

1 MEASUREMENT OF ELECTROWEAK PRODUCTION OF
2 SAME-SIGN W BOSON PAIRS WITH ATLAS (WORKING
3 TITLE)

4 William Kennedy DiClemente

5 A DISSERTATION
6 in
7 Physics and Astronomy

8 Presented to the Faculties of The University of Pennsylvania
9 in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy

10 2019 *Last compiled: February 5, 2019*

11
12 I. Joseph Kroll, Professor, Physics
13 Supervisor of Dissertation

14
15 Joshua Klein, Professor, Physics
16 Graduate Group Chairperson

17 Dissertation Committee
18 Elliot Lipeles, Associate Professor, Physics
19 Christopher Mauger, Associate Professor, Physics
20 Burt Ovrut, Professor, Physics
21 Justin Khoury, Professor, Physics
22 I. Joseph Kroll, Professor, Physics

23 MEASUREMENT OF ELECTROWEAK PRODUCTION OF SAME-SIGN W BOSON PAIRS
24 WITH ATLAS (WORKING TITLE)

25 COPYRIGHT
26 2019
27 William Kennedy DiClemente

28 All rights reserved.

Acknowledgements

³⁰ I'd like to thanks the Ghosts of Penn Students Past for providing me with such an amazing thesis
³¹ template.

ABSTRACT

33 MEASUREMENT OF ELECTROWEAK PRODUCTION OF SAME-SIGN W BOSON PAIRS
 34 WITH ATLAS (WORKING TITLE)

35 William Kennedy DiClemente

36 J. Kroll

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

Contents

48	Acknowledgements	iii
49	Abstract	iv
50	Contents	v
51	List of Tables	ix
52	List of Figures	xii
53	Preface	xviii
54	1 Introduction	1
55	2 Theoretical Framework	3
56	2.1 Introduction to the Standard Model	3
57	2.2 Electroweak symmetry breaking and the Higgs boson	5
58	2.3 Electroweak vector boson scattering	8
59	3 LHC and the ATLAS Detector	12
60	3.1 The Large Hadron Collider	12
61	3.2 The ATLAS Detector	12
62	3.2.1 The Inner Detector	12
63	3.2.1.1 Pixel Detector	12
64	3.2.1.2 Semiconductor Tracker	12
65	3.2.1.3 Transition Radiation Tracker	12

66	3.2.2	The Calorimeters	13
67	3.2.2.1	Liquid Argon Calorimeters	13
68	3.2.2.2	Tile Calorimeters	13
69	3.2.3	The Muon Spectrometer	13
70	3.2.4	Particle reconstruction	14
71	3.2.4.1	Track reconstruction	14
72	3.2.4.2	Muon reconstruction	14
73	3.2.4.3	Electron reconstruction	14
74	3.2.4.4	Jet reconstruction	14
75	4	Alignment of the ATLAS Inner Detector	15
76	4.1	The alignment method	16
77	4.1.1	Alignment levels	19
78	4.1.2	Alignment coordinate systems	20
79	4.2	Early 2015 alignment of the ATLAS detector	21
80	4.2.1	June alignment procedure	23
81	4.2.2	Alignment results	24
82	4.2.2.1	Residual distributions from collisions	25
83	4.2.2.2	Track parameter resolution from cosmic rays	27
84	4.2.3	Error scaling	28
85	4.3	Level 2 alignment of the TRT	31
86	4.4	Momentum bias from sagitta deformations	32
87	4.4.1	Sagitta bias monitoring with electron E/p	34
88	4.4.1.1	Measuring $\langle E/p \rangle$	35
89	4.4.1.2	Results in 13 TeV data	36
90	5	Measurement of same-sign WW production at $\sqrt{s} = 13$ TeV with ATLAS	40
91	5.0.2	Experimental overview of vector boson scattering	40
92	5.0.3	Same-sign $W^\pm W^\pm$ scattering	41
93	5.0.4	Overview of backgrounds	43
94	5.1	Data and Monte Carlo samples	46
95	5.1.1	Monte Carlo samples	46
96	5.2	Object and event selection	47

97	5.2.1	Object selection	48
98	5.2.1.1	Muon candidate selection	48
99	5.2.1.2	Electron candidate selection	49
100	5.2.1.3	Jet candidate selection	50
101	5.2.1.4	Treatment of overlapping objects	51
102	5.2.2	Signal event selection	52
103	5.3	Background estimations	53
104	5.3.1	Estimation of the WZ background	54
105	5.3.2	Estimation of the $V\gamma$ background	56
106	5.3.3	Estimation of backgrounds from charge misidentification	57
107	5.3.3.1	Validation of the charge misidentification estimate	59
108	5.3.4	Estimation of non-prompt backgrounds with the fake factor method	60
109	5.3.4.1	Overview of the default fake factor method	61
110	5.3.4.2	The fake factor with p_T^{cone}	62
111	5.3.4.3	Application of the fake factor	65
112	5.3.4.4	Systematic uncertainties	68
113	5.3.4.5	Results of the fake factor	69
114	5.3.4.6	Validation of the fake factor	72
115	5.3.5	Reduction of WZ background using custom overlap removal	72
116	5.4	Cross section measurement	77
117	5.4.1	Maximum likelihood fit	77
118	5.4.2	Definition of the fiducial volume	79
119	5.4.3	Cross section extraction	80
120	5.5	Summary of uncertainties	81
121	5.5.1	Experimental uncertainties	81
122	5.5.2	Theoretical uncertainties	84
123	5.5.2.1	Uncertainties from EWK-QCD interference	84
124	5.6	Results	85
125	6	Prospects for same-sign WW at the High Luminosity LHC	89
126	6.0.1	Analysis Overview	90
127	6.1	Theoretical motivation	90
128	6.1.1	Experimental sensitivity to longitudinal polarization	91

129	6.2 Monte Carlo samples	92
130	6.3 Background estimations	93
131	6.3.1 Truth-based isolation	93
132	6.4 Object and event selection	94
133	6.4.1 Object selection	94
134	6.4.2 Event selection	95
135	6.5 Selection optimization	96
136	6.5.1 Random grid search algorithm	96
137	6.5.2 Inputs to the optimization	98
138	6.5.3 Results of the optimization	99
139	6.6 Results	100
140	6.6.1 Event yields	100
141	6.6.2 Uncertainties	103
142	6.6.3 Cross section measurement	104
143	6.6.4 Longitudinal scattering significance	104
144	7 Conclusion	108
145	A Additional material on $W^\pm W^\pm jj$ measurement at $\sqrt{s} = 13\text{TeV}$	109
146	A.1 Impact of experimental uncertainty on MC background estimations	109
147	A.2 Additional signal region plots	111
148	B Additional material on $W^\pm W^\pm jj$ prospects at the HL-LHC	112
149	B.1 Truth isolation	112
150	B.1.1 TRUTH1++ derivations	113
151	B.1.2 Check of truth-based isolation	114
152	B.1.3 Loose isolation working point	114
153	B.2 Plots of other optimization variables	117
154	Bibliography	119

List of Tables

156	4.1	The four alignment levels for each of the detector subsystems. The total number of alignable structures and degrees of freedom (DoF) to be aligned are given for each level.	21
158	4.2	Summary of the highest level of alignment applied to each ID subsystem when deriving the June alignment.	24
160	4.3	Estimated value of the error scaling term b for each subdetector component with the June alignment.	31
162	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 $m_{jj} > 10\text{ GeV}$	43
166	5.2	Summary of MC samples used in the analysis.	47
167	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.	49
169	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.	50
172	5.5	Jet selection criteria. All jets are required to pass the above selection in order to be used in the analysis.	51
174	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.	52
177	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.	52
179	5.8	The signal event selection.	54
180	5.9	Event yields in the WZ control region before normalization. All lepton flavor channels are combined.	56
182	5.10	Selection criteria for the $V\gamma$ control region.	56
183	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.	57
186	5.12	Selection criteria for the same-sign inclusive validation region.	60

