

¹ STANDARD MODEL IS BEST MODEL (WORKING TITLE)

² William Kennedy DiClemente

³ A DISSERTATION
⁴ in
⁵ Physics and Astronomy

⁶ Presented to the Faculties of The University of Pennsylvania
⁷ in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy
⁸ 2019 Last compiled: January 18, 2019

⁹
¹⁰ I. Joseph Kroll, Professor, Physics
¹¹ Supervisor of Dissertation

¹²
¹³ Joshua Klein, Professor, Physics
¹⁴ Graduate Group Chairperson

¹⁵ Dissertation Committee
¹⁶ (Committee Prof. 1), Professor, Physics
¹⁷ (Committee Prof. 2), Associate Professor, Physics
¹⁸ (Committee Prof. 3), Professor, Physics
¹⁹ (Committee Prof. 4), Professor, Physics
²⁰ I. Joseph Kroll, Professor, Physics

21

S T A N D A R D M O D E L I S B E S T M O D E L (W O R K I N G T I T L E)

22
23
24

C O P Y R I G H T
2 0 1 9
William Kennedy DiClemente

25

All rights reserved.

Acknowledgements

27 I'd like to thanks the Ghosts of Penn Students Past for providing me with such an amazing thesis
28 template.

29

ABSTRACT

30

STANDARD MODEL IS BEST MODEL (WORKING TITLE)

31

William Kennedy DiClemente

32

J. Kroll

33

This is the abstract text.

Contents

35	Acknowledgements	iii
36	Abstract	iv
37	Contents	v
38	List of Tables	ix
39	List of Figures	xi
40	Preface	xv
41	1 Introduction	1
42	2 Theoretical Framework	2
43	2.1 Introduction to the Standard Model	2
44	2.2 Electroweak Mixing and the Higgs Field	2
45	3 LHC and the ATLAS Detector	3
46	3.1 The Large Hadron Collider	3
47	3.2 The ATLAS Detector	3
48	3.2.1 The Inner Detector	3
49	3.2.1.1 Pixel Detector	3
50	3.2.1.2 Semiconductor Tracker	3
51	3.2.1.3 Transition Radiation Tracker	3
52	3.2.2 The Calorimeters	4

53	3.2.2.1	Liquid Argon Calorimeters	4
54	3.2.2.2	Tile Calorimeters	4
55	3.2.3	The Muon Spectrometer	4
56	3.2.4	Particle reconstruction	5
57	3.2.4.1	Track reconstruction	5
58	3.2.4.2	Muon reconstruction	5
59	3.2.4.3	Electron reconstruction	5
60	3.2.4.4	Jet reconstruction	5
61	4	Alignment of the ATLAS Inner Detector	6
62	4.1	Effects of Misalignment	6
63	4.2	The Alignment Method	6
64	4.3	Momentum Bias Corrections	6
65	4.4	Alignment of the IBL	7
66	4.5	Alignment Monitoring	7
67	5	Measurement of same-sign WW production at $\sqrt{s} = 13$ TeV with ATLAS	8
68	5.0.1	Theoretical overview of vector boson scattering	8
69	5.0.2	Same-sign $W^\pm W^\pm$ scattering	10
70	5.0.3	Overview of backgrounds	12
71	5.1	Data and Monte Carlo samples	14
72	5.1.1	Monte Carlo samples	14
73	5.2	Object and event selection	15
74	5.2.1	Object selection	15
75	5.2.1.1	Muon candidate selection	16
76	5.2.1.2	Electron candidate selection	18
77	5.2.1.3	Jet candidate selection	18
78	5.2.1.4	Treatment of overlapping objects	18
79	5.2.2	Signal event selection	20
80	5.3	Background estimations	22
81	5.3.1	Estimation of the WZ background	22
82	5.3.2	Estimation of the $V\gamma$ background	23
83	5.3.3	Estimation of backgrounds from charge misidentification	25

84	5.3.3.1	Validation of the charge misidentification estimate	28
85	5.3.4	Estimation of non-prompt backgrounds with the fake factor method	29
86	5.3.4.1	Overview of the default fake factor method	29
87	5.3.4.2	The fake factor with p_T^{cone}	30
88	5.3.4.3	Application of the fake factor	32
89	5.3.4.4	Systematic uncertainties	37
90	5.3.4.5	Results of the fake factor	37
91	5.3.4.6	Validation of the fake factor	39
92	5.3.5	Reduction of WZ background using custom overlap removal	42
93	5.4	Cross section measurement	45
94	5.4.1	Maximum likelihood fit	46
95	5.4.2	Cross section extraction	48
96	5.4.2.1	Fiducial region definition	48
97	5.5	Results	48
98	6	Prospects for same-sign WW at the High Luminosity LHC	49
99	6.0.1	Analysis Overview	50
100	6.1	Theoretical motivation	50
101	6.1.1	Experimental sensitivity to longitudinal polarization	51
102	6.2	Monte Carlo samples	51
103	6.3	Background estimations	53
104	6.3.1	Truth-based isolation	54
105	6.4	Object and event selection	55
106	6.4.1	Object selection	55
107	6.4.2	Event selection	55
108	6.5	Selection optimization	56
109	6.5.1	Random grid search algorithm	56
110	6.5.2	Inputs to the optimization	58
111	6.5.3	Results of the optimization	59
112	6.6	Results	60
113	6.6.1	Event yields	60
114	6.6.2	Uncertainties	66
115	6.6.3	Cross section measurement	66

116	6.6.4 Longitudinal scattering significance	67
117	7 Conclusion	71
118	A Additional material on truth isolation	72
119	Bibliography	73

List of Tables

121	5.1	Predicted cross sections for EQK and QCD production of diboson processes relevant to VBS at $\sqrt{s} = 8\text{TeV}$ using the SHERPA MC generator. Loose generator level cuts are applied on lepton $p_T > 5\text{ GeV}$, dilepton invariant mass $m_{ll} > 4\text{ GeV}$, and at least two jets with $m_{jj} > 10\text{ GeV}$	11
125	5.2	Summary of MC samples used in the analysis.	16
126	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.	17
128	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.	19
131	5.5	Jet selection criteria. All jets are required to pass the above selection in order to be used in the analysis.	19
133	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.	20
136	5.7	Summary of trigger requirements for electrons and muons for $\sqrt{s} = 13\text{TeV}$ data collected in 2015 and 2016. At least one of the triggers must be satisfied.	21
138	5.8	The signal event selection.	22
139	5.9	Event yields in the WZ control region before normalization. All lepton flavor channels are combined.	23
141	5.10	Selection criteria for the $V\gamma$ control region.	24
142	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 $Z+\text{jets}$ backgrounds to account for the difference between the data and predicted total background.	25
145	5.12	Selection criteria for the same-sign inclusive validation region.	28
146	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 $p_T > 27\text{ GeV}$ requirement is replaced with $p_T > 15\text{ GeV}$	34
149	5.14	Values of the fake factor in each p_T bin and for each individual systematic source.	38

150	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.	38
155	5.16	Selection criteria for the same-sign top fakes validation region.	39
156	5.17	Custom OR definition. Leptons must pass this selection in order to be counted for the trilepton veto.	45
158	5.18	Definition of the fiducial volume.	48
159	6.1	Summary of MC samples used in the analysis.	53
160	6.2	Truth-based isolation requirements for electrons and muons.	54
161	6.3	Summary of the signal event selection.	56
162	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.	60
164	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.	64
167	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.	64
170	6.7	Summary of estimated experimental and rate uncertainties.	66
171	A.1	Event yields prior to applying any form of truth-based isolation criteria.	72
172	A.2	Event yields after applying a test version of the truth-based isolation.	72

List of Figures

174	3.1	General cut-away view of the ATLAS detector.	4
175	5.1	Cross sections in nanobarns for five different scattering processes of longitudinally polarized vector bosons as a function of center of mass energy \sqrt{s} . Without a SM Higgs boson (left), the cross sections grow unbounded with \sqrt{s} ; however with a 120 GeV Higgs boson (right), the cross sections no longer diverge.	9
179	5.2	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 ($V = W, Z$).	10
183	5.3	Tree-level Feynman diagrams for non-VBS EWK $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).	10
185	5.4	Tree-level Feynman diagrams for QCD $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).	11
187	5.5	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. TODO: Make diagrams consistent with others	12
190	5.6	$W^\pm W^\pm jj$ 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 .	12
193	5.7	Generator level comparisons at $\sqrt{s} = 8\text{TeV}$ 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. Both data sets have been normalized to the same area.	13
196	5.8	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 [1].	13
201	5.9	Leading lepton p_T (left) and η (right) distributions in the WZ control region before normalization. All lepton channels are combined.	24
203	5.10	Trilepton invariant mass m_{lll} distribution in the WZ control region before normalization. All lepton channels are combined.	24

205	5.11 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.	26
208	5.12 Dilepton invariant mass distribution m_{ll} for the ee channel in the same-sign inclusive VR.	28
209	5.13 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.	29
212	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.	31
215	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).	33
219	5.16 Distributions of p_T^{cone}/p_T for nominal (black) and loose (red) muons in simulated $t\bar{t}$ events.	34
220	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.	35
222	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.	35
225	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.	36
229	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.	39
232	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.	40
236	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.	41
239	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.	43
243	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.	43
248	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.	44

253	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.	44
258	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.	45
262	6.1 Comparison of the leading (top) and subleading (bottom) lepton p_T distributions for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan) $W^\pm W^\pm jj$ events.	52
264	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.	53
266	6.3 A visual representation of a rectangular grid search algorithm. The signal events are the blue triangles, and the red circles are the background events. TODO: replace with own figure	57
269	6.4 A visual representation of a random grid search algorithm. The signal events are the blue triangles, and the red circles are the background events. TODO: replace with own figure	58
272	6.5 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). TODO: Move to appendix or omit	61
276	6.6 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). TODO: Move to appendix or omit	61
280	6.7 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).	62
284	6.8 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). TODO: Move to appendix or omit	63
288	6.9 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).	63
291	6.10 p_T distributions for the leading jet using the default (left) and optimized (right) event selections for all channels combined.	65
293	6.11 p_T distributions for the subleading jet using the default (left) and optimized (right) event selections for all channels combined.	65
295	6.12 p_T distributions for lepton-jet centrality ζ using the default (left) and optimized (right) event selections for all channels combined.	65
297	6.13 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.	67

300 6.14 Dijet azimuthal separation ($|\Delta\phi_{jj}|$) for the low m_{jj} region ($520 < m_{jj} < 1100$ GeV, top)
 301 and the high m_{jj} region ($m_{jj} > 1100$ GeV, bottom). The purely longitudinal (LL, gray)
 302 is plotted separately from the mixed and transverse (LT+TT, cyan) polarizations.
 303 6.15 Projections of the expected longitudinal scattering significance as a function of integrated
 304 luminosity when considering all sources of uncertainties (black) or only statistical
 305 uncertainties (red).

306

Preface

307 This is the preface. It's optional, but it's nice to give some context for the reader and stuff.

308

Will K. DiClemente

Philadelphia, February 2019

309

CHAPTER 1

310

Introduction

311 The Standard Model (SM)¹ has been remarkably successful...

¹Here's a footnote.

312

CHAPTER 2

313

Theoretical Framework

314 (Some example introductory text for this chapter)...

315 2.1 Introduction to the Standard Model

316 Modern particle physics is generally interpreted in terms of the Standard Model (SM). This is a
317 quantum field theory which encapsulates our understanding of the electromagnetic, weak, and strong
318 interactions...

319 2.2 Electroweak Mixing and the Higgs Field

320 When the theory of the electroweak interaction was first developed [2, 3], the W and Z bosons were
321 predicted to be massless (a typical mass term in the Lagrangian would violate the $SU(2)$ symmetry).
322 However, these were experimentally observed to have masses...

323

CHAPTER 3

324

LHC and the ATLAS Detector

325 **3.1 The Large Hadron Collider**

326 The Large Hadron Collider (LHC) [4] is...

327 **3.2 The ATLAS Detector**

328 ATLAS is a general-purpose particle detector...

329 **3.2.1 The Inner Detector**

330 The Inner Detector serves the primary purpose of measuring the trajectories of charged particles...

331 **3.2.1.1 Pixel Detector**

332 The Pixel detector consists of four cylindrical barrel layers and three disk-shaped endcap layers...

333 **3.2.1.2 Semiconductor Tracker**

334 The Semiconductor Tracker uses the same basic technology as the Pixels, but the fundamental unit
335 of silicon is a larger “strip”...

336 **3.2.1.3 Transition Radiation Tracker**

337 The Transition Radiation Tracker is the outermost component of the ID...

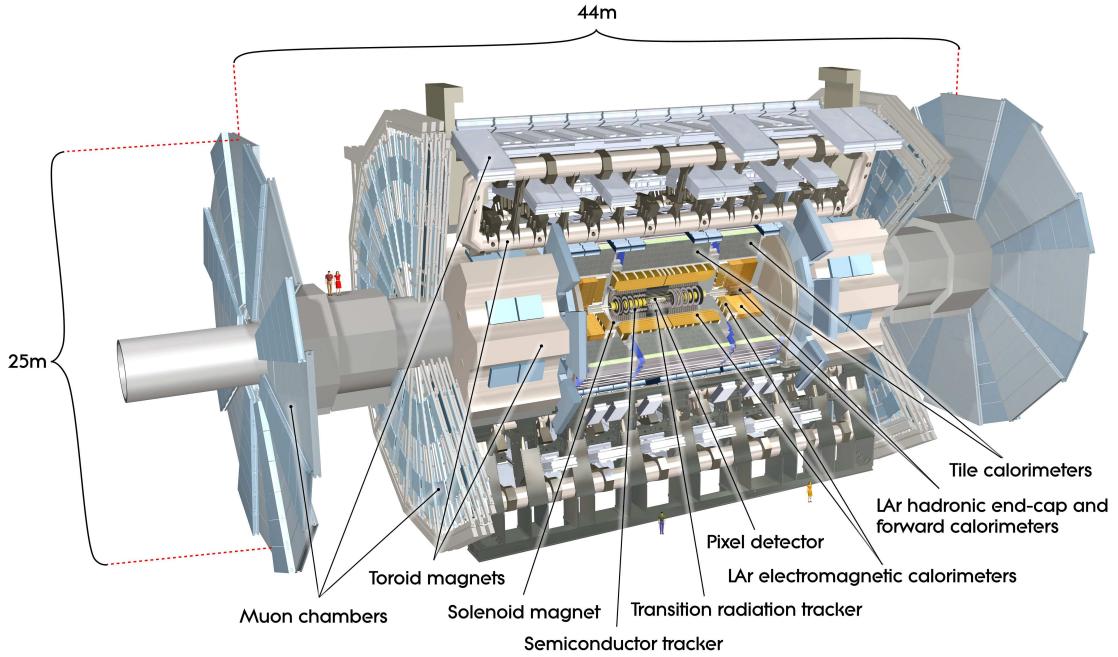


Figure 3.1: General cut-away view of the ATLAS detector [5].

³³⁸ 3.2.2 The Calorimeters

³³⁹ ATLAS includes two types of calorimeter system for measuring electromagnetic and hadronic showers. These are the Liquid Argon (LAr) calorimeters and the Tile calorimeters. Together, these cover
³⁴⁰ the region with $|\eta| < 4.9\dots$

³⁴² 3.2.2.1 Liquid Argon Calorimeters

³⁴³ The Liquid Argon system consists of...

³⁴⁴ 3.2.2.2 Tile Calorimeters

³⁴⁵ The Tile calorimeter provides coverage for hadronic showers...

³⁴⁶ 3.2.3 The Muon Spectrometer

³⁴⁷ Muon spectrometer stuff.

348 **3.2.4 Particle reconstruction**

349 Particle reconstruction algorithms

350 **3.2.4.1 Track reconstruction**

351 **3.2.4.2 Muon reconstruction**

352 **3.2.4.3 Electron reconstruction**

353 **3.2.4.4 Jet reconstruction**

CHAPTER 4

355 Alignment of the ATLAS Inner Detector

356 In order for the subdetectors of the ID to operate at their designed precisions, it is essential that
357 the locations of the sensors be known as precisely as possible. Differences between the expected and
358 actual positions of a sensor can result in displaced particle hits and degrade track reconstruction
359 quality. These misalignments can occur for any number of reasons, including but not limited to
360 elements shifting during maintenance periods or cycles in ATLAS's magnetic field, or simply small
361 movements during normal detector operations. Since it is not practical to physically realign hundreds
362 of thousands of detector elements to μm precision by hand, an iterative track-based alignment
363 algorithm is used to determine the physical positions and orientations of these elements [6]. The
364 effects of misalignments and the steps taken to correct and monitor them are detailed in this chapter.

365 4.1 Effects of Misalignment

366 Hello world!

367 4.2 The Alignment Method

368 Hello world!

369 4.3 Momentum Bias Corrections

370 Hello world!

³⁷¹ **4.4 Alignment of the IBL**

³⁷² Hello world!

³⁷³ **4.5 Alignment Monitoring**

³⁷⁴ Hello world!

CHAPTER 5

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

378 Production of same-sign W boson pairs is a particularly interesting SM process. When produced
 379 via vector boson scattering (VBS), $W^\pm W^\pm jj$ is particularly sensitive to the electroweak symmetry
 380 breaking (EWSB) mechanism as well as potential “beyond the Standard Model” (BSM) physics.
 381 $W^\pm W^\pm jj$ events can be produced via electroweak-mediated (EWK) diagrams, of which VBS is a
 382 subset, or QCD-mediated diagrams. The biggest advantage of same-sign $W^\pm W^\pm jj$ lies in its ratio
 383 of electroweak (EWK) to QCD production cross sections. Despite the opposite-sign $W^\pm W^\mp$ having
 384 a considerably larger total cross section, its EWK-mediated diagrams are considerably smaller than
 385 its QCD-mediated diagrams, while for same-sign $W^\pm W^\pm$ the ratio is approximately one to one.
 386 This makes $W^\pm W^\pm jj$ one of the best channels for studying VBS at the LHC.

387 The first evidence of electroweak (EWK) $W^\pm W^\pm jj$ production was seen by the ATLAS and CMS
 388 experiments at $\sqrt{s} = 8$ TeV with excesses of 3.6σ [7] and 2.0σ [8] over backgrounds, respectively. More
 389 recently, ATLAS and CMS have both observed the EWK process at $\sqrt{s} = 13$ TeV with significances
 390 of 6.9σ [1] and 5.5σ [9], respectively. The analysis presented in this chapter is based off of the ATLAS
 391 $\sqrt{s} = 13$ TeV observation and cross section measurement of EWK $W^\pm W^\pm jj$ production [1, 10].

392 5.0.1 Theoretical overview of vector boson scattering

393 VBS processes are very important to understand due to their sensitivity to the EWSB mechanism.
 394 The scattering amplitude of longitudinally polarized vector bosons grows with center-of-mass energy
 395 and ultimately violates unitarity above $\sqrt{s} = 1$ TeV in the absence of a light SM Higgs boson [11, 12].
 396 However, once the Higgs is introduced, the divergences cancel and the cross section no longer grows

397 unbounded, as can be seen in Figure 5.1, which consists of plots from [13].

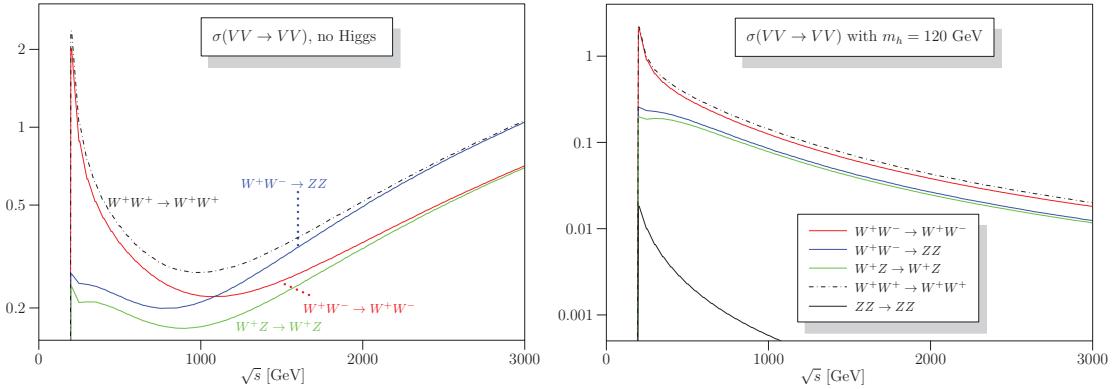


Figure 5.1: Cross sections in nanobarns for five different scattering processes of longitudinally polarized vector bosons as a function of center of mass energy \sqrt{s} . Without a SM Higgs boson (left), the cross sections grow unbounded with \sqrt{s} ; however with a 120 GeV Higgs boson (right), the cross sections no longer diverge. Plots taken from [13].

