons passing
 1766 the preselection are vetoed.

1767 Missing transverse energy (E_T^{miss}) represents any particles that escape the detector without being
 1768 measured, such as neutrinos, and it is defined as the magnitude of the vector sum of transverse
 1769 momenta of all reconstructed objects. It can be difficult to calculate accurately, as it involves
 1770 measurements from all subsystems within the detector, and it is sensitive to any corrections that may
 1771 be applied to the reconstructed physics objects [109]. These corrections, including the momentum
 1772 smearing for muons, energy scale and smearing for electrons, and jet calibrations, are propagated
 1773 to the E_T^{miss} calculation. Events are required to contain $E_T^{\text{miss}} > 30$ GeV in order to account for the
 1774 two neutrinos from the W boson decays.

1775 At least two jets are required. The leading and subleading jets must have $p_T > 65$ GeV and
 1776 $p_T > 35$ GeV, respectively, and are referred to as the *tagging jets*. Events are vetoed if they contain
 1777 one or more jets that have been tagged as a b -jet to suppress backgrounds from heavy flavor decays
 1778 (especially top quark events). The b -tagging algorithm used by ATLAS is a boosted decision tree
 1779 (BDT) called MV2c10, and this analysis uses a working point with 85% efficiency [110].

1780 Finally, cuts are applied on the VBS signature outlined in Section 5.0.2. The tagging jets are
 1781 required to have a dijet invariant mass $m_{jj} > 200$ GeV and be separated in rapidity by $|\Delta y_{jj}| > 2.0$.
 1782 This preferentially selects the VBS EWK events over the QCD-produced $W^\pm W^\pm jj$ events.

1783 5.3 Background estimations

1784 The major sources of background events are summarized in Section 5.0.3, and the methods used to
 1785 estimate them are detailed in this section. Prompt backgrounds from ZZ and $t\bar{t} + V$ are estimated

Event selection	
Event preselection	Pass at least one trigger with a matched lepton Pass event cleaning At least one reconstructed vertex
Lepton selection	Exactly two leptons passing signal selection Both signal leptons with the same electric charge Dilepton mass $m_{ll} > 20$ GeV $ \eta < 1.37$ and $ M_{ee} - M_Z > 15$ GeV (ee-channel only) Veto events with more than two preselected leptons
Missing transverse energy	$E_T^{\text{miss}} \geq 30$ GeV
Jet selection	At least two jets Leading jet $p_T > 65$ GeV Subleading jet $p_T > 35$ GeV $m_{jj} > 200$ GeV $N_{b\text{-jet}} = 0$ $ \Delta y_{jj} > 2.0$

Table 5.8: The signal event selection.

1786 directly from MC simulations. The shape of the WZ and $V\gamma$ backgrounds are taken from MC, and
 1787 the predicted yeilds are normalized to the data predictions in dedicated control regions, as outlined
 1788 in Sections 5.3.1 and 5.3.2, respectively. Opposite sign events with a charge misidentified electron
 1789 are estimated by a data-driven background method which is summarized in Section 5.3.3. Finally, a
 1790 *fake-factor* method is used to estimate the contributions from non-prompt backgrounds and is the
 1791 subject of Section 5.3.4.

1792 5.3.1 Estimation of the WZ background

1793 The dominant background involving prompt leptons comes from WZ +jets events. The contribution
 1794 is estimated from MC simulation and normalized to data in a control region enriched in WZ events.
 1795 This region is defined by the same event selection as the signal region in Table 5.8, with the following
 1796 changes applied to increase the purity of the WZ process:

- 1797 • The third lepton veto is inverted, requiring a third lepton with $p_T > 15$ GeV
- 1798 • Two of the leptons must make a same-flavor opposite-sign pair. If more than one pair exists,
 1799 the one with m_{ll} closest to the Z boson mass is chosen.
- 1800 • The trilepton invariant mass is required to be $m_{lll} > 106$ GeV to reduce contributions from
 1801 $Z\gamma$ and Z +jets

Once the event yields in the control region are calculated, they are propagated to the final signal region fit, detailed in Section 5.4.1, in a single bin combining all the lepton channels. The systematic uncertainties of the WZ background are also calculated at this time. The event yields for the WZ control region are listed in Table 5.9, and distributions of the leading lepton p_T and η as well as trilepton invariant mass m_{lll} are found in Figures 5.9 and 5.8, respectively.

Event yields in the WZ control region	
WZ	197.9 ± 1.4
ZZ	14.1 ± 0.3
Triboson	1.26 ± 0.1
top	10.8 ± 1.1
$Z\gamma$	3.1 ± 1.1
$Z+jets$	2.5 ± 1.4
Total prediction	229.7 ± 2.5
Data	201 ± 14.2

Table 5.9: Event yields in the WZ control region before normalization. All lepton flavor channels are combined.

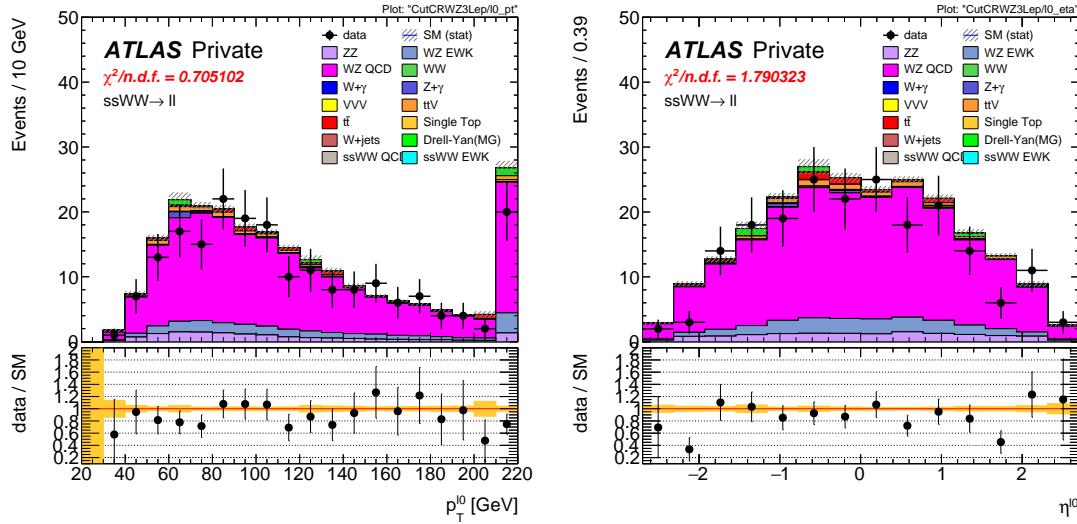


Figure 5.8: Leading lepton p_T (left) and η (right) distributions in the WZ control region before normalization. All lepton channels are combined.

5.3.2 Estimation of the $V\gamma$ background

Events from $V\gamma$ processes can pass selection if the photon converts into an e^+e^- pair and one of the electrons passes the selection criteria. The background is estimated from MC simulations which are

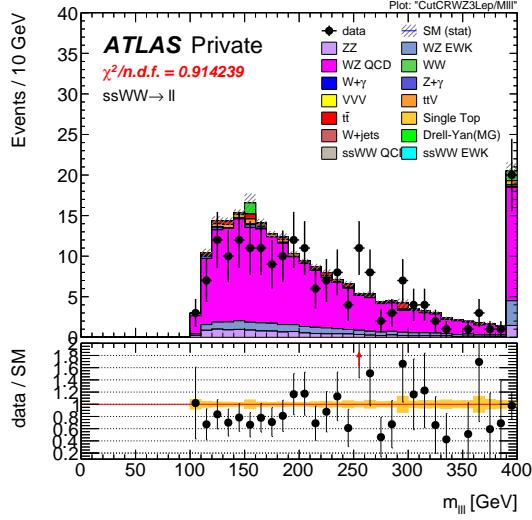


Figure 5.9: Trilepton invariant mass m_{lll} distribution in the WZ control region before normalization. All lepton channels are combined.

1810 then scaled by a normalization factor calculated from a control region enriched in $Z(\mu^+\mu^-)\gamma$ events.
 1811 This control region selects two opposite-sign muons and an additional electron that is assumed to
 1812 come from the photon conversion. The full event selection is detailed in Table 5.10.

$V\gamma$ control region
Exactly two muons with $p_T > 27$ GeV and $p_T > 20$ GeV
Exactly one additional electron with $p_T > 15$ GeV
Remove overlap between $Z+jets$ and $Z\gamma$
Di-muon + photon invariant mass $75 < M_{\mu\mu\gamma} < 100$ GeV
$E_T^{\text{miss}} < 30$ GeV

Table 5.10: Selection criteria for the $V\gamma$ control region.

1813 The $Z\gamma$ MC samples available do not cover the full range of p_T^γ and $\Delta R(\gamma, l)$; thus, additional
 1814 Drell-Yan samples ($Z+jets$) are used to fill out the phase space. Overlap between the two samples
 1815 are removed based to avoid double counting. Events with final state photons are checked at truth
 1816 level¹⁷ to ensure that the photon did not originate from a hadronic decay. Cuts on $p_T^\gamma > 10$ GeV and
 1817 $\Delta R(\gamma, l) > 0.1$ are then applied at generator level, and $Z\gamma$ events that fail this additional selection
 1818 and $Z+jets$ events that pass it are removed.

1819 The normalization factor is calculated directly from the event yields in the $V\gamma$ control region

¹⁷Truth particles are the particles produced directly by the MC generator before being passed through the full detector simulation, at which point they are considered *reconstruction-level* (or *reco-level*) particles.

rather than in the signal fit, as is done for the WZ background. The event yields are listed in Table 5.11, and the normalization factor is determined to be 1.77. No MC events from $Z\gamma$ processes survive the full event selection; thus, the scaling is only applied to the $W\gamma$ background in the signal region. A systematic uncertainty of 44% is assigned to the background based off of the uncertainties in the calculation of the normalization factor.

Event yields in the $V\gamma$ control region	
$Z\gamma$	24.6 ± 3.3
$Z+jets$	3.0 ± 1.5
diboson + triboson	6.7 ± 0.3
top	1.5 ± 0.5
Total prediction	35.8 ± 3.7
Data	57 ± 7.6

Table 5.11: Event yields in the $V\gamma$ control region. The $V\gamma$ scale factor of 1.77 is calculated by scaling up the $Z\gamma$ and $Z+jets$ backgrounds to account for the difference between the data and predicted total background.

5.3.3 Estimation of backgrounds from charge misidentification

If an electron's charge is mis-reconstructed, it can lead to a real opposite-sign lepton pair passing the same-sign requirement in the event selection. There are two primary reasons this can occur:

1. An electron emits a photon via bremsstrahlung which then converts into an electron-positron pair, and the conversion track with the wrong electric charge is matched to the original electron. This is the dominant process leading to charge flip, and it is highly dependent on the electron η due to the different amount of detector material the electron passes through.
2. The curvature of the electron's track is mis-measured, resulting in the wrong charge being assigned. This process is dependent on the momentum of the electron, as its track becomes more straight as the momentum of the electron increases.

In order to estimate this background, the rate at which an electron's charge is misidentified is calculated from $Z \rightarrow e^+e^-$ MC simulation. It is known that the MC does not perfectly model the material effects leading to charge flip; as a result, scale factors are applied to the MC in order for it to better reflect the real performance. These scale factors are obtained from the ratio of charge mis-ID rates in data and uncorrected MC in [83] following the method outlined in [111]. Once the scale factors are applied, the charge misidentification rate ε can be extracted by comparing the

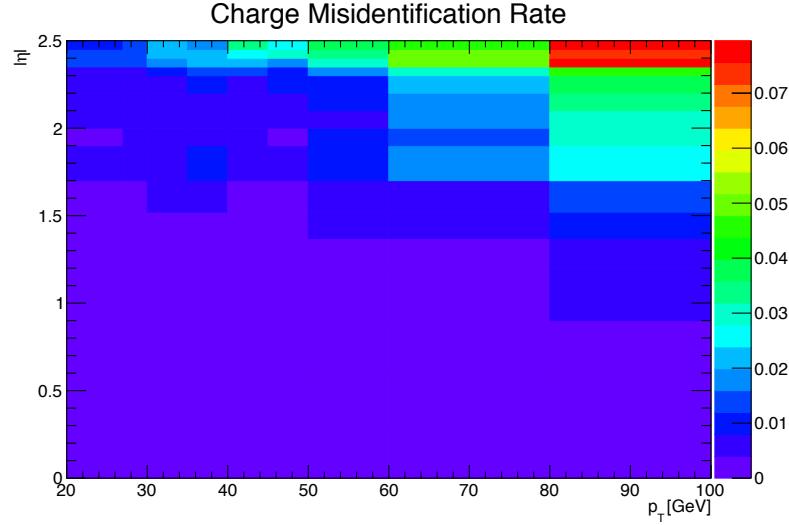


Figure 5.10: Charge misidentification rates for electrons as a function of $|\eta|$ and p_{T} . Rates are calculated from $Z \rightarrow e^+e^-$ MC after applying scale factors to approximate the charge mis-ID rates in data.

1841 electron's reconstructed charge with the charge of its truth particle:

$$\varepsilon(\eta, p_{\text{T}}) = \frac{N_{\text{wrong charge}}}{N_{\text{prompt electrons}}} \quad (5.1)$$

1842 The charge mis-ID rate is calculated in bins of electron $|\eta|$ and p_{T} , and it varies from below 0.1%
 1843 in the central region of the detector up to 8% in the forward regions for high p_{T} (above 90 GeV)
 1844 electrons. A two-dimensional plot of ε can be found in Figure 5.10.

1845 Given the charge flip rate $\varepsilon(\eta, p_{\text{T}})$, the rate at which an electron has its charge correctly recon-
 1846 structed is $(1 - \varepsilon)$. Thus there are three possible combinations of charge identification, assuming a
 1847 two-electron event:

- 1848 1. Both electrons are reconstructed correctly: $(1 - \varepsilon)^2$
- 1849 2. Both electrons are mis-reconstructed: ε^2
- 1850 3. Only one electron is mis-reconstructed: $2\varepsilon(1 - \varepsilon)$

1851 In order to estimate the size of the background from charge misidentification, opposite-sign events
 1852 are selected using the default event selection for a given signal or control region with the same-sign
 1853 requirement inverted. These events are then weighted by the probability for one of the electrons to

1854 be reconstructed with the wrong charge:

$$\omega = \frac{\varepsilon_1(1 - \varepsilon_2) + \varepsilon_2(1 - \varepsilon_1)}{(1 - \varepsilon_1)(1 - \varepsilon_2) + \varepsilon_1\varepsilon_2} \quad (5.2)$$

1855 where the subscripts 1 and 2 refer to the leading and subleading electrons, respectively, and ε_i is a
 1856 function of the η and p_T of the i^{th} electron. In the case of an event with only one electron and one
 1857 muon, Equation 5.2 simplifies:

$$\omega = \frac{\varepsilon}{1 - \varepsilon} \quad (5.3)$$

1858 This method assumes that there is little contamination from fake electrons in the opposite-sign
 1859 sample, and this has been verified with MC simulation.

1860 Additionally, charge-flipped electrons tend to be reconstructed with lower energy when compared
 1861 to electrons with the correct charge. This is due to energy loss from the material interactions that
 1862 can cause the charge to be misidentified in the first place. A correction factor is calculated from
 1863 MC simulations, comparing the p_T of the truth electron to its reconstructed counterpart:

$$\alpha = \frac{\left(\frac{p_T^{\text{reco}}}{p_T^{\text{truth}}} - 1\right)_{\text{correct charge}}}{\left(\frac{p_T^{\text{reco}}}{p_T^{\text{truth}}} - 1\right)_{\text{wrong charge}}} \quad (5.4)$$

1864 The correction is then applied to the p_T of the charge-flipped electron via

$$p_T = p_T^0 / (1 + \alpha) + dE \quad (5.5)$$

1865 where p_T^0 is the uncorrected p_T of the electron and dE is a gaussian smearing factor centered at zero
 1866 with a width related to the energy resolution. Since which electron is mis-reconstructed is never
 1867 determined in this method, in the case of a two-electron event, the energy correction is applied
 1868 randomly to one of the two electrons based on the probabilities for them to be charge-flipped. This
 1869 also determines the overall sign of the event; the charge of the electron that does not receive the
 1870 correction is taken to be the charge for both.

1871 Systematic uncertainties on the charge mis-ID rates are calculated by generating two additional
 1872 sets of rates with the uncertainties on the scale factors varied up and down. The size of the esti-
 1873 mated charge flip background without the energy correction applied is also taken as a systematic
 1874 uncertainty. These systematic uncertainties are estimated to be approximately $\pm 15\%$.

1875 5.3.3.1 Validation of the charge misidentification estimate

1876 The performance of the charge misidentification estimation is tested in the same-sign inclusive
 1877 validation region (VR), defined in Table 5.12. For ee events, the mass of the dilepton pair is required

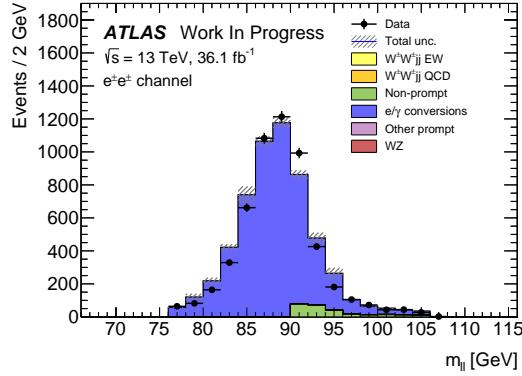


Figure 5.11: Dilepton invariant mass distribution m_{ll} for the ee channel in the same-sign inclusive VR.

1878 to lie within 15 GeV of the Z boson mass to increase the purity of the charge flip background.
 1879 $t\bar{t}$ production, which can contribute to both the charge mis-ID and fake lepton backgrounds, is
 1880 suppressed by the b -jet veto. The di-electron invariant mass is shown in Figure 5.11, and distributions
 1881 of the leading and subleading electron p_T in the ee -channel are shown in Figure 5.12 with the Z
 1882 mass cut inverted. Agreement between data and prediction is seen within the total statistical and
 1883 systematic uncertainties in the VR.

Same-sign inclusive VR
Exactly 2 same-sign signal leptons
$p_T > 27$ GeV for both leptons
$m_{ll} > 20$ GeV
$ m_{ee} - m_Z > 15$ GeV ($e^\pm e^\pm$ -channel only)
$N_{b\text{-jet}} = 0$

Table 5.12: Selection criteria for the same-sign inclusive validation region.

1884 5.3.4 Estimation of non-prompt backgrounds with the fake-factor method

1885 Events with one prompt lepton produced in association with hadronic jets can pass the event selection
 1886 if a jet is misidentified as a charged lepton or if a non-prompt lepton from the decay of a heavy
 1887 flavor particle (such as b - and c -hadrons) passes the signal lepton criteria. These misidentified jets
 1888 and non-prompt leptons are collectively referred to as *fake leptons*, or simply *fakes*. The rate at
 1889 which a fake lepton is misidentified is generally not modelled well enough by the MC to accurately
 1890 estimate their contributions directly from simulation. Therefore, a data-driven technique called the

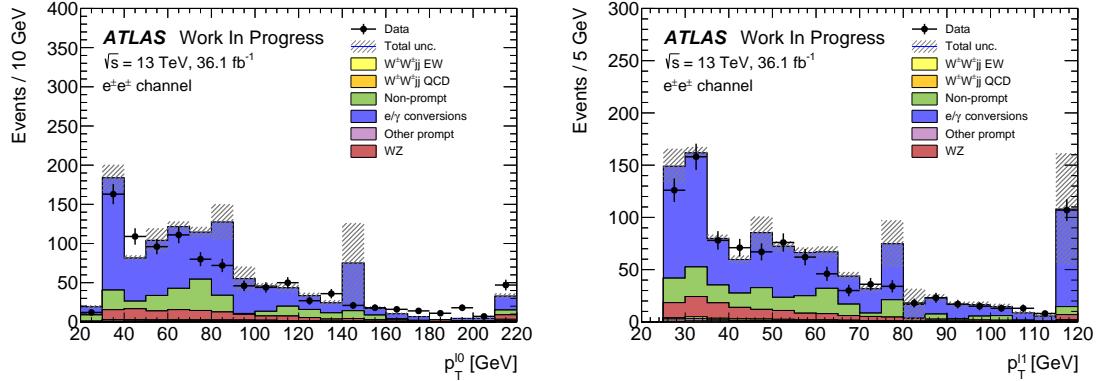


Figure 5.12: p_T distributions for the leading (left) and subleading (right) electron for the ee channel in the same-sign inclusive VR. In these plots, the cut requiring m_{ee} to fall within the Z mass window has been inverted in order to test the modelling away from the Z peak.

1891 *fake-factor* is used to estimate the size and shape of background processes from fake leptons. In
 1892 this analysis, a new modification to the fake-factor is used involving the particle isolation variables;
 1893 the method is outlined in the context of the *default* fake-factor in Section 5.3.4.1, and the modified
 1894 fake-factor is outlined in Section 5.3.4.2.