187	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.	66
188			71
190	5.14	Values of the fake factor in each p_T bin and for each individual systematic source.	71
191	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.	71
196	5.16	Selection criteria for the same-sign top fakes validation region.	72
197	5.17	Custom OR definition. Leptons must pass this selection in order to be counted for the trilepton veto.	76
199	5.18	Definition of the fiducial volume.	79
200	5.19	Impact of various systematic effects on the fiducial cross section measurement. The impact of a given source of uncertainty is computed by performing the fit with the corresponding nuisance parameter varied up or down by one standard deviation from its nominal value.	82
204	5.20	List of sources of experimental uncertainties on the reconstruction of physics objects.	83
205	5.21	Impact of experimental uncertainties for the $W^\pm W^\pm jj$ EWK processes in all channels.	83
206	5.22	Impact of experimental uncertainties for the WZ process in all channels.	83
207	5.23	The set of generator level cuts used for generating the interference samples with <code>MadGraph</code>	85
208	5.24	Cross sections for each different $W^\pm W^\pm jj$ production mode (inclusive, EWK only, QCD only, and interference only) generated using <code>MadGraph</code> . The cross sections are calculated using a minimal set of generator level cuts from events where the W decays to a muon.	85
211	5.25	Table of the data and prediction event yields in the signal region before the fit. Numbers are shown for the six lepton flavor and charge channels and for all channels combined. Here the WZ background yields are normalized to the data in the WZ control region. The background estimations from the fake factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t}V$ backgrounds are combined in the “Other prompt” category.	86
218	5.26	Table of the data and prediction event yields in the signal region after the fit. Numbers are shown for the six lepton flavor and charge channels and for all channels combined. The background estimations from the fake factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t}V$ backgrounds are combined in the “Other prompt” category.	86
224	6.1	Summary of MC samples used in the analysis.	93
225	6.2	Truth-based isolation requirements for electrons and muons.	94
226	6.3	Summary of the signal event selection.	96
227	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.	99
229	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.	101
232	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.	102

235	6.7 Summary of estimated experimental and rate uncertainties.	103
236	A.1 Impact of experimental uncertainties for the $W^\pm W^\pm jj$ QCD processes in all channels. .	109
237	A.2 Impact of experimental uncertainties for triboson process in all channels.	110
238	A.3 Impact of experimental uncertainties for $t\bar{t}V$ processes in all channels.	110
239	A.4 Impact of experimental uncertainties for the $W\gamma$ process in all channels.	110
240	A.5 Impact of experimental uncertainties for the $Z\gamma$ process in all channels.	110
241	A.6 Impact of experimental uncertainties for the ZZ process in all channels.	111
242	B.1 Event yields prior to applying any form of truth-based isolation criteria.	112
243	B.2 Event yields after applying a test version of the truth-based isolation.	113
244	B.3 Electron and muon isolation requirements for the loose working point.	114
245	B.4 Event yields broken down by sample and by background type using the loose isolation 246 workingpoint. Events containing a fake or charge-flipped electron are removed from their 247 respective sample and added to the “fakes” and “charge flip” rows, respectively. Errors 248 include statistical uncertainty and estimated systematic rate uncertainty based on the 249 background process.	115
250	B.5 Event yields broken down by background type using the tight isolation workingpoint. 251 Events containing a fake or charge-flipped electron are removed from their respective 252 sample and added to the “fakes” and “charge flip” rows, respectively. Errors include sta- 253 tistical uncertainty and estimated systematic rate uncertainty based on the background 254 process.	116

List of Figures

256	2.1	An illustration of the potential term $V(\phi)$ in the cases where $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). The right-hand plot shows the Higgs potential, or ‘‘Mexican hat potential’’, with the minimum at $ \phi = \sqrt{-\frac{\mu^2}{\lambda}}$ rather than at $ \phi = 0$ as in the left-hand plot.	6
259	2.2	Feynman diagram of a generic VBS process. The gray circle represents any interaction with two incoming and two outgoing vector bosons, including any of the diagrams shown in Figures 2.3 and 2.4.	9
262	2.3	Leading order $VV \rightarrow VV$ Feynman diagrams involving EWK bosons. From left to right: s -channel, t -channel, u -channel, and the quartic gauge coupling.	9
265	2.4	Leading order $VV \rightarrow VV$ Feynman diagrams involving the exchange of a Higgs boson. From left to right: s -channel, t -channel, and u -channel.	9
266	2.5	Cross sections in nanobarns for five different longitudinally polarized VBS processes as a function of center of mass energy \sqrt{s} . Without a Higgs boson (left), the cross sections grow unbounded with \sqrt{s} . With a 120 GeV Higgs boson (right), the cross sections no longer diverge.	11
270	3.1	General cut-away view of the ATLAS detector.	13
271	4.1	Graphical representation of the effect of a misaligned detector element. The reconstructed particle track (dashed arrow) differs from the actual trajectory of the particle (solid arrow) due to the shift in one of the detector elements. The cyan lines represent the track-to-hit residuals.	16
275	4.2	Graphical representation of the ID alignment chain.	19
276	4.3	A schematic representation of the Inner Detector in the longitudinal plane with the global coordinate system overlaid on top. The Pixel detector and IBL are shown in blue, the SCT in green, and the TRT in red. The local coordinates for each subdetector module are inset on the right.	22
280	4.4	The d_0 distributions with respect to the reconstructed primary vertex using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.	25

284	4.5	Local x (left) and local y (right) residual distributions of the IBL planar sensors using the $\sqrt{s} = 13\text{TeV}$ collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.	26
288	4.6	The mean of the local x (left) and local y (right) residual distributions as a function of the global z position of each IBL module using the $\sqrt{s} = 13\text{TeV}$ collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red).	27
292	4.7	Local x (top) and local y (bottom) residual distributions for the Pixel barrel (excluding the IBL, left) and end-caps (right) using the $\sqrt{s} = 13\text{TeV}$ collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.	28
297	4.8	Local x residual distributions for the SCT barrel (left) and end-caps (right) using the $\sqrt{s} = 13\text{TeV}$ collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.	29
301	4.9	Residual distributions for the TRT barrel (left) and end-caps (right) using the $\sqrt{s} = 13\text{TeV}$ collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to the same number of entries.	29
305	4.10	Representation of splitting a single cosmic ray track passing through the entire detector (left) into two separate tracks (right).	30
307	4.11	Distribution of the difference in the impact parameter Δd_0 (left) and charge over transverse momentum $\Delta q/p_T$ (right) between the two cosmic ray split tracks. The June (black) and March (green) alignments are compared. The distributions are normalized to the same number of entries.	30
311	4.12	Pull distributions in local x (left) and y (right) for the IBL using the $\sqrt{s} = 13\text{TeV}$ collision data sample after applying the error scaling.	31
313	4.13	Residual means by straw layer in two TRT ϕ -sectors affected by a tilt misalignment. The tilts in each of the three modules are clearly visible in the red points representing the reconstructed data prior to alignment. After four iterations of L2 alignment, the residual means in the gray points are flat.	32
317	4.14	Two dimensional map of residuals in the first layer of the TRT barrel vs z and ϕ . Each bin represents the mean of a Gaussian fit to the TRT residuals in that bin. The map on the left is after the L3 (wire-by-wire) alignment of the TRT performed in 2010, and the map on the right is after the L2 alignment at the end of 2015. The z -axis for both plots use the same scale.	33
322	4.15	Representation of a curl distortion in the detector. The image shows a cutaway in the transverse plane. The deformation is represented by the red arrows, and the impact on the reconstructed positive (blue) and negative (green) tracks are shown. The dashed lines represent the true particle trajectories, and the solid lines represent the reconstructed trajectories.	34
327	4.16	Geometric definition of the sagitta s in relation to the length of the chord l and the radius r of a circular arc.	34
329	4.17	E/p distributions of electrons and positrons in two different $\eta\phi$ bins of the detector. The left hand plot is taken from a region with no momentum bias where $\langle E/p \rangle^+ = \langle E/p \rangle^-$, while the right hand plot shows an 8% disagreement in $\langle E/p \rangle$ between electrons and positrons.	36