398 With the discovery of the Higgs boson in 2012 [14, 15], the EWSB mechanism can now be directly
 399 studied. Due to the exchange of a Higgs in the s - and t -channel VBS diagrams ($W^\pm W^\pm jj$ itself only
 400 contains the t -channel diagram), VBS processes are directly sensitive to properties of the Higgs. For
 401 example, the high-mass tail in the VV scattering system allows an approximation of the effective
 402 coupling strength of the Higgs to vector bosons that is independent of any assumptions on the Higgs
 403 width [16]. Additionally, the center of mass energy dependence of the VV scattering can reveal
 404 whether the Higgs boson unitarizes the longitudinal scattering amplitude fully or only partially [17].

405 VBS events are characterized by two quarks from the colliding protons each radiating a massive
 406 vector boson which then scatter and decay in the detector. The incoming quarks carry a large
 407 amount of momentum and only deflect a small amount upon radiating the vector boson; as a result,
 408 they often travel very close to the beam line. Ignoring the decay products of the bosons, these VBS
 409 events result in a final state of two vector bosons (V) and two jets (j) at high pseudorapidities
 410 (called *forward jets*) from the outgoing quarks. The shorthand $VVjj$ is used to represent this final
 411 state.

412 $VVjj$ events can be produced via two different physical processes. The first involves purely
 413 electroweak interactions in the tree-level diagrams, with $\mathcal{O}(\alpha_{EWK}) = 6$ and will be referred to as
 414 *EWK production*. This can be further broken down into VBS and non-VBS production. In the
 415 VBS EWK production, the scattering occurs via triple or quartic gauge couplings, as well as the
 416 s - or t -channel exchange of a Higgs boson. The non-VBS EWK production contains the same final

state of two vector bosons and two outgoing quarks, but the bosons do not scatter. Due to gauge invariance, it is not possible to separate the VBS from the non-VBS productions [18]; therefore, both are included in the signal generation and are indistinguishable from one another. The second process involves a mix of the EWK and strong interactions, of order $\mathcal{O}(\alpha_s) = 2 \otimes \mathcal{O}(\alpha_{EWK}) = 4$ and will be referred to as *QCD production*. The tree-level Feynman diagrams for VBS EWK, non-VBS EWK, and QCD $VVjj$ production are found in Figures 5.2, 5.3, and 5.4, respectively.

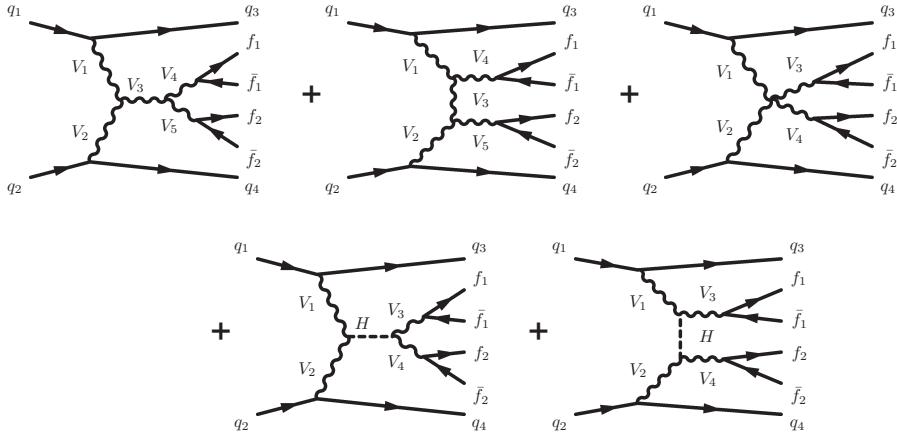


Figure 5.2: Tree-level Feynman diagrams for VBS EWK $VVjj$ production including triple gauge couplings involving W and/or Z bosons (top left and top middle), quartic gauge coupling (top right), or the exchange of a Higgs boson (*s*-channel bottom left and *t*-channel bottom right). The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).

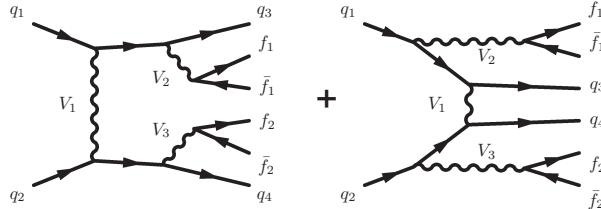


Figure 5.3: Tree-level Feynman diagrams for non-VBS EWK $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).

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

Same-sign $W^\pm W^\pm jj$ scattering is considered to be one of the best channels for studying VBS at the LHC [16]. This is due primarily to the ratio of the EWK to the QCD production, which matters a great deal due to the VBS events being a subset of the total EWK production. In an analysis

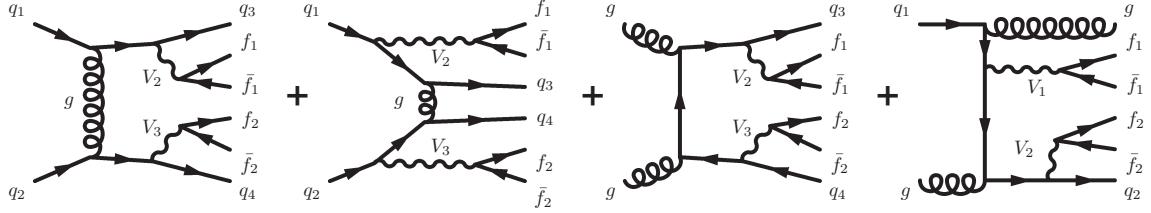


Figure 5.4: Tree-level Feynman diagrams for QCD $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).

427 the EWK production would be considered the signal and the QCD production a background, so a
 428 favorable ratio of the two helps greatly when comparing the size of the signal to the backgrounds.
 429 A study at $\sqrt{s} = 8$ TeV [19] was done using the **SHERPA** Monte Carlo (MC) generator to calculate
 430 QCD production cross sections at leading order for a variety of $VVjj$ processes decaying
 431 to leptons and can be found in Table 5.1. Despite its lower cross section compared to other $VVjj$
 432 processes, the EWK to QCD ratio for $W^\pm W^\pm jj$ is approximately one-to-one, whereas for opposite-
 433 sign $W^\pm W^\mp jj$ the ratio is closer to 3%.

Process	Final state	σ_{EWK}	σ_{QCD}
$W^\pm W^\pm$	$l^\pm l^\pm \nu\nu jj$	19.5 fb	18.8 fb
$W^\pm W^\mp$	$l^\pm l^\mp \nu\nu jj$	91.3 fb	3030 fb
$W^\pm Z$	$l^\pm l^\pm l^\mp \nu\nu jj$	30.2 fb	687 fb
ZZ	$l^+ l^- \nu\nu jj$	2.4 fb	162 fb
ZZ	$l^+ l^- l^+ l^- jj$	1.5 fb	106 fb

Table 5.1: Predicted cross sections for EQK and QCD production of diboson processes relevant to VBS at $\sqrt{s} = 8$ TeV using the **SHERPA** MC generator. Loose generator level cuts are applied on lepton $p_T > 5$ GeV, dilepton invariant mass $m_{ll} > 4$ GeV, and at least two jets with $m_{jj} > 10$ GeV. Numbers taken from [19].

434 This analysis studies $W^\pm W^\pm jj$ scattering where both W bosons decay leptonically to $e\nu$ or $\mu\nu$ ².
 435 The $W^\pm W^\pm jj$ VBS final state consists of two leptons with the same electric charge, two neutrinos,
 436 and two high energy forward jets with a large invariant mass. Tree-level Feynman diagrams of VBS
 437 $W^\pm W^\pm jj$ production can be found in Figure 5.5 and a visual representation of the VBS topology
 438 can be found in Figure 5.6. The two forward jets also serve as a powerful tool to suppress the
 439 QCD production mode. In EWK events, the two jets tend to have much higher separation and a
 440 larger combined invariant mass than the two leading jets in a QCD event. The two plots shown in

²Throughout the rest of this chapter, l denotes either electrons (e) or muons (μ) unless stated otherwise. Additionally, e , μ , and ν (neutrino) with no charge or anti-particle designation refer interchangeably to either the particle or anti-particle.

441 Figure 5.7 highlight the differences in these dijet quantities between the two production modes. An
442 ATLAS event display of a real $W^\pm W^\pm jj$ candidate event is shown in Figure 5.8.

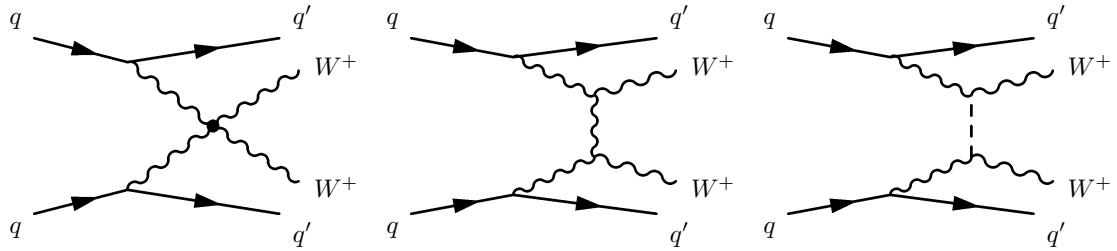


Figure 5.5: Feynman diagrams for VBS EWK production of $W^\pm W^\pm jj$ events. The leftmost diagram contains a quartic gauge coupling vertex, and the rightmost diagram contains an exchange of a Higgs boson. **TODO: Make diagrams consistent with others**

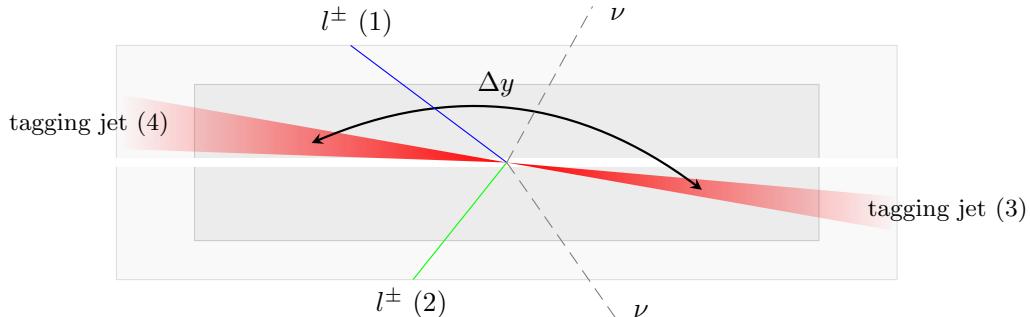


Figure 5.6: $W^\pm W^\pm jj$ VBS event topology containing two leptons (1 and 2) with the same electric charge, two neutrinos, and two forward tagging jets (3 and 4) with large rapidity separation Δy .

443 5.0.3 Overview of backgrounds

444 In addition to QCD production of $W^\pm W^\pm jj$ events, there are several other processes that can end
445 up with a final state of two same-sign leptons, two neutrinos, and two jets. However, due to the ±2
446 final state charge, there is a considerable reduction in SM backgrounds (such as Z boson events)
447 when compared to an analysis like opposite-sign $W^\pm W^\mp jj$.

448 One of the largest sources of background involves processes with prompt leptons³. These are
449 events that contain two leptons with the same electric charge and one or more additional leptons

³Prompt 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.

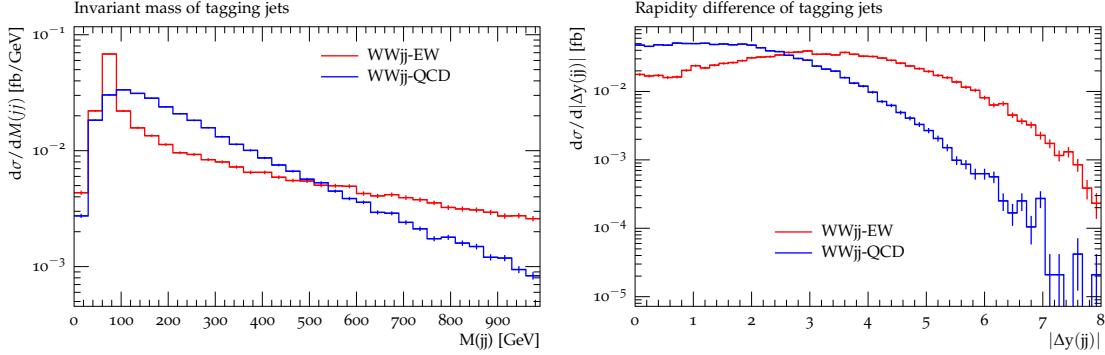


Figure 5.7: Generator level comparisons at $\sqrt{s} = 8$ TeV of dijet invariant mass (m_{jj} , left) and dijet rapidity (Δy_{jj} , right) in EWK (red) and QCD (blue) $W^\pm W^\pm jj$ events. Both data sets have been normalized to the same area. Plots taken from [19].

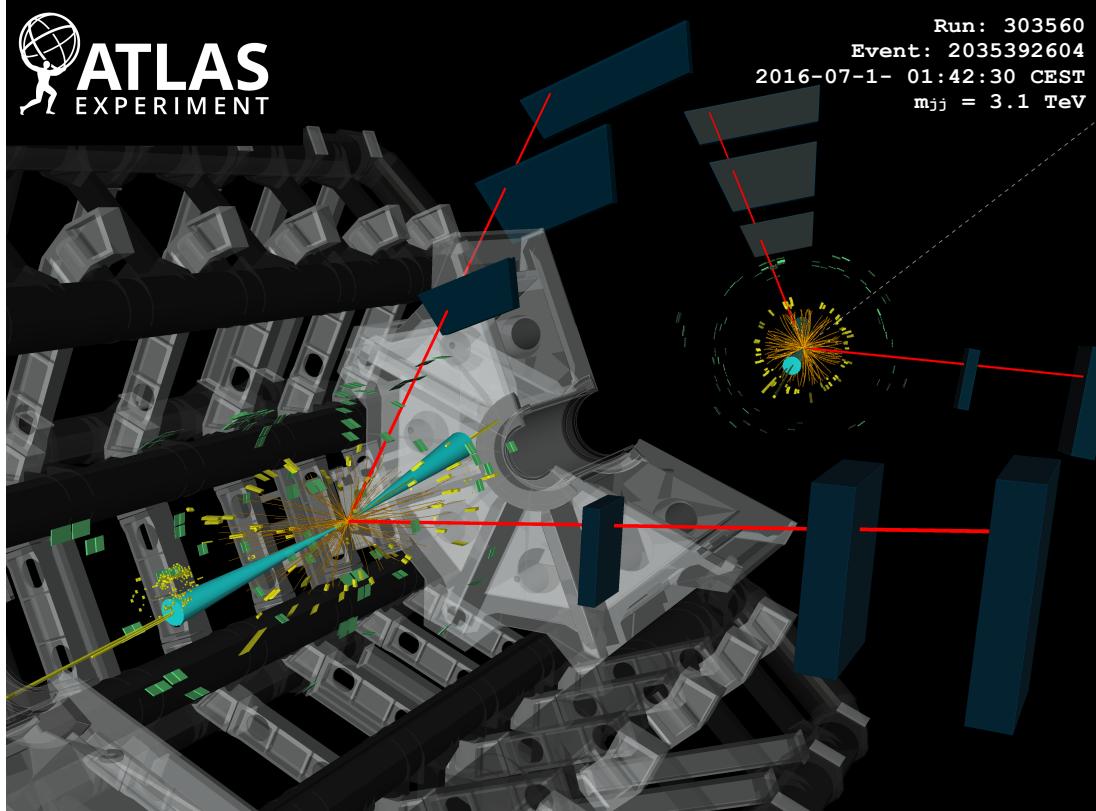


Figure 5.8: ATLAS event display of a $pp \rightarrow W^\pm W^\pm \rightarrow \mu^\pm \nu_\mu \mu^\pm \nu_\mu jj$ event. The muons are represented by the red lines travelling from the ID through the MS, and the forward jets are represented by the blue cones with yellow energy deposits in the calorimeters. 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 [1].

450 that are “lost”, either by failing the selection criteria or falling outside of the detector’s acceptance.
 451 The number of processes that can contribute is limited by the requirement of same-sign leptons, and
 452 as a result this background is dominated by processes involving two or more vector bosons, with the
 453 largest contribution coming from WZ events and smaller contributions from ZZ and $t\bar{t}V$ events.
 454 Triboson events where one boson decays hadronically also contribute to this background; however,
 455 the jets are generally softer and more central than in a typical VBS event, and the cuts applied on
 456 the forward jets suppress these contributions.

457 The other dominant background comes from non-prompt, or “fake”, leptons. Here one or more
 458 leptons originate from the decay of another particle unrelated to the signal process, such as a
 459 heavy-flavor decay or photon conversion, or come from a jet that is misidentified as a lepton. This
 460 background is mostly made up of events from $t\bar{t}$ and $W+\text{jets}$ processes, with a much smaller contribu-
 461 tion from $V\gamma$ events. **TODO: check whether $V\gamma$ really qualifies as non-prompt, we lump $Z\gamma$ in**
 462 **with the charge flip background in the paper...**

463 Finally, opposite-sign lepton pairs can enter the signal region if one of the leptons is reconstructed
 464 with the wrong charge (called *charge misidentification*⁴). In practice, this only affects events with
 465 electrons, as the charge misidentification rate for muons is negligible [20]. This is a major background
 466 in events with two electrons, but is a much smaller contribution for events with one electron and
 467 one muon.

468 5.1 Data and Monte Carlo samples

469 This analysis uses 36.1 fb^{-1} of $\sqrt{s} = 13$ TeV proton-proton collision data recorded by ATLAS
 470 during 2015 and 2016. The uncertainty in the combined integrated luminosity is 2.1%. It is derived
 471 following a methodology similar to that detailed in [21] and using the LUCID-2 detector for the
 472 baseline luminosity measurements [22] from calibration of the luminosity scale using x - y beam-
 473 separation scans.

474 5.1.1 Monte Carlo samples

475 A number of Monte Carlo (MC) simulations are employed to model signal and background pro-
 476 cesses. In order to model the real collision data as closely as possible, each MC has been run through
 477 a full simulation of the ATLAS detector [23] in GEANT4 [24], and events have been reconstructed

⁴Charge misidentification is also referred to interchangeably as *charge mis-ID* and *charge flip*.

478 using the same algorithms as the data. The simulation reproduces as closely as possible the momentum
 479 resolutions and calorimeter responses of the detector, and also includes the effects of pileup by
 480 including soft QCD interactions using PYTHIA v8.1 [25]. The MC samples used in this analysis are
 481 detailed in this section and summarized in Table 5.2.

482 The $W^\pm W^\pm jj$ samples are modeled using SHERPA v2.2.2 [26, 27, 28] with the NNPDF3.0 PDF
 483 set [29]. The EWK signal samples are generated by fixing the electroweak coupling constant to
 484 $\mathcal{O}(\alpha_W) = 6$, and a QCD background sample was also generated with $\mathcal{O}(\alpha_W) = 4$. SHERPA includes
 485 up to one parton at next-to-leading order (NLO) and up to three at leading order (LO) in the
 486 strong coupling constant α_s . A second $W^\pm W^\pm jj$ EWK sample is generated using POWHEG-BOX
 487 v2 [30] with the NNPDF3.0 PDF set and at NLO accuracy. This sample is only used for systematic
 488 studies, as POWHEG-BOX does not include resonant triboson contributions in its matrix element, which
 489 are non-negligible at NLO [31].

490 Diboson processes (VV where $V = W, Z$) are simulated with SHERPA v2.2.2 for mixed hadronic
 491 and leptonic decays and SHERPA v2.2.1 for fully leptonic decays of the bosons. Similarly, triboson
 492 (VVV) and $V\gamma$ processes are simulated using SHERPA v2.1.1 with up to one parton at NLO and up
 493 to three at LO. $W+jets$ processes are simulated with SHERPA2.2.1 with up to two partons at NLO
 494 and four at LO. All the above SHERPA samples use the NNPDF3.0 PDF set and SHERPA's own parton
 495 showering. The $Z+jets$ events are generated with Madgraph5_aMC@NLO [32] at LO and interfaced
 496 with PYTHIA v8.1 for parton showering.

497 $t\bar{t}$ events are generated using POWHEG-BOX v2 with the CT10 PDF set [33]. $t\bar{t}V$ samples are
 498 generated at NLO with Madgraph5_aMC@NLO and the NNPDF3.0 PDF set interfaced with PYTHIA v8
 499 for parton showering. Finally, single top events are generated with POWHEG-BOX v1 and the CT10f4
 500 PDF set interfaced with PYTHIA v6 [34] for parton showering.

501 5.2 Object and event selection

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

504 5.2.1 Object selection

505 Muons, electrons, and jets all must pass strict selection requirements to ensure that only high quality,
 506 well measured objects are used. For leptons, a baseline selection is defined (called the *preselection*),
 507 which all leptons must pass in order to be considered for the analysis. This preselection is an

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 ($llll$, $lll\nu$, $ll\nu\nu$)
Triboson	SHERPA v2.2.1	One boson decays leptonically, the other hadronically
$W + \text{jets}$	SHERPA v2.2.1	
$Z + \text{jets}$	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.