1895 5.3.4.1 Overview of the default fake-factor method

1896 The goal of the fake-factor method is to measure the fake rate from real collision events in a region
 1897 enriched in fake leptons and use it to estimate the size of the fake lepton background in a chosen
 1898 signal or control region. This is done by creating two samples using different lepton definitions:

- 1899 1. The *nominal* sample is made up of leptons passing the signal selection.
 - 1900 2. The *loose* sample is made up of leptons that fail the signal selection while still passing a
 1901 loosened set of criteria. This sample is enriched in fake leptons and is orthogonal to the set of
 1902 signal leptons.
- 1903 Using the sets of nominal and loose leptons, a fake-factor f can be calculated in a region enriched
 1904 in processes that are prone to producing fake leptons:

$$f = \frac{N_{\text{nominal}}}{N_{\text{loose}}} \quad (5.6)$$

1905 Since the fake rate is not expected to be constant over the entire phase space, the fake-factor can
 1906 be divided into bins:

$$f(b) = \frac{N_{\text{nominal}}(b)}{N_{\text{loose}}(b)} \quad (5.7)$$

1907 where b represents the bin number. In this analysis, the fake-factor is binned in lepton p_T .

1908 In order to estimate the fake background contribution in a given signal or control region, the
 1909 fake-factor is applied to a second control region with a selection identical to the region of interest
 1910 except one of the leptons required to satisfy the loose criteria. The region for which the background
 1911 is estimated contains two nominal leptons and is referred to as *nominal+nominal* (*NN*), and the
 1912 associated control region where the fake-factor is applied contains one nominal and one loose lepton
 1913 and is referred to as *nominal+loose* (*NL*). The fake background in a *NN* region can then be
 1914 calculated as:

$$N_{NN}^{\text{fake bkg.}} = \sum_b f(b) N_{NL}(b) \quad (5.8)$$

1915 Backgrounds containing two prompt leptons can also enter the *NL* region if one of the leptons
 1916 passes the nominal selection and the other passes the loose selection. Since the fake-factor method
 1917 estimates the fake background by scaling the amount of non-prompt events in the *NL* region, if these
 1918 prompt contributions are not removed, they will be included in the scaling and the background
 1919 will be overpredicted. The final estimate of the fake background becomes:

$$N_{NN}^{\text{fake bkg.}} = \sum_b f(b) (N_{NL}(b) - N_{NL}^{\text{prompt}}(b)) \quad (5.9)$$

1920 A visual representation of the fake background estimation process is shown in Figure 5.13.

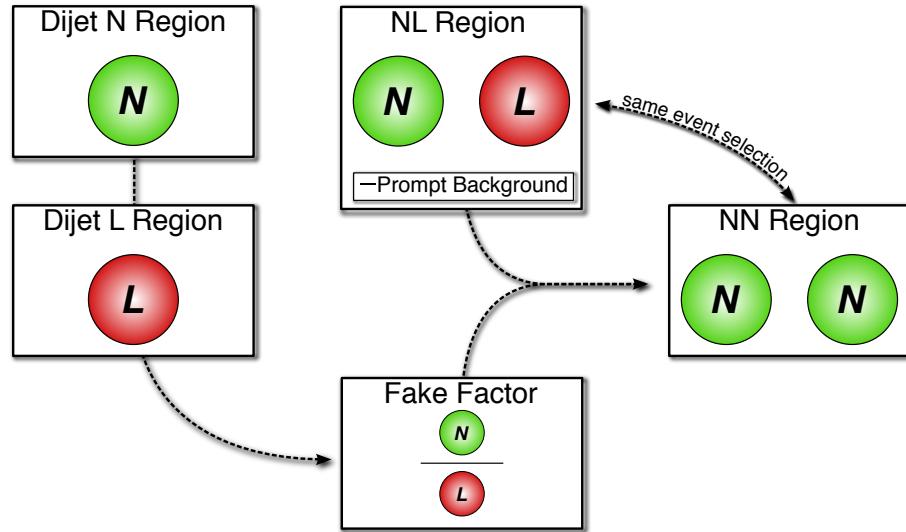


Figure 5.13: Graphical representation of how the fake factor method is used to estimate the fake background in a given *NN* region.

1921 **5.3.4.2 The fake-factor with p_T^{cone}**

1922 When a jet produces a non-prompt lepton, that lepton only carries a fraction of the underlying jet's
 1923 total momentum. Due to the isolation cut applied to the nominal leptons, they typically carry a
 1924 much larger percentage of the underlying jet momentum than the loose leptons. Since the isolation
 1925 essentially sets a limit on the amount of detector activity allowed around the lepton, if other nearby
 1926 particles carried a significant amount of momentum, the lepton would likely fail this cut.

1927 This discrepancy in the underlying jet momentum fraction can cause problems in the calculation
 1928 of the fake-factor f . Consider the case where two separate events have jets of identical momentum,
 1929 but one produces a non-prompt lepton that passes the nominal selection, and the other produces a
 1930 non-prompt lepton that passes the loose selection. The loose lepton on average will have lower p_T
 1931 than the nominal lepton despite both originating from jets with the same momentum. This can be
 1932 seen explicitly when comparing the p_T of a muon to its associated truth jet:

$$\Delta p_T(\mu, j) = \frac{p_T(j) - p_T(\mu)}{p_T(j) + p_T(\mu)} \quad (5.10)$$

1933 Since muons are not included in the jet reconstruction algorithm, Δp_T approximates the momentum
 1934 of the muon compared to the rest of the jet. For muons that carry more than 50% of the jet's
 1935 momentum, Δp_T will be negative and vice-versa. The Δp_T distributions for nominal and loose
 1936 muons in $t\bar{t}$ MC events is shown Figure 5.14, where a 50 GeV jet on average corresponds to a
 1937 35 GeV nominal muon and a 20 GeV loose muon¹⁸.

1938 Since the default fake-factor defined in Equation 5.7 is binned in lepton p_T , within a given bin,
 1939 the underlying jet p_T spectrum can differ substantially between the numerator and the denominator.
 1940 Additionally, these differences can vary depending on the process producing the non-prompt leptons
 1941 or on the specific kinematic selections of the signal or control regions where the fake-factor is applied.

1942 Fortunately, the majority of the jet momentum not carried by the non-prompt lepton (excluding
 1943 neutrinos) can be recovered using isolation variables. A track-based isolation is chosen, referred to
 1944 as p_T^{cone} , and it contains the sum of the p_T of all particle tracks originating from the primary vertex
 1945 within a cone of $\Delta R < 0.3$ around the lepton. Thus, the sample of loose leptons in the denominator
 1946 of the fake-factor calculation is binned in $p_T + p_T^{\text{cone}}$ rather than simply lepton p_T . Adding the
 1947 isolation cone greatly reduces the difference in the fraction of the underlying jet momentum carried
 1948 by the nominal and loose leptons. To check this, a new Δp_T is calculated between a lepton and its

¹⁸To better illustrate the point, here the muon is added back into the jet p_T , and the corresponding muon p_T is obtained via $\Delta p_T(\mu, j) = \frac{(p_T(j) - p_T\mu) - p_T(\mu)}{(p_T(j) - p_T\mu) + p_T(\mu)} = \frac{p_T(j) - 2p_T(\mu)}{p_T(j)}$.

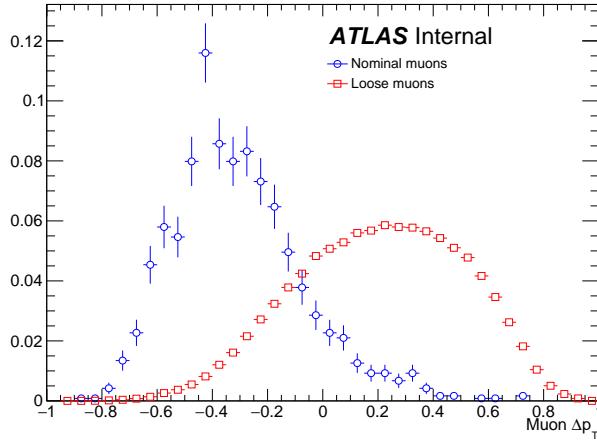


Figure 5.14: Δp_T distributions for nominal (blue) and loose (red) muons in simulated $t\bar{t}$ events. Each muon has been matched to a truth-level jet. Both distributions are normalized to unit area.

1949 matched truth jet, where the truth jet p_T has been corrected to include all muons within a cone of
 1950 $\Delta R < 0.4$:

$$p_T(j) = p_T(j_{\text{truth}}) + \sum_{\Delta R < 0.4} p_T(\mu_{\text{truth}}) \quad (5.11)$$

1951 The Δp_T distributions comparing p_T and $p_T + p_T^{\text{cone}}$ for nominal and loose leptons using the corrected
 1952 jet p_T are found in Figure 5.15, and better agreement is seen between the numerator (nominal) and
 1953 denominator (loose with $p_T + p_T^{\text{cone}}$) distributions.

1954 The numerator remains binned in lepton p_T , due to the fact that it is meant to mirror the signal
 1955 region as closely as possible, and the signal lepton selection does not use $p_T + p_T^{\text{cone}}$. The impact of
 1956 this is expected to be negligible due to the p_T^{cone} isolation being small for signal leptons, as shown
 1957 for muons in Figure 5.16. Finally, the fake-factor f becomes:

$$f(b) = \frac{N_{\text{nominal}}(b(p_T))}{N_{\text{loose}}(b(p_T + p_T^{\text{cone}}))} \quad (5.12)$$

1958 5.3.4.3 Application of the fake-factor

1959 The fake-factor itself is measured from a sample data events passing a dijet selection requiring
 1960 exactly one lepton (either passing the nominal or loose selections) and at least one jet. The leading
 1961 jet must also be b -tagged and approximately back-to-back with the lepton in order to enhance non-
 1962 prompt lepton contributions while reducing contributions from processes involving W and Z bosons.

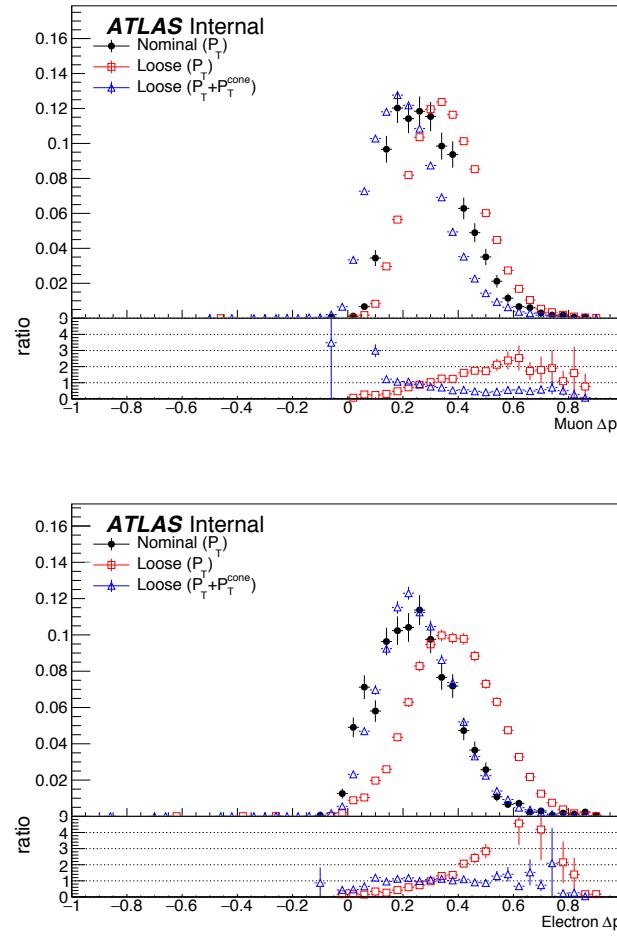


Figure 5.15: Δp_T distributions for muons (top) and electrons (bottom) in simulated $t\bar{t}$ events. Each lepton has been matched to a truth-level jet, and that truth jet has had its p_T corrected to include all truth muons within a cone of $\Delta R < 0.4$. The nominal leptons are in black. Δp_T is calculated for the loose leptons using p_T (red) and $p_T + p_T^{\text{cone}}$ (blue).

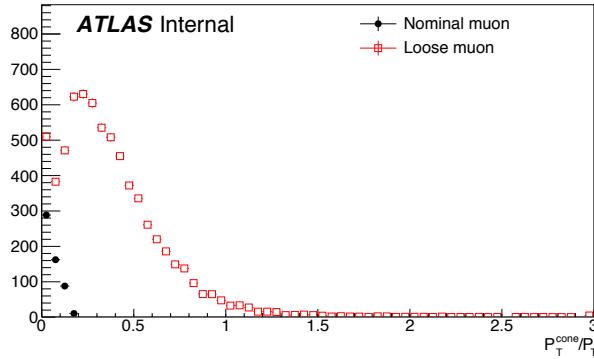


Figure 5.16: Distributions of p_T^{cone}/p_T for nominal (black) and loose (red) muons in simulated $t\bar{t}$ events.

1963 W boson events are further suppressed by requiring the sum of the E_T^{miss} and the transverse mass
 1964 of the lepton to be less than 50 GeV. The full event selection for the dijet region is summarized in
 1965 Table 5.13.

Dijet event selection	
Event preselection	
Exactly one lepton with $p_T > 15$ GeV	
$N_{\text{jet}} > 0$	
Leading jet is b -tagged	
$p_T^{\text{lead. jet}} > 25$ GeV	
$p_T^{\text{lead. jet}} > 30$ GeV if $ \eta_j > 2.5$	
$ \Delta\phi(l, \text{lead. jet}) > 2.8$	
$m_T(l, E_T^{\text{miss}}) + E_T^{\text{miss}} < 50$ GeV	

Table 5.13: Event selection for the dijet region used for calculating the fake-factor. The selected lepton can pass either the nominal (signal) or loose selections. In the case of the nominal leptons, the $p_T > 27$ GeV requirement is replaced with $p_T > 15$ GeV.

1966 The numerator sample is constructed from dijet events in which the lepton passes the nominal
 1967 (signal) selection and is binned in the lepton p_T . Similarly, the denominator sample is made up of
 1968 the remaining dijet events where the lepton passes the loose selection and is binned in the lepton
 1969 $p_T + p_T^{\text{cone}}$. The nominal and loose leptons pass the signal selection¹⁹ and loose selection, respectively,
 1970 defined earlier in Table 5.3 for muons and Table 5.4 for electrons. Backgrounds from W +jets,
 1971 Z +jets, $t\bar{t}$, and single top processes are estimated from MC simulations requiring one lepton to be
 1972 prompt using the truth information; these contributions are subtracted from the dijet data. The

¹⁹The $p_T > 27$ GeV cut in the signal lepton selection is dropped in favor of the $p_T > 15$ GeV requirement in the dijet selection.

fake-factor is then calculated using Equation 5.12 for muons and for central and forward electrons separately. The muon fake-factor is shown in Figure 5.17, and the two electron fake-factors are shown in Figure 5.18. The numerical values of the fake-factors, including their systematic uncertainties which will be discussed in Section 5.3.4.4, are listed in Table 5.14.

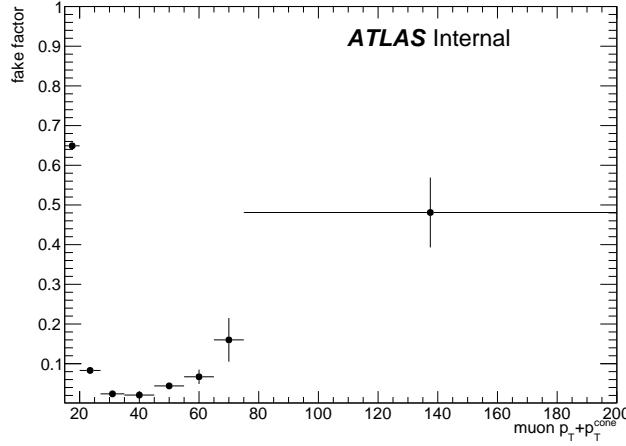


Figure 5.17: The measured fake-factor as a function of muon $p_T + p_T^{\text{cone}}$. The error bars represent the statistical uncertainty only.

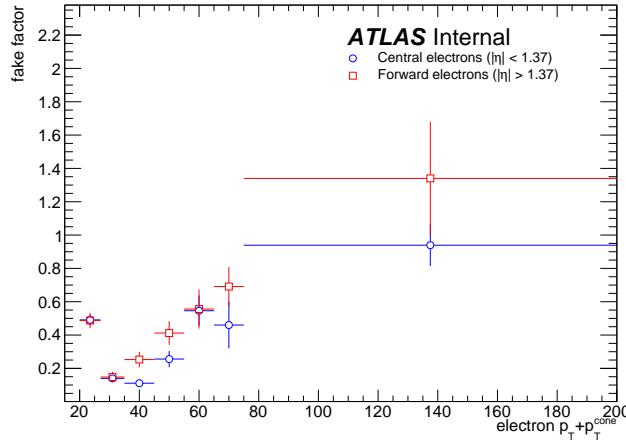


Figure 5.18: The measured fake-factor as a function of electron $p_T + p_T^{\text{cone}}$ in the central ($|\eta| < 1.37$, blue) and forward ($|\eta| > 1.37$, red) regions of the detector. The error bars represent the statistical uncertainty only.

In order to properly account for the denominator being binned in $p_T + p_T^{\text{cone}}$, special care needs

1978 to be taken when estimating the fake background from the *NL* regions. For the purposes of the
 1979 fake-factor calculation, it is perhaps more intuitive to consider a loose *object* with $p_T = p_T + p_T^{\text{cone}}$
 1980 instead of simply a loose *lepton*, as the lepton and the underlying jet are treated as a whole with this
 1981 method. When the lepton p_T cuts required by a particular signal or control region are applied to
 1982 nominal and loose leptons, the cut is applied to the p_T of the nominal lepton and to the $p_T + p_T^{\text{cone}}$
 1983 of the loose object. Similarly, when looking up the fake-factor weight for a given *NL* event, the
 1984 value taken from the bin corresponding to the $p_T + p_T^{\text{cone}}$ of the loose object. Finally, when applying
 1985 the weight to the event, $p_T + p_T^{\text{cone}}$ is assigned as the p_T of the loose object. Figure 5.19 contains a
 1986 graphical representation of this procedure.

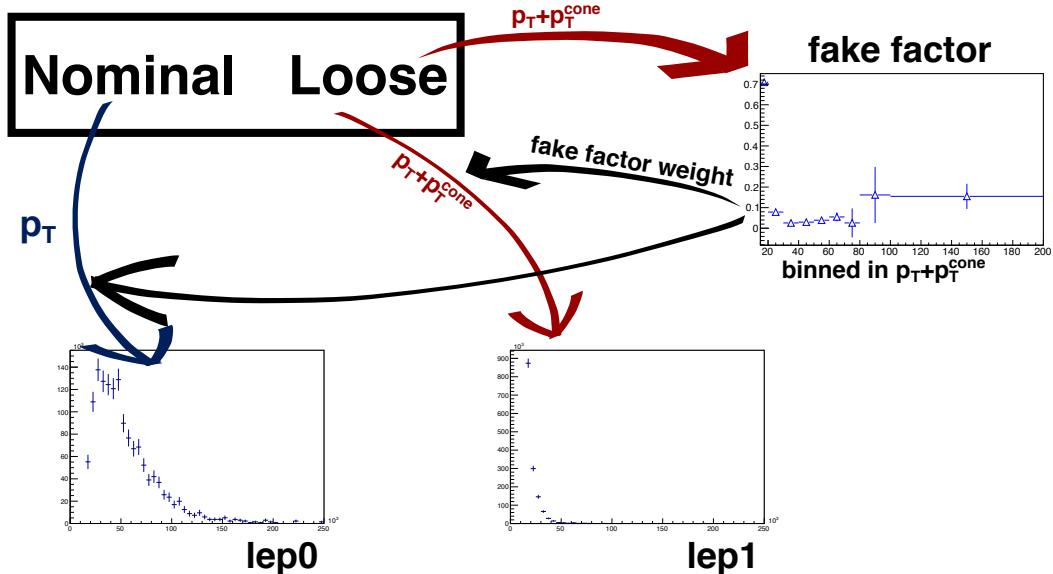


Figure 5.19: Graphical representation of the fake-factor application using $p_T + p_T^{\text{cone}}$. The value of $p_T + p_T^{\text{cone}}$ for the loose lepton is used to “look up” the fake-factor weight which is then applied to the event. The loose lepton’s p_T becomes $p_T + p_T^{\text{cone}}$ for the purpose of the fake background estimation.
 TODO: Update figure to match style of Fig. 5.13.

1987 Finally, it should be noted that the addition of p_T^{cone} to the loose object may cause the loose
 1988 leptons in the denominator sample to migrate into higher bins. This results in an overall decrease in
 1989 the number of loose objects in the lower $p_T + p_T^{\text{cone}}$ bins due to there not being additional leptons at
 1990 lower p_T to replace them. Since the fake-factor is a ratio of the number of events in a bin, this effect
 1991 causes the first few bins of the fake-factor to increase, as can be seen clearly in Figure 5.17. However,
 1992 the signal and control regions (and their corresponding *NL* regions) contain a $p_T > 27$ GeV cut that
 1993 prevents these migrations from negatively impacting the fake estimation.

1994 5.3.4.4 Systematic uncertainties

1995 Four sources of systematic uncertainty are considered: the dijet event selection, the prompt back-
1996 ground subtraction, the jet flavor composition, and residual dependence on the underlying jet p_T
1997 spectrum. In order to measure the impact of these systematics, new fake-factors are computed
1998 with each of the systematic variations and the differences from the nominal values are taken as the
1999 uncertainty.