333	4.18	Sagitta bias in the $\sqrt{s} = 13\text{TeV}$ data collected by ATLAS in 2016 as a function of η and ϕ for the prompt (left) and reprocessed (right) alignments using the E/p method.	37
334	4.19	Sagitta bias in the $\sqrt{s} = 13\text{TeV}$ data collected by ATLAS in 2016 projected along η for the prompt (gray) and reprocessed (blue) alignments using the E/p method.	38
335	4.20	Sagitta bias in the $\sqrt{s} = 13\text{TeV}$ data collected by ATLAS in 2017 as a function of η and ϕ in reconstructed electrons (left) and after two iterations of momentum corrections (right) from the E/p method.	38
336	4.21	Sagitta bias in the $\sqrt{s} = 13\text{TeV}$ data collected by ATLAS in 2017 projected along η in reconstructed electrons (gray) and after one (red) and two (blue) iterations of momentum corrections from the E/p method.	39
343	5.1	Tree-level Feynman diagrams for VBS EWK $VVjj$ production including triple gauge couplings involving W and/or Z bosons (top left and top middle), quartic gauge coupling (top right), or the exchange of a Higgs boson (s -channel bottom left and t -channel bottom right). The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).	42
344	5.2	Tree-level Feynman diagrams for non-VBS EWK $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).	42
345	5.3	Tree-level Feynman diagrams for QCD $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).	42
346	5.4	Leading order Feynman diagrams for VBS EWK production of $W^\pm W^\pm jj$ events. The leftmost diagram contains a quartic gauge coupling vertex, and the rightmost diagram contains an exchange of a Higgs boson.	44
347	5.5	$W^\pm W^\pm jj$ VBS event topology containing two leptons (1 and 2) with the same electric charge, two neutrinos, and two forward tagging jets (3 and 4) with large rapidity separation Δy	44
348	5.6	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.	44
349	5.7	ATLAS event display of a $pp \rightarrow W^+ W^+ \rightarrow \mu^+ \nu_\mu \mu^+ \nu_\mu jj$ event. The muons are represented by the red lines travelling from the ID through the MS, and the forward jets are represented by the blue cones with yellow energy deposits in the calorimeters. The direction of the E_T^{miss} in the transverse plane is indicated by the gray dashed line in the inset image.	45
350	5.8	Leading lepton p_T (left) and η (right) distributions in the WZ control region before normalization. All lepton channels are combined.	55
351	5.9	Trilepton invariant mass m_{lll} distribution in the WZ control region before normalization. All lepton channels are combined.	55
352	5.10	Charge misidentification rates for electrons as a function of $ \eta $ and p_T . Rates are calculated from $Z \rightarrow e^+ e^-$ MC after applying scale factors to approximate the charge mis-ID rates in data.	58
353	5.11	Dilepton invariant mass distribution m_{ll} for the ee channel in the same-sign inclusive VR.	60
354	5.12	p_T distributions for the leading (left) and subleading (right) electron for the ee channel in the same-sign inclusive VR. In these plots, the cut requiring m_{ee} to fall within the Z mass window has been inverted in order to test the modelling away from the Z peak.	61
355	5.13	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.	63

379	5.14 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).	64
380		
381		
382		
383	5.15 Distributions of p_T^{cone}/p_T for nominal (black) and loose (red) muons in simulated $t\bar{t}$ events.	65
384		
385	5.16 The measured fake factor as a function of muon $p_T + p_T^{\text{cone}}$. The error bars represent the statistical uncertainty only.	66
386		
387	5.17 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.	67
388		
389	5.18 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.	68
390		
391		
392		
393	5.19 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.	69
394		
395		
396	5.20 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.	70
397		
398		
399		
400	5.21 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.	73
401		
402		
403	5.22 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.	74
404		
405		
406		
407	5.23 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.	74
408		
409		
410		
411		
412	5.24 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.	75
413		
414		
415		
416		
417	5.25 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.	75
418		
419		
420		
421		
422	5.26 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.	76
423		
424		
425		

426	5.27 Visual representation of the different kinematic regions relevant to the cross section measurement. The acceptance factor \mathcal{A} converts from the truth level total phase space to the truth level fiducial region, and the efficiency correction \mathcal{C} translates the fiducial region in to the reconstruction level signal region.	80
430	5.28 The dijet invariant mass m_{jj} distributions for data and predicted signal and background in the signal region after the fit. The shaded band represents the statistical and systematic uncertainties added in quadrature. Note that the bins have been scaled such that they represent the number of events per 100 GeV in m_{jj} . The background estimations from the fake factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t}V$ backgrounds are combined in the “Other prompt” category.	87
438	5.29 The event yields for data and predicted signal and background in the WZ and low- m_{jj} control regions after the fit. The shaded band represents the statistical and systematic uncertainties added in quadrature. The background estimations from the fake factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t}V$ backgrounds are combined in the “Other prompt” category.	87
444	5.30 Comparison of the measured $W^\pm W^\pm jj$ EWK fiducial cross section with theoretical calculations from SHERPA v2.2.2 and POWHEG-BOX v2. The light orange band represents the total experimental uncertainty on the measured value, and the dark orange hashed band is the statistical uncertainty. For the simulations, the light blue band represents the total theoretical uncertainty, and the dark blue hashed band are the scale uncertainties. The theory predictions do not include the interference between the EWK and QCD production.	88
451	6.1 Comparison of the leading (left) and subleading (right) lepton p_T distributions for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan) $W^\pm W^\pm jj$ events.	91
453	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.	92
455	6.3 A visual representation of a two-dimensional rectangular grid (left) and a random grid (right) in variables x and y . The signal events are the black circles, and the red squares are the background events. Each intersection of gray dashed lines represents a cut point to be evaluated by the optimization.	97
459	6.4 Leading (top) and subleading (bottom) jet p_T distributions. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).	100
463	6.5 Lepton-jet centrality distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).	101
466	6.6 p_T distributions for the leading jet using the default (left) and optimized (right) event selections for all channels combined.	102
468	6.7 p_T distributions for the subleading jet using the default (left) and optimized (right) event selections for all channels combined.	102
470	6.8 p_T distributions for lepton-jet centrality ζ using the default (left) and optimized (right) event selections for all channels combined.	103

472	6.9	Projections of the statistical (black), theoretical (blue), systematic (yellow), and total (red) uncertainties on the measured cross section as a function of integrated luminosity using the optimized event selection.	105
475	6.10	Dijet azimuthal separation ($ \Delta\phi_{jj} $) for the low m_{jj} region ($520 < m_{jj} < 1100$ GeV, top) and the high m_{jj} region ($m_{jj} > 1100$ GeV, bottom). The purely longitudinal (LL, gray) is plotted separately from the mixed and transverse (LT+TT, cyan) polarizations.	106
478	6.11	Projections of the expected longitudinal scattering significance as a function of integrated luminosity when considering all sources of uncertainties (black) or only statistical uncertainties (red).	107
481	B.1	Number of truth particles within $\Delta R < 0.4$ of a selected muon or electron using the ATLAS standard TRUTH1 (left) and the custom TRUTH1++ (right) derivations in $t\bar{t}$ simulation. The complete truth record is stored in the TRUTH1++ derivation, and this is best seen in the first bin, where the lepton has no nearby truth particles.	113
485	B.2	Leading lepton p_T distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).	117
488	B.3	Dilepton invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).	117
491	B.4	Dijet invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).	118

Preface

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

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

507 My work with the alignment group would continue for the duration of my time here at Penn. In
508 early 2015, at the start of the LHC's second data-taking run (Run 2), I worked assisted in validating
509 the first set of alignment constants using $\sqrt{s} = 8$ TeV proton-proton collision data. At this point
510 I took over the responsibility of alignment of the TRT subdetector. The TRT was aligned to high
511 accuracy in Run 1, and over the course of my time working on alignment, the TRT never required
512 a straw-by-straw alignment; however it did require a module-level alignment at the end of 2015.
513 My final responsibility in the alignment group was monitoring momentum biases using the energy-
514 momentum ratio (E/p) of electrons. For the large data reprocessing, the E/p method served as a
515 cross check to a similar method using Z boson events for monitoring and aligning out momentum
516 biases in the detector. The results from both methods were also used in the uncertainties for the
517 tracking measurements.

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

527 The final two analyses I worked on involve the scattering of same-sign W bosons, and they make
528 up the majority of this thesis. The first analysis is a measurement of the $W^\pm W^\pm jj$ cross section
529 at $\sqrt{s} = 13$ TeV. This measurement along with that of the CMS collaboration represent the first
530 observation of the $W^\pm W^\pm jj$ scattering process. My primary contribution to the analysis is in the
531 estimation of the fake lepton background, where we implemented a brand new version of the fake
532 factor method using particle isolation variables. I also did a preliminary study of the interference
533 between electroweak and strong production of $W^\pm W^\pm jj$ events, assisted in the production of private
534 data samples for use with the analysis framework, and used my familiarity with the WZ process
535 to optimize the rejection of the background. Ultimately the majority of the WZ rejection was not
536 included in the final result; however, it is still covered in the thesis in the hopes that it will be useful
537 for similar analyses in the future. The formal publication for this measurement will likely be coming
538 out within the next few months.