508 intentionally loose set of criteria in order to have high acceptance for rejecting backgrounds with
 509 additional leptons (i.e. $WZ \rightarrow 3l\nu jj$). Signal leptons are then required to satisfy a much tighter
 510 *signal selection* aimed at suppressing backgrounds from non-prompt or fake leptons. A third set of
 511 lepton selection criteria, the *loose selection*, defines a sample enriched in non-prompt leptons, and
 512 it is used in the fake factor method for estimating the non-prompt background, discussed in detail
 513 in Section 5.3.4. Jets are only required to pass one set of selection criteria. These selections are
 514 detailed in the following sections and summarized in Table 5.3 for muons, Table 5.4 for electrons,
 515 and Table 5.5 for jets.

516 5.2.1.1 Muon candidate selection

517 Cuts on muon p_T serve to reject low momentum leptons from background processes and additional
 518 collisions from pileup events. Preselected muons must have $p_T > 6$ GeV and signal muons $p_T >$
 519 27 GeV. The p_T requirement for loose muons is lower than for signal muons, $p_T > 15$ GeV, for
 520 reasons that are discussed in Section 5.3.4. **TODO:** reference proper subsection when it's done
 521 Muons are required to fall within the detector's η acceptance: $|\eta| < 2.7$ for preselected muons,
 522 which is tightened to $|\eta| < 2.5$ for the signal muons.

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

Finally, the muon candidates are required to pass a particle identification and an isolation criteria as defined in [35]. The methods used in constructing the identification and isolation workingpoints are described in more detail in Section 3.2.4.2. The muon identification serves to select prompt muons with high efficiency and well measured momenta. This analysis uses two different workingpoints, **Loose** for preselected muons and **Medium** for loose and signal muons, where **Medium** muons are a tighter subset of those that pass the **Loose** requirement. Muon isolation is a measurement of detector activity around the muon candidate, and it is measured with both track-based and calorimeter-based variables. The isolation workingpoint used for the signal muons, **Gradient**, is defined such that there is 90% or better background rejection efficiency for 25 GeV muons, and 99% efficiency at 60 GeV. There is no minimum isolation requirement for preselected or loose muons. Loose muons are additionally required to fail one or both of the signal transverse impact parameter 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.

540 **5.2.1.2 Electron candidate selection**

541 The electron candidate selections are very similar to those for muons. The p_T cut starts at $p_T >$
 542 6 GeV for the preselection, increases to $p_T > 20$ GeV for loose electrons, and finally to $p_T > 27$ GeV
 543 for signal electrons. The $|\eta|$ cut for electrons requires $|\eta| < 2.47$ for all electrons, with the region
 544 $1.37 \leq |\eta| \leq 1.52$ removed from loose and signal electrons. This region is where the electromagnetic
 545 calorimeter transitions from the barrel to the endcaps and is not fully instrumented. Both the
 546 transverse and longitudinal impact parameter cuts are the same for all electron selections.

547 The electron particle identification uses a multivariate likelihood technique (LH) [36] detailed
 548 in Section 3.2.4.3. Preselected electrons must pass the loosest LH workingpoint `LooseLH` with
 549 an additional requirement that there be a reconstructed track hit in the first layer of the pixel
 550 detector (a so-called B -layer hit). The LH requirement for the loose and signal electrons the tightness
 551 of the identification using `MediumLH` and `TightLH`, respectively. As for isolation, the `Gradient`
 552 workingpoint is required for signal electrons only. The loose electrons must fail one or both of the
 553 signal identification and isolation requirements.

554 **5.2.1.3 Jet candidate selection**

555 The final objects that need to pass selection are jets. Jets are clustered using the anti- k_t algo-
 556 rithm [37] within a radius of $\Delta R = 0.4$. The jets are then calibrated using E_T - and η -dependent
 557 correction factors that are trained using MC simulations [38]. These calibrated jets are then re-
 558 quired to have $p_T > 30$ GeV if they lie in the forward regions of the detector ($2.4 < |\eta| < 4.5$) and
 559 $p_T > 25$ GeV in the central region ($|\eta| \leq 2.4$). In order to suppress pileup jets, the so-called jet-
 560 vertex-tagger (JVT) discriminant associates a jet with the primary interaction vertex [39]; central
 561 jets with $p_T > 60$ GeV are required to pass the `Medium` JVT workingpoint, which corresponds to
 562 an average efficiency of over 92%. Finally, the jets are required to be separated by selected prompt
 563 leptons by at least $\Delta R(j, l) > 0.3$.

564 **5.2.1.4 Treatment of overlapping objects**

565 In the event that one or more objects are reconstructed very close to each other, there is the
 566 possibility for double-counting if both originated from the same object. The procedure by which
 567 this ambiguity is resolved is called *overlap removal* (OR). The standard ATLAS recommendation
 568 for OR is implemented in this analysis [40, 41] and is summarized in Table 5.6.

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	LooseLH + 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	TightLH
Particle isolation	Gradient

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	MediumLH
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.

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.

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

574 High energy muons can produce photons via bremsstrahlung radiation or collinear final state
 575 radiation which results in a nearby energy deposit in the calorimeters. Non-prompt muons from
 576 hadronic decays produce a similar signature; however, in this case the jet has a higher track multiplicity
 577 in the ID. It is possible to address both cases by rejecting the jet when the ID track multiplicity
 578 is less than three and otherwise rejecting the muon for jets and muons within $\Delta R(\mu, j) < 0.4$.

579 In addition to the case above where muon bremsstrahlung results in a nearby reconstructed jet,
 580 the ID track from the muon and the calorimeter energy deposit can lead to it being reconstructed
 581 as an electron. In this case, if both a muon and an electron share a track in the ID, the muon is
 582 kept and the electron is rejected, unless the muon is calorimeter-tagged⁵, in which case the muon is
 583 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.

584 5.2.2 Signal event selection

585 After the objects have been selected, cuts are applied on a per-event level to select $W^\pm W^\pm jj$ signal
 586 events. The event selection is summarized in Table 5.8 and is detailed in this section. It includes
 587 the results of an optimization performed using a multidimensional grid scan.

588 The initial event selection begins by choosing events that pass one or more of the trigger re-
 589 quirements listed in Table 5.7. At least one signal lepton is “matched” to a passed trigger in order

⁵A 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 [35].

590 to ensure that it was indeed a signal lepton that fired the trigger. A collection of *event cleaning*
 591 cuts must also be passed in order to remove events collected during periods in which one or more
 592 components of the detector was not operating optimally. Finally, the events are required to contain
 593 at least one interaction vertex. An event can have multiple reconstructed vertices from additional
 594 proton-proton collisions that occurred in the same bunch crossing. In this case, the *primary vertex*
 595 is determined by choosing the vertex with the largest sum of the p_T^2 of its associated tracks.

	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.

596 Events are then required to contain exactly two signal leptons with the same electric charge.
 597 The dilepton pair must have a combined invariant mass of $m_{ll} \geq 20$ GeV in order to suppress low
 598 mass Drell-Yan backgrounds. Two additional selections are applied to events in the ee -channel:
 599 both electrons are required to have $|\eta| < 1.37$ with an invariant mass at least 15 GeV away from
 600 the Z -boson mass to reduce events where one electron is reconstructed with the wrong charge (this
 601 background will be discussed in more detail in Section 5.3 TODO: Replace with proper subsection
 602 once it's written). To suppress backgrounds from events with more than two leptons, events with
 603 more than two leptons passing the preselection are vetoed.

604 Missing transverse energy (E_T^{miss}) represents any particles that escape the detector without
 605 being measured, such as neutrinos, and is defined as the magnitude of the vector sum of transverse
 606 momenta of all reconstructed objects. It can be difficult to calculate accurately, as it involves
 607 measurements from all subsystems within the detector, and it is sensitive to any corrections that
 608 may be applied to the reconstructed physics objects [42]. These corrections, including the momentum
 609 smearing for muons, energy scale and smearing for electrons, and jet calibrations, are propagated
 610 to the E_T^{miss} calculation. Events are required to contain $E_T^{\text{miss}} > 30$ GeV in order to account for the
 611 two neutrinos from the W boson decays.

612 At least two jets are required. The leading and subleading jets must have $p_T > 65$ GeV and
 613 $p_T > 35$ GeV, respectively, and are referred to as the *tagging jets*. Events are vetoed if they contain
 614 one or more jets that have been tagged as a b -jet to suppress backgrounds from heavy flavor decays

615 (especially top quark events). The b -tagging algorithm used by ATLAS is a boosted decision tree
 616 (BDT) called MV2c10, and this analysis uses a workingpoint with 85% efficiency [43].

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

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 $ \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.

620 5.3 Background estimations

621 The major sources of background events are summarized in Section 5.0.3, and the methods used to
 622 estimate them are detailed in this section. Prompt backgrounds from ZZ and $t\bar{t}V$ are estimated
 623 directly from MC simulations. The shape of the WZ and $V\gamma$ backgrounds are taken from MC, and
 624 the predicted yeilds are normalized to the data predictions in dedicated control regions, as outlined
 625 in Sections 5.3.1 and 5.3.2, respectively. Opposite sign events with a charge misidentified electron
 626 are estimated by a data-driven background method which is summarized in Section 5.3.3. Finally, a
 627 *fake factor* method is used to estimate the contributions from non-prompt backgrounds and is the
 628 subject of Section 5.3.4.

629 5.3.1 Estimation of the WZ background

630 The dominant background involving prompt leptons comes from $WZ + \text{jets}$ events. The contribution
 631 is estimated from MC simulation and normalized to data in a control region enriched in WZ events

defined by the same event selection as Table 5.8 for the signal region, with the following changes applied to increase the purity of the WZ process:

- The third lepton veto is inverted, requiring a third lepton with $p_T > 15$ GeV
- Two of the leptons must make a same-flavor opposite-sign pair. If more than one pair exists, the one with m_{ll} closest to the Z boson mass is chosen.
- The trilepton invariant mass is required to be $m_{lll} > 106$ GeV to reduce contributions from $Z\gamma$ 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 5.10 and 5.9, 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.

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

The $Z\gamma$ MC samples available do not cover the full range of p_T^γ and $\Delta R(\gamma, l)$; thus, additional Drell-Yan samples ($Z+jets$) are used to fill out the phase space. Overlap between the two samples

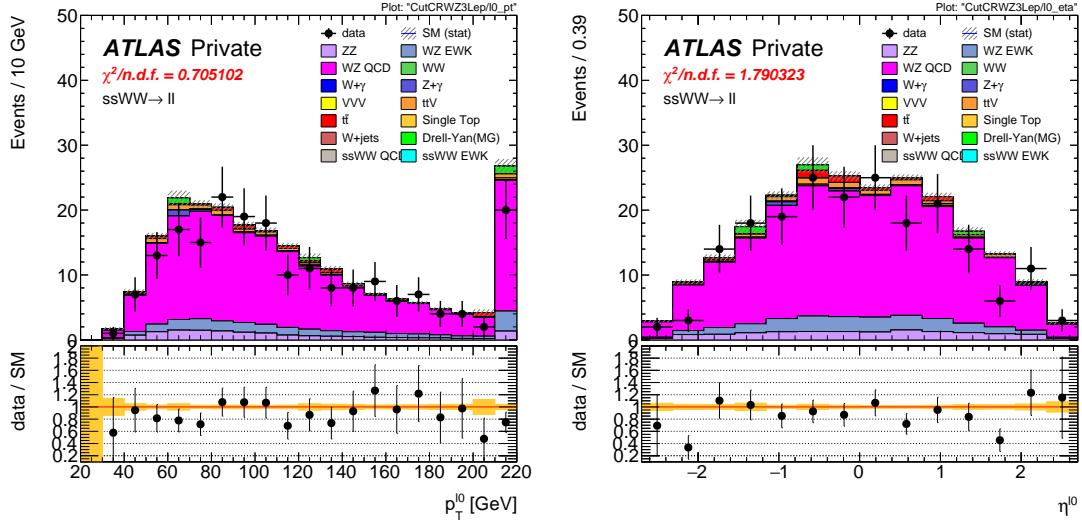


Figure 5.9: Leading lepton p_T (left) and η (right) distributions in the WZ control region before normalization. All lepton channels are combined.

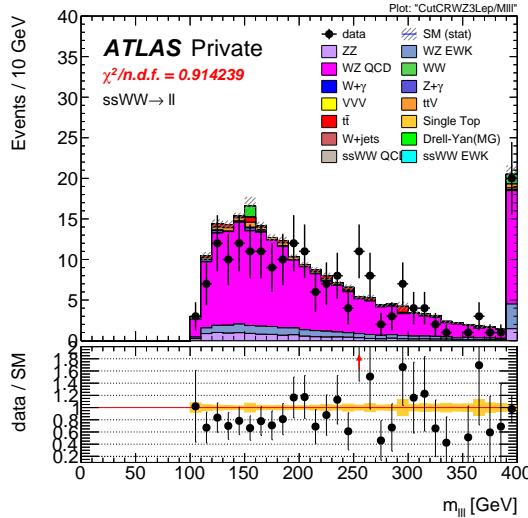


Figure 5.10: Trilepton invariant mass m_{lll} distribution in the WZ control region before normalization. All lepton channels are combined.

$V\gamma$ 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.

are removed based to avoid double counting. Events with final state photons at truth level are checked to ensure that the photon did not originate from a hadronic decay. Cuts on $p_T^\gamma > 10$ GeV and $\Delta R(\gamma, l) > 0.1$ are then applied at generator level, and $Z\gamma$ events that fail and $Z+jets$ events that pass this additional selection are removed.

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

- 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.
- The curvature of the electron's track is mismeasured, 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

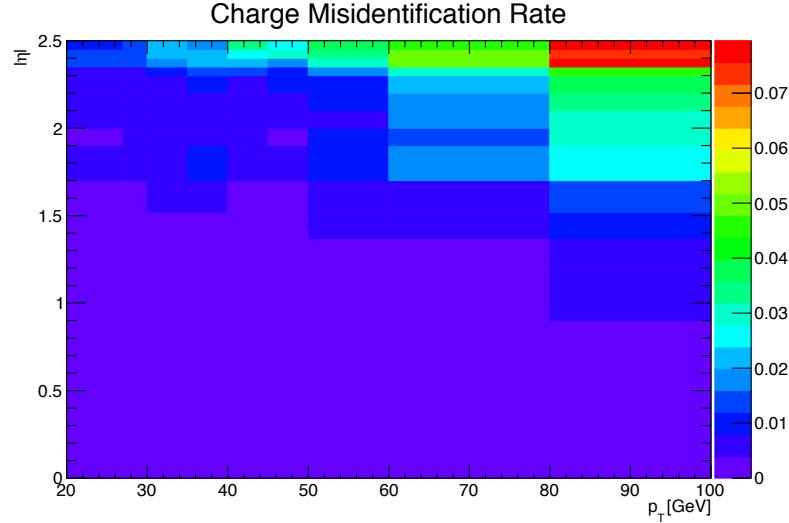


Figure 5.11: Charge misidentification rates for electrons as a function of $|\eta|$ and p_{T} . Rates are calculated from $Z \rightarrow e^+e^-$ MC after applying scale factors to approximate the charge mis-ID rates in data.

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 [10] following the method outlined in [44]. Once the scale factors are applied, the charge misidentification rate ε can be extracted by comparing the electron's reconstructed charge with the charge of its truth particle:

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

The charge mis-ID rate is calculated in bins of electron $|\eta|$ and p_{T} and varies from below 0.1% in the

central region of the detector up to 8% in the forward regions for high p_{T} (above 90 GeV) electrons.

A two-dimensional plot of ε can be found in Figure 5.11.

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

- 685 1. Both electrons are reconstructed correctly: $(1 - \varepsilon)^2$
- 686 2. Both electrons are mis-reconstructed: ε^2
- 687 3. Only one electron is mis-reconstructed: $2\varepsilon(1 - \varepsilon)$

688 In order to estimate the size of the background from charge misidentification, opposite-sign events
 689 are selected using the default event selection for a given signal or control region with the same-sign
 690 requirement inverted. These events are then weighted by the probability for one of the electrons to
 691 be reconstructed with the wrong charge:

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

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

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

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

697 Additionally, charge-flipped electrons tend to be reconstructed with lower energy when compared
 698 to electrons with the correct charge. This is due to energy loss from the material interactions that
 699 can cause the charge to be misidentified. A correction factor is calculated from MC simulations,
 700 comparing the p_T of the truth electron to its reconstructed counterpart:

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

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

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

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

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

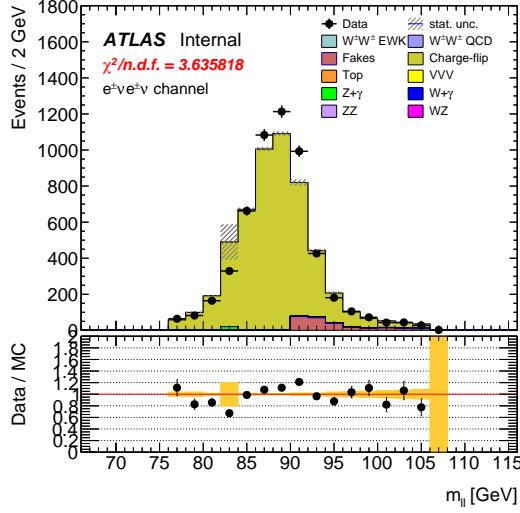


Figure 5.12: Dilepton invariant mass distribution m_{ll} for the ee channel in the same-sign inclusive VR.

5.3.3.1 Validation of the charge misidentification estimate

The performance of the charge misidentification estimation is tested in the same-sign inclusive validation region (VR), defined in Table 5.12. For ee events, the mass of the dilepton pair is required to lie within 15 GeV of the Z boson mass to increase the purity of the charge flip background. $t\bar{t}$ production, which can contribute to both the charge mis-ID and fake lepton backgrounds, is suppressed by the b -jet veto. The di-electron invariant mass is shown in Figure 5.12, and distributions of the leading and subleading electron p_T in the ee -channel are shown in Figure 5.13 with the Z mass cut inverted. Agreement between data and prediction is seen within the total statistical and 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.

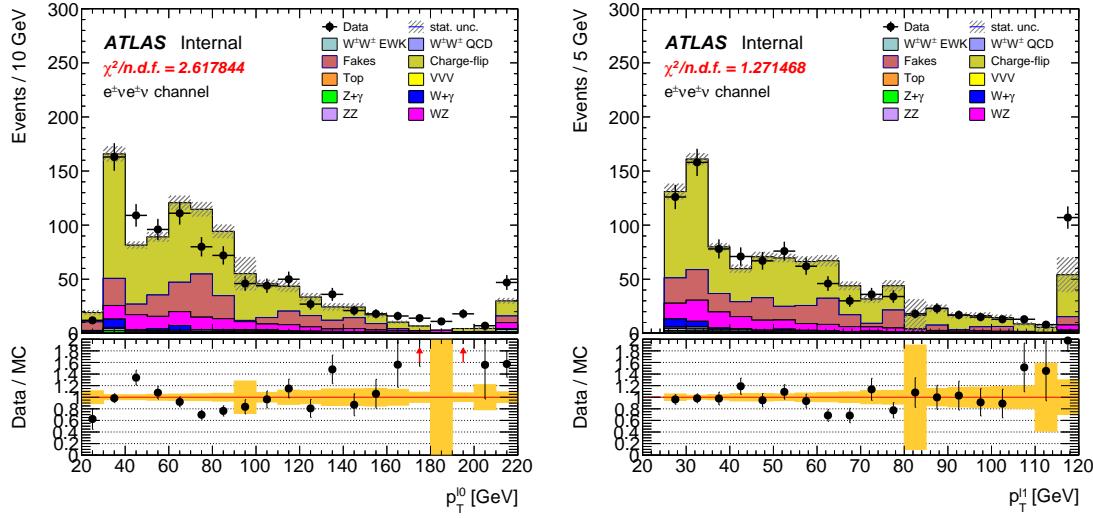


Figure 5.13: p_T distributions for the leading (left) and subleading (right) electron for the ee channel in the same-sign inclusive VR. In these plots, the cut requiring m_{ee} to fall within the Z mass window has been inverted in order to test the modelling away from the Z peak.

721 5.3.4 Estimation of non-prompt backgrounds with the fake factor method

722 Events with one prompt lepton produced in association with hadronic jets can pass the event selection
 723 if a jet is misidentified as a charged lepton or if a non-prompt lepton from the decay of a heavy
 724 flavor particle (such as b - and c -hadrons) passes the signal lepton criteria. These misidentified jets
 725 and non-prompt leptons are collectively referred to as *fake leptons*, or simply *fakes*. The rate at
 726 which a fake lepton is misidentified is generally not modelled well enough by the MC to accurately
 727 estimate their contributions directly from simulation. Therefore, a data-driven technique called the
 728 *fake factor* is used to estimate the size and shape of background processes from fake leptons. In this
 729 analysis, a new modification to the fake factor is used involving the particle isolation variables; the
 730 method is outlined in the context of the *default* fake factor in Section 5.3.4.1, and the modified fake
 731 factor is outlined in Section 5.3.4.2.

732 5.3.4.1 Overview of the default fake factor method

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

- 736 1. The *nominal* sample is made up of leptons passing the signal selection.

737 2. The *loose* sample is made up of leptons that fail the signal selection while still passing a
 738 loosened set of criteria. This sample is enriched in fake leptons and is orthogonal to the set of
 739 signal leptons.