- 2000 1. In order to estimate uncertainties due to the dijet selection, the cut on $M_T + E_T^{\text{miss}}$ is varied
2001 by ± 5 GeV, the jet-lepton separation $\Delta\phi(l, j)$ by ± 0.1 , and the jet p_T cut by $+5$ GeV.
- 2002 2. To estimate the systematic uncertainty on the prompt background subtraction, the MC pre-
2003 dictions in a $W+\text{jets}$ control region is compared to data. The discrepancy between data and
2004 MC is found to be approximately 10% [83]. Therefore, the prompt background used for the
2005 subtraction is scaled up and down by $\pm 10\%$.
- 2006 3. The difference in the jet flavor composition between the dijet events and the events in the
2007 NL regions can affect the accuracy of the fake background estimation. The dijet sample is
2008 dominated by light jets, while the NL regions tend to be dominated by heavy flavor from $t\bar{t}$.
2009 To account for this, the fake-factor is computed with a b -jet veto.
- 2010 4. To measure any residual dependence on the underlying jet p_T spectrum, the leading jet p_T
2011 distribution is reweighted to match the p_T spectrum of truth jets that produce fake leptons
2012 in MC simulations. This results in an increase in the number of nominal and loose leptons at
2013 high momentum [83].

2014 5.3.4.5 Results of the fake-factor

2015 The fake background contribution in the signal region is estimated by applying the fake-factors
2016 to the equivalent NL region using Equation 5.9, where the fake-factor used corresponds to the
2017 flavor of the loose lepton in the event. As usual, the prompt background is subtracted from the
2018 NL events using MC simulation. Charge misidentification is handled using the same method as
2019 in Section 5.3.3, with an additional set of charge flip rates calculated for loose leptons. The fake
2020 background yields in the signal region are listed in Table 5.15. An overall uncertainty of 50% is
2021 assigned to the fake background estimation in $\mu^\pm\mu^\pm$ events, and between 40% to 90% for $e^\pm e^\pm$ and
2022 $\mu^\pm e^\pm$ events, including both statistical and systematic effects.

fake-factor	$p_T[15, 20]$	$p_T[20, 27]$	$p_T[27, 35]$	$p_T[35, 45]$	$p_T[45, 55]$	$p_T[55, 65]$	$p_T[65, 75]$	$p_T[75, 200]$
nominal	0.649 ± 0.007	0.083 ± 0.002	0.024 ± 0.002	0.021 ± 0.003	0.044 ± 0.007	0.067 ± 0.018	0.160 ± 0.055	0.481 ± 0.088
MT+MET	0.649 ± 0.007	0.082 ± 0.002	0.082 ± 0.002	0.020 ± 0.003	0.045 ± 0.007	0.068 ± 0.018	0.207 ± 0.062	0.523 ± 0.086
$\Delta\phi(\ell, j)$	0.645 ± 0.008	0.083 ± 0.003	0.024 ± 0.002	0.021 ± 0.004	0.045 ± 0.008	0.064 ± 0.021	0.064 ± 0.058	0.438 ± 0.092
Jet p_T	0.650 ± 0.007	0.083 ± 0.002	0.024 ± 0.002	0.021 ± 0.003	0.045 ± 0.007	0.069 ± 0.018	0.159 ± 0.018	0.481 ± 0.088
$N_{b\text{-jet}} = 0$	0.724 ± 0.003	0.094 ± 0.001	0.035 ± 0.001	0.025 ± 0.002	0.022 ± 0.004	0.060 ± 0.015	0.026 ± 0.053	0.044 ± 0.134
Bkg. subtraction	0.648 ± 0.007	0.083 ± 0.002	0.024 ± 0.002	0.019 ± 0.003	0.037 ± 0.007	0.044 ± 0.019	0.096 ± 0.062	0.370 ± 0.082
Jet p_T Reweighting	0.649 ± 0.007	0.083 ± 0.002	0.025 ± 0.002	0.022 ± 0.003	0.050 ± 0.007	0.090 ± 0.017	0.224 ± 0.052	0.591 ± 0.099

(a) fake-factor for muons.

fake-factor	$p_T[20, 27]$	$p_T[27, 35]$	$p_T[35, 45]$	$p_T[45, 55]$	$p_T[55, 65]$	$p_T[65, 75]$	$p_T[75, 200]$
nominal	0.491 ± 0.031	0.140 ± 0.020	0.111 ± 0.023	0.256 ± 0.049	0.546 ± 0.091	0.460 ± 0.140	0.939 ± 0.125
MT+MET	0.493 ± 0.030	0.138 ± 0.019	0.115 ± 0.022	0.261 ± 0.045	0.559 ± 0.084	0.656 ± 0.091	0.802 ± 0.016
$\Delta\phi(\ell, j)$	0.488 ± 0.032	0.137 ± 0.020	0.110 ± 0.025	0.283 ± 0.053	0.503 ± 0.097	0.351 ± 0.149	1.117 ± 0.255
Jet p_T	0.489 ± 0.035	0.134 ± 0.021	0.105 ± 0.025	0.224 ± 0.048	0.593 ± 0.093	0.356 ± 0.144	0.928 ± 0.177
$N_{b\text{-jet}} = 0$	0.506 ± 0.029	0.140 ± 0.018	0.111 ± 0.022	0.260 ± 0.046	0.545 ± 0.084	0.546 ± 0.120	0.882 ± 0.103
Bkg. subtraction	0.493 ± 0.032	0.146 ± 0.021	0.115 ± 0.024	0.259 ± 0.049	0.550 ± 0.091	0.460 ± 0.140	0.939 ± 0.125
Jet p_T Reweighting	0.387 ± 0.009	0.130 ± 0.008	0.321 ± 0.012	0.473 ± 0.015	0.716 ± 0.180	0.716 ± 0.180	0.716 ± 0.180

(b) fake-factor for central electrons ($|\eta| < 1.37$).

fake-factor	$p_T[20, 27]$	$p_T[27, 35]$	$p_T[35, 45]$	$p_T[45, 55]$	$p_T[55, 65]$	$p_T[65, 75]$	$p_T[75, 200]$
nominal	0.487 ± 0.046	0.148 ± 0.031	0.253 ± 0.046	0.412 ± 0.071	0.556 ± 0.117	0.691 ± 0.117	1.340 ± 0.340
MT+MET	0.483 ± 0.045	0.152 ± 0.031	0.241 ± 0.043	0.443 ± 0.070	0.565 ± 0.106	0.668 ± 0.117	1.075 ± 0.189
$\Delta\phi(\ell, j)$	0.495 ± 0.047	0.156 ± 0.033	0.271 ± 0.052	0.364 ± 0.074	0.664 ± 0.107	0.749 ± 0.056	0.885 ± 0.084
Jet p_T	0.471 ± 0.051	0.158 ± 0.035	0.247 ± 0.051	0.474 ± 0.085	0.283 ± 0.107	0.546 ± 0.149	1.189 ± 0.266
$N_{b\text{-jet}} = 0$	0.478 ± 0.042	0.170 ± 0.031	0.274 ± 0.046	0.389 ± 0.066	0.645 ± 0.104	0.757 ± 0.102	1.319 ± 0.326
Bkg. subtraction	0.523 ± 0.048	0.149 ± 0.033	0.235 ± 0.045	0.429 ± 0.073	0.555 ± 0.117	0.691 ± 0.117	1.340 ± 0.340
Jet p_T Reweighting	0.525 ± 0.011	0.234 ± 0.013	0.644 ± 0.016	0.710 ± 0.014	0.274 ± 0.316	0.274 ± 0.316	0.274 ± 0.316

(c) fake-factor for forward electrons ($1.37 < |\eta|$).Table 5.14: Values of the fake-factor in each p_T bin and for each individual systematic source.

	estimated yield	f_e stat. up	f_e stat. dn	f_e syst. up	f_e syst. dn	f_μ stat. up	f_μ stat. dn	f_μ syst. up	f_μ syst. dn
$e^\pm e^\pm$	11.42 ± 3.13	—	—	—	—	—	—	—	—
$\mu^\pm \mu^\pm$	4.82 ± 0.77	—	—	—	—	0.65	-0.65	3.64	-0.61
$\mu^\pm e^\pm$	37.08 ± 5.16	4.90	-4.90	5.59	-14.34	1.39	-1.39	16.10	-1.98

Table 5.15: Estimated yields for the fake lepton background. The estimated yield is shown in the first column together with the statistical uncertainty followed by the systematic uncertainties from variations of the the fake-factors within their statistical (stat.) and systematic (syst.) uncertainties. The labels f_e and f_μ indicate the fake-factors for electrons and muons, respectively.

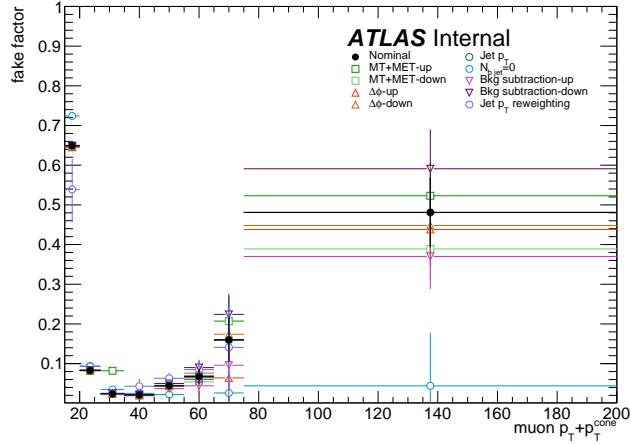


Figure 5.20: Systematic variations in the fake-factor as a function of muon $p_T + p_T^{\text{cone}}$. The individual fake-factors obtained for each systematic variation are displayed with their statistical uncertainties.

2023 5.3.4.6 Validation of the fake-factor

2024 The accuracy of the fake-factor method is tested in several validation regions, the most sensitive
 2025 of which is the same-sign top fakes VR (SS top VR), defined in Table 5.16. This region inverts
 2026 the signal region's b -jet veto to accept events with exactly one b -jet. Due to this requirement, the
 2027 dominant source of events comes from the $t\bar{t}$ process where a b -jet fakes an isolated lepton. The
 2028 distribution of the subleading lepton p_T in this VR is shown in Figure 5.22 for all lepton flavor
 2029 combinations. There is good agreement between the data and the prediction, even when only taking
 2030 into account the statistical uncertainty and not the large systematic uncertainties assigned to the
 2031 fake estimation.

Same-sign top fakes VR
Exactly 2 same-sign signal leptons
$p_T > 27$ GeV for both leptons
$m_{ll} > 20$ GeV
$ m_{ee} - m_Z > 15$ GeV ($e^\pm e^\pm$ -channel only)
$N_{b\text{-jet}} = 1$
$N_{\text{jet}} \geq 2$
Leading jet $p_T > 65$ GeV
Subleading jet $p_T > 35$ GeV

Table 5.16: Selection criteria for the same-sign top fakes validation region.

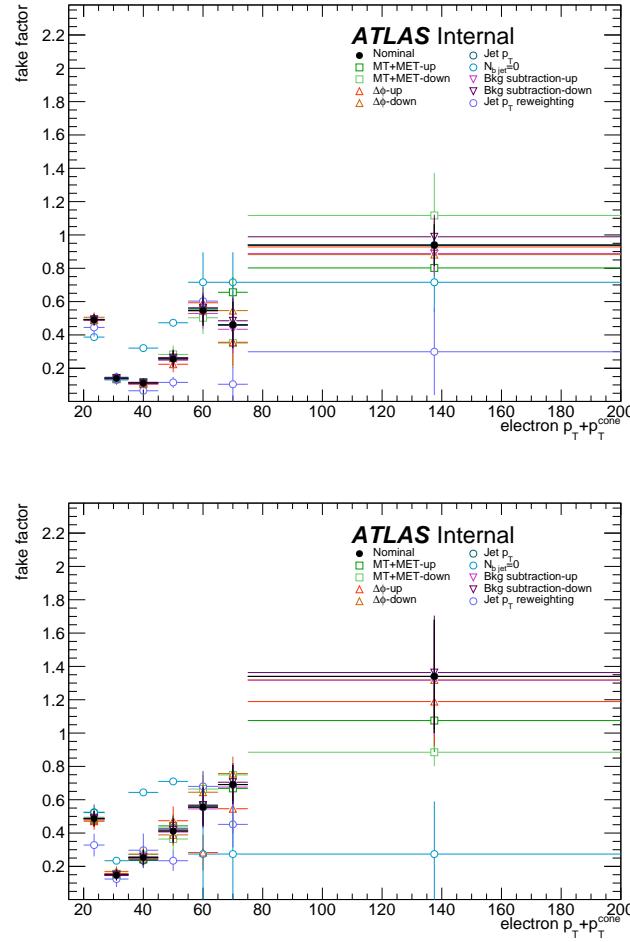


Figure 5.21: Systematic variations in the fake-factor as a function of electron $p_T + p_T^{\text{cone}}$ in the central ($|\eta| < 1.37$, top) and forward ($|\eta| > 1.37$, bottom) regions of the detector. The individual fake-factors obtained for each systematic variation are displayed with their statistical uncertainties.

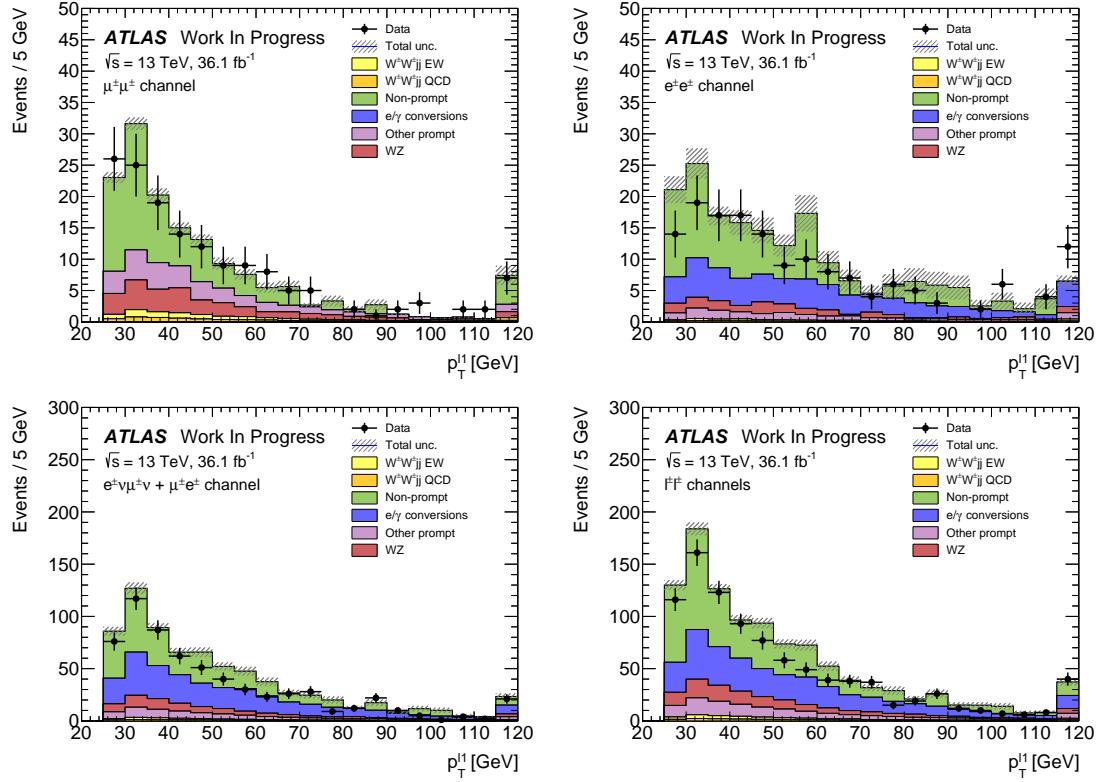


Figure 5.22: Distributions of the subleading lepton p_T in the same-sign top fakes VR for $\mu^\pm\mu^\pm$ events (top right), $e^\pm e^\pm$ events (top left), $\mu^\pm e^\pm$ events (bottom left), and all events combined (bottom right). All errors are statistical only.

2032 5.3.5 Reduction of WZ background using custom overlap removal

2033 The dominant source of prompt background in this analysis comes from WZ events where both
 2034 bosons decay leptonically. Traditionally, the background is dealt with by imposing a veto on any
 2035 event with a third lepton passing some loose identification criteria (the so-called *trilepton veto*).
 2036 In the case of this analysis, if one or more leptons in addition to the two signal leptons pass the
 2037 preselection criteria, the event is rejected. However, WZ events can still enter the signal region if
 2038 one of the leptons fails the preselection or falls outside of the detector’s acceptance.

2039 In order to understand the sources of WZ events that are not removed by the trilepton veto, a
 2040 study was performed on truth-level leptons in $W^\pm W^\pm jj$ and WZ MC samples. Events with three
 2041 truth leptons were selected, and each was matched to its reconstruction-level partner by finding the
 2042 closest $\Delta R(\text{truth}, \text{reco})$ and $\Delta p_T(\text{truth}, \text{reco})$ match. For events surviving the trilepton veto, the
 2043 two signal leptons were removed, and the remaining leptons represent real leptons that failed to

be selected for the veto. Between 40-50% of these leptons fall outside of the eta acceptance of the analysis (see Figure 5.23) and are unrecoverable. The second largest source of leptons failing the preselection is the OR, defined in Section 5.2.1.4. The standard OR procedure appears to be too aggressive in removing leptons in favor of jets, causing many three lepton events to “lose” their third lepton and pass the trilepton veto. Therefore a *custom OR* is investigated which would replace the standard OR in the preselection and allow for better WZ rejection by removing fewer third leptons.

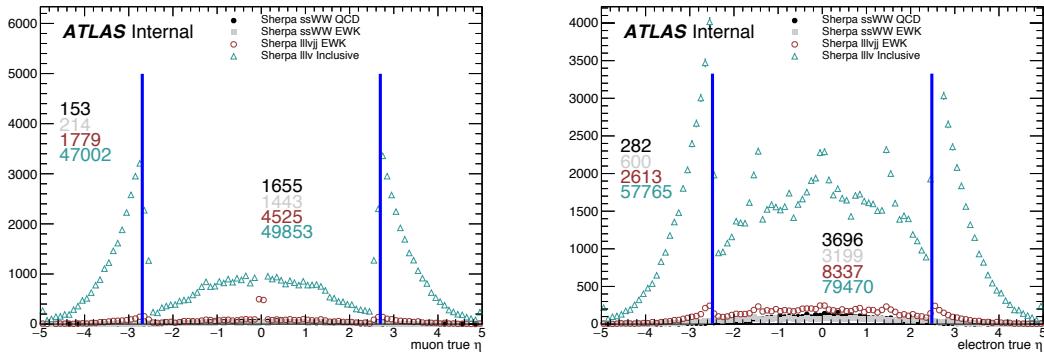


Figure 5.23: Pseudorapidity (η) distributions of truth muons (top) and electrons (bottom) for Sherpa $W^\pm W^\pm jj$ and WZ MC samples. The blue vertical lines represent the allowed η range for each lepton flavor. The numbers correspond to the number of raw MC events that fall within and outside of the allowed η range for each MC sample.

In order to construct this custom OR, a new quantity is defined between a lepton (l) and a nearby jet (j)

$$p_{\text{T},\text{ratio}}(l,j) = \frac{p_{\text{T}}l}{p_{\text{T}}j} \quad (5.13)$$

which, along with $\Delta R(l,j)$, will make up the custom OR criteria. The idea behind including $p_{\text{T},\text{ratio}}$ is to be able to preferentially remove background leptons originating from jets (i.e. those that carry a low percentage of the total jet momentum) instead of removing *any* lepton near a jet. The distributions of $p_{\text{T},\text{ratio}}$ and the associated efficiency curves for muons and electrons can be found in Figures 5.24 and 5.26, respectively, and the distributions for $\Delta R(\mu,j)$ for muons can be found in Figure 5.25. Since all electrons have an associated jet in the calorimeters, the $\Delta R(e,j)$ variable is not a good quantity to use for this custom OR.

A working point for the Custom OR was chosen by requiring 90% signal retention for muons and 90% background rejection for electrons. The cut on electrons was allowed to be much tighter because the number of signal events with a third electron is considerably smaller than for muons. It should be emphasized that the signal events present in Figures 5.24-5.26 do not represent the full

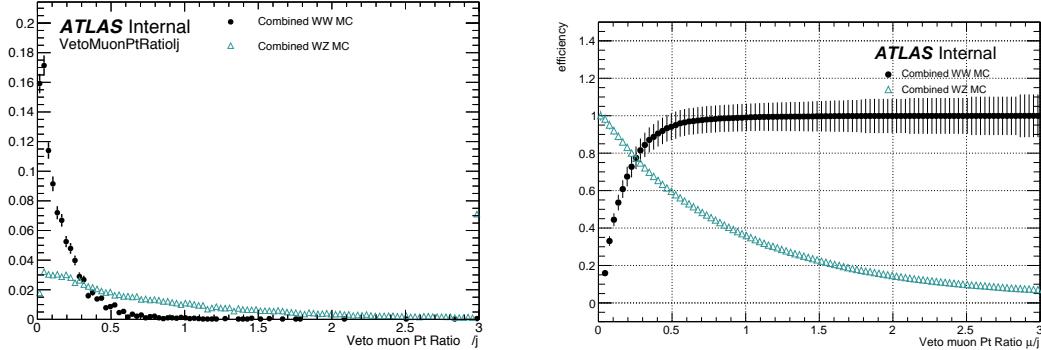


Figure 5.24: Distributions of $p_{T,\text{ratio}}(\mu, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and WZ background (teal) for truth-matched third muons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right where efficiency is defined as the percentage of total events that would pass a cut on $p_{T,\text{ratio}}(\mu, j)$ at a given value on the x -axis.