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

Will K. DiClemente
Philadelphia, February 2019

CHAPTER 1

Introduction

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

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

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

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

578 In addition to the SM measurements, a part of this thesis is devoted to the detector components
579 making up ATLAS’s Inner Detector (ID). Precise knowledge of the locations of detector elements is
580 essential for accurate particle track reconstruction, which in turn results in improved resolutions for
581 physics measurements. Special emphasis is given to the monitoring of momentum biases that may
582 exist in the ID even after alignment.

583 This first few chapters of this thesis are intended to provide context for the main topics. Chapter 2
584 gives a brief introduction to the Standard Model with a focus on the mechanism of electroweak
585 symmetry breaking and vector boson scattering. The experimental apparatus—the LHC and the
586 ATLAS detector—are detailed in Chapter 3. The next three chapters present the main body of
587 work. Chapter 4 covers the alignment of the ATLAS Inner Detector. Finally, Chapters 5 and
588 6 detail the ATLAS $\sqrt{s} = 13$ TeV $W^\pm W^\pm jj$ cross section measurement and the $\sqrt{s} = 14$ TeV
589 HL-LHC $W^\pm W^\pm jj$ prospects study, respectively.

CHAPTER 2

Theoretical Framework

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

596 **2.1 Introduction to the Standard Model**

597 The Standard Model of particle physics serves as a mathematical description of the fundamental
 598 particles of the universe and their interactions. It has been developed over the course of the past
 599 century, incorporating both predictions from theory and results from experiments. All in all, the SM
 600 has proven remarkably successful in accurately describing particle interactions seen in experiments.

601 The SM is a quantum field theory (QFT) [2, 3] in which the fundamental particles are represented
 602 as excited states of their corresponding fields. The spin- $\frac{1}{2}$ fermionic fields give rise to the quarks
 603 and leptons comprising ordinary matter, the spin-1 fields correspond to the electroweak bosons and
 604 the gluon which mediate the electroweak and strong forces, respectively, and finally the scalar Higgs
 605 field is responsible for electroweak symmetry breaking. The excitations and interactions of the fields
 606 are governed by the SM Lagrangian, which is invariant under local transformations of the group
 607 $SU(3) \times SU(2) \times U(1)$. **TODO: need more detail/refinement here**

608 The first quantum field theory to be developed is quantum electrodynamics (QED) [4], which
 609 describes the electromagnetic interaction. The theory predicts the existence of a $U(1)$ gauge field
 610 that interacts with the electrically charged fermions. This field corresponds to the photon. A key
 611 aspect of QED is that it is perturbative. The coupling constant $\alpha = e^2/4\pi$ is small, where e is

612 electrical charge of the field, allowing for the use of perturbation theory in calculations. In this case,
 613 calculations can be written as a power series in α , where successive higher order terms contribute
 614 less to the final result. **TODO: renormalizability here?**

615 The strong interaction—the theory of quarks and gluons—has also been described using QFT
 616 as quantum chromodynamics (QCD). The symmetry group for QCD is $SU(3)$, and its eight gen-
 617 erators correspond to the eight differently charged, massless gluons [5]. Unlike in QED, which has
 618 positive and negative charges, the strong force has three “colors”. Color charge combined with the
 619 non-Abelian nature of $SU(3)$, which allows the gluons to interact with each other, result in the
 620 most well-known property of QCD: color confinement. In order to increase the separation between
 621 two color-charged quarks, the amount of energy required increases until it becomes energetically
 622 favorable to pair-produce a new quark-antiquark pair, which then bind to the original quarks. The
 623 end result of this is that only color-neutral objects exist in isolation. What this means for the strong
 624 coupling constant α_s is that its value at the low energies where confinement occurs is large, on
 625 the order of $\alpha_s \sim 1$. The consequence of this is that perturbation theory cannot be used to accu-
 626 rately approximate interactions. While this appears at first to be a critical problem for predictions,
 627 fortunately it turns out that α_s “runs”, or decreases in magnitude at higher energy [6, 7]. This so-
 628 called “asymptotic freedom” allows QCD to be calculated perturbatively [8] at energies accessible
 629 by collider experiments including the LHC.

630 The last gauge field corresponds to the weak interaction. Ultimately, the weak $SU(2)$ and the
 631 electromagnetic $U(1)$ mix to form the $SU(2) \times U(1)$ *electroweak* (EWK) interaction [9, 10]. A
 632 more detailed description of the mixing will be discussed in conjunction with electroweak symmetry
 633 breaking (EWSB) in Section 2.2; however, a summary of the resulting EWK interaction is presented
 634 here, at the risk of some repeated information to follow. There are three weak isospin bosons arising
 635 from the $SU(2)$ group (W_μ^1 , W_μ^2 , and W_μ^3) and one weak hypercharge boson from the $U(1)$ group
 636 (B_μ). The W_3 and B bosons mix according to the weak mixing angle θ_W to form the Z boson and
 637 the photon according to:

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

638 The value of θ_W is not predicted by the SM; it is one example of an experimental input to the
 639 theory, measured to be $\sin^2 \theta_W = 0.23153 \pm 0.00016$ [11]. The charged W^\pm bosons are a mixture of
 640 the remaining W_μ^1 and W_μ^2 bosons:

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

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

645 One final field remains within the SM: the scalar Higgs field. It was originally proposed in the
 646 1960's to explain the masses of the W^\pm and Z bosons [12, 13, 14] and is the mechanism for the
 647 EWSB process. The particle associated with the field is a massive scalar boson, which was at last
 648 discovered by ATLAS and CMS in 2012 [15, 16] with a mass of 125 GeV.

649 2.2 Electroweak symmetry breaking and the Higgs boson

650 The results of electroweak mixing and the implications of the Higgs field have been introduced
 651 in the previous section. If the EWK theory were an unbroken symmetry, the associated W^\pm and
 652 Z bosons would be massless; however, when observed experimentally, they were found to be quite
 653 heavy [17, 18], at around 80 GeV and 91 GeV, respectively [19]. Here, a more detailed explanation
 654 of the Higgs mechanism and how it “spontaneously breaks” the EWK symmetry, resulting in the
 655 three massive bosons (W^\pm and Z) and one massless boson (photon), is presented.

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

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

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

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

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

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

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

663 Isolating the potential term:

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

664 a choice must be made on the sign of μ^2 , and the case of interest is for $\mu^2 < 0$. This results in
 665 the famous “mexican hat potential” shown in Figure 2.1, which is minimized along the collection of
 666 points:

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

667 This means that the minimum of the potential is not at $\phi = 0$ (as it would be in the case where
 668 $\mu^2 > 0$), but rather at a value:

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

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

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

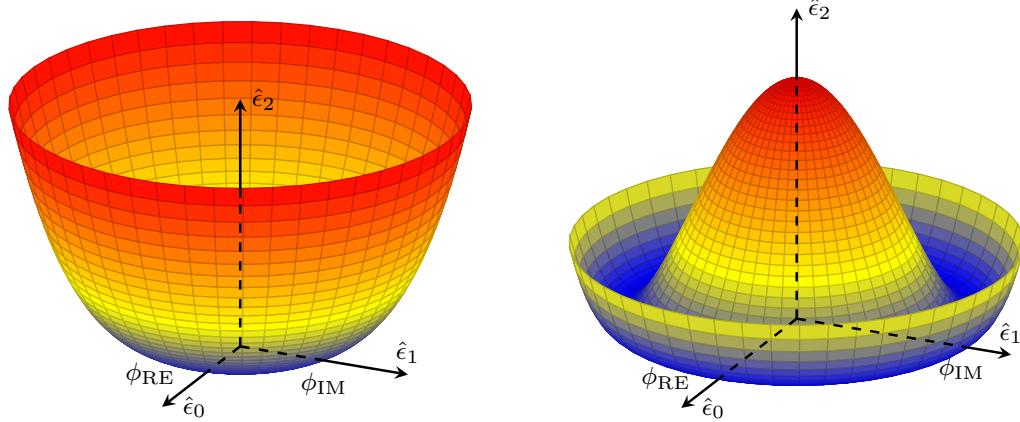


Figure 2.1: An illustration of the potential term $V(\phi)$ in the cases where $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). The right-hand plot shows the Higgs potential, or “Mexican hat potential”, with the minimum at $|\phi| = \sqrt{-\frac{\mu^2}{\lambda}}$ rather than at $|\phi| = 0$ as in the left-hand plot.