740 Using the sets of nominal and loose leptons, a fake factor f can be calculated in a region enriched
 741 in processes that are prone to producing fake leptons:

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

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

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

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

745 In order to estimate the fake background contribution in a given signal or control region, the
 746 fake factor is applied to a second control region with a selection identical to the region of interest
 747 with one of the leptons required to satisfy the loose criteria. The region for which the background
 748 is estimated contains two nominal leptons and is referred to as *nominal+nominal* (NN), and the
 749 associated control region where the fake factor is applied contains one nominal and one loose lepton
 750 and is referred to as *nominal+loose* (NL). The fake background in a NN region can then be
 751 calculated as:

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

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

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

757 5.3.4.2 The fake factor with p_T^{cone}

758 When a jet produces a non-prompt lepton, that lepton only carries a fraction of the underlying jet's
 759 total momentum. Due to the isolation cut applied to the nominal leptons, they typically carry a

760 much larger percentage of the underlying jet momentum⁶ than the loose leptons (which are allowed
 761 to fail this criteria).

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

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

768 Since muons are not included in the jet reconstruction algorithm, Δp_T approximates the momentum
 769 of the muon compared to the rest of the jet. For muons that carry more than 50% of the jet's
 770 momentum, Δp_T will be negative and vice-versa. The Δp_T distributions for nominal and loose
 771 muons in $t\bar{t}$ MC events is shown Figure 5.14, where a 50 GeV jet on average corresponds to a
 772 35 GeV nominal muon and a 20 GeV loose muon⁷.

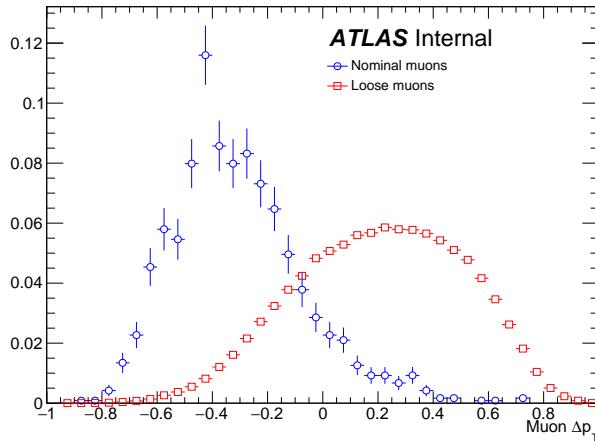


Figure 5.14: Δp_T distributions for nominal (blue) and loose (red) muons in simulated $t\bar{t}$ events. Each muon has been matched to a truth-level jet. Both distributions are normalized to unit area.

773 Since the default fake factor defined in Equation 5.7 is binned in lepton p_T , within a given bin,

⁶Since the isolation variables are a measure of detector activity around the lepton, if other nearby particles carried a significant portion of the jet's momentum, the lepton would likely fail this cut.

⁷To better illustrate the point, here the muon is added back into the jet p_T , and the corresponding muon p_T is obtained via $\Delta p_T(\mu, j) = \frac{(p_T(j) - p_T(\mu)) - p_T(\mu)}{(p_T(j) - p_T(\mu)) + p_T(\mu)} = \frac{p_T(j) - 2p_T(\mu)}{p_T(j)}$.

774 the underlying jet p_T spectrum can differ substantially between the numerator and the denominator.
 775 Additionally, these differences can vary depending on the process producing the non-prompt leptons
 776 or on the specific kinematic selections of the signal or control regions where the fake factor is applied.

777 Fortunately, the majority of the jet momentum not carried by the non-prompt lepton (excluding
 778 neutrinos) can be recovered using isolation variables. A track-based isolation is chosen, referred to
 779 as p_T^{cone} , and it contains the sum of the p_T of all particle tracks originating from the primary vertex
 780 within a cone of $\Delta R < 0.3$ around the lepton. Thus, the sample of loose leptons in the denominator
 781 of the fake factor calculation is binned in $p_T + p_T^{\text{cone}}$ rather than simply lepton p_T . Adding the
 782 isolation cone greatly reduces the difference in the fraction of the underlying jet momentum carried
 783 by the nominal and loose leptons. To check this, a new Δp_T is calculated between a lepton and its
 784 matched truth jet, where the truth jet p_T has been corrected to include all muons within a cone of
 785 $\Delta R < 0.4$:

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

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

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

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

793 5.3.4.3 Application of the fake factor

794 The fake factor itself is measured from a sample data events passing a dijet selection requiring
 795 exactly one lepton (either passing the nominal or loose selections) and at least one jet. The leading
 796 jet must also be b -tagged and approximately back-to-back with the lepton in order to enhance non-
 797 prompt lepton contributions while reducing contributions from processes involving W and Z bosons.
 798 W boson events are further suppressed by requiring the sum of the E_T^{miss} and the transverse mass
 799 of the lepton and E_T^{miss} to be less than 50 GeV. The full event selection for the dijet region is
 800 summarized in Table 5.13.

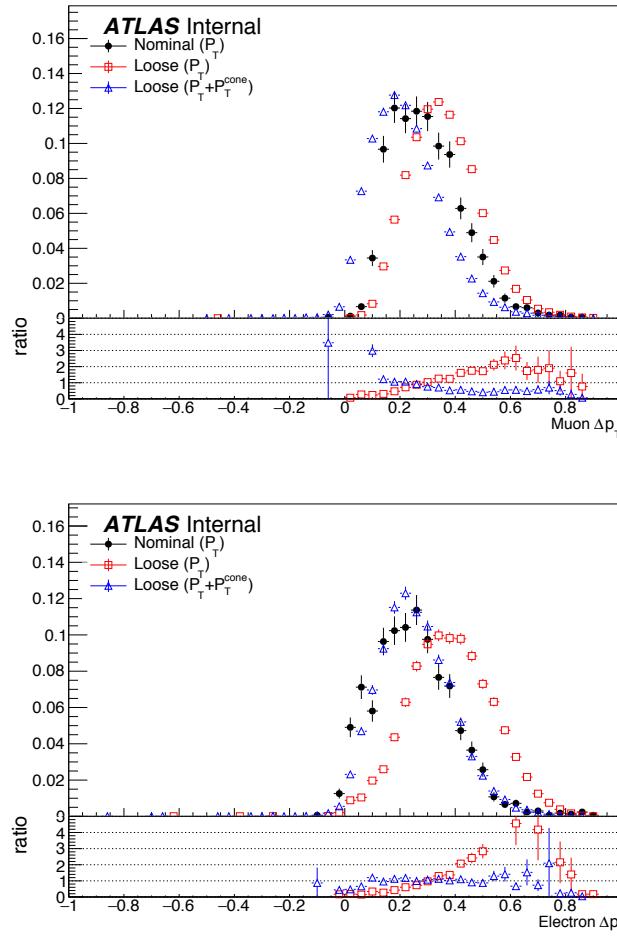


Figure 5.15: Δp_T distributions for muons (top) and electrons (bottom) in simulated $t\bar{t}$ events. Each lepton has been matched to a truth-level jet, and that truth jet has had its p_T corrected to include all truth muons within a cone of $\Delta R < 0.4$. The nominal leptons are in black. Δp_T is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

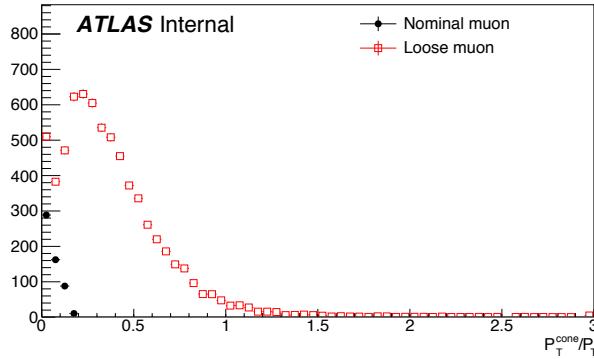


Figure 5.16: Distributions of p_T^{cone}/p_T for nominal (black) and loose (red) muons in simulated $t\bar{t}$ events.

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.

801 The numerator sample is constructed from dijet events in which the lepton passes the nominal
 802 (selection) and is binned in the lepton p_T . Similarly, the denominator sample is made up of
 803 the remaining dijet events where the lepton passes the loose selection and is binned in the lepton
 804 $p_T + p_T^{\text{cone}}$. The nominal and loose leptons pass the signal selection⁸ and loose selection, respectively,
 805 defined earlier in Table 5.3 for muons and Table 5.4 for electrons. Backgrounds from $W+\text{jets}$, $Z+\text{jets}$,
 806 $t\bar{t}$, and single top processes are estimated from MC simulations requiring one lepton to be prompt
 807 using the truth information; these contributions are subtracted from the dijet data. The fake factor
 808 is then calculated using Equation 5.12 for muons and for central and forward electrons separately.
 809 The muon fake factor is shown in Figure 5.17, and the two electron fake factors are shown in
 810 Figure 5.18. The numerical values of the fake factors, including their systematic uncertainties which

⁸The $p_T > 27$ GeV cut in the signal lepton selection is dropped in favor of the $p_T > 15$ GeV requirement in the dijet selection.

⁸¹¹ will be discussed in Section 5.3.4.4, are listed in Table 5.14.

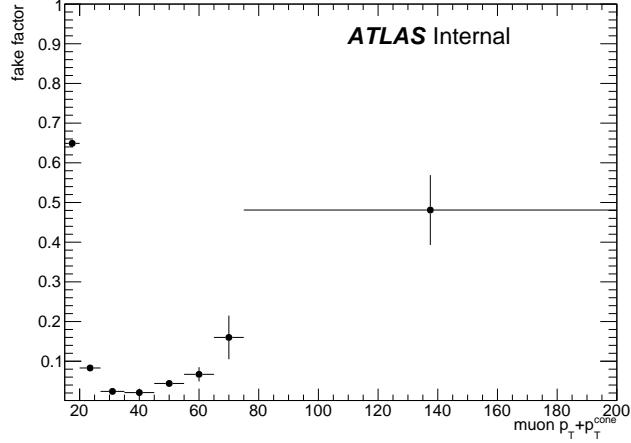


Figure 5.17: The measured fake factor as a function of muon $p_T + p_T^{\text{cone}}$. The error bars represent the statistical uncertainty only.

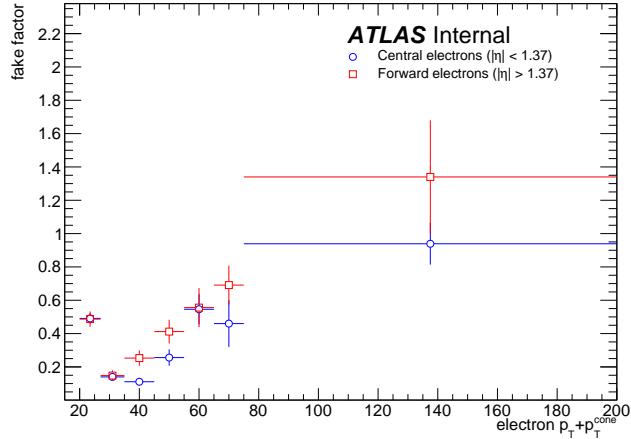


Figure 5.18: The measured fake factor as a function of electron $p_T + p_T^{\text{cone}}$ in the central ($|\eta| < 1.37$, blue) and forward ($|\eta| > 1.37$, red) regions of the detector. The error bars represent the statistical uncertainty only.

⁸¹² In order to properly account for the denominator being binned in $p_T + p_T^{\text{cone}}$, special care needs
⁸¹³ to be taken when estimating the fake background from the NL regions. For the purposes of the
⁸¹⁴ fake factor calculation, it is perhaps more intuitive to consider a loose *object* with $p_T = p_T + p_T^{\text{cone}}$
⁸¹⁵ instead of simply a loose *lepton*, as the lepton and the underlying jet are treated as a whole with this

method. When the lepton p_T cuts required by a particular signal or control region are applied to nominal and loose leptons, the cut is applied to the p_T of the nominal lepton and to the $p_T + p_T^{\text{cone}}$ of the loose object. Similarly, when looking up the fake factor weight for a given NL event, the value taken from the bin corresponding to the $p_T + p_T^{\text{cone}}$ of the loose object. Finally, when applying 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 graphical representation of this procedure.

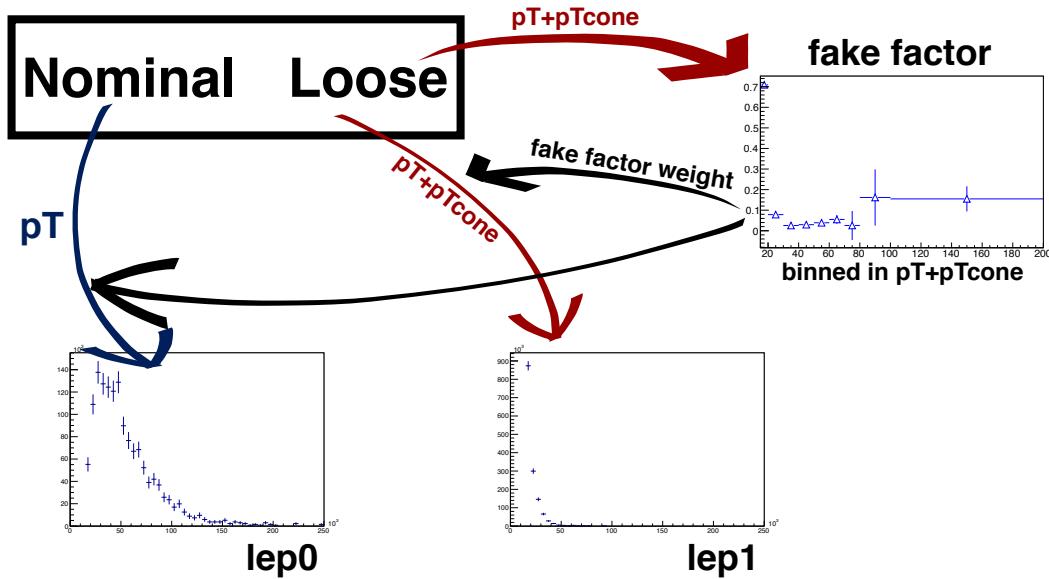


Figure 5.19: Graphical representation of the fake factor application using $p_T + p_T^{\text{cone}}$. The value of $p_T + p_T^{\text{cone}}$ for the loose lepton is used to “look up” the fake factor weight which is then applied to the event. The loose lepton’s p_T becomes $p_T + p_T^{\text{cone}}$ for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

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

829 **5.3.4.4 Systematic uncertainties**

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

- 835 1. In order to estimate uncertainties due to the dijet selection, the cut on $M_T + MET$ is varied
836 by ± 5 GeV, $\Delta\phi(l, j)$ by ± 0.1 , and the jet p_T cut by $+5$ GeV.
- 837 2. To estimate the systematic uncertainty on the prompt background subtraction, the MC pre-
838 diction in a $W+jets$ control region is compared to data. The discrepancy between data and
839 MC is found to be approximately 10% [10]. Therefore, the prompt background used for the
840 subtraction is scaled up and down by $\pm 10\%$.
- 841 3. The difference in the jet flavor composition between the dijet events and the events in the
842 *NL* regions can affect the accuracy of the fake background estimation. The dijet sample is
843 dominated by light jets, while the *NL* regions tend to be dominated by heavy flavor from $t\bar{t}$.
844 To account for this, the fake factor is computed with a b -jet veto.
- 845 4. To measure any residual dependence on the underlying jet p_T spectrum, the leading jet p_T
846 distribution is reweighted to match the p_T spectrum of truth jets that produce fake leptons
847 in MC simulations. This results in an increase in the number of nominal and loose leptons at
848 high momentum [10].

849 **5.3.4.5 Results of the fake factor**

850 The fake background contribution in the signal region is estimated by applying the fake factors
851 to the equivalent *NL* region using Equation 5.9, where the fake factor used corresponds to the
852 flavor of the loose lepton in the event. As usual, the prompt background is subtracted from the
853 *NL* events using MC simulation. Charge misidentification is handled using the same method as
854 in Section 5.3.3, with an additional set of charge flip rates calculated for loose leptons. The fake
855 background yields in the signal region are listed in Table 5.15. An overall uncertainty of 50% is
856 assigned to the fake background estimation in $\mu^\pm\mu^\pm$ events, and between 40% to 90% for $e^\pm e^\pm$ and
857 $\mu^\pm e^\pm$ 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
$\Delta\phi(\ell, j)$	0.648 ± 0.007	0.083 ± 0.003	0.024 ± 0.002	0.022 ± 0.004	0.044 ± 0.007	0.054 ± 0.020	0.207 ± 0.060	0.389 ± 0.081
Jet p_T	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
$N_{b\text{-jet}} = 0$	0.646 ± 0.006	0.083 ± 0.002	0.024 ± 0.002	0.020 ± 0.003	0.043 ± 0.006	0.076 ± 0.017	0.174 ± 0.050	0.448 ± 0.078
Bkg. subtraction	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
Jet p_T Reweighting	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
	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
	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
	0.539 ± 0.077	0.093 ± 0.007	0.025 ± 0.004	0.043 ± 0.019	0.063 ± 0.014	0.085 ± 0.025	0.141 ± 0.110	1.962 ± 0.492

(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
Jet p_T	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
$N_{b\text{-jet}} = 0$	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
Bkg. subtraction	0.488 ± 0.031	0.138 ± 0.020	0.106 ± 0.023	0.248 ± 0.049	0.529 ± 0.092	0.434 ± 0.143	0.888 ± 0.115
Jet p_T Reweighting	0.493 ± 0.031	0.142 ± 0.020	0.115 ± 0.023	0.264 ± 0.049	0.563 ± 0.090	0.485 ± 0.136	0.989 ± 0.132

(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
Jet p_T	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
$N_{b\text{-jet}} = 0$	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
Bkg. subtraction	0.484 ± 0.046	0.146 ± 0.031	0.248 ± 0.046	0.406 ± 0.071	0.545 ± 0.118	0.676 ± 0.118	1.317 ± 0.337
Jet p_T Reweighting	0.489 ± 0.046	0.151 ± 0.031	0.257 ± 0.046	0.419 ± 0.071	0.568 ± 0.117	0.705 ± 0.115	1.363 ± 0.342

(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.

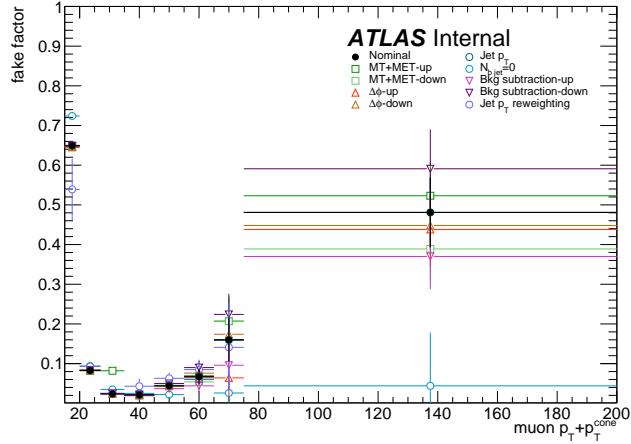


Figure 5.20: Systematic variations in the fake factor as a function of muon $p_T + p_T^{\text{cone}}$. The individual fake factors obtained for each systematic variation are displayed with their statistical uncertainties.

5.3.4.6 Validation of the fake factor

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

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)	
$N_{b\text{-jet}} = 1$	
$N_{\text{jet}} \geq 2$	
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.