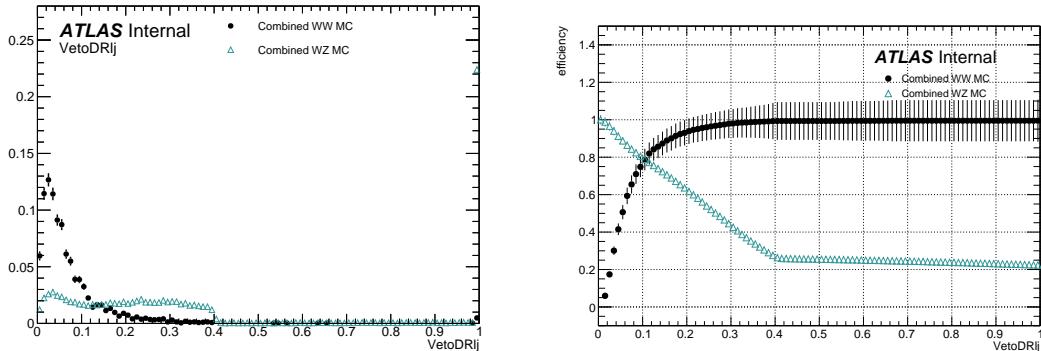


Figure 5.25: Distributions of $\Delta R(\mu, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and WZ background (teal) for truth-matched third muons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right where efficiency is defined as the percentage of total events that would pass a cut on $\Delta R(\mu, j)$ at a given value on the x -axis.

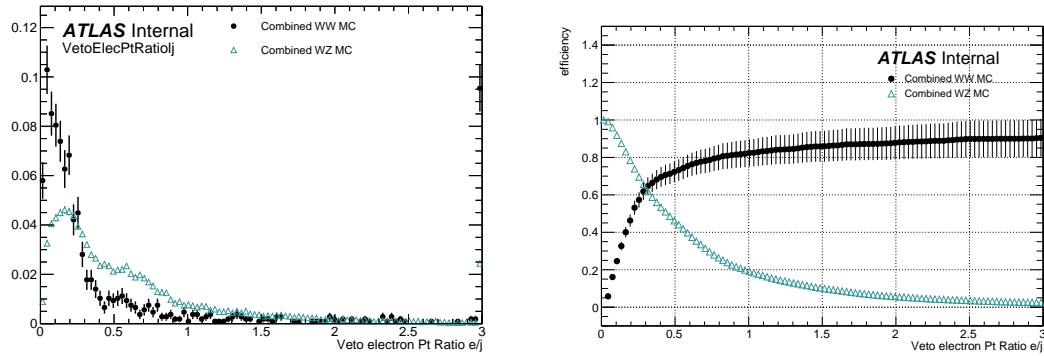


Figure 5.26: Distributions of $p_{T,\text{ratio}}(e,j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and WZ background (teal) for truth-matched third electrons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right where efficiency is defined as the percentage of total events that would pass a cut on $p_{T,\text{ratio}}(e,j)$ at a given value on the x -axis.

2063 set of signal events, but only those with a real third lepton (which must come from some source
 2064 other than the signal $W^\pm W^\pm jj$ process). For muons, a logical ‘or’ of $p_{T,\text{ratio}}(\mu,j)$ and $\Delta R(\mu,j)$ is
 2065 used to maximize the third lepton acceptance due to correlations between the quantities, as shown
 2066 in Figure 5.27; for electrons, only a cut on $p_{T,\text{ratio}}(e,j)$ is used. The Custom OR working point is
 2067 defined in Table 5.17.

Custom OR Definition	
Muons	$p_{T,\text{ratio}}(\mu,j) > 0.40$ or $\Delta R(\mu,j) > 0.15$
Electrons	$p_{T,\text{ratio}}(e,j) > 0.18$

Table 5.17: Custom OR definition. Leptons must pass this selection in order to be counted for the trilepton veto.

2068 Initial tests of the performance of the Custom OR yielded promising results, with approximately
 2069 20% reduction in WZ background compared to less than 2% signal loss in the signal region. Unfor-
 2070 tunately, due to differences between the primary analysis framework and the one used for testing,
 2071 in practice the gains in WZ rejection were not nearly as substantial, and ultimately the Custom
 2072 OR was not included in the final analysis. However, it is still a potentially useful tool for improving
 2073 background rejection based on lepton counting in analyses with overly aggressive OR procedures.

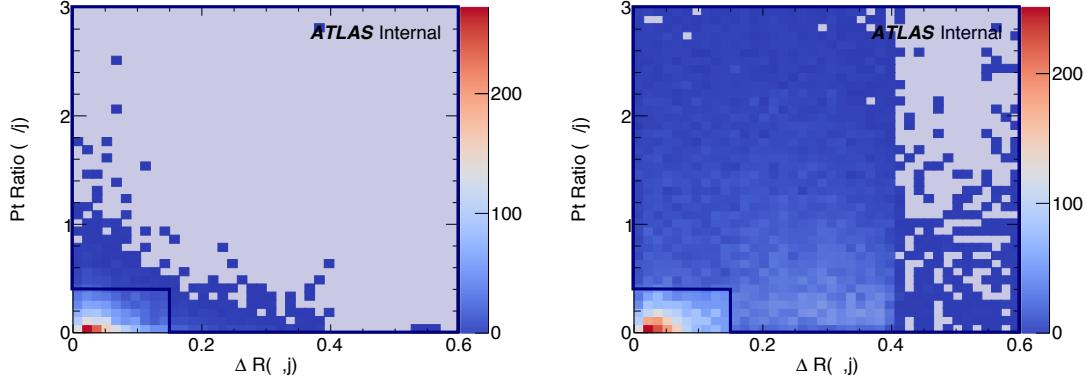


Figure 5.27: Two-dimensional plots of $p_{T,\text{ratio}}(\mu, j)$ vs $\Delta R(\mu, j)$ for truth-matched third muons in events that pass the trilepton veto for EWK and QCD $W^\pm W^\pm jj$ signal (left) and WZ background (right). The blue overlay indicates the area in which the third leptons will pass the custom OR and result in the event failing the trilepton veto.

2074 5.4 Cross section measurement

2075 The $W^\pm W^\pm jj$ EWK cross section is extracted from the signal region using a maximum-likelihood
 2076 fit applied simultaneously to four m_{jj} bins in the signal region as well as to the low- m_{jj} and WZ
 2077 control regions. For the fit and cross section extraction, the signal region is defined as in Table 5.8
 2078 with the dijet invariant mass requirement raised to $m_{jj} > 500$ GeV. The low- m_{jj} region is defined
 2079 to mirror the signal region exactly with the dijet invariant mass inverted to $200 < m_{jj} < 500$ GeV,
 2080 and the WZ control region is defined previously in Section 5.3.1.

2081 The signal and low- m_{jj} regions are split into six channels based on the flavor and charge of
 2082 the dilepton pair: $\mu^+\mu^+$, $\mu^-\mu^-$, μ^+e^+ , μ^-e^- , e^+e^+ , and e^-e^- . This split by charge increases the
 2083 sensitivity of the measurement due to the W^+/W^- charge asymmetry at hadron colliders favoring
 2084 the production of W^+ bosons [112]. Since the signal events contain two W bosons, the signal
 2085 strength compared to charge-symmetric backgrounds is much greater in the $++$ channels for both
 2086 charges combined. The WZ control region is included in the fit as a single bin ($l^\pm l^\mp l^\pm$).

2087 The maximum likelihood fit and cross section extractions are outlined in Sections 5.4.1 and
 2088 5.4.3, respectively. The results of the cross section measurement and of the analysis as a whole are
 2089 presented in Section 5.6.

2090 **5.4.1 Maximum likelihood fit**

2091 The number of predicted signal events in each channel c and m_{jj} bin b can be calculated from the SM
 2092 predicted total production cross section $\sigma_{\text{theo}}^{\text{tot}}$ scaled by the total integrated luminosity \mathcal{L} , the signal
 2093 acceptance \mathcal{A} , and the efficiency corrections $\mathcal{C}(\theta)$. Here θ represents the set of nuisance parameters
 2094 that parameterize the effects of each systematic uncertainty on the signal and background expec-
 2095 tations. The acceptance and efficiency corrections will be covered in more detail in Section 5.4.2.

2096

$$N_{cb}^{\text{sig}}(\theta) = \sigma_{\text{theo}}^{\text{tot}} \mathcal{A}_b \mathcal{C}_b(\theta) \mathcal{L} \quad (5.14)$$

2097 A signal strength parameter μ is defined as the ratio of the measured cross section to the SM
 2098 predicted cross section. The expected number of events in a given channel and bin can then be
 2099 expressed as the sum of the estimated background ($N_{cb}^{\text{bkg}}(\theta)$) and the number of predicted signal
 2100 events scaled by μ :

$$\begin{aligned} N_{cb}^{\text{exp}}(\theta) &= \mu N_{cb}^{\text{sig}}(\theta) + N_{cb}^{\text{bkg}}(\theta) \\ &= \mu \sigma_{\text{theo}}^{\text{tot}} \mathcal{A}_b \mathcal{C}_b(\theta) \mathcal{L} + N_{cb}^{\text{bkg}}(\theta) \end{aligned} \quad (5.15)$$

2101 The nuisance parameters are constrained by Gaussian probability distribution functions, and
 2102 the normalization of the WZ background mentioned in Section 5.3.1 is included in the fit as a free
 2103 parameter. The expected yields for signal and background processes are adjusted by the set of
 2104 nuisance parameters within the constraints of the systematic uncertainties. The yields after the fit
 2105 correspond to the value that best matches the observed data.

2106 The number of events per channel and bin after the fit can be written as a sum of the predicted
 2107 event yields for each sample s :

$$\nu_{cb}(\phi, \theta, \gamma_{cb}) = \gamma_{cb} \sum_s [\eta_{cs}(\theta) \phi_{cs}(\theta) \lambda] h_{cbs}(\theta) \quad (5.16)$$

2108 In this equation, the fitted number of events in a given channel and bin is obtained by weighting
 2109 the histogram of predicted yields h_{cbs} by the product of a given luminosity λ and any normaliza-
 2110 tion factors ϕ_{cs} that may be given for each channel and sample. The input histogram and the normal-
 2111 ization factors may depend on the nuisance parameters θ taking into account sources of systematic
 2112 uncertainty. Uncertainties on the normalization factors $\eta_{cs}(\theta)$ are also included. Finally, bin-by-bin
 2113 scale factors γ_{cb} are included to parameterize the statistical uncertainties of the MC predictions.

2114 The binned likelihood function is given by a product of Gaussian functions for the luminosity
 2115 and for the background uncertainties and a product of Poisson functions for the number of observed

2116 events in each bin and channel:

$$L(\mu|\theta) = \mathcal{G}(\mathcal{L}|\theta_{\mathcal{L}}, \sigma_{\mathcal{L}}) \cdot \prod_c \prod_b \mathcal{P}(N_{cb}^{\text{meas.}} | \nu_{cb}(\mu)) \prod_p \mathcal{G}(\theta_p^0 | \theta_p) \quad (5.17)$$

2117 where \mathcal{G} and \mathcal{P} are the Gaussian and Poisson functions, respectively. As before, \mathcal{L} represents the
 2118 integrated luminosity with uncertainty $\sigma_{\mathcal{L}}$ and associated nuisance parameter $\theta_{\mathcal{L}}$. The number of
 2119 measured events in a given bin and channel is represented by $N_{cb}^{\text{meas.}}$, and $\nu_{cb}(\mu)$ is the predicted
 2120 number of events defined in Equation 5.16 expressed as a function of the signal strength μ . Finally,
 2121 the set of nuisance parameters θ and any auxiliary measurements used to constrain them (θ^0) are
 2122 multiplied for each parameter p .

2123 The profile likelihood ratio is defined as

$$q_{\mu} = -2 \ln \frac{L(\mu, \hat{\theta}_{\mu})}{L(\hat{\mu}, \hat{\theta})} \quad (5.18)$$

2124 where $\hat{\mu}$ and $\hat{\theta}$ are the unconditional maximum likelihood estimates, and $\hat{\theta}$ is the conditional maxi-
 2125 mum likelihood estimate for a given value of μ . The fitted signal strength $\hat{\mu}$ is obtained by maximiz-
 2126 ing the likelihood function with respect to all parameters. The compatibility of the observed data
 2127 with the background-only hypothesis can then be calculated by setting $\mu = 0$. Observation of the
 2128 $W^{\pm}W^{\pm}jj$ EWK process is claimed if the data is found to be inconsistent with the background-only
 2129 hypothesis by more than 5σ .

2130 5.4.2 Definition of the fiducial volume

2131 Before extracting the cross section, it is necessary to define the fiducial volume, or the phase space
 2132 of measureable events. It is a subset of the total phase space defined by selection requirements
 2133 designed to mirror those applied in the analysis as closely as possible. The selection criteria for the
 2134 fiducial volume are listed in Table 5.18.

2135 In MC simulations the total phase space is generated, providing the total theoretical cross section
 2136 $\sigma_{\text{theo}}^{\text{tot}}$ and the total number of signal events $\mathcal{N}_{\text{sig}}^{\text{tot}}$ ²⁰. After applying the fiducial selection at truth
 2137 level, the total number of signal events in the fiducial region $\mathcal{N}_{\text{sig}}^{\text{fid}}$ is obtained. An acceptance factor
 2138 \mathcal{A} is used to represent the efficiency of events falling inside the fiducial region at truth level:

$$\mathcal{A} = \frac{\mathcal{N}_{\text{sig}}^{\text{fid}}}{\mathcal{N}_{\text{sig}}^{\text{tot}}} \quad (5.19)$$

²⁰For the purpose of clarity, the number of events at truth level is represented by a script \mathcal{N} , and the number of events at reconstruction level uses a regular N .

Fiducial region selection	
Lepton selection	Two prompt leptons (e, μ) $p_T > 27$ GeV and $ \eta < 2.5$ for both leptons Both leptons with the same electric charge Dilepton invariant mass $m_{ll} > 20$ GeV Dilepton separation $\Delta R(ll) > 0.3$
Missing transverse energy	Two neutrino system with $p_T^{\nu\nu} > 30$ GeV
Jet selection	At least two jets Leading jet $p_T > 65$ GeV Subleading jet $p_T > 35$ GeV Leading and subleading jet $ \eta < 4.5$ Jet-lepton separation $\Delta R(l, j) > 0.3$ Dijet invariant mass $m_{jj} > 500$ GeV Dijet separation $\Delta y_{jj} > 2.0$

Table 5.18: Definition of the fiducial volume.

2139 A correction factor \mathcal{C} is also necessary to translate from the truth level fiducial volume to the
 2140 reconstruction level signal region and is defined in terms of the number of reconstruction level MC
 2141 events in the signal region $N_{\text{sig},\text{MC}}^{\text{SR}}$:

$$\mathcal{C} = \frac{N_{\text{sig},\text{MC}}^{\text{SR}}}{N_{\text{sig}}^{\text{fid}}} \quad (5.20)$$

2142 Since the fit is binned in m_{jj} , the acceptance and efficiency correction factors must be as well.
 2143 Therefore, \mathcal{A}_i and \mathcal{C}_{ij} are written in terms of truth m_{jj} bins i and reconstruction m_{jj} bins j . A
 2144 graphical representation of these regions and the use of the acceptance and correction factors can
 2145 be seen in Figure 5.28.

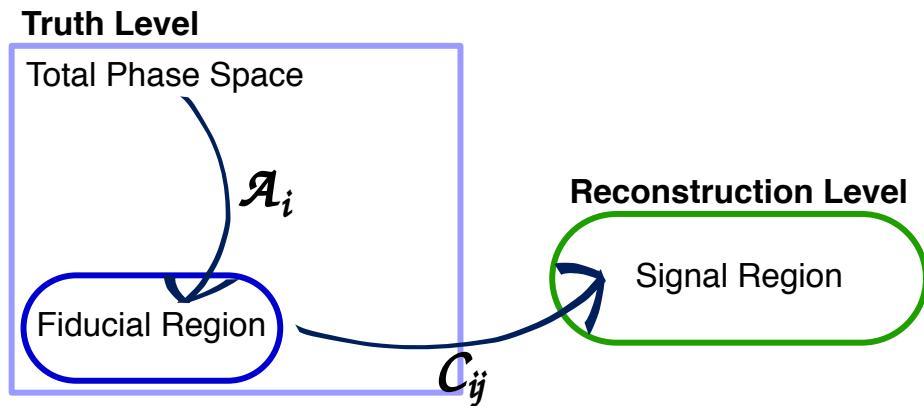


Figure 5.28: Visual representation of the different kinematic regions relevant to the cross section measurement. The acceptance factor \mathcal{A} converts from the truth level total phase space to the truth level fiducial region, and the efficiency correction \mathcal{C} translates the fiducial region into the reconstruction level signal region.

2146 **5.4.3 Cross section extraction**

2147 The $W^\pm W^\pm jj$ EWK fiducial cross section is measured using the signal strength parameter μ that is
 2148 determined by the maximum likelihood fit. This parameter is dependent on the nuisance parameters
 2149 θ and can be written explicitly in terms of the measured and theoretical cross sections as:

$$\mu(\theta) = \frac{\sigma_{\text{meas}}^{\text{SR}}}{\sigma_{\text{theo}}^{\text{SR}}} \quad (5.21)$$

2150 In the simple case with only one bin, the equation for the total number of expected events in the
 2151 signal region first introduced in Equation 5.15 can be written as:

$$N_{\text{exp}}^{\text{SR}}(\theta) = \mu(\theta) \cdot \sigma_{\text{theo}}^{\text{tot}} \cdot \mathcal{L} \cdot \mathcal{A} \cdot \mathcal{C}(\theta) + N_{\text{bkg}}^{\text{SR}}(\theta) \quad (5.22)$$

2152 with the non-binned versions of \mathcal{A} and \mathcal{C} defined in Equations 5.19 and 5.20, respectively.

2153 If the measured fiducial cross section is written as:

$$\sigma_{\text{meas}}^{\text{fid}} = \mu \cdot \mathcal{A} \cdot \sigma_{\text{theo}}^{\text{tot}} \quad (5.23)$$

2154 then Equation 5.22 can be rearranged to read:

$$\sigma_{\text{meas}}^{\text{fid}} = \frac{N_{\text{exp}}^{\text{SR}}(\theta) - N_{\text{bkg}}^{\text{SR}}(\theta)}{\mathcal{L} \cdot \mathcal{C}(\theta)} \quad (5.24)$$

2155 The measured fiducial cross section can finally be rewritten in terms of $\hat{\mu}$, which is the best estimator
 2156 of the signal strength as extracted from the fit:

$$\begin{aligned} \sigma_{\text{meas}}^{\text{fid}} &= \hat{\mu}(\theta) \cdot \sigma_{\text{theo}}^{\text{tot}} \cdot \mathcal{A} \\ &= \hat{\mu}(\theta) \cdot \sigma_{\text{theo}}^{\text{fid}} \end{aligned} \quad (5.25)$$

2157 In practice, however, the cross section is not extracted from a single bin, and Equation 5.22
 2158 becomes:

$$N_{\text{exp}}^{\text{SR}}(\theta) = \mu(\theta) \cdot \sigma_{\text{theo}}^{\text{tot}} \cdot \mathcal{L} \cdot \sum_i \mathcal{A}_i \cdot \sum_j \mathcal{C}_{ij} + \sum_j N_{\text{bkg},j}^{\text{SR}}(\theta) \quad (5.26)$$

2159 for a single channel in truth and reconstruction level m_{jj} bins i and j , respectively, where the binned
 2160 versions of \mathcal{A}_i and \mathcal{C}_{ij} are used. This equation can be extended to include all the analysis channels
 2161 by increasing the number of bins i and j . Additionally, it can be shown that Equation 5.25 holds
 2162 for this more complex case as well [83], provided care is taken to ensure that all the uncertainties
 2163 are handled properly.

²¹⁶⁴ **5.5 Summary of uncertainties**

²¹⁶⁵ Systematic uncertainties enter the final fit as nuisance parameters which can impact the estimated
²¹⁶⁶ signal and background yields and the shapes of the m_{jj} distributions. These uncertainties can arise
²¹⁶⁷ from the experimental methods or from the theoretical calculations used in the analysis. This section
²¹⁶⁸ summarizes the systematic uncertainties; the experimental uncertainties are detailed in Section 5.5.1,
²¹⁶⁹ and the theoretical uncertainties are covered in Section 5.5.2. The impacts of the systematic uncer-
²¹⁷⁰ tainties on the final cross section measurement are summarized in Table 5.19.