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

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

⁶⁷⁴ Focusing on the first term for the moment, substituting in Equation 2.2 for the physical W^\pm bosons,
⁶⁷⁵ the mass term can be seen clearly:

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

⁶⁷⁶

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

⁶⁷⁷ With a bit of clever forward-thinking, the second term of Equation 2.10 can be rewritten as:

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

⁶⁷⁸ where Z_μ^2 and A_μ^2 represent the physical Z boson and photon, respectively, and are defined as:

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

⁶⁷⁹

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

⁶⁸⁰ From this, it can be seen that the photon is massless, and the mass of the Z boson is identified as:

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

⁶⁸¹ Lastly, the Higgs field can couple directly to the fermions. Taking the electron as an example,
⁶⁸² an additonal Lagrangian term can be written:

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

⁶⁸³ where e_L and e_R are the left-handed doublet and right-handed singlet, respectively, and ϕ is as in
⁶⁸⁴ Equation 2.3. The symmetry can be spontaneously broken by a perturbation about the VEV:

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

⁶⁸⁵ which, when substituted into \mathcal{L}_e gives:

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

⁶⁸⁶ for electron mass $m_e = \frac{G_e v}{\sqrt{2}}$. From the second term, it can be seen that the strength of the Higgs
⁶⁸⁷ coupling to the electron is proportional to the mass of the electron. The rest of the fermion couplings
⁶⁸⁸ follow from this example.

689 What is accomplished here is quite remarkable. The weak and electromagnetic interactions have
 690 been unified into a single $SU(2) \times U(1)$ interaction, and the physical bosons observed in nature arise
 691 as mixtures of the four gauge fields. Three of the four degrees of freedom in the scalar field ϕ of
 692 Equation 2.3, are absorbed by the W^\pm and Z bosons, and the fourth generates the Higgs boson.
 693 Additionally, it is shown that the Higgs couples to fermions in proportion to their mass. From
 694 experimental measurements, the value of the VEV has been determined to be $v \approx 246$ GeV [19].
 695 However, it should be noted that the theory does not predict the mass of the Higgs boson or of the
 696 fermions; these must all be determined from experiment.

697 2.3 Electroweak vector boson scattering

698 Due to the non-Abelian nature of the EWK interaction, the associated gauge bosons are allowed
 699 to self-interact. This results in triple and quartic couplings of gauge bosons (TGCs and QGCs,
 700 respectively). The SM allowed TGCs are the $WW\gamma$ and WWZ vertices, which can be measured
 701 experimentally via diboson production or through vector boson fusion (VBF). QGCs predicted by the
 702 model include $WWZ\gamma$, $WW\gamma\gamma$, $WWZZ$, and $WWWW$ vertices accessible in triboson production
 703 or via vector boson scattering (VBS)¹ [20]. VBS processes are defined by a $VV \rightarrow VV$ signature,
 704 where V represents one of the EWK gauge bosons (W^\pm , Z , or γ), as shown in Figure 2.2. The actual
 705 interaction between the incoming and outgoing vector bosons can be mediated by the exchange of
 706 a virtual V or directly via a QGC (as in Figure 2.3), or by the exchange of a Higgs boson (as in
 707 Figure 2.4).

708 As detailed in the previous section, the Higgs mechanism produces three Goldstone bosons and a
 709 Higgs boson. The Goldstone bosons are then “eaten” by the physical gauge bosons, giving them mass
 710 and consequently a longitudinal polarization². In fact, according to the Electroweak Equivalence
 711 Theorem, the high-energy interactions of longitudinal gauge bosons can be accurately described by
 712 the Goldstone bosons of the EWSB mechanism [21]. Thus, the scattering of the massive gauge
 713 bosons are inextricably linked to EWSB.

714 It turns out that without a light SM Higgs boson, the scattering amplitude of longitudinally
 715 polarized vector bosons grows with center-of-mass energy and ultimately violates unitarity above

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

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

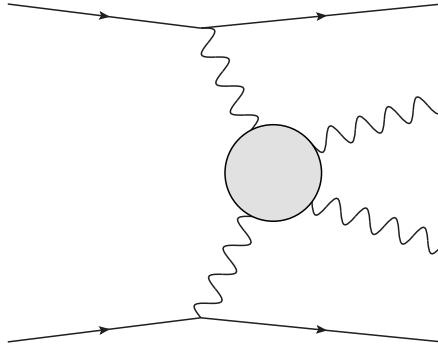


Figure 2.2: Feynman diagram of a generic VBS process. The gray circle represents any interaction with two incoming and two outgoing vector bosons, including any of the diagrams shown in Figures 2.3 and 2.4.

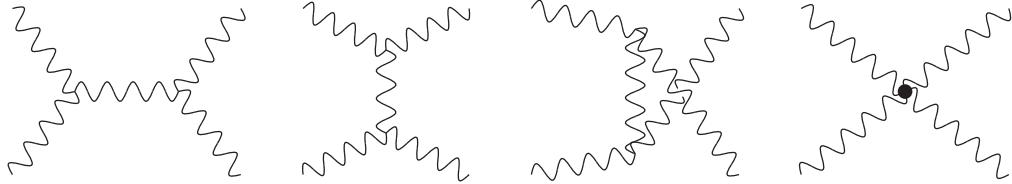


Figure 2.3: Leading order $VV \rightarrow VV$ Feynman diagrams involving EWK bosons. From left to right: s -channel, t -channel, u -channel, and the quartic gauge coupling.

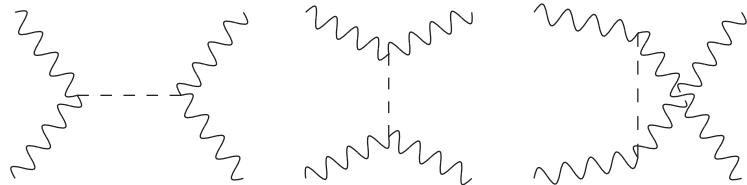


Figure 2.4: Leading order $VV \rightarrow VV$ Feynman diagrams involving the exchange of a Higgs boson. From left to right: s -channel, t -channel, and u -channel.

⁷¹⁶ $\sqrt{s} \approx 1.2$ TeV [22, 23]. Writing down the equations for the transverse and longitudinal polarization

⁷¹⁷ vectors for a gauge boson of mass M_V [24]:

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

⁷¹⁸

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

⁷¹⁹ where v^{μ} is of the order M_V/E and becomes small in the high energy limit, it can be seen that

⁷²⁰ ϵ_L^μ grows with the momentum of the boson p^μ . Therefore, the dominant contribution to the VBS
⁷²¹ process at high energy comes from the longitudinally polarized gauge bosons [25].

⁷²² The high-energy behavior of longitudinally polarized vector boson scattering can be explored in
⁷²³ the case of opposite-sign $W^+W^- \rightarrow W^+W^-$ scattering. In the high-energy limit ($s \gg M_W^2, M_H^2$),
⁷²⁴ the amplitude of W^+W^- scattering without considering the Higgs contributions (the relevant dia-
⁷²⁵ grams in Figure 2.3) can be written as [23]:

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

⁷²⁶ where g is the EWK coupling and u is one of the Mandelstam variables (the others being s and
⁷²⁷ t). The $\mathcal{O}(E^4)$ terms cancel out between the TGC and QGC diagrams [25]. What is left is an
⁷²⁸ amplitude proportional to E^2 that diverges as $E/M_W \rightarrow \infty$. However, the amplitude from the
⁷²⁹ diagrams involving the Higgs boson (the relevant diagrams in Figure 2.4) is:

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

⁷³⁰ which, in the high-energy limit, reduces to:

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

⁷³¹ Adding the two equations together cancels out the E^2 term and leaves only terms constant in
⁷³² energy. Therefore, with a SM Higgs, the scattering amplitude for longitudinally polarized W bosons
⁷³³ no longer diverges. Plots of the cross section of several $VV \rightarrow VV$ scattering processes are shown
⁷³⁴ in Figure 2.5 with and without a SM Higgs boson.