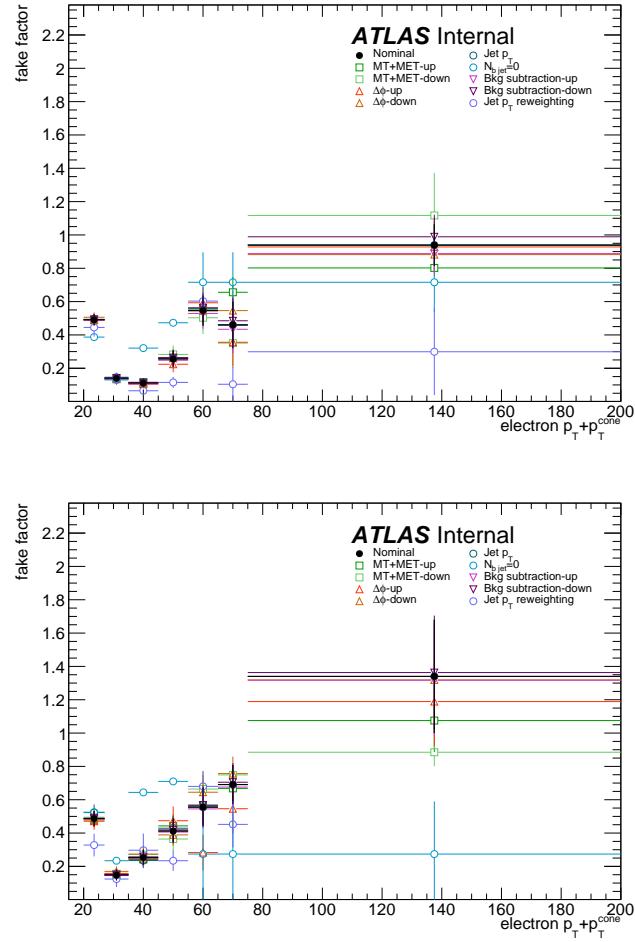


Figure 5.21: Systematic variations in the fake factor as a function of electron $p_T + p_T^{\text{cone}}$ in the central ($|\eta| < 1.37$, top) and forward ($|\eta| > 1.37$, bottom) regions of the detector. The individual fake factors obtained for each systematic variation are displayed with their statistical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

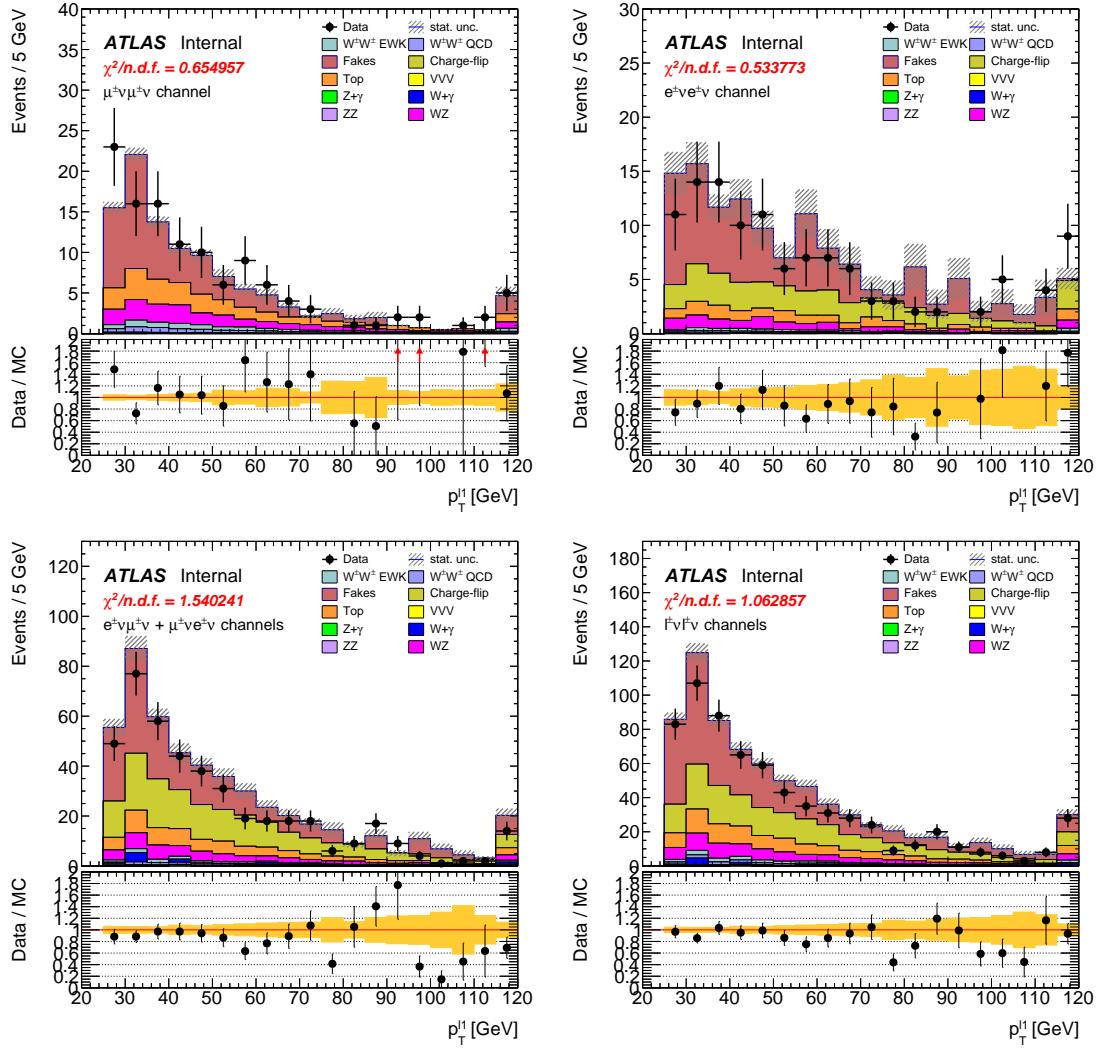


Figure 5.22: Distributions of the subleading lepton p_T in the same-sign top fakes VR for $\mu^\pm\mu^\pm$ events (top right), $e^\pm e^\pm$ events (top left), $\mu^\pm e^\pm$ events (bottom left), and all events combined (bottom right). All errors are statistical only.

867 **5.3.5 Reduction of WZ background using custom overlap removal**

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

874 In order to understand the sources of WZ events that are not removed by the trilepton veto, a
 875 study was performed on truth-level leptons⁹ on $W^\pm W^\pm jj$ and WZ MC samples. Events with three
 876 truth leptons were selected, and each was matched to its reconstruction-level partner by finding
 877 the closest $\Delta R(\text{truth}, \text{reco})$ and $\Delta p_{\text{T},\text{truth},\text{reco}}$ match. For events surviving the trilepton veto, the
 878 two signal leptons were removed, and the remaining leptons represent real leptons that failed to
 879 be selected for the veto. Between 40-50% of these leptons fell outside of the eta acceptance of the
 880 analysis (see Figure 5.23) and were unrecoverable. The second largest source of leptons failing the
 881 preselection was the OR, defined in Section 5.2.1.4. The standard OF procedure appeared to be
 882 too aggressive in removing leptons in favor of jets, causing many three lepton events to “lose” their
 883 third lepton and pass the trilepton veto. Therefore a *Custom OR* was investigated which would
 884 replace the standard OR in the preselection and allow for better WZ rejection by removing fewer
 885 third leptons.

886 **TODO:** Mention how the extra leptons in the $W^\pm W^\pm jj$ are background leptons since there are
 887 only 2 from the main decay

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

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

890 which, along with $\Delta R(l, j)$, will allow for more third leptons to pass the preselection. The idea
 891 behind including $p_{\text{T},\text{ratio}}$ is to be able to preferentially remove background leptons originating from
 892 jets (i.e. those that carry a low percentage of the total jet momentum) instead of removing *any*
 893 lepton near to jet. The distributions of $p_{\text{T},\text{ratio}}$ and the associated efficiency curves for muons and
 894 electrons can be found in Figures 5.24 and 5.26, respectively, and the distributions for $\Delta R(\mu, j)$ for

⁹Truth 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.

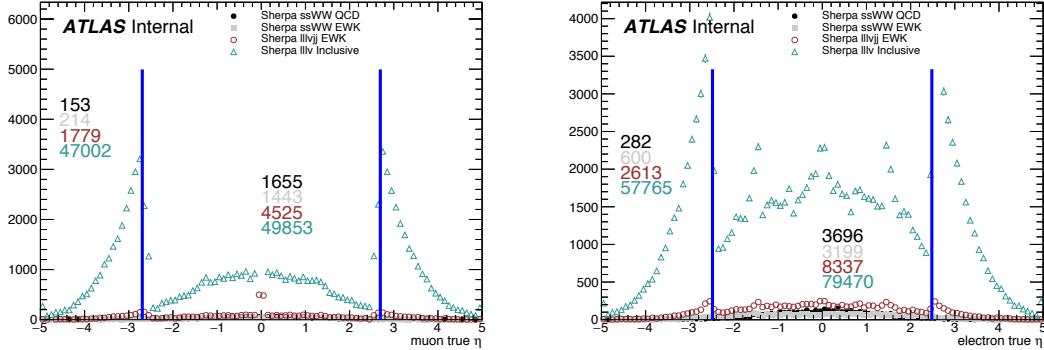


Figure 5.23: Pseudorapidity (η) distributions of truth muons (top) and electrons (bottom) for Sherpa $W^\pm W^\pm jj$ and WZ MC samples. The blue vertical lines represent the allowed η range for each lepton flavor. The numbers correspond to the number of raw MC events that fall within and outside of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

895 muons can be found in Figure 5.25. Since all electrons have an associated jet in the calorimeters,
896 the $\Delta R(e, j)$ variable is not a good quantity to use for this custom OR.

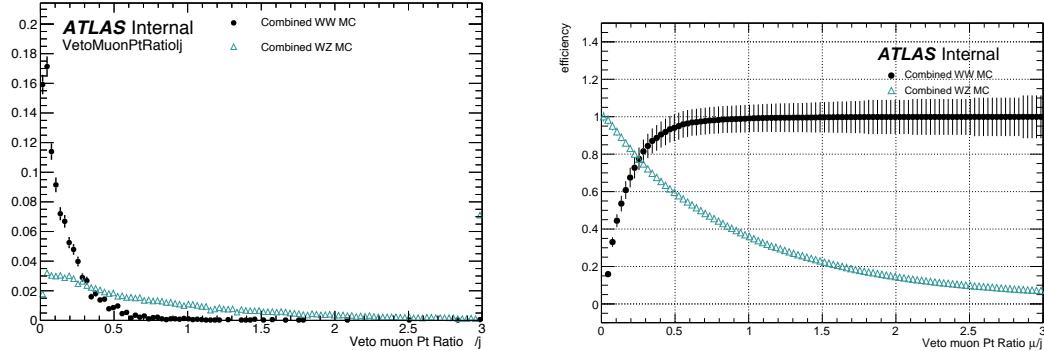


Figure 5.24: Distributions of $p_{T,\text{ratio}}(\mu, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and WZ background (teal) for truth-matched third muons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right where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

897 A workingpoint for the Custom OR was chosen by requiring 90% signal retention for muons
898 and 90% background rejection for electrons. The cut on electrons was allowed to be much tighter
899 because the number of signal events with a third electron is considerably smaller than for muons.
900 It should be re-emphasized the signal events that are present in Figures 5.24–5.26 do not represent
901 the full set of signal events, but only those with a real third lepton (which must come from some

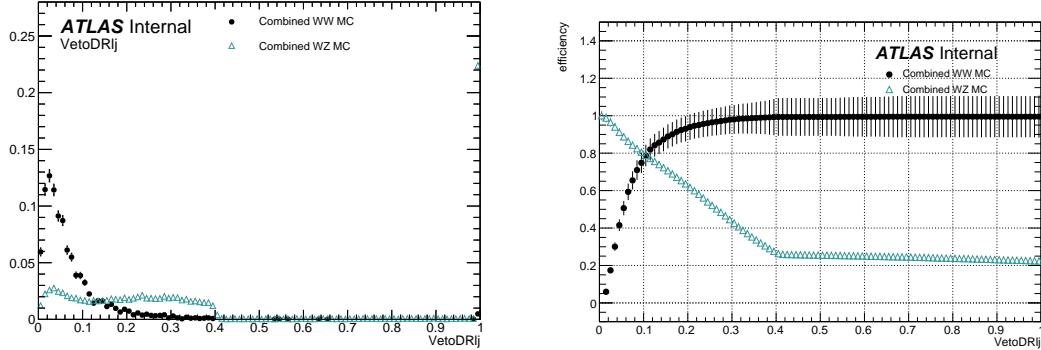


Figure 5.25: Distributions of $\Delta R(\mu, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and WZ background (teal) for truth-matched third muons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right where efficiency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

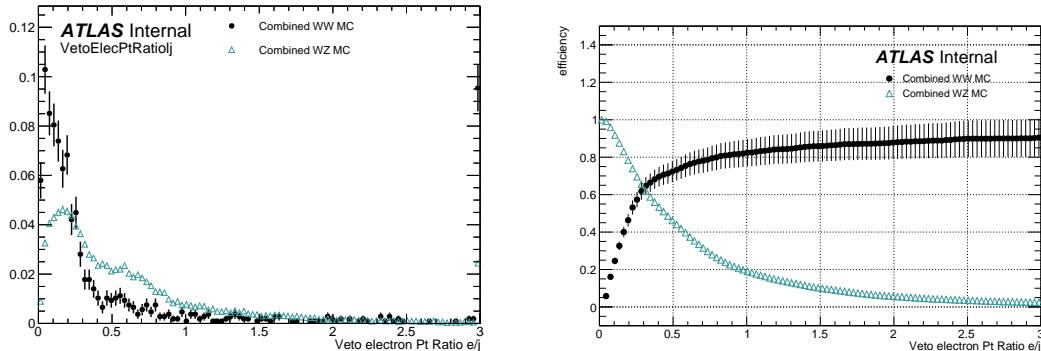


Figure 5.26: Distributions of $p_{T,\text{ratio}}(e, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and WZ background (teal) for truth-matched third electrons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right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

source other than the signal $W^\pm W^\pm jj$ process). For muons, an or of $p_{T,\text{ratio}}(\mu, j)$ and $\Delta R(\mu, j)$ is used to maximize the third lepton acceptance due to correlations between the quantities, as shown in Figure 5.27; for electrons, only a cut on $p_{T,\text{ratio}}(e, j)$ is used. The Custom OR workingpoint is outlined 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.

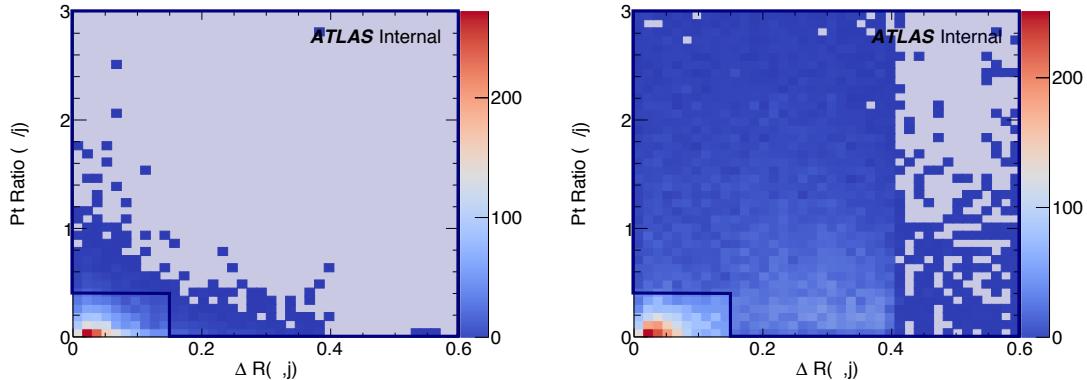


Figure 5.27: Two-dimensional plots of $p_{T,\text{ratio}}(\mu, j)$ vs $\Delta R(\mu, j)$ for truth-matched third muons in events that pass the trilepton veto for EWK and QCD $W^\pm W^\pm jj$ signal (left) and WZ background (right). The blue overlay indicates the area in which the third leptons will pass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

Tests of the performance of the Custom OR yield promising results, with approximately 20% reduction in WZ background compared to less than 2% signal loss in the signal region. Unfortunately, due to differences between the primary analysis framework and the one used for testing, in practice the gains in WZ rejection are not nearly as substantial, and ultimately the Custom OR is not included in the final analysis. However, it is still a potentially useful tool for improving background rejection via lepton number vetoes in analyses with overly aggressive OR procedures.

5.4 Cross section measurement

The $W^\pm W^\pm jj$ EWK cross section is extracted from the signal region using a maximum-likelihood fit applied simultaneously to four m_{jj} bins in the signal region as well as to the low- m_{jj} and WZ

control regions. For the cross section extraction, the signal region is defined as in Table 5.8 with the dijet invariant mass requirement raised to $m_{jj} > 500$ GeV. The low- m_{jj} region is defined to mirror the signal region exactly with the dijet invariant mass inverted to $200 < m_{jj} < 500$ GeV, and the WZ control region is defined previously in Section 5.3.1.

The signal and low- m_{jj} regions are split into six channels based on the flavor and charge of the dilepton pair: $\mu^+\mu^+$, $\mu^-\mu^-$, μ^+e^+ , μ^-e^- , e^+e^+ , and e^-e^- . This split by charge increases the sensitivity of the measurement due to the W^+/W^- charge asymmetry at hadron colliders favoring the production of W^+ bosons [45]. Since the signal events contain two W bosons, the signal strength compared to charge-symmetric backgrounds is much greater in the $++$ channels for both charges combined. The WZ control region is included in the fit as a single bin ($l^\pm l^\pm l^\pm$).

The maximum likelihood fit is outlined in Section 5.4.1 and the cross section extraction method in Section 5.4.2.

5.4.1 Maximum likelihood fit

TODO: This section is very similar to what is written in the support note... May need to put some work into flushing it out so it's not so close to copy-paste The number of predicted signal events in each channel c and m_{jj} bin b can be calculated from the SM predicted fiducial signal cross section σ^{fid} , the total integrated luminosity \mathcal{L} , the signal acceptance \mathcal{A}_b , and the efficiency corrections $\mathcal{C}(\theta)$, where θ represents the set of nuisance parameters that parameterize the effects of each systematic uncertainty on the signal and background expectations.

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

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

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

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

943 The expected number of events per channel and bin can be written as a sum of the predicted
 944 event yields for each sample s :

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

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

951 The binned likelihood function is given by a product of Gaussian functions for the luminosity
 952 and for the background uncertainties and a product of Poisson functions for the number of observed
 953 events in each bin and channel:

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

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

960 The profile likelihood ratio is defined as

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

961 with $\hat{\mu}$ and $\hat{\theta}$ as the unconditional maximum likelihood estimates and $\hat{\theta}$ as the conditional maximum
 962 likelihood estimate for a given value of μ . The fitted signal strength $\hat{\mu}$ is obtained by maximizing
 963 the likelihood function with respect to all parameters. The compatibility of the observed data
 964 with the background-only hypothesis can then be calculated by setting $\mu = 0$. Observation of the
 965 $W^{\pm}W^{\pm}jj$ EWK process is claimed if the data is found to be inconsistent with the background-only
 966 hypothesis by more than 5σ . The observed signal strength μ_{obs} is obtained by using the real data
 967 yields in each input bin to the fit; calculating the expected signal strength μ_{exp} follows the same
 968 method but with the data replaced by the predictions from simulation and data-driven estimations.

969 **5.4.2 Cross section extraction**

970 **TODO:** support note 9.9 p 164

971 **5.4.2.1 Fiducial region definition**

Table 5.18: Definition of the fiducial volume.

972 **5.5 Results**

973 **Results**

974 **TODO:** Observed fit results: support note 9.7 p. 138

CHAPTER 6

Prospects for same-sign WW at the High Luminosity LHC

978 On December 3, 2018, Run 2 of the LHC officially ended, and the collider was shut down to begin
 979 the first of two scheduled extended maintenance periods [46]. During these two long shutdowns,
 980 the Phase-I and Phase-II upgrades of the LHC and ATLAS will occur in order to prepare for the
 981 High-Luminosity LHC (HL-LHC) which is scheduled to begin operation in 2026 [47].

982 The HL-LHC is planned to run at a center-of-mass energy of $\sqrt{s} = 14$ TeV with an instantaneous
 983 luminosity of $\mathcal{L} = 5 \times 10^{34}$ cm $^{-2}$ s $^{-1}$ with up to 200 collisions per beam-crossing. Over the course
 984 of operation, the HL-LHC is expected to collect a total integrated luminosity of $\mathcal{L} = 3000$ fb $^{-1}$ by
 985 2035 [48]. **TODO: Compare to current LHC numbers?**

986 These run conditions will be much harsher than what ATLAS has experienced so far, and there
 987 are several upgrades planned for the detector to operate in the high luminosity environment. Most
 988 notably, the entire ID will be replaced with an all-silicon tracker which will extend the coverage from
 989 $|\eta| \leq 2.7$ up to $|\eta| \leq 4.0$. This will allow for reconstruction of charged particle tracks which can
 990 in turn be matched to clusters in the calorimeters for electron identification or forward jet tagging
 991 [49].

992 The upgraded detector, the higher beam energy, and the increased volume of data to be collected
 993 provides the opportunity to measure rarer processes with a much higher precision than what was
 994 possible in Run 1. Same-sign $W^\pm W^\pm jj$ production, is one such process. With greater statistics,
 995 the accuracy of the cross section measurement can be improved over the 13 TeV analysis detailed in
 996 Chapter 5, and it also will allow for more detailed physics studies, such as measuring the polarization
 997 of the W bosons. A measurement of the longitudinal polarization of the scattered W bosons has

998 not yet been possible, but it remains of great interest due to its sensitivity to electroweak symmetry
 999 breaking [50]. The analysis detailed in this chapter is based off of the 2018 ATLAS HL-LHC
 1000 $W^\pm W^\pm jj$ prospects study [51] which is itself an extension of the 2017 ATLAS study [52]. **TODO:**
 1001 mention CMS's study + yellow report?

1002 6.0.1 Analysis Overview

1003 The experimental signature of interest is identical to the 13 TeV analysis: two prompt leptons (either
 1004 electrons or muons) with the same charge, missing transverse energy, and two high energy, forward
 1005 jets. These jets are again required to have a large angular separation and a high combined invariant
 1006 mass to preferentially select EWK- over QCD-produced $W^\pm W^\pm jj$ events.