Source	Impact [%]
Reconstruction	± 4.0
Electrons	± 0.5
Muons	± 1.2
Jets and E_T^{miss}	± 2.8
b -tagging	± 2.0
Pileup	± 1.5
Background	± 5.0
Misid. leptons	± 3.9
Charge misrec.	± 0.3
WZ	± 1.3
$W^\pm W^\pm jj$ QCD	± 2.8
Other	± 0.8
Signal	± 3.6
Interference	± 1.0
EW Corrections	± 1.3
Shower, Scale, PDF & α_s	± 3.2
Total	± 7.4

Table 5.19: Impact of various systematic effects on the fiducial cross section measurement. The impact of a given source of uncertainty is computed by performing the fit with the corresponding nuisance parameter varied up or down by one standard deviation from its nominal value.

²¹⁷¹ **5.5.1 Experimental uncertainties**

²¹⁷² Experimental uncertainties include detector effects as well as uncertainties on the background es-
²¹⁷³ timation methods. Sources of systematic uncertainty on the measurement of physics objects are
²¹⁷⁴ listed in Table 5.20, grouped by the relevant object type. For backgrounds estimated from MC
²¹⁷⁵ simulations, variations in these sources of uncertainty are propagated through the analysis to obtain
²¹⁷⁶ the corresponding uncertainties on the event yields. Additional experimental uncertainties include
²¹⁷⁷ the integrated luminosity, the photon conversion rate from Section 5.3.2, and the data driven charge

2178 misidentification and fake lepton background estimations from Sections 5.3.3 and 5.3.4.5, respec-
 2179 tively.

2180 The largest sources of experimental uncertainty on the MC estimations come from the jet-related
 2181 uncertainties and the b -tagging efficiency, while the largest uncertainty on the background estimation
 2182 comes from the fake-factor. The effects of the uncertainties on the $W^\pm W^\pm jj$ EWK signal and the
 2183 dominant MC estimated background, WZ , are listed in Tables 5.21 and 5.22, respectively. Since
 2184 the overall contributions from other processes estimated with MC are small, the uncertainties on
 2185 these backgrounds have a lesser impact on the final measurement; these tables can be found in
 2186 Appendix A.1.

Experimental uncertainties	
Electrons	Energy resolution
	Energy scale
	Identification efficiency
	Isolation efficiency
	Reconstruction efficiency
	Trigger efficiency
Muons	Energy scale
	Identification efficiency
	Inner detector track resolution
	Muon spectrometer resolution
	Trigger efficiency
E_T^{miss}	Resolution
	Scale
Jets	Energy resolution
	Energy scale
	JVT cut efficiency
	b -tagging efficiency
	Jets from pileup

Table 5.20: List of sources of experimental uncertainties on the reconstruction of physics objects.

$W^\pm W^\pm jj$ EWK	$e^\pm e^\pm$ % Yield	$\mu^\pm e^\pm$ % Yield	$\mu^\pm \mu^\pm$ % Yield
Jet-related Uncertainties	2.28	2.22	2.28
b -tagging efficiency	1.81	1.76	1.74
Pile-up	0.48	0.97	2.42
Trigger efficiency	0.02	0.08	0.47
Lepton reconstruction/ID	1.45	1.14	1.83
MET reconstruction	0.26	0.17	0.21

Table 5.21: Impact of experimental uncertainties for the $W^\pm W^\pm jj$ EWK processes in all channels.

WZ	$e^\pm e^\pm$ % Yield	$\mu^\pm e^\pm$ % Yield	$\mu^\pm \mu^\pm$ % Yield
Jet-related Uncertainties	9.58	5.03	8.45
b-tagging efficiency	2.49	2.23	2.40
Pile-up	2.99	3.49	3.33
Trigger efficiency	0.03	0.09	0.43
Lepton reconstruction/ID	1.52	1.24	3.07
MET reconstruction	0.93	0.79	1.63

Table 5.22: Impact of experimental uncertainties for the WZ process in all channels.

2187 5.5.2 Theoretical uncertainties

2188 It is also necessary to consider uncertainties on the theoretical predictions in the fiducial region. They
 2189 include the choice of PDF set, the value of the strong coupling constant α_s , the renormalization
 2190 scale μ_R , the factorization scale μ_F , and the parton showering. The size of these uncertainties
 2191 are measured by generating new samples with variations in a chosen parameters and comparing
 2192 them to samples using the nominal choice of the parameter. Internal variations on the PDF sets
 2193 and using a different set entirely results in a relative uncertainty of up to 2.25% on the nominal
 2194 sample. The impact from varying α_s is very small, on the order of < 0.01%. The factorization and
 2195 renormalization scales are independently varied between 0.5-2.0 from their nominal values of 1.0.
 2196 This results in relative uncertainties on the prediction of up to 15%. Finally, varying the parameters
 2197 in the parton showering results in up to 8% uncertainty.

2198 5.5.2.1 Uncertainties from EWK-QCD interference

2199 As mentioned in Section 5.0.1, $W^\pm W^\pm jj$ production consists of both EWK processes. The two
 2200 production modes cannot be naively separated due to cross terms in the matrix element calculation.
 2201 These cross terms are referred to as *interference* terms. Since the $W^\pm W^\pm jj$ EWK production is
 2202 the focus of the analysis, and the signal region is designed to preferentially select those events, it is
 2203 important to measure the size of the EWK-QCD interference contributions.

2204 The interference effects are estimated using the `MadGraph` MC generator, as it has a feature that
 2205 allows direct modelling of the interference term. This allows four samples to be generated:

- 2206 1. Inclusive: All available diagrams are used in the matrix element calculation
- 2207 2. EWK only: Only EWK diagrams ($\mathcal{O}(\alpha_{\text{EWK}}) = 4$) are used
- 2208 3. QCD only: Only QCD diagrams ($\mathcal{O}(\alpha_s) = 2 \otimes \mathcal{O}(\alpha_{\text{EWK}}) = 2$) are used

- 2209 4. Interference: Only the interference terms are used
- 2210 A minimal set of generator level cuts, listed in Table 5.23, is applied in order to avoid biasing the
 2211 sample towards either production mode. The cross sections for each of the four channels can be
 2212 found in Table 5.24. The size of the interference is found to be approximately 6% of the total cross
 2213 section and is taken as a systematic uncertainty.

Generator level cuts
$\Delta\eta_{jj} < 10$
Jet $p_T > 20$ GeV
$M_{jj} > 10$ GeV

Table 5.23: The set of generator level cuts used for generating the interference samples with **MadGraph**.

Sample	σ (fb)
Inclusive	3.646 ± 0.0012
EWK only	2.132 ± 0.0005
QCD only	1.371 ± 0.0008
Interference	0.227 ± 0.0002

Table 5.24: Cross sections for each different $W^\pm W^\pm jj$ production mode (inclusive, EWK only, QCD only, and interference only) generated using **MadGraph**. The cross sections are calculated using a minimal set of generator level cuts from events where the W decays to a muon.

2214 5.6 Results

2215 After running the full analysis chain, the event yields in the signal region, low- m_{jj} control region,
 2216 and WZ control region as well as associated nuisance parameters representing the uncertainties are
 2217 passed to the maximum likelihood fit. From this fit, the normalization factor for the WZ control
 2218 region μ_{WZ} and the signal strength parameter in the signal region μ_{obs} are determined, and the
 2219 predicted yields in each input bin have been shifted according to the process detailed in Section 5.4.1.

2220 The WZ normalization factor is measured to be:

$$\mu_{WZ} = 0.88^{+0.07}_{-0.07}(\text{stat})^{+0.31}_{-0.21}(\text{theory})^{+0.22}_{-0.11}(\text{sys}) \quad (5.27)$$

2221 and is constrained primarily by the number of data events in the WZ control region. The observed
 2222 signal strength of $W^\pm W^\pm jj$ EWK production, defined in Equation 5.21, is extracted from the fit
 2223 and measured with respect to the prediction of the **SHERPA v2.2.2** MC generator:

$$\mu_{\text{obs}} = 1.45^{+0.25}_{-0.24}(\text{stat})^{+0.06}_{-0.08}(\text{theory})^{+0.27}_{-0.22}(\text{sys}) \quad (5.28)$$

2224 This corresponds to a rejection of the background-only hypothesis with a significance of 6.9σ .

2225 The observed number of data events are compared to the predicted signal and background yields
 2226 in the signal region in Table 5.25 before applying the fit and in Table 5.26 after the fit. 122 candidate
 2227 events are observed compared to a prediction of 60 signal and 69 background events.

2228 The m_{jj} distributions for data and prediction are shown in Figure 5.29 after the fit, and the
 2229 fitted event yields in the low- m_{jj} and WZ control regions are shown in Figure 5.30. Additional
 2230 distributions can be found in Appendix A.

	e^+e^+	e^-e^-	μ^+e^+	μ^-e^-	$\mu^+\mu^+$	$\mu^-\mu^-$	combined
WZ	1.9 ± 0.6	1.3 ± 0.4	14 ± 4	8.9 ± 2.6	5.5 ± 1.6	3.6 ± 1.1	35 ± 10
Non-prompt	4.1 ± 2.3	2.3 ± 1.7	9 ± 5	6 ± 4	0.57 ± 0.15	0.67 ± 0.25	23 ± 10
e/γ conversions	1.74 ± 0.29	1.8 ± 0.4	6.1 ± 1.6	3.7 ± 0.8	—	—	13.4 ± 2.5
Other prompt	0.17 ± 0.05	0.14 ± 0.04	0.90 ± 0.19	0.60 ± 0.14	0.36 ± 0.10	0.19 ± 0.05	2.4 ± 0.5
$W^\pm W^\pm jj$ QCD	0.38 ± 0.13	0.16 ± 0.05	3.0 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.25	7.3 ± 2.5
Expected background	8.2 ± 2.4	5.7 ± 1.8	33 ± 7	21 ± 5	8.2 ± 1.8	5.3 ± 1.2	81 ± 14
$W^\pm W^\pm jj$ EWK	3.8 ± 0.6	1.49 ± 0.22	16.5 ± 2.5	6.5 ± 1.0	9.1 ± 1.4	3.5 ± 0.5	41 ± 6
Data	10	4	44	28	25	11	122

Table 5.25: Table of the data and prediction event yields in the signal region before the fit. Numbers are shown for the six lepton flavor and charge channels and for all channels combined. Here the WZ background yields are normalized to the data in the WZ control region. The background estimations from the fake-factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t} + V$ backgrounds are combined in the “Other prompt” category.

	e^+e^+	e^-e^-	μ^+e^+	μ^-e^-	$\mu^+\mu^+$	$\mu^-\mu^-$	combined
WZ	1.49 ± 0.30	1.10 ± 0.26	11.7 ± 1.7	8.0 ± 1.3	5.0 ± 0.6	3.5 ± 0.6	31 ± 4
Non-prompt	2.2 ± 1.3	1.2 ± 0.7	5.7 ± 2.8	4.5 ± 1.8	0.57 ± 0.06	0.65 ± 0.14	15 ± 6
e/γ conversions	1.6 ± 0.4	1.6 ± 0.5	6.3 ± 1.6	4.3 ± 1.1	—	—	13.8 ± 2.9
Other prompt	0.16 ± 0.04	0.14 ± 0.04	0.90 ± 0.19	0.63 ± 0.13	0.39 ± 0.09	0.22 ± 0.05	2.4 ± 0.5
$W^\pm W^\pm jj$ QCD	0.35 ± 0.13	0.15 ± 0.05	2.9 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.25	7.2 ± 2.4
Expected background	5.8 ± 1.5	4.1 ± 1.1	27 ± 4	18.7 ± 2.6	7.7 ± 0.8	5.1 ± 0.6	69 ± 7
$W^\pm W^\pm jj$ EWK	5.6 ± 1.0	2.2 ± 0.4	24 ± 5	9.4 ± 1.8	13.5 ± 2.5	5.2 ± 1.0	60 ± 11
Data	10	4	44	28	25	11	122

Table 5.26: Table of the data and prediction event yields in the signal region after the fit. Numbers are shown for the six lepton flavor and charge channels and for all channels combined. The background estimations from the fake-factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t}V$ backgrounds are combined in the “Other prompt” category.

2231 The last ingredient necessary to measure the $W^\pm W^\pm jj$ EWK cross section is the theory predicted
 2232 cross section in the fiducial region defined in Table 5.18. SHERPA v2.2.2 is used for the calculation,
 2233 and the cross section in the total generator phase space is 40.81 ± 0.05 fb, and the fiducial cross section
 2234 is 2.01 ± 0.02 fb. This corresponds to an acceptance factor of $\mathcal{A} = 0.0493 \pm 0.0002$. Uncertainties on

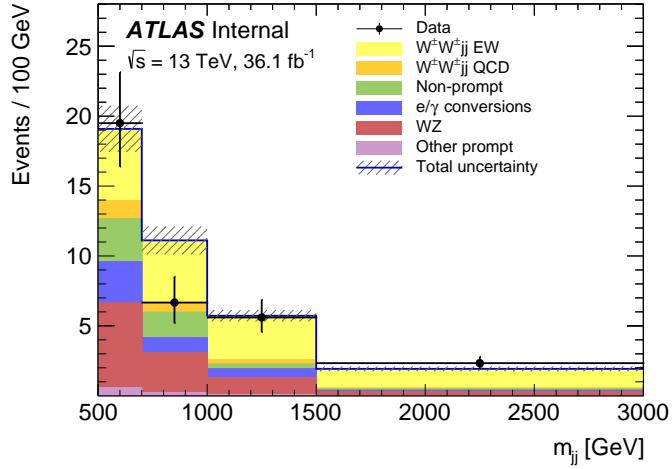


Figure 5.29: The dijet invariant mass m_{jj} distributions for data and predicted signal and background in the signal region after the fit. The shaded band represents the statistical and systematic uncertainties added in quadrature. Note that the bins have been scaled such that they represent the number of events per 100 GeV in m_{jj} . The background estimations from the fake-factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t} + V$ backgrounds are combined in the “Other prompt” category.

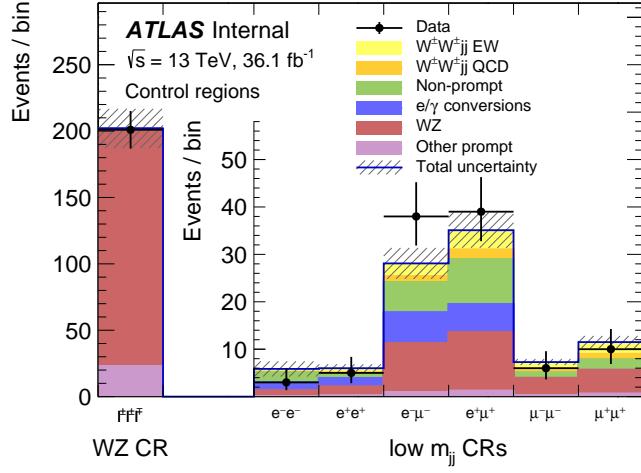


Figure 5.30: The event yields for data and predicted signal and background in the WZ and low- m_{jj} control regions after the fit. The shaded band represents the statistical and systematic uncertainties added in quadrature. The background estimations from the fake-factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t}V$ backgrounds are combined in the “Other prompt” category.

the simulation are estimated using variations of the scale, parton shower, and PDF set. The final prediction used in the cross section measurement including uncertainties from Section 5.5.2 is:

$$\sigma_{\text{SHERPA}}^{\text{fid}} = 2.01 \pm 0.02(\text{stat}) \pm^{+0.29}_{-0.23}(\text{scale}) \pm^{+0.16}_{-0.02}(\text{parton shower}) \pm^{+0.05}_{-0.03}(\text{PDF}) \text{ fb} \quad (5.29)$$

Combining this **SHERPA** prediction with the measured signal strength μ_{obs} from Equation 5.28, the measured fiducial cross section $\sigma_{\text{meas}}^{\text{fid}}$ can be calculated using Equation 5.25:

$$\sigma_{\text{meas}}^{\text{fid}} = 2.91 \pm^{+0.51}_{-0.47}(\text{stat}) \pm^{+0.12}_{-0.16}(\text{theory}) \pm^{+0.24}_{-0.23}(\text{sys}) \pm^{+0.08}_{-0.06}(\text{luminosity}) \text{ fb} \quad (5.30)$$

A plot comparing the measured fiducial cross section to two theoretical calculations is shown in Figure 5.31. The measured value is compared to the **SHERPA v2.2.2** prediction used to calculate μ_{obs} as well as to **POWHEG-BOX v2**. As mentioned in Section 5.1.1, this **POWHEG** sample does not include the resonant triboson diagrams and is only used here for a visual comparison.

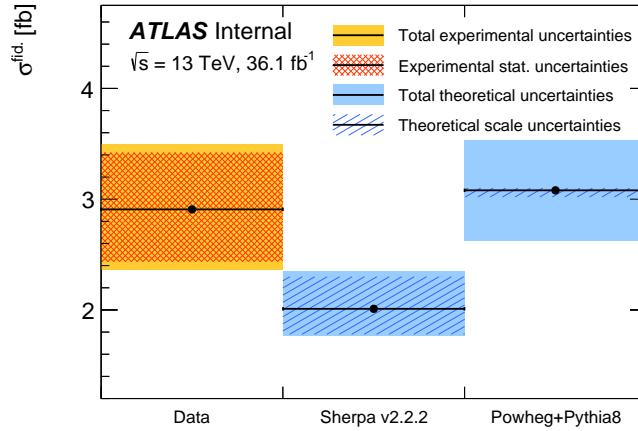


Figure 5.31: Comparison of the measured $W^\pm W^\pm jj$ EWK fiducial cross section with theoretical calculations from **SHERPA v2.2.2** and **POWHEG-BOX v2**. The light orange band represents the total experimental uncertainty on the measured value, and the dark orange hashed band is the statistical uncertainty. For the simulations, the light blue band represents the total theoretical uncertainty, and the dark blue hashed band are the scale uncertainties. The theory predictions do not include the interference between the EWK and QCD production.

2243

CHAPTER 6

2244

Prospects for same-sign WW at the High 2245 Luminosity LHC

2246 On December 3, 2018, Run 2 of the LHC officially ended, and the collider was shut down to begin
2247 the first of two scheduled extended maintenance periods [113]. During these two long shutdowns,
2248 the Phase-I and Phase-II upgrades of the LHC and ATLAS will occur in order to prepare for the
2249 High-Luminosity LHC (HL-LHC) which is scheduled to begin operation in 2026 [114].

2250 The HL-LHC is planned to run at a center-of-mass energy of $\sqrt{s} = 14$ TeV with an instantaneous
2251 luminosity of $\mathcal{L} = 5 \times 10^{34}$ cm $^{-2}$ s $^{-1}$ with up to 200 collisions per beam-crossing. Over the course
2252 of operation, the HL-LHC is expected to collect a total integrated luminosity of $\mathcal{L} = 3000$ fb $^{-1}$ by
2253 2035 [115].

2254 These run conditions will be much harsher than what ATLAS has experienced so far, and there
2255 are several upgrades planned to adapt the detector to the high luminosity environment. Most
2256 notably, the entire ID will be replaced with an all-silicon tracker which will extend the coverage
2257 from $|\eta| \leq 2.7$ up to $|\eta| \leq 4.0$. This will allow for forward particle tracks to be reconstructed, which
2258 can in turn be matched to clusters in the calorimeters for use in electron identification or forward
2259 jet tagging [116].

2260 The upgraded detector, the higher beam energy, and the increased volume of data to be col-
2261 lected provides the opportunity to measure rare processes to a much higher precision than what
2262 is possible with the current LCH dataset. Same-sign $W^\pm W^\pm jj$ production is one such process.
2263 With greater statistics, the accuracy of the cross section measurement can be improved over the
2264 13 TeV analysis detailed in Chapter 5, and it also will allow for more detailed physics studies, such
2265 as measuring the polarization state of the scattered W bosons. A measurement of the cross section

of longitudinally polarized $W^\pm W^\pm jj$ scattering is one of the most enticing extensions of the existing $W^\pm W^\pm jj$ measurements due to its sensitivity to the EWSB mechanism [117], and it is expected to be measurable for the first time at the HL-LHC. The analysis detailed in this chapter is based off of the 2018 ATLAS HL-LHC $W^\pm W^\pm jj$ prospects study [118] which extends upon the results of the previous year's study [119].

6.0.1 Analysis Overview

The experimental signature of interest is identical to the 13 TeV analysis (see Chapter 5): two prompt leptons (either electrons or muons) with the same electric charge, missing transverse energy, and two high energy forward jets. These jets are again required to have a large angular separation and a high combined invariant mass to preferentially select EWK-produced $W^\pm W^\pm jj$ events.

Background processes are not expected to change with respect to the 13 TeV analysis and are summarized here. The dominant source of prompt background comes from $WZ+jets$ events where both bosons decay leptonically. If the lepton from the Z -decay with opposite charge from the W falls outside of the detector acceptance or is not identified, the remaining two leptons will form a same-sign pair, and the event may pass the signal lepton criteria. To a much lesser extent, $ZZ+jets$ events can enter the signal region this way provided two leptons are “lost”. Other prompt sources include $t\bar{t}+V$ and multiple parton interactions, however both contributions are small. Overall, prompt backgrounds are expected to contribute less than in current analyses due to the addition of forward tracking in the upgraded ATLAS detector reducing the probability of leptons falling outside the detector acceptance. Jets mis-reconstructed as leptons or leptons from hadronic decays (such as $t\bar{t}$ and $W+jets$ production) comprise the non-prompt lepton background. Lastly, events with two prompt, opposite-charge electrons can appear as a same-sign event provided one of the electrons is mis-reconstructed and assigned the wrong charge.