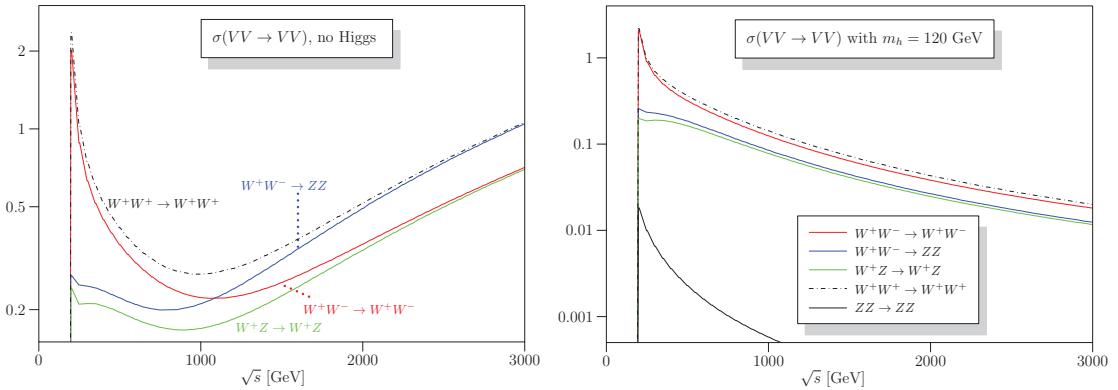


Figure 2.5: Cross sections in nanobarns for five different longitudinally polarized VBS processes as a function of center of mass energy \sqrt{s} . Without a Higgs boson (left), the cross sections grow unbounded with \sqrt{s} . With a 120 GeV Higgs boson (right), the cross sections no longer diverge. Plots taken from [26].

735

CHAPTER 3

736

LHC and the ATLAS Detector

737 **3.1 The Large Hadron Collider**

738 The Large Hadron Collider (LHC) [27] is...

739 **3.2 The ATLAS Detector**

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

741 **3.2.1 The Inner Detector**

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

743 **3.2.1.1 Pixel Detector**

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

745 **3.2.1.2 Semiconductor Tracker**

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

748 **3.2.1.3 Transition Radiation Tracker**

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

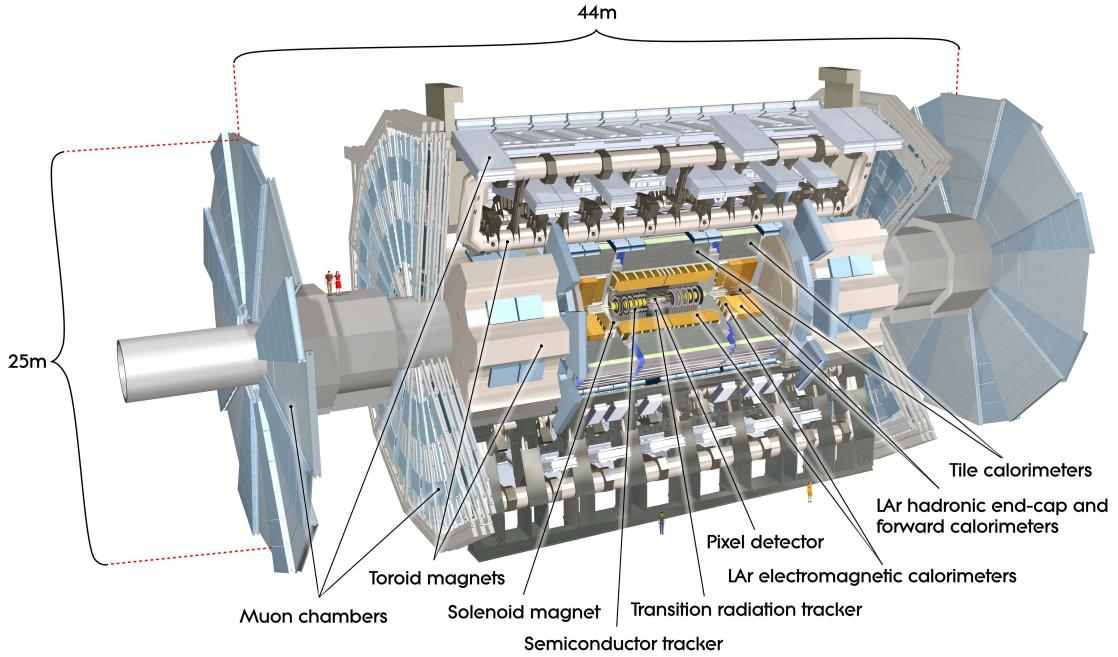


Figure 3.1: General cut-away view of the ATLAS detector [28].

750 3.2.2 The Calorimeters

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

754 3.2.2.1 Liquid Argon Calorimeters

755 The Liquid Argon system consists of...

756 3.2.2.2 Tile Calorimeters

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

758 3.2.3 The Muon Spectrometer

759 Muon spectrometer stuff.

⁷⁶⁰ **3.2.4 Particle reconstruction**

⁷⁶¹ Particle reconstruction algorithms

⁷⁶² **3.2.4.1 Track reconstruction**

⁷⁶³ **3.2.4.2 Muon reconstruction**

⁷⁶⁴ **3.2.4.3 Electron reconstruction**

⁷⁶⁵ **3.2.4.4 Jet reconstruction**

CHAPTER 4

767 Alignment of the ATLAS Inner Detector

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

777 In order to correct the misalignments, the ID alignment procedure is applied to accurately
778 determine the physical position and orientation of each detector element. The baseline accuracy of
779 the alignment is required to be such that the track parameter resolutions are not degraded by more
780 than 20% with respect to those derived from a perfect detector geometry³. This corresponds to a
781 precision of better than $10\mu\text{m}$ in the positioning of the elements of the silicon detectors [29].

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

³The so-called *perfect geometry* refers to the description of the ATLAS detector in which every sensor precisely matches its design specifications. The perfect geometry contains no misalignments, and the position of each sensor is known exactly.

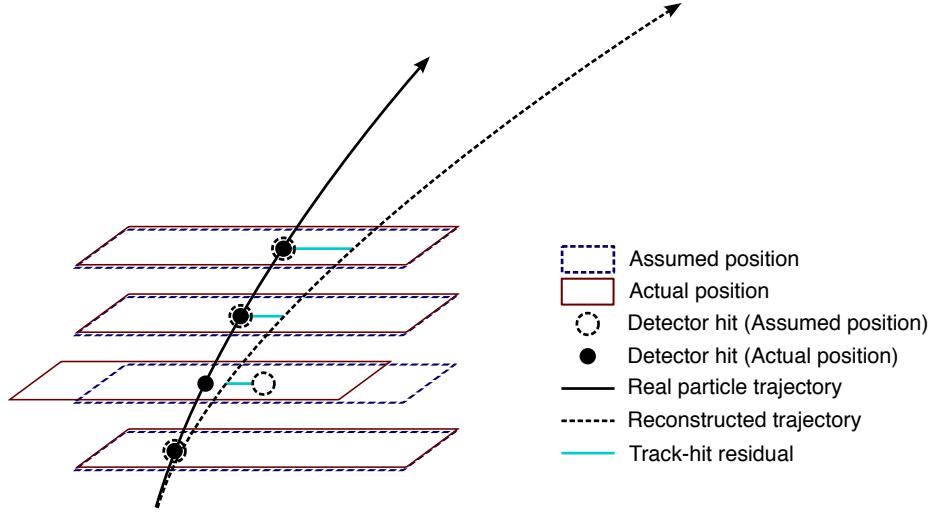


Figure 4.1: Graphical representation of the effect of a misaligned detector element. The reconstructed particle track (dashed arrow) differs from the actual trajectory of the particle (solid arrow) due to the shift in one of the detector elements. The cyan lines represent the track-to-hit residuals.

784 4.1 The alignment method

785 The alignment procedure uses track-based algorithm that updates the locations of detector elements
 786 in order to minimize the set of track-hit *residuals*. These residuals are defined as the distance between
 787 the fitted track position in a given detector element to the position of the hit recorded by the same
 788 element, and are shown by the cyan lines in Figure 4.1. Tracks in ATLAS are parameterized as
 789 five-dimensional vectors [30]:

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

790 where d_0 and z_0 are the transverse and longitudinal impact parameters with respect to the origin,
 791 respectively, ϕ_0 is the azimuthal angle of the track at the point of closest approach to the origin, θ
 792 is the polar angle, and q/p is the charge of the track divided by its momentum. The residual for the
 793 i^{th} hit of a given track can then be written in terms of the track parameters $\vec{\tau}$ and a set of alignment
 794 parameters \vec{a} that describe the hit location [31]:

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

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

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

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

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

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

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

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

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

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

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

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

808

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

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

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

810 which is a linear system of equations with a number of equations equal to the number of alignment
811 degrees of freedom [32].