1007 Background processes are again similar to the 13 TeV analysis and are summarized again here.
 1008 The dominant source of prompt background from $WZ+jets$ events where both bosons decay lepton-
 1009 ically. If the lepton from the Z -decay with opposite charge from the W falls outside of the detector
 1010 acceptance or is not identified, the remainder could appear to be a $W^\pm W^\pm jj$ signal event. To a
 1011 lesser extent, $ZZ+jets$ events can enter the signal region in much the same way provided two lep-
 1012 tons are “lost”. Other prompt sources include $t\bar{t}+V$ and multiple parton interactions, however
 1013 these processes do not contribute much. These prompt backgrounds are expected to contribute
 1014 less than in Run 2 with the addition of forward tracking in the upgraded ATLAS detector. Jets
 1015 mis-reconstructed as leptons or leptons from hadronic decays (such as $t\bar{t}$ and $W+jets$ production)
 1016 comprise the non-prompt lepton background. Lastly, events with two prompt, opposite-charge elec-
 1017 trons can appear as a same-sign event provided one of the electrons is mis-reconstructed as the
 1018 wrong charge.

1019 In this analysis, the EWK production of $W^\pm W^\pm jj$ is studied in the context of the planned
 1020 HL-LHC run conditions and upgraded ATLAS detector. An optimized event selection (referred to
 1021 as the *optimized selection*) is also explored in an effort to gain increased signal significance over
 1022 the *default selection*. The cross section of the inclusive EWK production is measured for both the
 1023 default and optimized selections, and the extraction of the longitudinal scattering significance is
 1024 measured with the optimized selection.

1025 6.1 Theoretical motivation

1026 The theoretical motivation for studying the ssWW process—and VBS in general—is detailed in Sec-
 1027 tion 5.0.1. Since it is specifically the scattering of *longitudinally polarized* vector bosons that violates

1028 unitarity without a SM Higgs boson, a direct measurement of this cross section will be very useful
 1029 for understanding how the Higgs unitarizes the process [50].

1030 6.1.1 Experimental sensitivity to longitudinal polarization

1031 **TODO:** mention that since there are so many polarization possibilities, a large integrated luminosity
 1032 is needed to measure just one of them individually There are three possible polarization states for
 1033 a massive vector boson: two transverse (+ or -) and one longitudinal (0). Therefore, in a system
 1034 with two W bosons, the overall polarization can be purely longitudinal (00), purely transverse (++,
 1035 --, and +-), or mixed (+0 and -0). The three combinations will be referred to as LL , TT , and
 1036 LT respectively.

1037 In order extract the longitudinal scattering component, it is necessary to find variables that
 1038 distinguish the LL from the TT and LT . Several were studied, and those with the best discriminating
 1039 power between the polarizations are the leading and subleading lepton p_T as well as the azimuthal
 1040 separation ($|\Delta\phi_{jj}|$) of the two VBS jets. The LL events prefer lower p_T for both signal leptons
 1041 (see Figure 6.1), which motivates keeping cuts on these quantities as low as possible in the event
 1042 selection. In the case of $|\Delta\phi_{jj}|$, the LL events generally had a larger dijet separation (see Figure 6.2),
 1043 and this variable is used in a binned likelihood fit to extract the longitudinal scattering significance.

1044 6.2 Monte Carlo samples

1045 As no real HL-LHC data will be available for many years, all signal and background processes
 1046 are modeled using MC simulations generated at $\sqrt{s} = 14$ TeV, with the event yields scaled to the
 1047 anticipated HL-LHC integrated luminosity of $\mathcal{L} = 3000 \text{ fb}^{-1}$. The MC samples used in the analysis
 1048 are generated at particle-level and have not been run through the typical full simulation of the
 1049 ATLAS detector. Instead, smearing functions derived from a **GEANT4** simulation of the upgraded
 1050 ATLAS detector are used to estimate detector effects such as momentum resolution. In addition,
 1051 pileup events are fully simulated. The MC samples used in this analysis are summarized in Table 6.1.

1052 The signal sample consists of both VBS and non-VBS electroweak (EWK) $W^\pm W^\pm jj$ production,
 1053 and it is simulated with the **Madgraph5_aMC@NLO** generator using the NNPDF3.0 PDF set and in-
 1054 terfaced with **PYTHIA v8** [53] for hadronization and parton showering. To study the longitudinal
 1055 polarization more directly, two additional **Madgraph5_aMC@NLO** $W^\pm W^\pm jj$ samples are used: one
 1056 containing only the longitudinal contribution (LL) and a second containing the transverse (TT) and
 1057 mixed (LT) contributions.

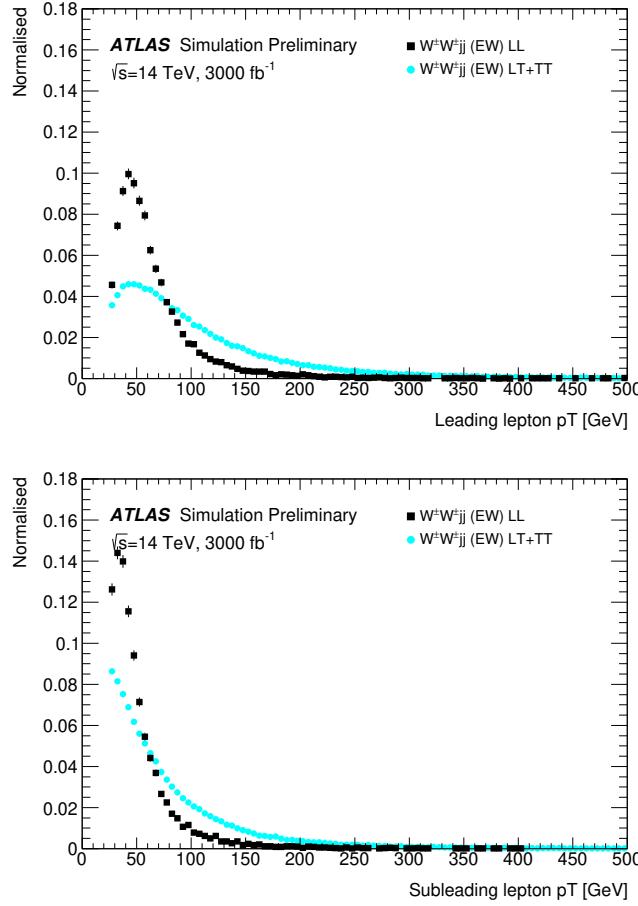


Figure 6.1: Comparison of the leading (top) and subleading (bottom) lepton p_T distributions for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan) $W^\pm W^\pm jj$ events.

1058 There are many other processes that can produce the same final state as the $W^\pm W^\pm jj$ and
1059 must also be accounted for using MC simulations. WZ events are generated using **SHERPA v2.2.0**,
1060 which includes up to one parton at NLO in the strong coupling constant and up to three addi-
1061 tional partons at LO. Both EWK and QCD production are included in these samples. ZZ and
1062 triboson VVV ($V = W, Z$) events are generated using **SHERPA v2.2.2** with up to two additional
1063 partons in the final state. For the triboson backgrounds, the bosons can decay leptonically or
1064 hadronically. $W+jets$ backgrounds are generated for electron, muon, and tau final states at LO
1065 with **Madgraph5_aMC@NLO** and the **NNPDF3.0** set with showering from **PYTHIA v8**. $Z+jets$ events are
1066 produced using **POWHEG-BOX v2** and the **CT10** PDF set interfaced with **PYTHIA v8**. Finally, $t\bar{t}$ and
1067 single-top events are generated using **POWHEG-BOX** with showering from **PYTHIA v6**.

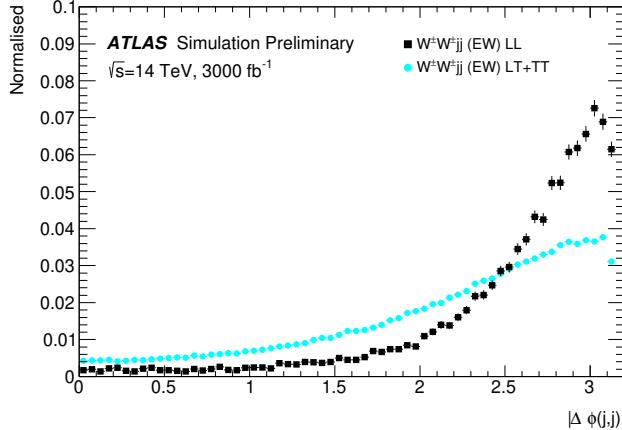


Figure 6.2: Comparison of the azimuthal dijet separation ($|\Delta\phi_{jj}|$) for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan) $W^\pm W^\pm jj$ events.

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

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

1068 6.3 Background estimations

1069 In this analysis, all background contributions are estimated using MC simulations. Backgrounds such
 1070 as electron charge misidentification and fake electrons from jets (which are traditionally estimated
 1071 using data-driven techniques) are estimated using a set of parameterization functions applied to the
 1072 MC. These functions calculate the probability that an electron is assigned the wrong charge or a
 1073 jet is mis-reconstructed as an electron parameterized by the p_T and η of the electron or jet. The
 1074 probabilities are derived from studies on expected electron performance with the upgraded ATLAS
 1075 detector [54].

1076 Processes involving two W and 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 $W+\text{jets}$ or top events that pass selection and do not contain a fake electron, as well as any $Z+\text{jets}$ events without an electron identified as having its charge misidentified are combined as *other non-prompt* backgrounds.

6.3.1 Truth-based isolation

To properly calculate particle isolation, it requires information from several detector subsystems including tracking and calorimeter responses. Since the MC samples used in this analysis have not been run through a full detector simulation, it is not possible to construct the canonical isolation variables used in analyses. At truth-level, this is generally not a serious concern as p_T signal leptons tend to be well isolated to begin with. However, isolation is one of the most powerful tools for rejecting leptons from non-prompt sources such as top events, which are produced in association with additional nearby particles from b and c quark decays. In this analysis, with the absence of any sort of isolation requirement, contributions from top backgrounds (including single top, $t\bar{t}$ and $t\bar{t} + V$) are more than an order of magnitude higher than expected.

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

The truth-based isolation requirement reduces the top background by over 99%, and the percentage of the total background consisting of top events is reduced from 83% to 2%. Additional details on the truth-based isolation studies are presented in Appendix A.

1102 **6.4 Object and event selection**

1103 **6.4.1 Object selection**

1104 Electrons and muons are preselected to have $p_T > 7$ and 6 GeV, respectively, and $|\eta| \leq 4.0$. The
 1105 likelihood of a given lepton to pass the trigger and identification requirements is estimated by
 1106 calculating an efficiency dependent on the p_T and η of the lepton. The leptons are also required to
 1107 pass the isolation criteria detailed in Table 6.2. Jets that have been tagged as a fake electron by the
 1108 functions described in Section 6.3 are treated as electrons for the purpose of the object selection and
 1109 are subject to the same criteria. In order to be considered a signal lepton, an additional requirement
 1110 of $p_T > 25$ GeV is applied on top of the preselection. The two highest p_T leptons passing this
 1111 selection are chosen to be the leading and subleading signal leptons.

1112 Jets are clustered using the anti- k_t algorithm [37] from final-state particles within a radius of
 1113 $\Delta R = 0.4$ (excluding muons and neutrinos). Jets are required to have $p_T > 30$ GeV and lie within
 1114 $|\eta| < 4.5$, with an additional cut of $p_T > 70$ GeV for jets above $|\eta| \geq 3.8$ in order to suppress jets
 1115 from pileup interactions. Jets overlapping with a preselected electron within $\Delta R(e, j) < 0.05$ are
 1116 removed in order to prevent double counting. The two highest p_T jets are defined as the leading
 1117 and subleading *tag jets*.

1118 **6.4.2 Event selection**

1119 The default event selection is summarized in Table 6.3 and described here. Exactly two signal
 1120 leptons are required with the same electric charge and separated from each other by $\Delta R(l l) > 0.3$.
 1121 In order to suppress contributions from Drell-Yan backgrounds, the two signal leptons must have
 1122 an invariant mass m_{ll} greater than 20 GeV. Additionally, if both signal leptons are electrons, their
 1123 mass must be at least 10 GeV from the Z -boson mass in order to reduce background from Z -boson
 1124 decays¹⁰. The event is required to have at least 40 GeV of missing transverse energy (E_T^{miss}) to
 1125 account for the two neutrinos from the W decays. Events with additional preselected leptons are
 1126 vetoed, which greatly reduces WZ and ZZ backgrounds.

1127 Each event must have at least two jets, and both tag jets are required to not overlap with the
 1128 signal leptons, and there is a veto on events with one or more b -jets. In order to preferentially select
 1129 EWK production, the tag jets are also required to have a large separation between them and a large

¹⁰The 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.

invariant mass. Finally, a cut on the lepton centrality¹¹, ζ , defined in Equation 6.1 enhances the EWK $W^\pm W^\pm jj$ signal.

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

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	$N_{b\text{-jet}} = 0$
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.

6.5 Selection optimization

An upgraded detector along with an increase in center of mass energy and integrated luminosity provides an opportunity to study whether the event selection can be optimized to improve the signal to background ratio.

6.5.1 Random grid search algorithm

The chosen method for optimizing the event selection is a cut-based algorithm known as the Random Grid Search (RGS) [55]. Consider a simple case of two variables x and y chosen to differentiate signal from background. In order to be considered a signal event, a given event would be required to pass a set of selection criteria, called a *cut point*: $c = \{x > x_c, y > y_c\}$. A simple method to choose the optimal cut point (i.e. the “best” values of the cuts x_c and y_c) would be to construct an $n \times m$

¹¹ 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.

1142 rectangular grid in x and y consisting of points $(x_0, y_0), (x_1, y_1), \dots, (x_n, y_m)$, as in Figure 6.3. One
 1143 can then choose a cut point $c_k = \{x > x_i, y > y_j\}$ that maximizes the signal significance as measured
 1144 by a chosen metric. This would be considered a *rectangular grid search*.

1145 While effective in principle, a rectangular grid search comes with two major drawbacks:

- 1146 1. The algorithm scales exponentially as the number of variables to be optimized increases, as
 1147 this is effectively increasing the dimensionality of the grid. In the simple case of a square grid
 1148 with N bins per variable v , the number of cut points to be evaluated grows as N^v .
- 1149 2. Signal and background samples are rarely evenly distributed over the entire grid, resulting
 1150 in many cut points being sub-optimal and evaluating them would be a waste of computing
 1151 resources.

1152 To combat these limitations, the RGS algorithm constructs a grid of cut points directly from
 1153 the signal sample itself. In the two-dimensional example, this means that the variables x_i and y_j
 1154 making up the cut point $c_k = \{x > x_i, y > y_j\}$ take their values directly from a given signal event.
 1155 This has the benefit of creating a *random grid* of cut points that is biased towards regions of high
 1156 signal concentration by construction. This reduces the need for exponentially increasing numbers of
 1157 cut points while ensuring that computing resources are not wasted in regions with few to no signal
 1158 events. An example of the the two-dimensional random grid is shown in Figure 6.4.

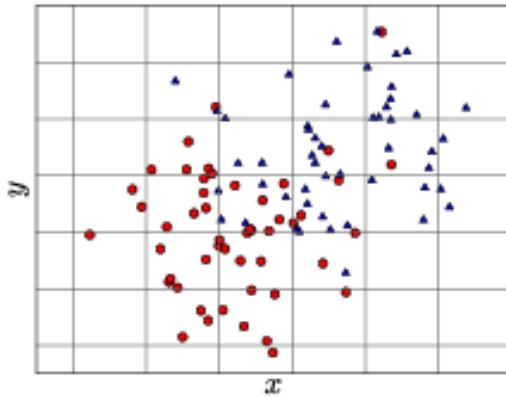


Figure 6.3: A visual representation of a rectangular grid search algorithm. The signal events are the blue triangles, and the red circles are the background events. **TODO: replace with own figure**

1159 Once the random grid of cut points is constructed, the optimal cut point can be chosen using any
 1160 number of metrics, such as signal to background ratio. For the purpose of the $W^\pm W^\pm jj$ upgrade

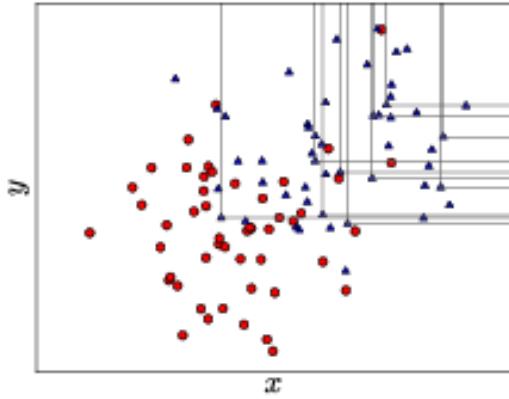


Figure 6.4: A visual representation of a random grid search algorithm. The signal events are the blue triangles, and the red circles are the background events. **TODO: replace with own figure**

study, the optimal cut point is chosen to be the one that maximizes the signal significance Z as defined in Equation 6.2 [56].

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

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 $s \ll b$.

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

1173 allows the optimization to favor the longitudinally polarized events as much as possible, even though
 1174 they both contribute to the EWK signal.

1175 The following variables are chosen for optimization:

- 1176 • Leading lepton p_T
- 1177 • Dilepton invariant mass (m_{ll})
- 1178 • Leading and subleading jet p_T
- 1179 • Dijet invariant mass (m_{jj})
- 1180 • Lepton-jet centrality (ζ)

1181 Subleading lepton p_T is omitted as it is desirable to keep the cut value as low as possible due to
 1182 its sensitivity to the longitudinal polarization (as discussed in Section 6.1.1). Additionally, the dijet
 1183 separation $\Delta\eta_{jj}$ was included in the optimization originally, however it was dropped from the list due
 1184 to the cut value being motivated by differences between EWK and QCD produced $W^\pm W^\pm jj$ events.

1185 Two additional constraints were imposed when selecting the optimal cut point:

- 1186 1. At least 1000 signal events must survive in order to prevent the optimization from being too
 1187 aggressive and unnecessarily reducing signal statistics.
- 1188 2. The dijet invariant mass may only vary within a 50 GeV range of the default value (from
 1189 450 – 550 GeV) due to the cut being physically motivated by the VBS event topology (see
 1190 Section 5.0.2).

1191 Lastly, the signal significance is calculated without taking into account the uncertainty of the
 1192 background using Equation 6.4. This is due to the fact that the statistical uncertainties of the fake
 1193 electron and charge misidentification backgrounds are quite large, owing to poor MC statistics in a
 1194 few of the samples. If Equation 6.2 were used instead, the optimization will cut unreasonably hard
 1195 against these backgrounds. Since Monte Carlo statistics is not expected to be a limiting factor when
 1196 this analysis is performed at the HL-LHC, it is more realistic to simply ignore these large statistical
 1197 uncertainties for the purpose of the optimization.

1198 6.5.3 Results of the optimization

1199 Ultimately, the random grid is constructed from over 38,000 LL-polarized $W^\pm W^\pm jj$ events in the
 1200 six variables listed above. After applying the constraints, the optimal cut point reduces the total

background from 9900 to 2310 while reducing the signal from 3489 to 2958. This corresponds to an increase in signal significance from $Z = 33.26$ to $Z = 52.63$ as calculated by Equation 6.4. The updates to the event selection are listed in Table 6.4.

The large reduction in the background is primarily a result of the increase in the leading and subleading jet p_T from 30 GeV to 90 GeV and 45 GeV, respectively. As can be seen in Figure 6.7, this increase removes a significant portion of the backgrounds from jets faking electrons and charge mis-ID. Additionally, the loosening of the lepton-jet centrality cut ζ allows more signal events to survive the event selection (see Figure 6.9). Other changes to the event selection are minor and do not individually have a large impact on the signal or background yields.

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

TODO: It's a bit awkward to reference the results of the default/optimized before they're properly presented. Maybe move the sections around? not sure...

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.