In this analysis, the EWK production of $W^\pm W^\pm jj$ is studied in the context of the planned HL-LHC run conditions and upgraded ATLAS detector. An optimized event selection (referred to as the *optimized selection*) is also explored in an effort to gain increased signal significance over the *default selection*. The cross section of the inclusive EWK production is measured for both the default and optimized selections, and the extraction of the expected longitudinal scattering significance is measured with the optimized selection.

2295 **6.1 Theoretical motivation**

2296 The motivation for studying the $W^\pm W^\pm jj$ process as well as VBS in general has been established
 2297 previously in Sections 2.3 and 5.0.1. Since only the longitudinally polarized vector bosons that is
 2298 sensitive to the EWSB mechanism, a direct measurement of this cross section will be very useful for
 2299 understanding how the Higgs unitarizes the scattering amplitude [117].

2300 **6.1.1 Experimental sensitivity to longitudinal polarization**

2301 There are three possible polarization states for a massive vector boson: two transverse (+ or -)
 2302 and one longitudinal (0). Therefore, in a system with two W bosons, the overall polarization can be
 2303 purely longitudinal (00), purely transverse (++, --, and +-), or mixed (+0 and -0). The three
 2304 combinations will be referred to as *LL*, *TT*, and *LT* respectively.

2305 In order extract the longitudinal scattering component, it is necessary to find variables that can
 2306 help distinguish the LL from the TT and LT events. Several were studied, and those with the best
 2307 discriminating power between the different polarization states are the leading and subleading lepton
 2308 transverse momenta as well as the azimuthal separation of the two VBS jets $|\Delta\phi_{jj}|$. Both leptons
 2309 in LL events tend to be softer than the TT and LT events (see Figure 6.1), which motivates keeping
 2310 cuts on the lepton p_T as low as possible in the event selection. In the case of the dijet separation, LL
 2311 events prefer the tag jets to be back-to-back (see Figure 6.2). $|\Delta\phi_{jj}|$ is passed to a binned likelihood
 2312 fit to extract the longitudinal scattering significance.

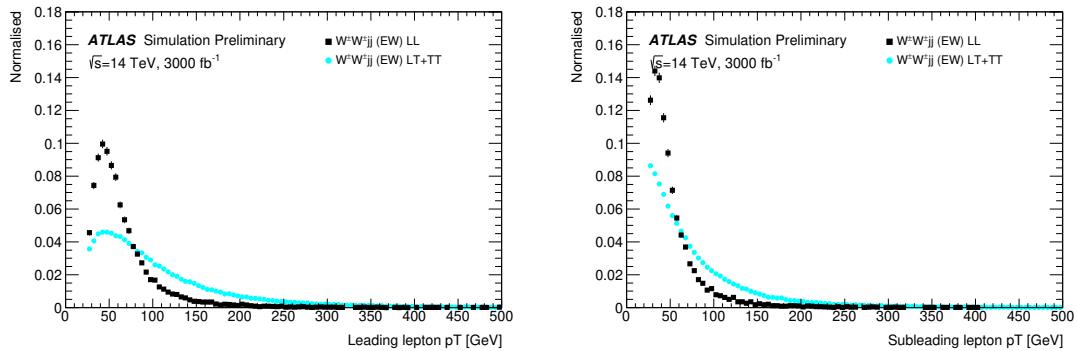


Figure 6.1: Comparison of the leading (left) and subleading (right) lepton p_T distributions for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan) $W^\pm W^\pm jj$ events.

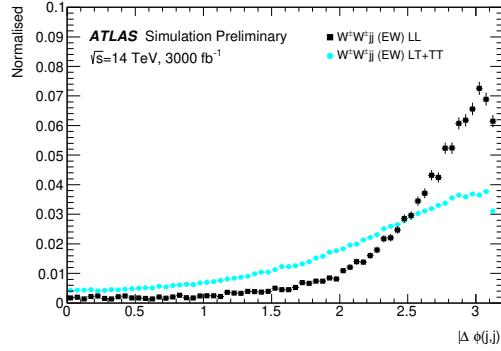


Figure 6.2: Comparison of the azimuthal dijet separation ($|\Delta\phi_{jj}|$) for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan) $W^\pm W^\pm jj$ events.

2313 6.2 Monte Carlo samples

2314 As this is a prospects study for a future collider, all signal and background processes are modeled
 2315 using MC simulations. The samples are generated at the expected HL-LHC center of mass energy
 2316 $\sqrt{s} = 14$ TeV, and the event yields are scaled to the anticipated integrated luminosity of $\mathcal{L} =$
 2317 3000 fb^{-1} . The MC samples used in the analysis are generated at particle-level and have not been
 2318 run through the full simulation of the ATLAS detector. Instead, smearing functions derived from
 2319 a GEANT4 simulation of the upgraded ATLAS detector are used to estimate detector effects such as
 2320 momentum resolution. In addition, pileup events are fully simulated. The MC samples used in this
 2321 analysis are summarized in Table 6.1.

2322 The signal sample consists of both VBS and non-VBS electroweak (EWK) $W^\pm W^\pm jj$ production,
 2323 and it is simulated with the `Madgraph5_aMC@NLO` generator using the NNPDF3.0 PDF set and in-
 2324 terfaced with PYTHIA v8 [120] for hadronization and parton showering. To study the longitudinal
 2325 polarization more directly, two additional `Madgraph5_aMC@NLO` $W^\pm W^\pm jj$ samples are used: one
 2326 containing only the longitudinal contribution (LL) and a second containing the transverse (TT) and
 2327 mixed (LT) contributions.

2328 There are many other processes that can produce the same final state as the $W^\pm W^\pm jj$ and must
 2329 also be accounted for using MC simulations. WZ events are generated using `SHERPA v2.2.0`, which
 2330 includes up to one parton at NLO in the strong coupling constant and up to three additional partons
 2331 at LO. Both EWK and QCD production are included in these samples. ZZ and triboson VVV
 2332 ($V = W, Z$) events are generated using `SHERPA v2.2.2` with up to two additional partons in the
 2333 final state. For the triboson backgrounds, the bosons can decay leptonically or hadronically. $W+jets$

Process	Generator	Comments
$W^\pm W^\pm jj$ (EWK)	<code>Madgraph5_aMC@NLO</code>	Signal sample
$W^\pm W^\pm jj$ (QCD)	<code>Madgraph5_aMC@NLO</code>	
$W^\pm W^\pm jj$ (LL)	<code>Madgraph5_aMC@NLO</code>	Pure longitudinal polarization sample
$W^\pm W^\pm jj$ (TT+LT)	<code>Madgraph5_aMC@NLO</code>	Mixed and transverse polarization sample
Diboson	<code>SHERPA v2.2.0</code>	WZ events
	<code>SHERPA v2.2.2</code>	ZZ events
Triboson	<code>SHERPA v2.2.2</code>	
$W+jets$	<code>Madgraph5_aMC@NLO</code>	
$Z+jets$	<code>POWHEG-BOX v2</code>	
$t\bar{t}$	<code>POWHEG-BOX</code>	
Single top	<code>POWHEG-BOS</code>	

Table 6.1: Summary of MC samples used in the analysis.

backgrounds are generated for electron, muon, and tau final states at LO with `Madgraph5_aMC@NLO` and the `NNPDF3.0` PDF set with showering from `PYTHIA v8`. $Z+jets$ events are produced using `POWHEG-BOX v2` and the `CT10` PDF set interfaced with `PYTHIA v8`. Finally, $t\bar{t}$ and single-top events are generated using `POWHEG-BOX` with showering from `PYTHIA v6`.

6.3 Background estimations

In this analysis, all background contributions are estimated using MC simulations. Backgrounds from electron charge misidentification and fake electrons from jets, which are traditionally estimated using data-driven techniques, are instead estimated using a set of parameterization functions applied to the MC. These functions calculate the probability that an electron is assigned the wrong charge or a jet is mis-reconstructed as an electron parameterized by the p_T and η of the respective electron or jet. The probabilities are derived from studies on expected electron performance with the upgraded ATLAS detector [121].

Processes involving two W or Z bosons are grouped together as *diboson* backgrounds, with the exception of $W^\pm W^\pm jj$ events produced via QCD interactions, which are kept separate. Similarly, all backgrounds with three vector bosons are combined and labeled as *triboson*. Any $W+jets$ or top events that pass selection and do not contain a fake electron, as well as any $Z+jets$ events without an electron identified as having its charge misidentified are combined as *other non-prompt* backgrounds.

2351 **6.3.1 Truth-based isolation**

2352 The canonical isolation variables used in ATLAS analyses require detailed information from many
 2353 detector subsystems including particle tracks and calorimeter responses. Since the MC samples used
 2354 in this analysis have not been run through a full detector simulation, it is not possible to reproduce
 2355 the official isolation variables. For truth-level analysis, this is generally not a serious concern, as
 2356 high- p_T signal leptons tend to be well isolated to begin with. However, isolation is one of the
 2357 most powerful tools for rejecting leptons from non-prompt sources, such as top events, which are
 2358 produced in association with additional nearby particles from b and c hadron decays. It was seen in
 2359 the early stages of this analysis that without any sort of isolation requirement, contributions from
 2360 top backgrounds (including single top, $t\bar{t}$ and $t\bar{t} + V$) were more than an order of magnitude higher
 2361 than expected.

2362 As a result, it is necessary to find one or more quantities that are comparable to the isolation
 2363 information that is available in fully-simulated samples. Analogues to track- and calorimeter-based
 2364 isolation are constructed by summing the momentum and energy, respectively, of stable truth parti-
 2365 cles with $p_T > 1$ GeV within a specified radius of each signal lepton. For the track-based isolation,
 2366 only charged truth particles are used; both charged and neutral particles (excluding neutrinos) are
 2367 included for the calorimeter-based isolation. Ultimately, a set of isolation cuts are chosen that are
 2368 similar to those recommended by ATLAS for Run 2 analyses. The truth-based isolation requirements
 2369 are listed in Table 6.2.

	Electron Isolation	Muon Isolation
Track-based isolation cone size	$\Delta R < 0.2$	$\Delta R < 0.3$
Track-based isolation requirement	$\sum p_T/p_T^e < 0.06$	$\sum p_T/p_T^\mu < 0.04$
Calorimeter-based isolation cone size	$\Delta R < 0.2$	$\Delta R < 0.2$
Calorimeter-based isolation requirement	$\sum E_T/p_T^e < 0.06$	$\sum E_T/p_T^\mu < 0.15$

Table 6.2: Truth-based isolation requirements for electrons and muons.

2370 With no cut on truth-based isolation, 83% of the total background consists of top events without
 2371 including contributions to the fake electron background. The isolation requirement reduces the top
 2372 background by over 99%, and the percentage of the total background from top events is reduced to
 2373 2%. Additional studies on the truth-based isolation as well as full event yields with and without the
 2374 isolation requirement can be found in Appendix B.1.

2375 **6.4 Object and event selection**

2376 The majority of the default object and event selections were determined in the preceeding $W^\pm W^\pm jj$
 2377 HL-LHC prospects study [119], which focused on the impact of the upgraded detector's forward
 2378 tracking capabilities. Several different combinations of lepton and jet η ranges were tested, and the
 2379 results are used in this study.

2380 **6.4.1 Object selection**

2381 Electrons and muons are preselected to have $p_T > 7$ and 6 GeV, respectively, and lie within $|\eta| \leq 4.0$.
 2382 The likelihood of a given lepton to pass the trigger and identification requirements is estimated by
 2383 calculating an efficiency dependent on the p_T and η of the lepton. The leptons are also required to
 2384 pass the isolation criteria detailed in Table 6.2. Jets that have been tagged as a fake electron by the
 2385 functions described in Section 6.3 are treated as electrons for the purpose of the object selection and
 2386 are subject to the same criteria. In order to be considered a signal lepton, the transverse momentum
 2387 requirement is raised to $p_T > 25$ GeV. The two highest p_T leptons passing this selection are chosen
 2388 to be the leading and subleading signal leptons.

2389 Jets are clustered using the anti- k_t algorithm from final-state particles within a radius of $\Delta R =$
 2390 0.4 (excluding muons and neutrinos). All jets are required to have $p_T > 30$ GeV and lie within $|\eta| <$
 2391 4.5 ; in order to suppress jets from pileup interactions, jets outside of $|\eta| \geq 3.8$ must pass an higher
 2392 momentum cut of $p_T > 70$ GeV. Jets overlapping a preselected electron within $\Delta R(e, j) < 0.05$ are
 2393 removed in order to prevent double counting. The two highest p_T jets are defined as the leading
 2394 and subleading tag jets.

2395 **6.4.2 Event selection**

2396 The default event selection is summarized in Table 6.3 and described here. Exactly two signal
 2397 leptons are required with the same electric charge and separated from each other by $\Delta R(ll) > 0.3$.
 2398 In order to suppress contributions from Drell-Yan backgrounds, the two signal leptons must have
 2399 an invariant mass m_{ll} greater than 20 GeV. Additionally, if both signal leptons are electrons, their
 2400 mass must be at least 10 GeV away from the Z -boson mass in order to reduce background from
 2401 Z -boson decays²¹. The event is required to have at least 40 GeV of missing transverse energy (E_T^{miss})

²¹The electron charge misidentification rate in the upgraded ATLAS detector is estimated to be high enough that contributions from $Z \rightarrow ee$ backgrounds are non-negligible.

Selection requirement	Selection value
Lepton kinematics	$p_T > 25 \text{ GeV}$ $ \eta \leq 4.0$
Jet kinematics	$p_T > 30 \text{ GeV}$ for $ \eta \leq 4.5$ $p_T > 70 \text{ GeV}$ for $ \eta > 3.8$
Dilepton charge	Exactly two signal leptons with same charge
Dilepton separation	$\Delta R_{l,l} \geq 0.3$
Dilepton mass	$m_{ll} > 20 \text{ GeV}$
Z boson veto	$ m_{ee} - m_Z > 10 \text{ GeV}$ (ee -channel only)
E_T^{miss}	$E_T^{\text{miss}} > 40 \text{ GeV}$
Jet selection	At least two jets with $\Delta R_{l,j} > 0.3$
b jet veto	$N_{\text{b-jet}} = 0$
Dijet separation	$\Delta \eta_{jj} > 2.5$
Trilepton veto	No additional preselected leptons
Dijet mass	$m_{jj} > 500 \text{ GeV}$
Lepton-jet centrality	$\zeta > 0$

Table 6.3: Summary of the signal event selection.

2402 to account for the two final-state neutrinos. Events with additional preselected leptons are vetoed,
 2403 which greatly reduces WZ and ZZ backgrounds.

2404 Each event must have at least two jets, and both tag jets are required to not overlap with the
 2405 signal leptons. Events with one or more b -jets are vetoed to suppress backgrounds from heavy-flavor
 2406 decays. In order to preferentially select EWK production, the tag jets are required to have a large
 2407 separation between them and a large invariant mass. Finally, a cut on the lepton centrality²², ζ ,
 2408 defined in Equation 6.1 further enhances the EWK $W^\pm W^\pm jj$ signal.

$$\zeta = \min[\min(\eta_{\ell 1}, \eta_{\ell 2}) - \min(\eta_{j 1}, \eta_{j 2}), \max(\eta_{j 1}, \eta_{j 2}) - \max(\eta_{\ell 1}, \eta_{\ell 2})] \quad (6.1)$$

2409

2410 6.5 Selection optimization

2411 The default event selection is optimized in order to improve the strength of the $W^\pm W^\pm jj$ EWK
 2412 signal. The expectation is that the increased detector acceptance from the forward tracking combined
 2413 with an increase in center of mass energy and much higher integrated luminosity will allow tighter
 2414 selection cuts without jeopardizing signal statistics.

²² ζ is a measurement of whether the two signal leptons lie between the two tagging jets in η , as is preferred by the VBS topology.

2415 **6.5.1 Random grid search algorithm**

2416 The chosen method for optimizing the event selection is a cut-based algorithm known as the Random
 2417 Grid Search (RGS) [122]. Consider a simple case of two variables x and y chosen to differentiate
 2418 signal from background. In order to be considered a signal event, a given event would be required
 2419 to pass a set of selection criteria, called a *cut point*: $c = \{x > x_c, y > y_c\}$. A simple method to
 2420 choose the optimal cut point (i.e. the “best” values of the cuts x_c and y_c) would be to construct an
 2421 $n \times m$ rectangular grid in x and y consisting of points $(x_0, y_0), (x_1, y_1), \dots, (x_n, y_m)$, as Figure 6.3a.
 2422 One can then choose a cut point $c_k = \{x > x_i, y > y_j\}$ that maximizes the signal significance as
 2423 given by a chosen metric. This would be considered a *rectangular grid search*.

2424 While effective in principle, a rectangular grid search comes with two major drawbacks:

- 2425 1. The algorithm scales exponentially as the number of variables to be optimized increases, as
 2426 this is effectively increasing the dimensionality of the grid. In the simple case of a square grid
 2427 with N bins per variable v , the number of cut points to be evaluated grows as N^v .
- 2428 2. Signal and background samples are rarely evenly distributed over the entire grid, resulting
 2429 in many cut points being sub-optimal and evaluating them would be a waste of computing
 2430 resources.

2431 To combat these limitations, the RGS algorithm constructs a grid of cut points directly from
 2432 the signal sample itself. In the two-dimensional example, this means that the variables x_i and y_j
 2433 making up the cut point $c_k = \{x > x_i, y > y_j\}$ take their values directly from a given signal event.
 2434 This has the benefit of creating a *random grid* of cut points that is biased towards regions of high
 2435 signal concentration by construction. This reduces the need for exponentially increasing numbers of
 2436 cut points while ensuring that computing resources are not wasted in regions with few to no signal
 2437 events. An example of a two-dimensional random grid is shown in Figure 6.3b.

2438 Once the random grid of cut points is constructed, the optimal cut point can be chosen using any
 2439 number of metrics, such as signal to background ratio. For the purpose of the $W^\pm W^\pm jj$ upgrade
 2440 study, the optimal cut point is chosen to be the one that maximizes the signal significance Z as
 2441 defined in Equation 6.2 [123]:

$$Z = \sqrt{2 \left[(s+b) \ln \left(\frac{s+b}{b_0} \right) + b_0 - s - b \right] + \frac{(b-b_0)^2}{\sigma_b^2}} \quad (6.2)$$

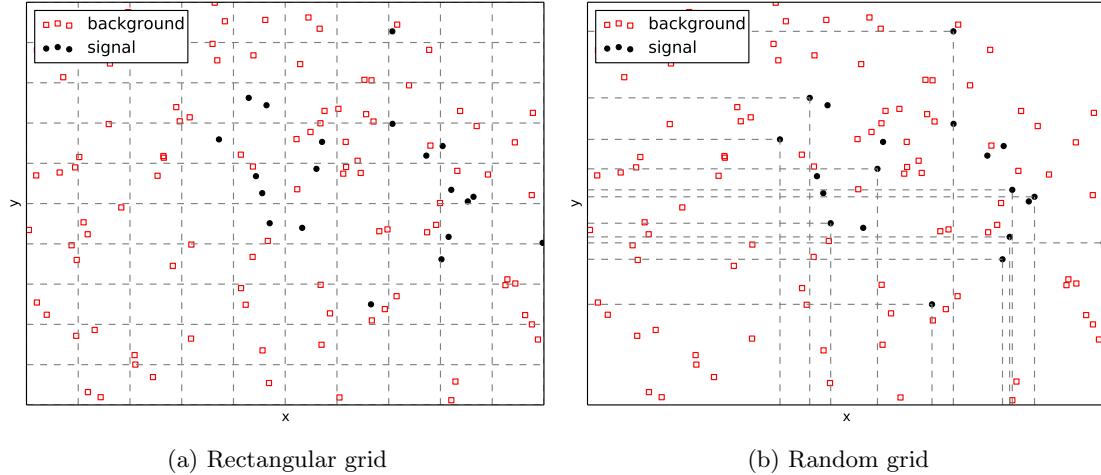


Figure 6.3: A visual representation of a two-dimensional rectangular grid (left) and a random grid (right) in variables x and y . The signal events are the black circles, and the red squares are the background events. Each intersection of gray dashed lines represents a cut point to be evaluated by the optimization.

where s and b are the number of signal and background events, respectively, σ_b is the total uncertainty on the background, and b_0 is defined as:

$$b_0 = \frac{1}{2} \left(b - \sigma_b^2 + \sqrt{(b - \sigma_b^2)^2 + 4(s + b)\sigma_b^2} \right) \quad (6.3)$$

In the case where the background is known precisely (i.e. $\sigma_b = 0$), Equation 6.2 simplifies to

$$Z = \sqrt{2 \left(b \left[(1 + s/b) \ln(1 + s/b) - s/b \right] \right)} \quad (6.4)$$

which further reduces to the familiar $Z = s/\sqrt{b}$ for the case when $s \ll b$.

2446 6.5.2 Inputs to the optimization

In order to train the RGS, signal and background samples are prepared from events passing the event selection outlined in Table 6.3 up through the b -jet veto. The signal sample is chosen to be the longitudinally polarized $W^\pm W^\pm jj$ EWK events, and the transverse and mixed polarizations are treated as background along with $W^\pm W^\pm jj$ events from QCD interactions and the traditional backgrounds listed in Section 6.3. Splitting the inclusive $W^\pm W^\pm jj$ EWK events by polarization allows the optimization to favor the longitudinally polarized events as much as possible, even though they both contribute to the EWK signal.