812 Inverting the matrix and solving this system of equations is referred to as *Global χ^2* align-
813 ment [31]. This can be useful, as \mathcal{M}_a contains all the correlations between the alignable structures.
814 However, inverting the matrix becomes difficult when the number of degrees of freedom becomes
815 large, and as the number of alignable structures increases, so too does the size of the matrix \mathcal{M}_a .
816 Eventually inverting the matrix becomes too computationally intensive to be practical.

817 This problem is solved by the *Local* χ^2 algorithm [33]. In this case, the alignment matrix is
 818 constructed to be block-diagonal, allowing for it to be inverted even for large numbers of degrees of
 819 freedom. This is achieved by replacing the full derivative in Equation 4.6 with the partial derivative
 820 $\frac{\partial \vec{r}}{\partial \vec{a}}$. The new alignment matrix \mathcal{M}'_a and alignment vector $\vec{\nu}'_a$ become:

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

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

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

823 Due to the Taylor expansion used in Equation 4.6, several iterations of the alignment algorithm
 824 may be necessary to converge on a final set of alignment constants. The Local χ^2 alignment typically
 825 requires more iterations due to the loss of the correlation information [34]. In practice, the ATLAS
 826 reconstruction is run over a set of events, and the resulting tracks are fed to the alignment algorithm.
 827 The residuals are calculated, the alignment matrix is built and inverted, and a new set of alignment
 828 constants is obtained. The convergence of the alignment can be checked by:

830 1. Measure the $\Delta\chi^2$ with the previous iteration. If it is near zero, then the χ^2 is approaching its
 831 minimum.

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

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

838 Since a χ^2 minimization is used to align the detector, if there is a systematic misalignments in
 839 the detector that does not adversely affect the χ^2 , the algorithm will be insensitive to it. These
 840 misalignments are referred to as *weak modes*, and special care is taken to remove them [35]. One
 841 potential impact of weak modes is a bias in the track momentum of reconstructed particles. This
 842 particular effect is the subject of Section 4.4.

843 In practice, the detector is aligned both in “real-time” as data is collected, and during dedicated
 844 offline alignment campaigns. The real-time alignment is run in ATLAS’s so-called *calibration loop*,

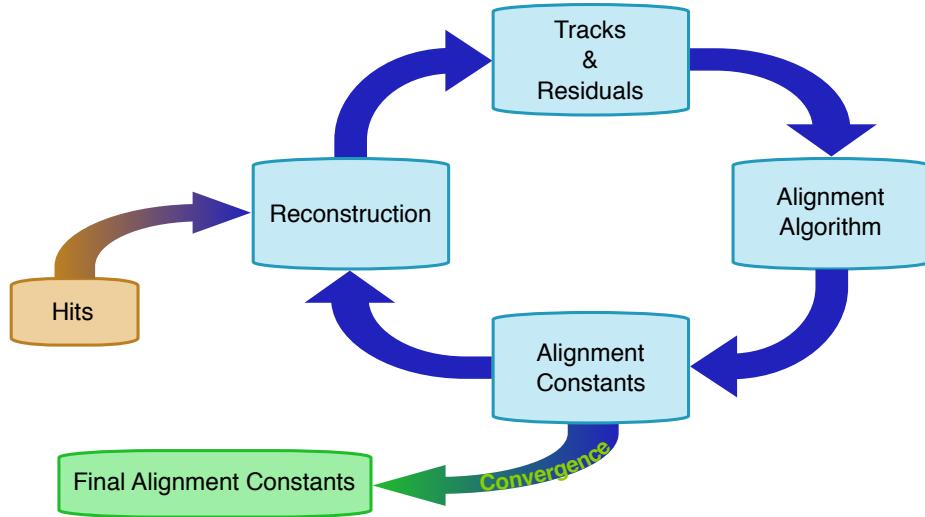


Figure 4.2: Graphical representation of the ID alignment chain.

which comprises the first stage in the preparation of data for physics analysis. The calibration loop requires the alignment as well as various other detector calibrations to be available within 48 hours for initial data processing. A fast, coarse-grained alignment⁴ is run on a subset of the available data containing full tracking information, and the results are propagated to the reconstruction of that particular run [36]. Due to the time constraints of the calibration loop, a full sensor-by-sensor alignment is not possible.

The more thorough and finely tuned alignments are reserved for the dedicated alignment campaigns. These generally occur early in data taking campaigns, typically once a sufficient amount of data is collected after a detector shutdown, in order to obtain a good baseline alignment for use in the remainder of the data collection period. Once data taking is complete, another campaign determines an improved set of alignment constants (divided into several “blocks” to account for time-dependent misalignments), and the full data is reprocessed using the newly derived detector geometry. The initial offline alignment of the ATLAS detector at the beginning of Run 2 in 2015 is the subject of Section 4.2.

4.1.1 Alignment levels

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

⁴The calibration loop runs up to a Level 2 alignment in the silicon detectors, which involves treating each layer of sensors as a single object, defined in greater detail in Table 4.1.

- misalignments to be corrected first before dealing with finer adjustments.
- Level 1 (L1) alignment involves moving entire subdetector components as a single unit, such as the entire Pixel detector, or the SCT barrel. These often have the largest misalignments, but they are easily corrected and do not require large volumes of data to do so.
 - Level 2 (L2) alignment treats individual layers in the silicon detectors (modules in the TRT) and end cap disks as individual alignable objects.
 - Level 2.7 (L27) alignment was introduced with the addition of the IBL to the ID in Run 2. It involves the stave-by-stave alignment of the IBL and Pixel barrel⁵.
 - Level 3 (L3) alignment treats each sensor in the silicon detectors and each straw in the TRT as an individual alignable object. It is the finest grained alignment available but also the most computationally intensive due to the large number of degrees of freedom. The large number of individual detector sensors being aligned also requires the largest amount of statistics.
- The different alignment levels are listed in more detail in Table 4.1, including the number of alignable structures and associated degrees of freedom for each detector component.
- The implementation of the alignment algorithm in the software is flexible enough to allow each subsystem to be aligned individually at a specified level. Each alignable structure has six degrees of freedom: 3 translations (T_x , T_y , T_z) and 3 rotations (R_x , R_y , R_z)⁶; however individual degrees of freedom may be turned on and off as required. In a typical alignment job, L1 and L2 contain few enough degrees of freedom that the Global χ^2 algorithm can be used, but L3 alignments (which can contain over 36,000 degrees of freedom in the silicon detectors alone) require the Local χ^2 algorithm.

4.1.2 Alignment coordinate systems

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

⁵For the purposes of this Chapter, the term “Pixel” will refer to the original three layers of the Pixel detector, and the IBL will be referenced separately.

⁶The TRT is an exception, as the subdetector does not have any resolution along the length of the straw. Therefore, for the barrel, T_z is omitted. Similarly for the straws themselves, only two parameters are defined: translation with respect to the radial direction (T_ϕ) and rotation with respect to the radial axis (R_r for the barrel and R_z for the end-caps) [37].

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

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

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

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

896 4.2 Early 2015 alignment of the ATLAS detector

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

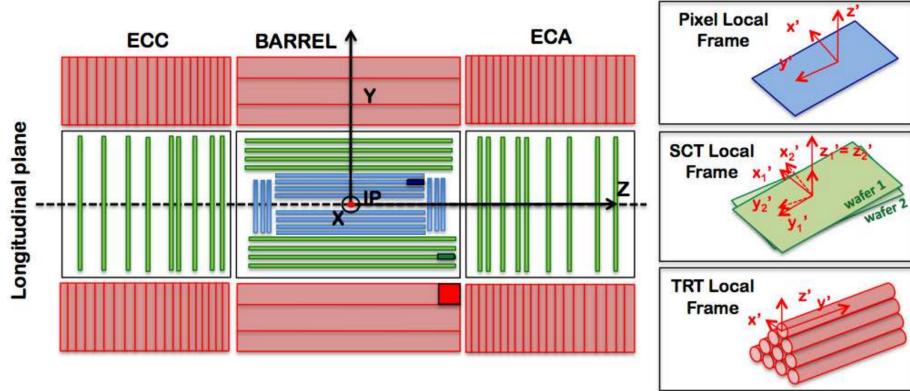


Figure 4.3: A schematic representation of the Inner Detector in the longitudinal plane with the global coordinate system overlaid on top. The Pixel detector and IBL are shown in blue, the SCT in green, and the TRT in red. The local coordinates for each subdetector module are inset on the right. Image taken from [38].