6.6 Results

6.6.1 Event yields

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

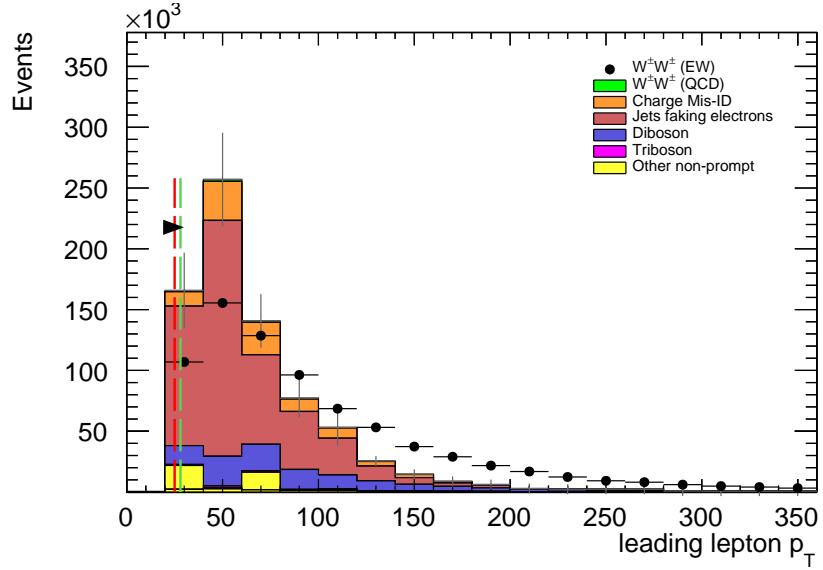


Figure 6.5: Leading lepton p_T distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram). **TODO: Move to appendix or omit**

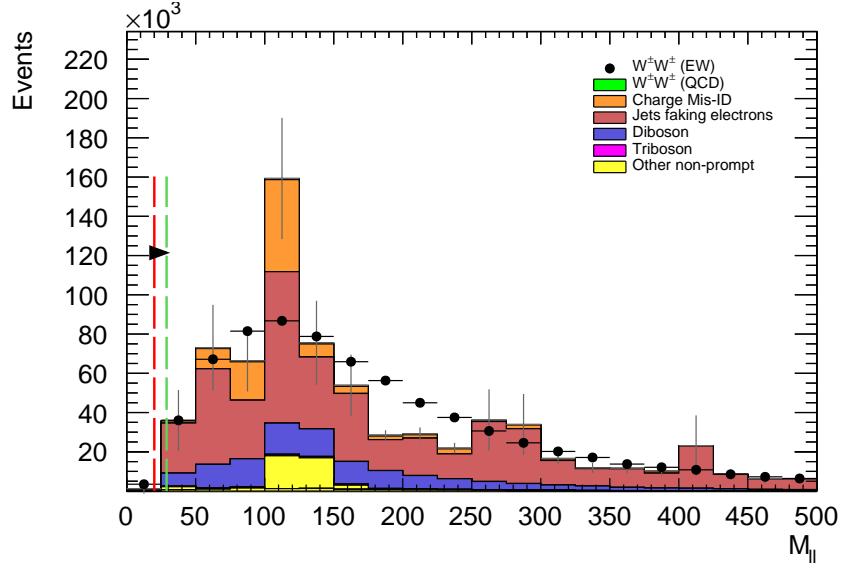


Figure 6.6: Dilepton invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram). **TODO: Move to appendix or omit**

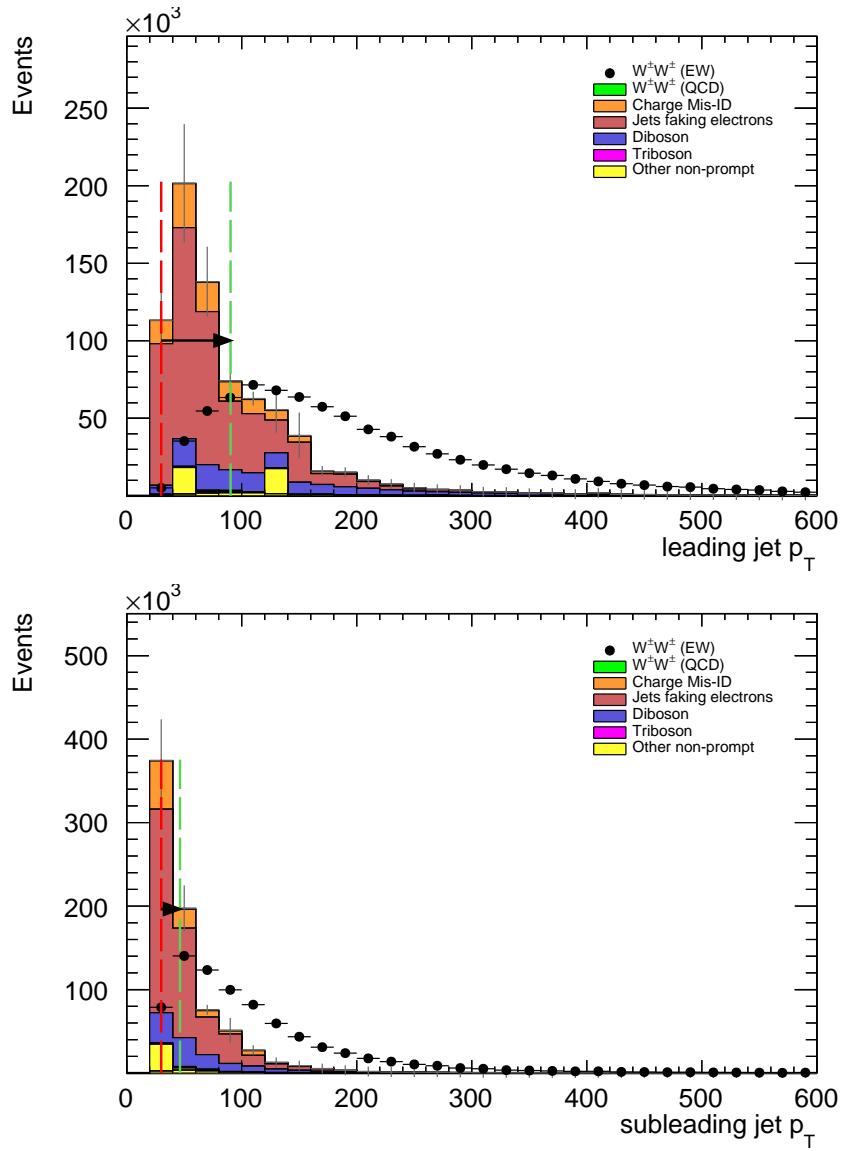


Figure 6.7: Leading (top) and subleading (bottom) jet p_T distributions. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

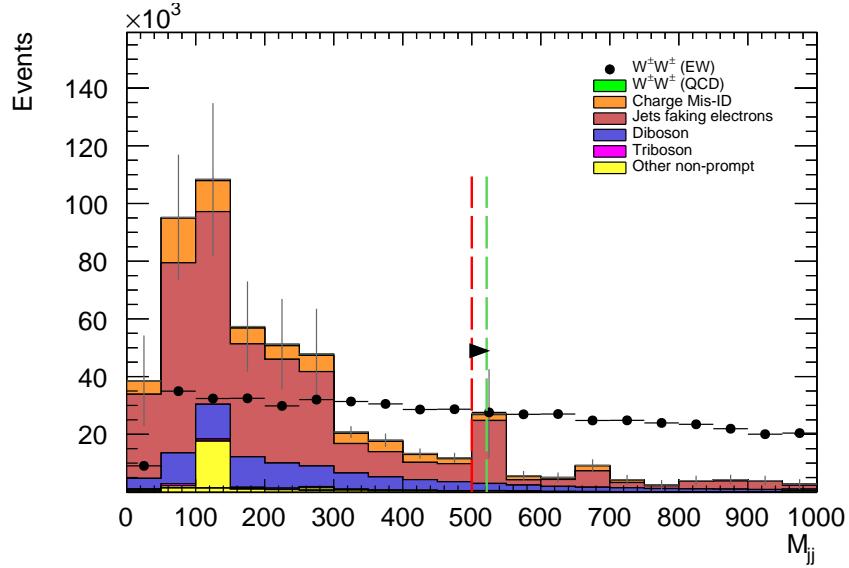


Figure 6.8: Dijet invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram). **TODO:** Move to appendix or omit

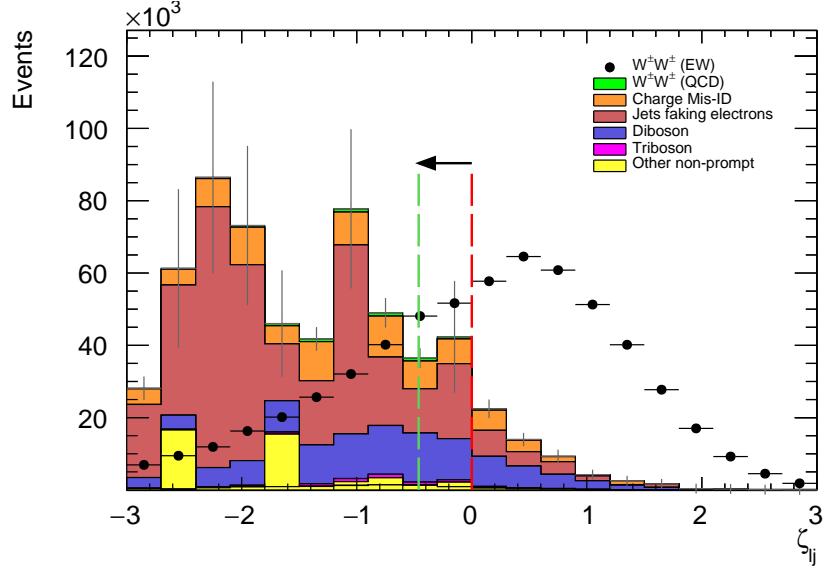


Figure 6.9: Lepton-jet centrality distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

	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.

1223 The event yields for the optimized selection detailed in Section 6.5.3 are listed in Table 6.6. After
 1224 optimization, 2958 signal events and just 2310 background events are expected. Diboson events are
 1225 now the primary source of background, as the optimization greatly reduces the fake and charge
 1226 misidentification backgrounds. As discussed earlier, the increase in the leading and subleading jet
 1227 p_T cuts as well as the loosening of the centrality cut are most responsible for the changes in the
 1228 signal and background yields; distributions of these quantities using the default and the optimized
 1229 event selections can be found in Figures 6.10, 6.11, and 6.12, 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.

1230 It is important to note, however, that the MC sample used to estimate $Z + \text{jets}$ events suffers from
 1231 poor statistics which results in large per-event weights once scaled to $\mathcal{L} = 3000 \text{ fb}^{-1}$. This sample
 1232 contributes heavily to the fake and charge misidentification backgrounds, and a handful of these
 1233 events being cut out by the optimization contributes has a large effect on the dramatic reduction
 1234 of these backgrounds. As a result, these particular optimized results are likely overly optimistic.
 1235 However, given proper MC statistics, it is still expected that the optimization will outperform the

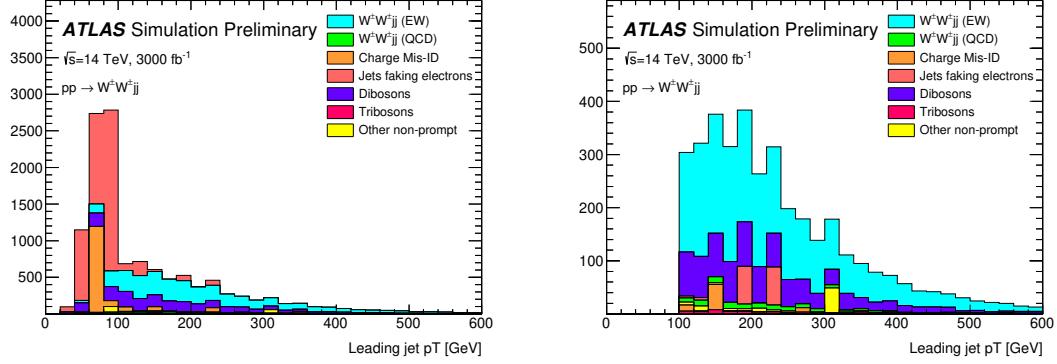


Figure 6.10: p_T distributions for the leading jet using the default (left) and optimized (right) event selections for all channels combined.

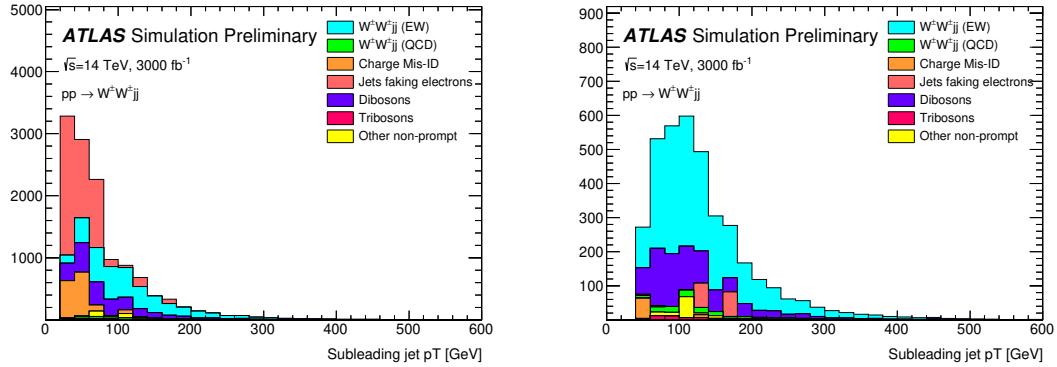


Figure 6.11: p_T distributions for the subleading jet using the default (left) and optimized (right) event selections for all channels combined.

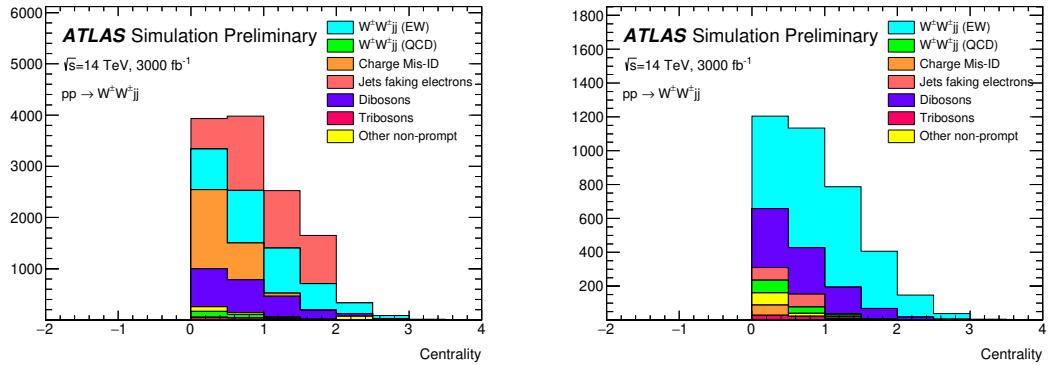


Figure 6.12: p_T distributions for lepton-jet centrality ζ using the default (left) and optimized (right) event selections for all channels combined.

1236 default selection.

1237 6.6.2 Uncertainties

1238 TODO: Ask for details on how some of these uncertainties were calculated – specifically the fakes and
 1239 charge mis-ID The uncertainties considered for the analysis are summarized in Table 6.7. Values for
 1240 experimental systematics on the trigger efficiency, lepton and jet reconstruction, and flavor tagging
 1241 are taken directly from the 13 TeV analysis [1]. The rate uncertainties for the background processes
 1242 are halved from the 13 TeV values.

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.

1243 6.6.3 Cross section measurement

1244 The cross section is calculated using the same method as in the 13 TeV analysis, detailed in Chapter
 1245 5. TODO: update from chapter reference to subsection reference (once it's written)... Once
 1246 again, each of the four lepton flavor channels is further split by charge (i.e. $\mu\mu \rightarrow \mu^+\mu^+ + \mu^-\mu^-$),
 1247 as this increases the sensitivity of the analysis. Each channel's m_{jj} distribution is combined in a
 1248 profile likelihood fit to extract the EWK $W^\pm W^\pm jj$ production cross section. The expected cross
 1249 section calculated using the default event selection is:

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

1250 The expected cross section calculated using the optimized event selection is:

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

1251 The optimized selection should not change the measured value of the cross section, and indeed both
 1252 are consistent with within uncertainties. The systematic uncertainty is reduced by approximately 7%
 1253 with the optimized selection. Projections of the total uncertainty on the cross section as a function
 1254 of integrated luminosity made by [TODO: how was this made?](#) is shown in Figure 6.13. As the
 1255 integrated luminosity increases past $\mathcal{L} > 3000 \text{ fb}^{-1}$, the statistical uncertainty reduces faster than
 1256 the systematic uncertainties. However, the total uncertainty is expected to reduce by less than a
 1257 percent with increased luminosity past the planned 3000 fb^{-1} .

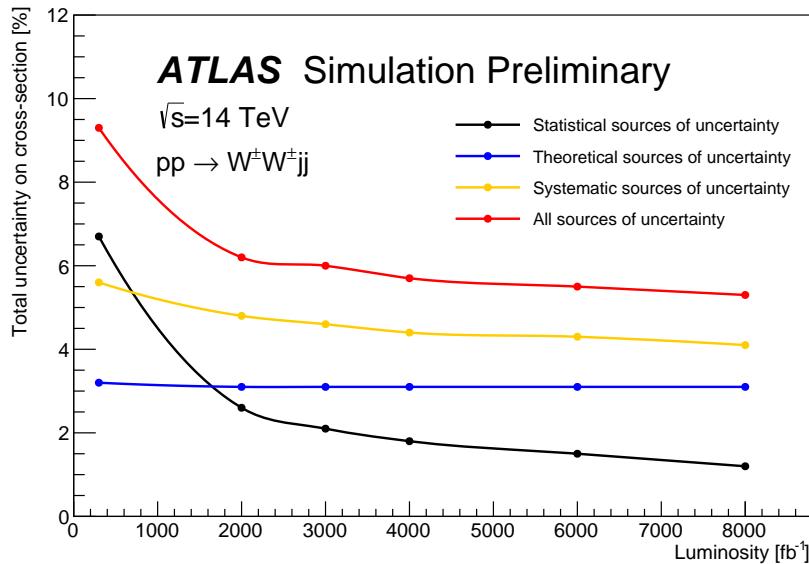


Figure 6.13: Projections of the statistical (black), theoretical (blue), systematic (yellow), and total (red) uncertainties on the measured cross section as a function of integrated luminosity using the optimized event selection.

1258 6.6.4 Longitudinal scattering significance

1259 [TODO: get some details on how this was all done...](#) The longitudinal scattering significance is
 1260 extracted from the $|\Delta\phi_{jj}|$ distribution using a simultaneous binned likelihood fit. In order to increase
 1261 sensitivity, the $|\Delta\phi_{jj}|$ distribution was split into two bins in m_{jj} , and an additional cut on the
 1262 pseudorapidity of the subleading lepton was applied ($|\eta| < 2.5$) to reduce background from fake and
 1263 charge misidentification. The $|\Delta\phi_{jj}|$ distributions used in the fit are shown in Figure 6.14. Due to
 1264 limited statistics, the four lepton flavor channels were not split by charge. The expected significance

¹²⁶⁵ of the $W_L^\pm W_L^\pm jj$ process is 1.8σ with a precision of 47% on the measurement. Projections of the
¹²⁶⁶ expected significance as a function of integrated luminosity is shown in Figure 6.15.

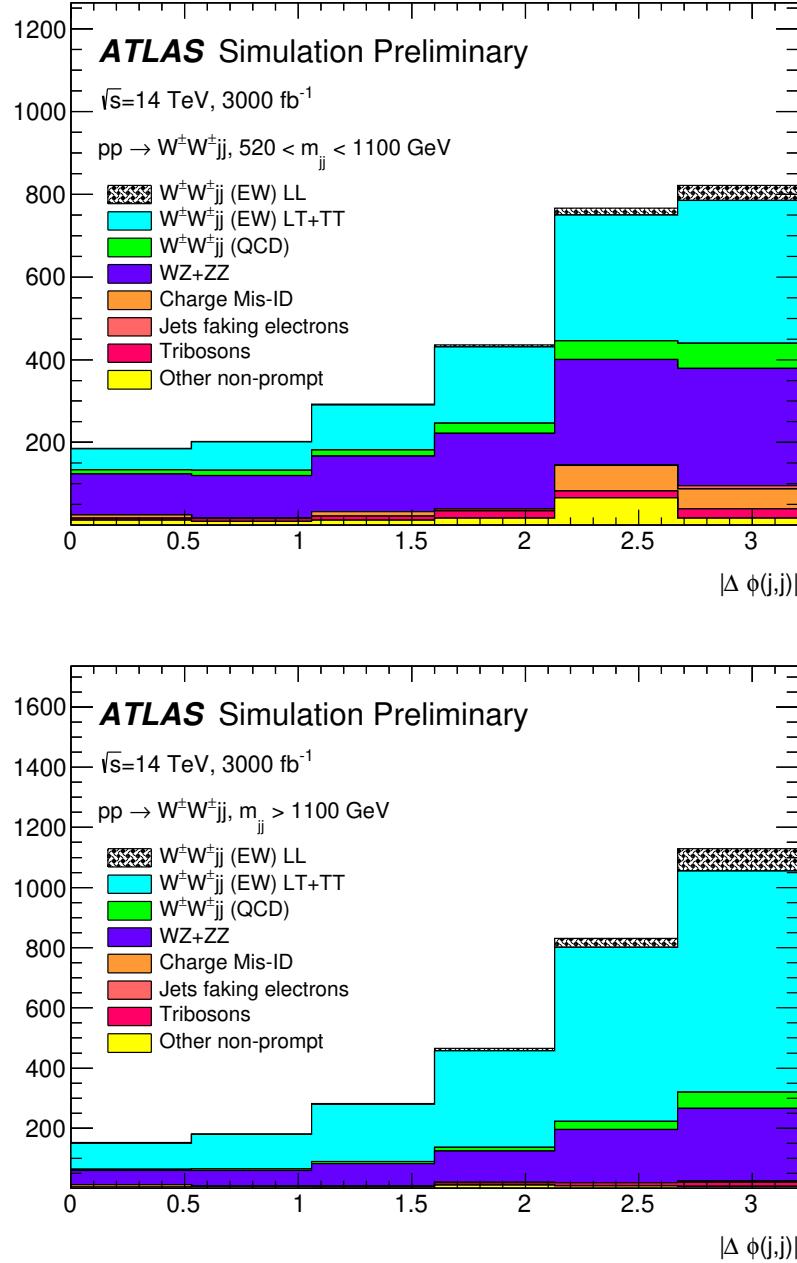


Figure 6.14: Dijet azimuthal separation ($|\Delta\phi_{jj}|$) for the low m_{jj} region ($520 < m_{jj} < 1100 \text{ GeV}$, top) and the high m_{jj} region ($m_{jj} > 1100 \text{ GeV}$, bottom). The purely longitudinal (LL, gray) is plotted separately from the mixed and transverse (LT+TT, cyan) polarizations.