2454 The following variables are chosen for optimization:

- 2455 ● Leading lepton p_T
- 2456 ● Dilepton invariant mass (m_{ll})
- 2457 ● Leading and subleading jet p_T
- 2458 ● Dijet invariant mass (m_{jj})
- 2459 ● Lepton-jet centrality (ζ)

2460 Subleading lepton p_T is omitted as it is desirable to keep the cut value as low as possible due
 2461 to its sensitivity to the longitudinal polarization (as discussed in Section 6.1.1); despite this, the
 2462 leading lepton p_T is still allowed to be optimized as it can have strong background rejection power.
 2463 Additionally, the dijet separation $\Delta\eta_{jj}$ was included in early studies of the optimization, however it
 2464 was dropped due to the cut value being motivated by well-studied differences between EWK- and
 2465 QCD-produced $W^\pm W^\pm jj$ events (as in Figure 5.6b).

2466 Two additional constraints were imposed when selecting the optimal cut point:

- 2467 1. At least 1000 signal events must survive in order to prevent the optimization from being too
 2468 aggressive and unnecessarily reducing signal statistics.
- 2469 2. The dijet invariant mass may only vary within a 50 GeV range of the default value (from
 2470 450–550 GeV) due to the cut being physically motivated by the VBS event topology described
 2471 in Section 5.0.2.

2472 Lastly, the signal significance is calculated without taking into account the uncertainty of the
 2473 background using Equation 6.4. This is due to the fact that the statistical uncertainties of the fake
 2474 electron and charge misidentification backgrounds are quite large, owing to poor MC statistics in a
 2475 few of the samples. If Equation 6.2 were used instead, the optimization would cut unreasonably
 2476 hard against these backgrounds. Since Monte Carlo statistics is not expected to be a limiting factor
 2477 when this analysis is performed at the HL-LHC, it is more realistic to simply ignore these large
 2478 statistical uncertainties for the purpose of the optimization.

2479 6.5.3 Results of the optimization

2480 Ultimately, the random grid is constructed from over 38,000 LL-polarized $W^\pm W^\pm jj$ events in the
 2481 six variables listed above. After applying the constraints, the optimal cut point reduces the total
 2482 background from 9900 to 2310 while reducing the signal from 3489 to 2958. This corresponds to

2483 an increase in signal significance from $Z = 33.26$ to $Z = 52.63$ as calculated by Equation 6.4. The
 2484 updates to the event selection are listed in Table 6.4.

2485 The large reduction in the background is primarily a result of increasing the leading and sub-
 2486 leading jet p_T from 30 GeV to 90 GeV and 45 GeV, respectively. As can be seen in Figure 6.4,
 2487 this increase removes a significant portion of the backgrounds from jets faking electrons and charge
 2488 mis-ID. Additionally, the loosening of the lepton-jet centrality cut ζ allows more signal events to
 2489 survive the event selection (see Figure 6.5). Other changes to the event selection are minor and
 2490 do not individually have a large impact on the signal or background yields; similar distributions of
 2491 these variables are shown in Appendix B.2.

2492 The full event yields after optimization as well as the cross section measurement are detailed
 2493 alongside those using the default selection in Section 6.6.

Selection requirement	Selection value
Lepton kinematics	$p_T > 28$ GeV (leading lepton only)
Jet kinematics	$p_T > 90$ GeV (leading jet) $p_T > 45$ GeV (subleading jet)
Dilepton mass	$m_{ll} > 28$ GeV
Dijet mass	$m_{jj} > 520$ GeV
Lepton-jet centrality	$\zeta > -0.5$

Table 6.4: Updates to the $W^\pm W^\pm jj$ event selection criteria after optimization. Cuts not listed remain unchanged from the default selection in Table 6.3.

2494 6.6 Results

2495 6.6.1 Event yields

2496 After applying the full event selection, the analysis is broken down into four channels based off of
 2497 the flavor of the signal leptons: $\mu\mu$, ee , μe , and $e\mu$. The full signal and background event yields are
 2498 shown in Table 6.5 for each channel separately and combined using the default event selection. 3489
 2499 EWK $W^\pm W^\pm jj$ events are expected compared to 9900 background events. The dominant sources
 2500 of background are jets faking electrons followed by charge misidentification and diboson processes.
 2501 Triboson events, QCD $W^\pm W^\pm jj$, and other non-prompt sources make up approximately 5% of the
 2502 total background combined.

2503 The event yields for the optimized selection detailed in Section 6.5.3 are listed in Table 6.6. After
 2504 optimization, 2958 signal events and just 2310 background events are expected. Diboson events are
 2505 now the primary source of background, as the optimization greatly reduces the fake and charge

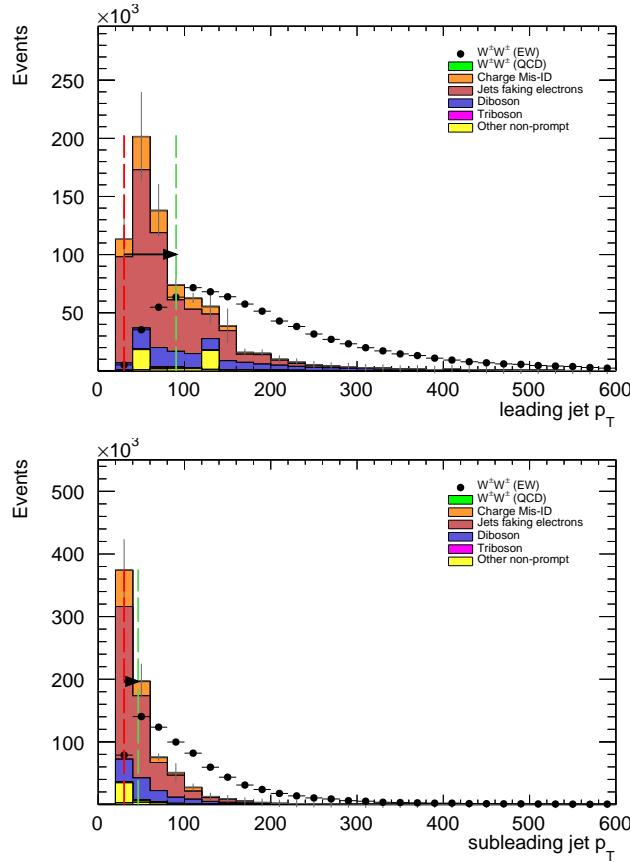


Figure 6.4: Leading (top) and subleading (bottom) jet p_T distributions. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

	All channels	$\mu\mu$	ee	μe	$e\mu$
$W^\pm W^\pm jj$ (QCD)	206.4	91.1	22.8	38.4	54.1
Charge Misidentification	2300	0.0	2100	90	160
Jets faking electrons	5000	0.0	3400	1200	340
$WZ + ZZ$	2040	500	438	423	680
Tribosons	115	47	15.4	21.6	31.2
Other non-prompt	210	110	20	60	27
Total Background	9900	750	6000	1900	1290
Signal $W^\pm W^\pm jj$ (EWK)	3489	1435	432	679	944

Table 6.5: Signal and background event yields using the default event selection for an integrated luminosity of $\mathcal{L} = 3000 \text{ fb}^{-1}$. Events containing a fake or charge-flipped electron are removed from their respective sources and combined into a single entry each.

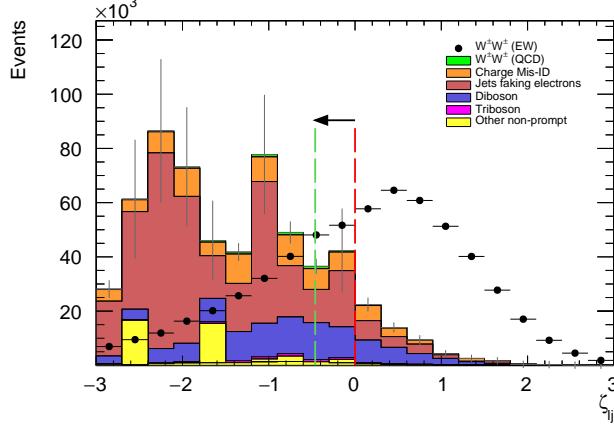


Figure 6.5: Lepton-jet centrality distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

mis-ID contributions. As discussed earlier, the increase in the leading and subleading jet p_T cuts as well as the loosening of the centrality cut are most responsible for the changes in the signal and background yields; distributions of these quantities using the default and the optimized event selections can be found in Figures 6.6, 6.7, and 6.8, respectively.

	All channels	$\mu\mu$	ee	μe	$e\mu$
$W^\pm W^\pm jj$ (QCD)	168.7	74.6	19.7	32.2	42.2
Charge Misidentification	200	0.0	11	30	160
Jets faking electrons	460	0.0	130	260	70
$WZ + ZZ$	1286	322	289	271	404
Tribosons	76	30.1	9.6	15.1	21.6
Other non-prompt	120	29	16.6	50	19
Total Background	2310	455	480	660	710
Signal $W^\pm W^\pm jj$ (EWK)	2958	1228	380	589	761

Table 6.6: Signal and background event yields using the optimized event selection for an integrated luminosity of $\mathcal{L} = 3000 \text{ fb}^{-1}$. Events containing a fake or charge-flipped electron are removed from their respective sources and combined into a single entry each.

It is important to note, however, that the MC sample used to estimate $Z+jets$ events suffers from poor statistics which results in large per-event weights once scaled to $\mathcal{L} = 3000 \text{ fb}^{-1}$. This sample contributes heavily to the fake and charge misidentification backgrounds, and a handful of these events being cut out by the optimization is largely responsible for the dramatic reduction of the corresponding backgrounds. As a result, the optimized results presented here are likely overly optimistic. However, given proper MC statistics, it is still expected that this optimization will

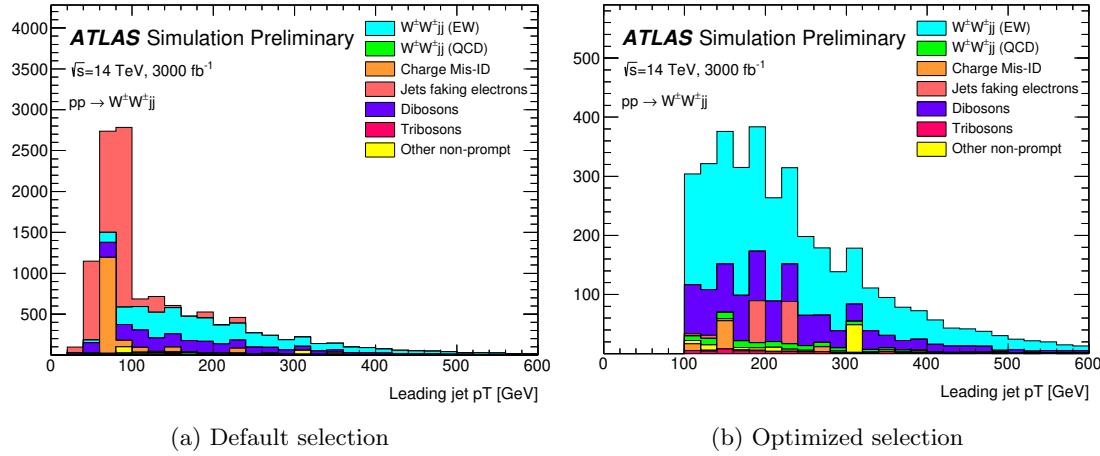


Figure 6.6: p_T distributions for the leading jet using the default (left) and optimized (right) event selections for all channels combined.

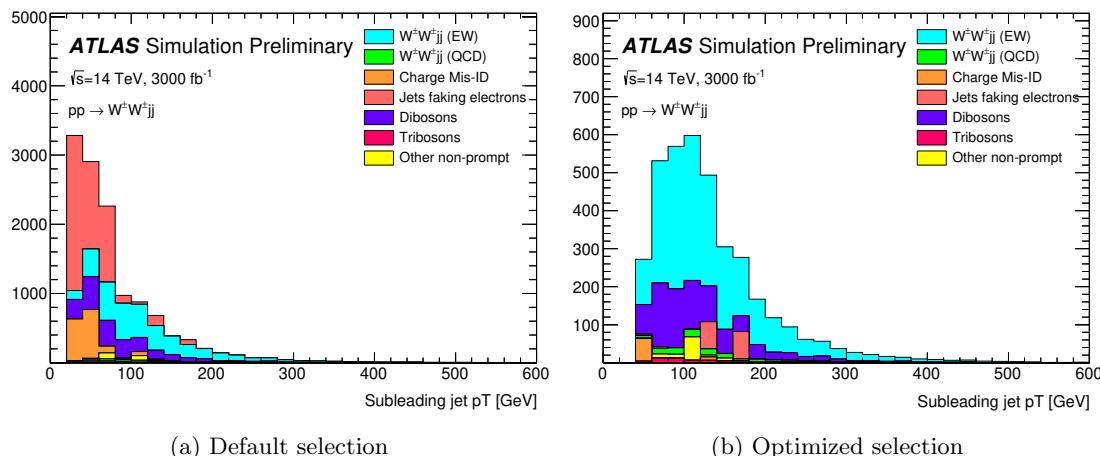


Figure 6.7: p_T distributions for the subleading jet using the default (left) and optimized (right) event selections for all channels combined.

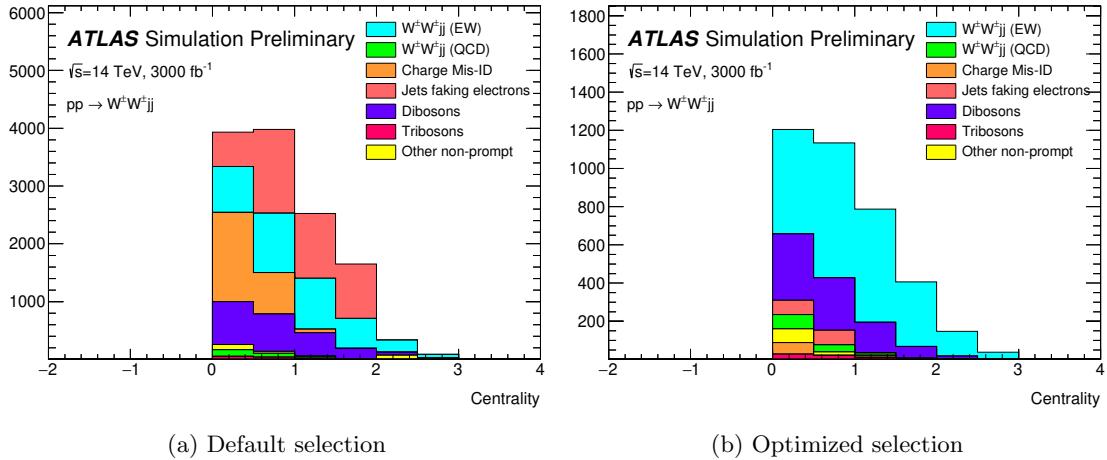


Figure 6.8: p_T distributions for lepton-jet centrality ζ using the default (left) and optimized (right) event selections for all channels combined.

2516 outperform the default selection.

2517 6.6.2 Uncertainties

2518 The uncertainties considered for the analysis are summarized in Table 6.7. Values for experimental
 2519 systematics on the trigger efficiency, lepton and jet reconstruction, and flavor tagging are taken
 2520 directly from the 13 TeV analysis [81]. The rate uncertainties for the background processes are
 2521 halved from the 13 TeV values according to ATLAS recommendations. The uncertainty on the fake
 2522 electron estimation is also halved from the 13 TeV analysis. Finally, a conservative estimate of the
 2523 uncertainty on the charge flip background is used as the electron charge mis-ID rate due to material
 2524 interactions is difficult to predict at this stage.

2525 6.6.3 Cross section measurement

2526 The cross section is calculated using the same method as in the 13 TeV analysis, detailed in Sec-
 2527 tion 5.4. Unlike the previous analysis, however, eight lepton channels are used here instead of six.
 2528 The μe and $e\mu$ channels remain separated in addition to the $\mu\mu$ and ee channels, and each lepton
 2529 flavor channel is further split by charge (i.e. $\mu\mu \rightarrow \mu^+\mu^+ + \mu^-\mu^-$), as this increases the sensitivity
 2530 of the analysis. Each channel's m_{jj} distribution is combined in a profile likelihood fit to extract
 2531 the EWK $W^\pm W^\pm jj$ production cross section. Using the default event selection, the expected cross

Source	Uncertainty (%)
$W^\pm W^\pm jj$ (EWK)	3
Luminosity	1
Trigger efficiency	0.5
Lepton reconstruction and identification	1.8
Jets	2.3
Flavor tagging	1.8
Jets faking electrons	20
Charge misidentification	25
$W^\pm W^\pm jj$ (QCD)	20
Top	15
Diboson	10
Triboson	15

Table 6.7: Summary of estimated experimental and rate uncertainties.

2532 section calculated to be:

$$\sigma_{W^\pm W^\pm jj}^{\text{expected}} = 16.89 \pm 0.36 \text{ (stat)} \pm 0.53 \text{ (theory)} \pm 0.84 \text{ (syst)} \text{ fb} \quad (6.5)$$

2533 and with the optimized event selection:

$$\sigma_{W^\pm W^\pm jj}^{\text{expected}} = 16.94 \pm 0.36 \text{ (stat)} \pm 0.53 \text{ (theory)} \pm 0.78 \text{ (syst)} \text{ fb} \quad (6.6)$$

2534 The optimized selection should not change the measured value of the cross section, and indeed both
 2535 are consistent with within uncertainties. The systematic uncertainty is reduced by approximately
 2536 7% with the optimized selection. The total uncertainty on the cross section measurement is approx-
 2537 imately 6%, compared to approximately 20% on the measured fiducial cross section of the 13 TeV
 2538 analysis reported in Equation 5.30.

2539 Projections of each uncertainty type and the total uncertainty on the cross section as a function of
 2540 integrated luminosity are shown in Figure 6.9. The predictions are made by scaling the event yields
 2541 by different luminosity values and re-running the fitting procedure. As the integrated luminosity
 2542 increases past $\mathcal{L} > 3000 \text{ fb}^{-1}$, the statistical uncertainty continues to reduce; however, the total
 2543 uncertainty becomes limited by the systematics. Additionally, the total uncertainty is expected to
 2544 reduce by less than a percent as the integrated luminosity increases past the planned 3000 fb^{-1} .

2545 6.6.4 Longitudinal scattering significance

2546 The longitudinal scattering significance is extracted in much the same way as the cross section, this
 2547 time using a binned likelihood fit on the $|\Delta\phi_{jj}|$ distribution. In order to increase sensitivity, the

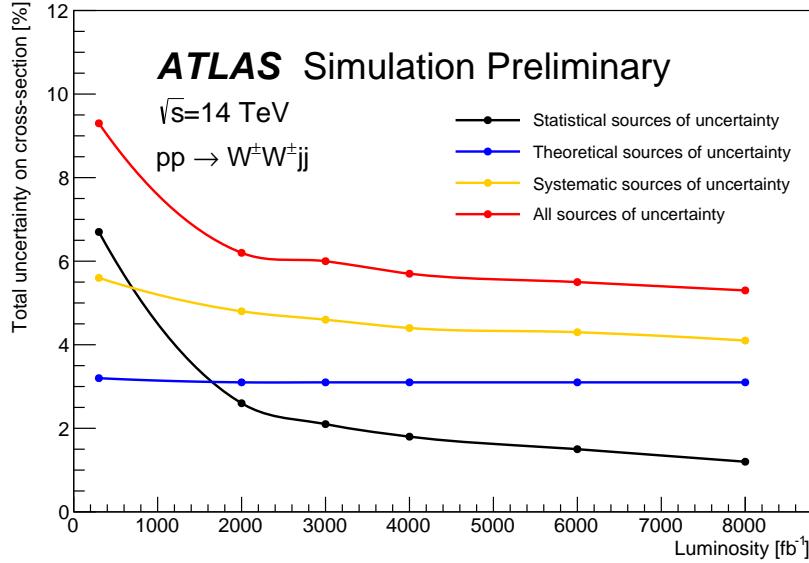


Figure 6.9: Projections of the statistical (black), theoretical (blue), systematic (yellow), and total (red) uncertainties on the measured cross section as a function of integrated luminosity using the optimized event selection.

2548 $|\Delta\phi_{jj}|$ distribution is split into two bins in m_{jj} , and an additional cut on the pseudorapidity of the
 2549 subleading lepton is applied ($|\eta| < 2.5$) to reduce background contributions from fake electrons and
 2550 charge flip. The $|\Delta\phi_{jj}|$ distributions used in the fit are shown in Figure 6.10. Due to limited statistics
 2551 in the LL events, the four lepton flavor channels are not split by charge. The expected significance
 2552 of the $W_L^\pm W_L^\pm jj$ process is 1.8σ with a precision of 47% on the measurement. Projections of the
 2553 expected significance as a function of integrated luminosity is shown in Figure 6.11.

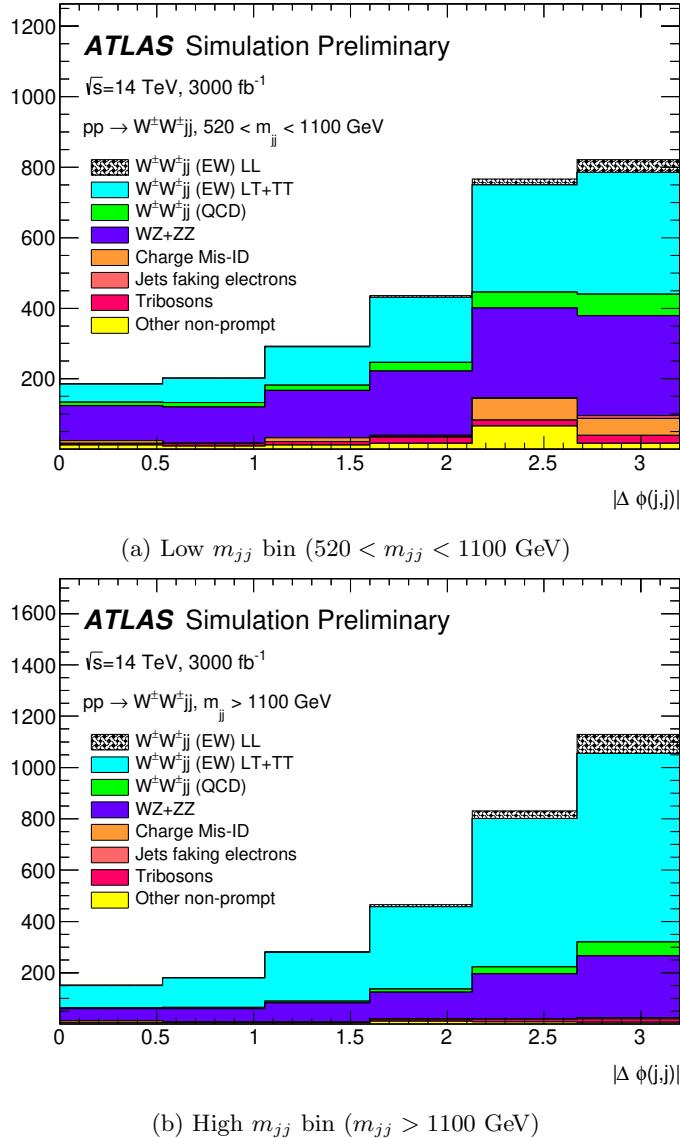


Figure 6.10: Dijet azimuthal separation ($|\Delta\phi_{jj}|$) for the low m_{jj} region ($520 < m_{jj} < 1100$ GeV, top) and the high m_{jj} region ($m_{jj} > 1100$ GeV, bottom). The purely longitudinal (LL, gray) is plotted separately from the mixed and transverse (LT+TT, cyan) polarizations.

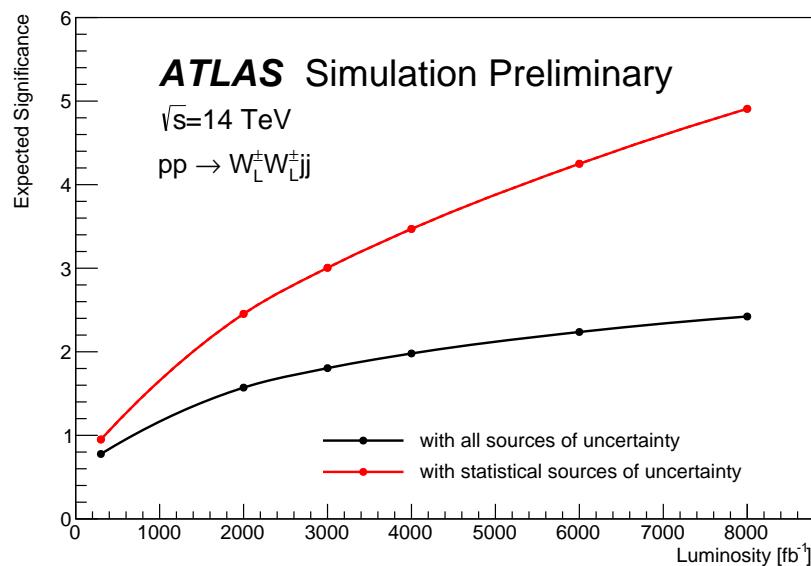


Figure 6.11: Projections of the expected longitudinal scattering significance as a function of integrated luminosity when considering all sources of uncertainties (black) or only statistical uncertainties (red).

2554

CHAPTER 7

2555

Conclusion

2556 Here's where you wrap it up.

2557

APPENDIX A

2558

2559

Additional material on $W^\pm W^\pm jj$ measurement at $\sqrt{s} = 13$ TeV

2560

A.1 Impact of experimental uncertainty on MC background estimations

Tables A.1-A.6 contain the impact of experimental systematic uncertainties for the remaining backgrounds estimated from MC simulation. The $W^\pm W^\pm jj$ EWK signal and WZ background systematics are listed in the main body of the document, in Tables 5.21 and 5.22, respectively. While the percentage of the contributions for some systematics appear large, the size of these backgrounds are quite small compared to the total background.

$W^\pm W^\pm jj$ QCD	ee % Yield	$e\mu$ % Yield	$\mu\mu$ % Yield
Jet-related Uncertainties	3.41	3.04	2.85
b-tagging efficiency	2.56	2.48	2.48
Pile-up	4.99	0.45	0.33
Trigger efficiency	0.02	0.08	0.41
Lepton reconstruction/ID	1.62	1.19	1.89
MET reconstruction	0.41	0.22	0.34

Table A.1: Impact of experimental uncertainties for the $W^\pm W^\pm jj$ QCD processes in all channels.

Triboson	ee % Yield	$e\mu$ % Yield	$\mu\mu$ % Yield
Jet-related Uncertainties	13.09	13.39	16.85
b-tagging efficiency	2.96	3.77	4.95
Pile-up	19.37	24.66	6.87
Trigger efficiency	0.02	0.07	0.47
Lepton reconstruction/ID	1.66	1.27	2.48
MET reconstruction	0.00	0.46	0.00

Table A.2: Impact of experimental uncertainties for triboson process in all channels.

$t\bar{t}V$	ee % Yield	$e\mu$ % Yield	$\mu\mu$ % Yield
Jet-related Uncertainties	17.65	11.97	14.27
b-tagging efficiency	15.02	9.04	13.83
Pile-up	8.73	10.69	4.18
Trigger efficiency	0.03	0.08	0.39
Lepton reconstruction/ID	2.57	3.27	2.66
MET reconstruction	1.75	4.16	1.62

Table A.3: Impact of experimental uncertainties for $t\bar{t}V$ processes in all channels.

$W\gamma$	ee % Yield	$e\mu$ % Yield	$\mu\mu$ % Yield
Jet-related Uncertainties	7.05	33.36	—
b-tagging efficiency	1.97	2.94	—
Pile-up	4.11	14.17	—
Trigger efficiency	0.01	0.14	—
Lepton reconstruction/ID	1.40	1.13	—
MET reconstruction	0.00	0.00	—

Table A.4: Impact of experimental uncertainties for the $W\gamma$ process in all channels.

$Z\gamma$	ee % Yield	$e\mu$ % Yield	$\mu\mu$ % Yield
Jet-related Uncertainties	16.22	370.44	—
b-tagging efficiency	1.08	3.10	—
Pile-up	12.57	11.51	—
Trigger efficiency	0.02	0.07	—
Lepton reconstruction/ID	1.26	22.01	—
MET reconstruction	0.00	0.00	—

Table A.5: Impact of experimental uncertainties for the $Z\gamma$ process in all channels.

ZZ	ee % Yield	$e\mu$ % Yield	$\mu\mu$ % Yield
Jet-related Uncertainties	15.71	15.76	35.18
b-tagging efficiency	2.23	2.35	2.89
Pile-up	1.22	3.20	4.58
Trigger efficiency	0.03	0.10	0.36
Lepton reconstruction/ID	3.59	3.10	5.70
MET reconstruction	4.84	3.26	3.24

Table A.6: Impact of experimental uncertainties for the ZZ process in all channels.

2566 **A.2 Additional signal region plots**

APPENDIX B

Additional material on $W^\pm W^\pm jj$ prospects at the HL-LHC

B.1 Truth isolation

2571 As mentioned in Section 6.3.1, the size of the background contribution from top processes are much
 2572 larger than expected when no isolation is applied. The event yields using an earlier version of the
 2573 event selection with no truth-based isolation requirement are listed in Table B.1. Here, top events
 2574 make up nearly 90% of the total background, and the contributions from fake and charge-flipped
 2575 electrons are also large. The event yields using the same event selection with the truth-based isolation
 2576 included are shown in Figure B.2. When comparing the two tables, the considerable reduction in
 the top background can be clearly seen.

yields by type	all channels	$\mu\mu$	ee	μe	$e\mu$
signal	4011	1583.2	531.7	793.1	1103.1
ww qcd	252.6	105.8	30.4	48	68.4
charge flip	2528.4	0.0	2075.4	255.1	197.8
fakes	7135.4	0.0	4675.1	1904.3	555.9
diboson	2370.4	581.2	491.8	517.9	779.6
triboson	125.5	49.1	17.8	24.6	34.1
top	90150.5	26618	15301.6	25277.9	22953.1
z+jets	241.2	0.0	0.0	0.0	241.2
w+jets	31.4	3.9	7.6	13.2	6.7
total bkg	102803.9	27354	22592	28027.8	24830.1
signal	4011	1583.2	531.7	793.1	1103.1

Table B.1: Event yields prior to applying any form of truth-based isolation criteria.

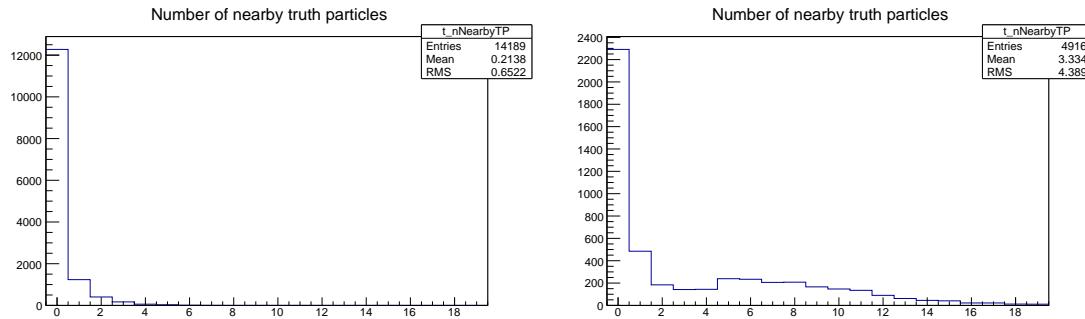
TODO: Add tables for tight vs loose working point, information on the necessity of TRUTH1++

yields by type	all channels	$\mu\mu$	ee	μe	$e\mu$
signal	3470.5	1427.3	428.8	675.8	938.7
ww qcd	205.8	90.8	22.7	38.3	54
charge flip	2398.3	0.0	2104.6	95.8	197.9
fakes	4309.7	0.0	3390.6	750.8	168.3
diboson	1552.4	311.3	355.6	346.8	538.7
triboson	115	46.8	15.4	21.6	31.2
top	156.9	42.3	14.8	76.6	23.3
$z+jets$	0.0	0.0	0.0	0.0	0.0
$w+jets$	0.3	0.0	0.0	0.3	0.0
total bkg	8738.1	491.3	5903.7	1329.8	1013.4
signal	3470.5	1427.3	428.8	675.8	938.7

Table B.2: Event yields after applying a test version of the truth-based isolation.

2579 **B.1.1 TRUTH1++ derivations**

2580 The ATLAS standard TRUTH1 derivations used for this analysis contain a slimmed truth particle
 2581 container in order to reduce the file size. As a result, many of the truth particles that would be
 2582 included in the isolation variables are missing, and the truth-based isolation will not accurately
 2583 model the reconstruction-level isolation variables. In order to recover the performance of the truth-
 2584 based isolation in the top MC samples (where it is most needed), a custom derivation was produced
 2585 privately that duplicated the default TRUTH1 data structure but includes the full truth particle
 2586 record. The reduced size of the truth particle information in the TRUTH1 derivation compared to the
 2587 TRUTH1++ derivation is shown in Figure B.1.

Figure B.1: Number of truth particles within $\Delta R < 0.4$ of a selected muon or electron using the ATLAS standard TRUTH1 (left) and the custom TRUTH1++ (right) derivations in $t\bar{t}$ simulation. The complete truth record is stored in the TRUTH1++ derivation, and this is best seen in the first bin, where the lepton has no nearby truth particles.

2588 **B.1.2 Check of truth-based isolation**

2589 Since the isolation variables are constructed from truth particles, there is an expectation that the
 2590 efficiency of the isolation selection will be higher than what would be seen in the full simulation.
 2591 In order to test this, a truth-level 13 TeV $t\bar{t}$ MC sample was run through a selection altered to
 2592 mimic the 13 TeV $W^\pm W^\pm jj$ measurement as closely as possible. The results were compared to the
 2593 $t\bar{t}$ background in the 13 TeV analysis extrapolated to 14 TeV and 3000 fb^{-1} , and the truth-based
 2594 isolation reduces the expected events by a factor of approximately 4. However, the statistics in the
 2595 13 TeV truth-level sample are low, and it is therefore difficult to measure precisely how much the
 2596 truth-based isolation overperforms.

2597 **B.1.3 Loose isolation working point**

2598 As another check on the truth-based isolation, a second isolation working point was constructed
 2599 to match the official ATLAS Fixed Cut Loose isolation working point. The definition of this loose
 2600 isolation are found in Table B.3.

2601 The primary impact of loosening the isolation is a substantial increase in the non-prompt back-
 2602 round from top processes, and a moderate increase in the charge mis-ID and fake backgrounds.
 2603 Backgrounds from prompt leptons only did not see major changes. As a result, the tight working
 2604 point is chosen for the analysis. The event yields by sample and by background type using the
 2605 loose working point are in Table B.4, and Table B.5 has the numbers using the tight working point
 2606 (defined in Table 6.2) for comparison.

	Electron Isolation	Muon Isolation
Track-based isolation cone size	$\Delta R < 0.2$	$\Delta R < 0.3$
Track-based isolation requirement	$\sum p_T/p_T^e < 0.15$	$\sum p_T/p_T^\mu < 0.15$
Calorimeter-based isolation cone size	$\Delta R < 0.2$	$\Delta R < 0.2$
Calorimeter-based isolation requirement	$\sum E_T/p_T^e < 0.2$	$\sum E_T/p_T^\mu < 0.3$

Table B.3: Electron and muon isolation requirements for the loose working point.

run number	all channels			mm			ee			me			em		
	events	stat	sys	events	stat	sys	events	stat	sys	events	stat	sys	events	stat	sys
signal	3783.21	22.08	0.00	1524.99	15.00	0.00	484.74	7.01	0.00	740.76	9.01	0.00	1032.72	11.50	0.00
ww qcd	223.95	3.54	44.79	97.17	2.51	19.43	25.51	1.03	5.10	42.23	1.40	8.45	59.04	1.80	11.81
charge flip	3025.40	1276.74	0.00	0.00	0.00	0.00	2615.30	1267.89	0.00	197.20	87.94	0.00	212.90	121.63	0.00
fakes	5315.55	1775.87	0.00	0.00	0.00	0.00	3524.24	1694.39	0.00	1356.74	450.60	0.00	434.57	282.33	0.00
diboson	2195.61	38.10	219.58	548.72	18.54	54.87	451.27	18.29	45.14	470.61	15.71	47.07	725.01	22.95	72.50
triboson	117.43	5.90	17.62	47.55	4.32	7.13	15.83	1.94	2.37	22.11	2.18	3.32	31.94	2.76	4.80
top	554.63	218.75	83.21	229.26	135.53	34.40	61.15	38.23	9.18	232.30	167.28	34.85	31.92	6.43	4.78
z+jets	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
w+jets	1.21	0.87	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
total bkg	11433.78	2198.44	239.70	922.70	136.88	67.99	6693.30	2116.67	46.41	2322.38	488.89	59.27	1495.40	308.36	73.77
signal	3783.21	22.08	0.00	1524.99	15.00	0.00	484.74	7.01	0.00	740.76	9.01	0.00	1032.72	11.50	0.00

Table B.4: Event yields broken down by sample and by background type using the loose isolation workingpoint. Events containing a fake or charge-flipped electron are removed from their respective sample and added to the ‘fakes’ and ‘charge flip’ rows, respectively. Errors include statistical uncertainty and estimated systematic rate uncertainty based on the background process.

run number	all channels			mm			ee			me			em		
	events	stat	sys	events	stat	sys	events	stat	sys	events	stat	sys	events	stat	sys
signal	3489.49	21.23	0.00	1434.85	14.55	0.00	431.75	6.61	0.00	679.09	8.63	0.00	943.8	11.00	0.00
ww qcd	206.42	3.41	41.28	91.12	2.43	18.22	22.84	0.98	4.57	38.37	1.34	7.67	54.09	1.72	10.82
charge flip	2335.73	1163.47	0.00	0.00	0.00	0.00	2087.78	1159.5	0.00	90.37	33.32	0.00	157.58	90.02	0.00
fakes	4979.27	1756.47	0.00	0.00	0.00	0.00	3406.20	1705.03	0.00	1230.80	362.15	0.00	342.27	216.54	0.00
diboson	2039.94	36.93	204.00	499.69	18.04	49.97	437.60	14.12	43.76	422.90	14.18	42.29	679.75	25.25	67.98
triboson	115.03	5.87	17.29	46.84	4.31	7.03	15.40	1.94	2.32	21.55	2.17	3.24	31.24	2.74	4.70
top	211.74	84.14	31.76	107.96	71.12	16.20	19.58	3.76	2.93	57.21	44.47	8.58	26.99	5.40	4.05
z+jets	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
w+jets	0.30	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.28	0.00	0.02	0.02	0.00
total bkg	9888.43	2108.87	211.25	745.61	73.54	56.04	5898.40	2061.99	44.16	1861.48	366.67	43.95	1291.94	235.95	69.11
signal	3489.49	21.23	0.00	1434.85	14.55	0.00	431.75	6.61	0.00	679.09	8.63	0.00	943.80	11.00	0.00

Table B.5: Event yields broken down by background type using the tight isolation workingpoint. Events containing a fake or charge-flipped electron are removed from their respective sample and added to the “fakes” and “charge flip” rows, respectively. Errors include statistical uncertainty and estimated systematic rate uncertainty based on the background process.

2607 **B.2 Plots of other optimization variables**

2608 Plots of the remaining optimization variables not shown in Section 6.5.3 are presented here for
 2609 reference. Figures B.2, B.3, and B.4 compare signal and background distributions for the default
 2610 and optimized cuts. None of these cuts change by much in the optimized selection and their impacts
 2611 on the overall event selection is minimal.

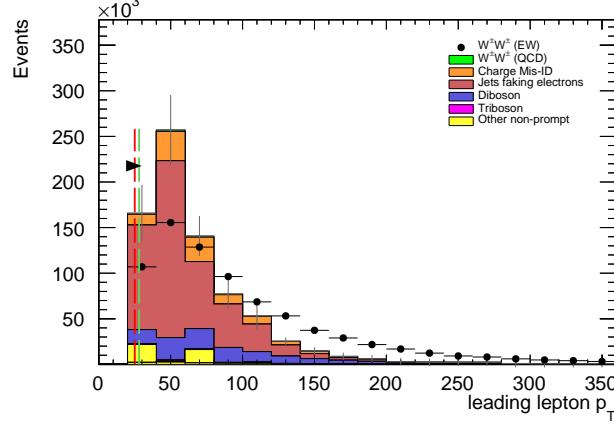


Figure B.2: Leading lepton p_T distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

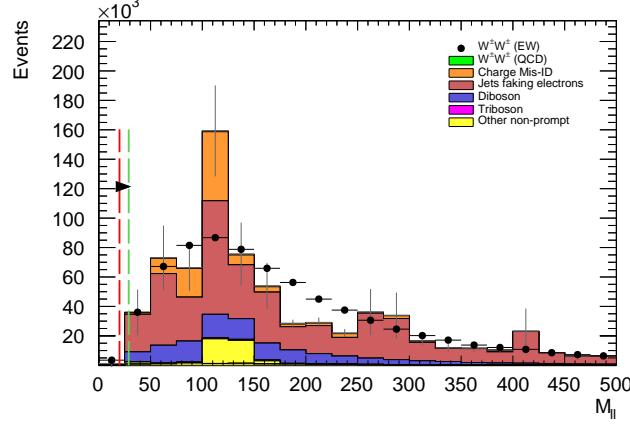


Figure B.3: Dilepton invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

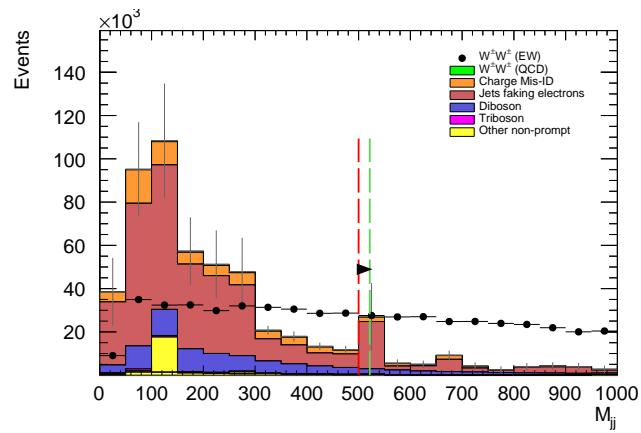


Figure B.4: Dijet invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

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