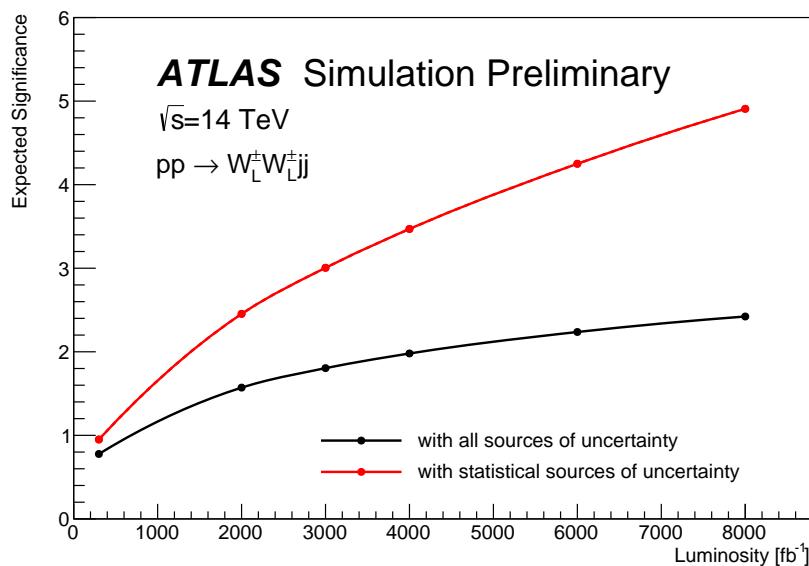


Figure 6.15: Projections of the expected longitudinal scattering significance as a function of integrated luminosity when considering all sources of uncertainties (black) or only statistical uncertainties (red).

1267

CHAPTER 7

1268

Conclusion

1269 Here's where you wrap it up.

1270 **Looking Ahead**

1271

1272 Here's an example of how to have an "informal subsection".

APPENDIX A

Additional material on truth isolation

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

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

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

Bibliography

- 1277 [1] ATLAS Collaboration Collaboration, *Observation of electroweak production of a same-sign W*
 1278 *boson pair in association with two jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS*
 1279 *detector*, Tech. Rep. ATLAS-CONF-2018-030, CERN, Geneva, Jul, 2018.
 1280 <https://cds.cern.ch/record/2629411>. (document), 5, 5.8, 6.6.2
- 1281 [2] S. L. Glashow, *The Renormalizability of Vector Meson Interactions*, Nucl. Phys. **10** (1959)
 1282 107–117. 2.2
- 1283 [3] A. Salam and J. C. Ward, *Weak and Electromagnetic Interactions*, Nuovo Cimento **11** (1959)
 1284 568–577. 2.2
- 1285 [4] L. R. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001.
 1286 <https://cds.cern.ch/record/1129806>. This report is an abridged version of the LHC
 1287 Design Report (CERN-2004-003). 3.1
- 1288 [5] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST
 1289 **3** (2008) S08003. 3.1
- 1290 [6] ATLAS Collaboration Collaboration, *Alignment of the ATLAS Inner Detector Tracking*
 1291 *System with 2010 LHC proton-proton collisions at $\sqrt{s} = 7$ TeV*, Tech. Rep.
 1292 ATLAS-CONF-2011-012, CERN, Geneva, Mar, 2011.
 1293 <https://cds.cern.ch/record/1334582>. 4
- 1294 [7] ATLAS Collaboration, ATLAS Collaboration, *Evidence for Electroweak Production*
 1295 *of $W^\pm W^\pm jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector*, Phys. Rev. Lett. **113**
 1296 (2014) no. 14, 141803, arXiv:1405.6241 [hep-ex]. 5
- 1297 [8] CMS Collaboration, V. Khachatryan et al., *Study of vector boson scattering and search for*
 1298 *new physics in events with two same-sign leptons and two jets*, Phys. Rev. Lett. **114** (2015)
 1299 no. 5, 051801, arXiv:1410.6315 [hep-ex]. 5
- 1300 [9] CMS Collaboration, CMS Collaboration, *Observation of electroweak production of same-sign*
 1301 *W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions*
 1302 *at $\sqrt{s} = 13$ TeV*, arXiv:1709.05822 [hep-ex]. 5
- 1303 [10] C. Bittrich, W. K. Di Clemente, E. M. Duffield, C. Geng, G. Gonella, J. Guo, B. Heinemann,
 1304 T. Herrmann, F. Iltzsche Speiser, M. Kobel, K. Koeneke, J. I. Kroll, S. Li, J. Liu, Y. Liu, J. A.

- 1305 Manjarres Ramos, G. Azuelos, C. A. Lee, M. Mittal, C. Mwewa, R. Ospanov, S. Pagan Griso,
 1306 K. J. Potamianos, M. Shapiro, P. Sommer, S. Todt, Y. Wu, W. Xu, S. Yacoob, H. Yang,
 1307 L. Zhang, Z. Zhao, B. Zhou, J. Zhu, and M.-A. Pleier, *Support note for measurement of*
 1308 *electroweak $W^\pm W^\pm jj$ production at $\sqrt{s} = 13$ TeV*, Tech. Rep. ATL-COM-PHYS-2018-252,
 1309 CERN, Geneva, Mar, 2018. <https://cds.cern.ch/record/2309552>. 5, 5.3.3, 2, 4
- 1310 [11] B. W. Lee, C. Quigg, and H. B. Thacker, *The Strength of Weak Interactions at Very*
 1311 *High-Energies and the Higgs Boson Mass*, *Phys. Rev. Lett.* **38** (1977) 883–885. 5.0.1
- 1312 [12] S. D. Rindani, *Strong gauge boson scattering at the LHC*, in *Physics at the Large Hadron*
 1313 *Collider*, A. Datta, B. Mukhopadhyaya, A. Raychaudhuri, A. K. Gupta, C. L. Khetrapal,
 1314 T. Padmanabhan, and M. Vijayan, eds., pp. 145–155. 2009. [arXiv:0910.5068 \[hep-ph\]](https://arxiv.org/abs/0910.5068). 5.0.1
- 1315 [13] A. Alboteanu, W. Kilian, and J. Reuter, *Resonances and Unitarity in Weak Boson Scattering*
 1316 *at the LHC*, *JHEP* **11** (2008) 010, [arXiv:0806.4145 \[hep-ph\]](https://arxiv.org/abs/0806.4145). 5.0.1, 5.1
- 1317 [14] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model*
 1318 *Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1,
 1319 [arXiv:1207.7214 \[hep-ex\]](https://arxiv.org/abs/1207.7214). 5.0.1
- 1320 [15] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS*
 1321 *experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30, [arXiv:1207.7235 \[hep-ex\]](https://arxiv.org/abs/1207.7235). 5.0.1
- 1322 [16] J. M. Campbell and R. K. Ellis, *Higgs Constraints from Vector Boson Fusion and Scattering*,
 1323 *JHEP* **04** (2015) 030, [arXiv:1502.02990 \[hep-ph\]](https://arxiv.org/abs/1502.02990). 5.0.1, 5.0.2
- 1324 [17] M. SZleper, *The Higgs boson and the physics of WW scattering before and after Higgs*
 1325 *discovery*, [arXiv:1412.8367 \[hep-ph\]](https://arxiv.org/abs/1412.8367). 5.0.1
- 1326 [18] E. Accomando, A. Ballestrero, A. Belhouari, and E. Maina, *Isolating Vector Boson Scattering*
 1327 *at the LHC: Gauge cancellations and the Equivalent Vector Boson Approximation vs complete*
 1328 *calculations*, *Phys. Rev. D* **74** (2006) 073010, [arXiv:hep-ph/0608019 \[hep-ph\]](https://arxiv.org/abs/hep-ph/0608019). 5.0.1
- 1329 [19] P. Anger, B. Axen, T. Dai, C. Gumpert, C. Hasterok, B. Heinemann, M. Hurwitz, N. Ilic,
 1330 M. Kobel, J. Liu, L. Liu, J. Metcalfe, S. Pagan Griso, B. Zhou, S. Hou, M.-A. Pleier,
 1331 U. Schnoor, J. Searcy, F. Socher, A. Sood, A. Vest, L. Xu, and J. Zhu, *Same Sign $W^\pm W^\pm$*
 1332 *Production and Limits on Anomalous Quartic Gauge Couplings*, Tech. Rep.
 1333 ATL-COM-PHYS-2013-990, CERN, Geneva, Jul, 2013.
 1334 <https://cds.cern.ch/record/1561731>. Internal note for approved paper STDM-2013-06
 1335 <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/STDM-2013-06/>. 5.0.2, 5.1,
 1336 5.7
- 1337 [20] J. Almond, L. Bianchini, C. Blocker, J. Klinger, A. Maslennikov, M. Owen, K. Skovpen,
 1338 Y. Tikhonov, and U. Yang, *Search for heavy neutrino, W_R and Z_R gauge bosons in events*
 1339 *with two high- P_T leptons and jets with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV*,
 1340 Tech. Rep. ATL-COM-PHYS-2013-810, CERN, Geneva, Jun, 2013.
 1341 <https://cds.cern.ch/record/1555805>. This is the supporting note for EXOT-2012-24,
 1342 which is now published as *JHEP* **07** (2015) 162. 5.0.3
- 1343 [21] ATLAS Collaboration, M. Aaboud et al., *Luminosity determination in pp collisions at $\sqrt{s} =$*
 1344 *8 TeV using the ATLAS detector at the LHC*, *Eur. Phys. J. C* **76** (2016) no. 12, 653,
 1345 [arXiv:1608.03953 \[hep-ex\]](https://arxiv.org/abs/1608.03953). 5.1

- 1346 [22] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in*
 1347 *ATLAS*, JINST **13** (2018) no. 07, P07017. 5.1
- 1348 [23] ATLAS Collaboration, G. Aad et al., *The ATLAS Simulation Infrastructure*, Eur. Phys. J.
 1349 **C70** (2010) 823–874, arXiv:1005.4568 [physics.ins-det]. 5.1.1
- 1350 [24] S. Agostinelli et al., *GEANT4 - a simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003)
 1351 250–303. 5.1.1
- 1352 [25] T. Sjostrand, S. Mrenna, and P. Skands, *A Brief Introduction to PYTHIA 8.1*, Comput.
 1353 Phys. Commun. **178** (2008) 852–867, arXiv:0710.3820 [hep-ph]. 5.1.1
- 1354 [26] T. Gleisberg et al., *Event generation with SHERPA 1.1*, JHEP **02** (2009) 007,
 1355 arXiv:0811.4622 [hep-ph]. 5.1.1
- 1356 [27] S. Schumann and F. Krauss, *A parton shower algorithm based on Catani-Seymour dipole*
 1357 *factorization*, JHEP **03** (2008) 038, arXiv:0709.1027 [hep-ph]. 5.1.1
- 1358 [28] S. Höche, F. Krauss, S. Schumann, and F. Siegert, *QCD matrix elements and truncated*
 1359 *showers*, JHEP **05** (2009) 053, arXiv:0903.1219 [hep-ph]. 5.1.1
- 1360 [29] R. D. Ball et al., *Parton distributions for the LHC Run II*, JHEP **04** (2015) 040,
 1361 arXiv:1410.8849 [hep-ph]. 5.1.1
- 1362 [30] S. Alioli, P. Nason, C. Oleari, and E. Re, *A general framework for implementing NLO*
 1363 *calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **06** (2010) 043,
 1364 arXiv:1002.2581 [hep-ph]. 5.1.1
- 1365 [31] A. Ballestrero et al., *Precise predictions for same-sign W-boson scattering at the LHC*, Eur.
 1366 Phys. J. **C78** (2018) no. 8, 671, arXiv:1803.07943 [hep-ph]. 5.1.1
- 1367 [32] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao,
 1368 T. Stelzer, P. Torrielli, and M. Zaro, *The automated computation of tree-level and*
 1369 *next-to-leading order differential cross sections, and their matching to parton shower*
 1370 *simulations*, JHEP **07** (2014) 079, arXiv:1405.0301 [hep-ph]. 5.1.1
- 1371 [33] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin, and C. P. Yuan, *New*
 1372 *parton distributions for collider physics*, Phys. Rev. D **82** (2010) 074024, arXiv:1007.2241
 1373 [hep-ph]. 5.1.1
- 1374 [34] T. Sjostrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006)
 1375 026, arXiv:0603175 [hep-ph]. 5.1.1
- 1376 [35] ATLAS Collaboration, G. Aad et al., *Muon reconstruction performance of the ATLAS*
 1377 *detector in protonproton collision data at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. **C76** (2016) no. 5, 292,
 1378 arXiv:1603.05598 [hep-ex]. 5.2.1.1, 5
- 1379 [36] ATLAS Collaboration Collaboration, *Electron efficiency measurements with the ATLAS*
 1380 *detector using the 2015 LHC proton-proton collision data*, Tech. Rep.
 1381 ATLAS-CONF-2016-024, CERN, Geneva, Jun, 2016.
 1382 <https://cds.cern.ch/record/2157687>. 5.2.1.2
- 1383 [37] M. Cacciari, G. P. Salam, G. Soyez, *The anti- k_t jet clustering algorithm*, JHEP **04** (2008) 063,
 1384 arXiv:0802.1189 [hep-ph]. 5.2.1.3, 6.4.1

- 1385 [38] ATLAS Collaboration, M. Aaboud et al., *Jet energy scale measurements and their systematic*
 1386 *uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys.
 1387 Rev. D96 (2017) no. 7, 072002, arXiv:1703.09665 [hep-ex]. 5.2.1.3
- 1388 [39] *Tagging and suppression of pileup jets with the ATLAS detector*, Tech. Rep.
 1389 ATLAS-CONF-2014-018, CERN, Geneva, May, 2014.
 1390 <http://cds.cern.ch/record/1700870>. 5.2.1.3
- 1391 [40] D. Adams, C. Anastopoulos, A. Andreatta, M. Aoki, L. Asquith, M. Begel, F. Bernlochner,
 1392 U. Blumenschein, A. Bocci, S. Cheatham, W. Davey, P.-A. Delsart, P.-O. DeViveiros,
 1393 A. Dewhurst, D. Duschinger, F. Filthaut, P. Francavilla, F. Garberson, S. Head, A. Henrichs,
 1394 A. Hoecker, M. Kagan, B. Kersevan, T. Khoo, B. Lenzi, D. Lopez Mateos, B. Malaescu,
 1395 Z. Marshall, T. Martin, C. Meyer, A. Morley, W. Murray, M. zur Nedden, R. Nicolaidou,
 1396 S. Pagan Griso, G. Pasztor, P. Petroff, C. Pizio, R. Polifka, X. Poveda, R. Reece, F. Ruehr,
 1397 F. Salvatore, R. Sandstroem, T. Scanlon, D. Scheirich, S. Schramm, A. Schwartzman,
 1398 K. Suruliz, M. Sutton, E. Thompson, M. Tripiana, A. Tuna, S. Viel, M. Vincter, I. Vivarelli,
 1399 M. Wielers, A. Wildauer, and Z. Zinonos, *Recommendations of the Physics Objects and*
 1400 *Analysis Harmonisation Study Groups 2014*, Tech. Rep. ATL-PHYS-INT-2014-018, CERN,
 1401 Geneva, Jul, 2014. <https://cds.cern.ch/record/1743654>. 5.2.1.4
- 1402 [41] ATLAS Collaboration, M. Aaboud et al., *Measurement of the cross-section for producing a W*
 1403 *boson in association with a single top quark in pp collisions at $\sqrt{s} = 13$ TeV with ATLAS*,
 1404 JHEP 01 (2018) 063, arXiv:1612.07231 [hep-ex]. 5.2.1.4
- 1405 [42] ATLAS Collaboration, M. Aaboud et al., *Performance of missing transverse momentum*
 1406 *reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV*, Eur.
 1407 Phys. J. C78 (2018) no. 11, 903, arXiv:1802.08168 [hep-ex]. 5.2.2
- 1408 [43] ATLAS Collaboration, M. Aaboud et al., *Measurements of b -jet tagging efficiency with the*
 1409 *ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13$ TeV*, JHEP 08 (2018) 089, arXiv:1805.01845
 1410 [hep-ex]. 5.2.2
- 1411 [44] J.-F. Arguin, J. Claude, G. Gonella, B. P. Kersevan, and K tech. rep. 5.3.3
- 1412 [45] C.-H. Kom and W. J. Stirling, *Charge asymmetry in $W + \text{jets}$ production at the LHC*, Eur.
 1413 Phys. J. C69 (2010) 67–73, arXiv:1004.3404 [hep-ph]. 5.4
- 1414 [46] R. Steerenberg, *LHC Report: Another run is over and LS2 has just begun...*,
 1415 [https://home.cern/news/news/accelerators/](https://home.cern/news/news/accelerators/lhc-report-another-run-over-and-ls2-has-just-begun)
 1416 [lhc-report-another-run-over-and-ls2-has-just-begun](https://home.cern/news/news/accelerators/lhc-report-another-run-over-and-ls2-has-just-begun), 2018. Accessed: 2018-12-14. 6
- 1417 [47] *Letter of Intent for the Phase-I Upgrade of the ATLAS Experiment*, Tech. Rep.
 1418 CERN-LHCC-2011-012. LHCC-I-020, CERN, Geneva, Nov, 2011.
 1419 <http://cds.cern.ch/record/1402470>. 6
- 1420 [48] G. Apollinari, I. Bjar Alonso, O. Brning, M. Lamont, and L. Rossi, *High-Luminosity Large*
 1421 *Hadron Collider (HL-LHC): Preliminary Design Report*. CERN Yellow Reports: Monographs.
 1422 CERN, Geneva, 2015. <https://cds.cern.ch/record/2116337>. 6
- 1423 [49] ATLAS Collaboration Collaboration, ATLAS Collaboration, *ATLAS Phase-II Upgrade*
 1424 *Scoping Document*, Cern-lhcc-2015-020, Geneva, Sep, 2015.
 1425 <http://cds.cern.ch/record/2055248>. 6

- 1426 [50] D. Espriu and B. Yencho, *Longitudinal WW scattering in light of the “Higgs boson”*
1427 *discovery*, Phys. Rev. D **87** (2013) 055017, arXiv:1212.4158 [hep-ph]. 6, 6.1
- 1428 [51] ATLAS Collaboration Collaboration, *Prospects for the measurement of the $W^\pm W^\pm$ scattering*
1429 *cross section and extraction of the longitudinal scattering component in pp collisions at the*
1430 *High-Luminosity LHC with the ATLAS experiment*, Tech. Rep. ATL-PHYS-PUB-2018-052,
1431 CERN, Geneva, Dec, 2018. <http://cds.cern.ch/record/2652447>. 6
- 1432 [52] ATLAS Collaboration Collaboration, *Studies on the impact of an extended Inner Detector*
1433 *tracker and a forward muon tagger on $W^\pm W^\pm$ scattering in pp collisions at the*
1434 *High-Luminosity LHC with the ATLAS experiment*, Tech. Rep. ATL-PHYS-PUB-2017-023,
1435 CERN, Geneva, Dec, 2017. <https://cds.cern.ch/record/2298958>. 6
- 1436 [53] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel,
1437 C. O. Rasmussen, and P. Z. Skands, *An Introduction to PYTHIA 8.2*, Comput. Phys.
1438 Commun. **191** (2015) 159–177, arXiv:1410.3012 [hep-ph]. 6.2
- 1439 [54] ATLAS Collaboration Collaboration, *Expected performance for an upgraded ATLAS detector*
1440 *at High-Luminosity LHC*, Tech. Rep. ATL-PHYS-PUB-2016-026, CERN, Geneva, Oct, 2016.
1441 <http://cds.cern.ch/record/2223839>. 6.3
- 1442 [55] P. C. Bhat, H. B. Prosper, S. Sekmen, and C. Stewart, *Optimizing Event Selection with the*
1443 *Random Grid Search*, Comput. Phys. Commun. **228** (2018) 245–257, arXiv:1706.09907
1444 [hep-ph]. 6.5.1
- 1445 [56] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Asymptotic formulae for likelihood-based*
1446 *tests of new physics*, Eur. Phys. J. **C71** (2011) 1554, arXiv:1007.1727 [physics.data-an].
1447 [Erratum: Eur. Phys. J.C73,2501(2013)]. 6.5.1