899 innermost layer of the Pixel detector, the Insertable B-Layer (IBL) [39]. TODO: This will certainly
 900 be defined in the detector description, so maybe the citation and abbreviation are not needed These
 901 changes to the ID required some detector components to be removed temporarily, and many elements
 902 shifted relative to each other over the course of the maintenance process. In order to correct for these
 903 large detector movements prior to $\sqrt{s} = 13$ TeV collision data taking, an alignment was performed
 904 using cosmic ray data collected in early 2015 [38]. This alignment was able to correct for the majority
 905 of the large detector-wide misalignments as well as determine the global position of the IBL at the
 906 micron level.

907 In June of 2015, shortly after the data taking period began, the first track-based alignment
 908 of the refurbished ID was performed using $\mathcal{L} = 7.9 \text{ pb}^{-1}$ of $\sqrt{s} = 13 \text{ TeV pp}$ collision data [40].
 909 Starting from the initial geometry determined by the cosmic ray alignment, referred to hereafter
 910 as the *March alignment*, an improved set of alignment constants, called the *June alignment*, was
 911 derived from a data set of approximately 1.4 million selected tracks. For comparison, a MC sample
 912 containing approximately 2.7 million tracks was constructed from dijet events simulated using a
 913 perfect detector geometry; the MC events are reweighted to match the η and p_T distributions found
 914 in the data. Additional validation of the alignment results uses a set of cosmic ray data collected
 915 by the detector during the LHC collisions.

916 4.2.1 June alignment procedure

917 The data set used as the input for the alignment contains a subset of physics events used for prompt
 918 reconstruction recorded at a rate of 10 Hz. To ensure that only high quality tracks are used for the
 919 alignment, each track is required to have transverse momentum $p_T > 3$ GeV, contain at least one
 920 hit in the Pixel detector, at least seven hits in the combined silicon detectors, and at least 25 hits
 921 in the TRT.

922 A full L3 alignment of the IBL was included in the March alignment; however, a realignment
 923 was necessary. Since the cosmic rays pass through the detector top-down, the staves on the sides of
 924 the IBL could not be aligned as precisely as those on the top and bottom due to lower statistics.
 925 Additionally, the IBL was operating at a temperature of -20°C during the cosmic data taking
 926 and at -10°C for collision data taking. This proved to be significant, as it was observed that
 927 the IBL staves experience a temperature-dependent, parabolic bowing in the local x' -direction of
 928 approximately $-10\mu\text{m/K}$ [41]. As a result, a full L3 alignment of the IBL was essential in order to
 929 correct for the bowing. Due to it being a brand new element of the detector as well as its importance
 930 in vertexing and b jet tagging, aligning the IBL sensors with a high degree of precision was of great
 931 importance.

932 The June alignment was performed in two stages, with the first pass focusing on relative move-
 933 ments of the big structures and correcting for the bowing of the IBL. The March alignment corrected
 934 for these larger movements as well; however, it was observed during Run 1 that these sort of mis-
 935 alignments are introduced by changing conditions in the detector [35], such as in the cooling system
 936 or magnet power cycling, which may have occurred between the early cosmic data taking and the
 937 first $\sqrt{s} = 13$ TeV collisions. The silicon detectors were aligned at several different levels and the
 938 IBL was aligned at the module level; the TRT detector was kept fixed to act as a global reference
 939 frame. The full alignment chain for the first pass consisted of the following steps:

- 940 1. The IBL, Pixel, and SCT detectors were aligned at L1. The SCT barrel was not aligned in
 941 T_z in order to constrain global displacements along the z -axis, as the TRT is not sensitive to
 942 that degree of freedom.
- 943 2. The IBL, and Pixel barrel and end-caps, and SCT barrel were aligned at L2. The SCT end-caps
 944 were aligned at L1.
- 945 3. The IBL and pixel barrel were aligned at L27, using all six degrees of freedom. The Pixel
 946 end-cap disks were only aligned in the plane (T_x , T_y , and R_z). The SCT was treated the same

947 as in the previous step.

948 4. The IBL was aligned at L3 using all six degrees of freedom for each module.

949 The primary goal for the second pass was to remove a bias in the transverse impact parameter
 950 d_0 present in the March alignment. The resolution of d_0 was also poorer than expected. In order
 951 to correct for this, an additional constraint was passed to the alignment by adding an impact
 952 parameter with respect to the beam spot as a pseudo-measurement [42]. When the alignment
 953 algorithm minimizes the χ^2 , it will take care of the impact parameter minimization as well. Only
 954 the IBL and Pixel detectors were aligned in this step. The stages of the second pass are listed below,
 955 and the beam spot constraint was used in each:

956 1. The IBL and Pixel detectors were aligned at L2 with the SCT fixed.

957 2. The IBL was aligned at L27

958 3. The IBL and Pixel barrel and end-caps were aligned at L3.

959 The set of alignment constants obtained at the end of the second pass represents the June alignment.

960 The highest level of alignment over the course of the two passes for each subdetector is listed in
 961 Table 4.2.

Detector		Highest level of alignment
IBL		L3
Pixel	Barrel	L3
	End-caps	L3 (T_x , T_y , and R_z only)
SCT	Barrel	L2 (except T_z)
	End-caps	L1
TRT		None

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

962 4.2.2 Alignment results

963 The primary measure of alignment quality is assessed by looking at the track-hit residual distri-
 964 butions. If the detector is well aligned, the residuals will be Gaussian-distributed with a mean
 965 of zero and a width approximating the detector's resolution. The residual distributions are con-
 966 structed from the same selection of tracks that were used to perform the alignment, and are the
 967 focus of Section 4.2.2.1. A second check on the alignment involves observables sensitive to the track

parameter resolution. In this case, cosmic rays are used, making use of a “split track” technique that takes advantage of the top-to-bottom cosmic ray trajectory (compared to the center-out trajectory of collision tracks). This method and the corresponding tests of the alignment are detailed in Section 4.2.2.2

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

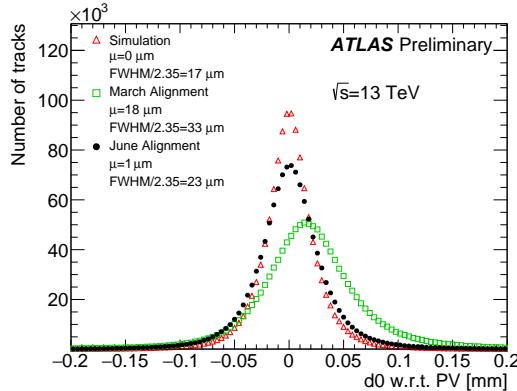


Figure 4.4: The d_0 distributions with respect to the reconstructed primary vertex using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions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

4.2.2.1 Residual distributions from collisions

As mentioned previously, the primary focus of the June alignment campaign was on the IBL and the Pixel detectors. The detectors are the closest to the beam line and have the finest resolutions of the ID subdetectors. The residual distributions in local x and y of the IBL planar sensors⁷ are shown in Figure 4.5. These and subsequent figures in this section compare the June and March alignments to the perfectly-aligned MC simulation. Noticeable improvement in the distribution widths can be

⁷The IBL contains 12 planar sensors in the center of a stave, with four 3D sensors on either end. Only the planar sensors are shown here due to low statistics in the 3D sensors as well as poor MC modeling of these sensors.

985 seen in both the local x - and y -directions, nearly matching the simulation in local x , which is the
 986 most sensitive direction.

987 Due to the temperature-dependent bowing of the IBL, it is also interesting to look at the means of
 988 the residual distributions for each ring of IBL sensors along the beam line, as shown in Figure 4.6. A
 989 deformation is clearly visible in the March alignment in both measurement directions, and the shape
 990 in the local x -direction is consistent with an average stave bowing due to the different operating
 991 temperature of the IBL during the March alignment and the 13 TeV collisions. This feature was
 992 nearly eliminated in both directions through the L3 alignment of the IBL sensors.

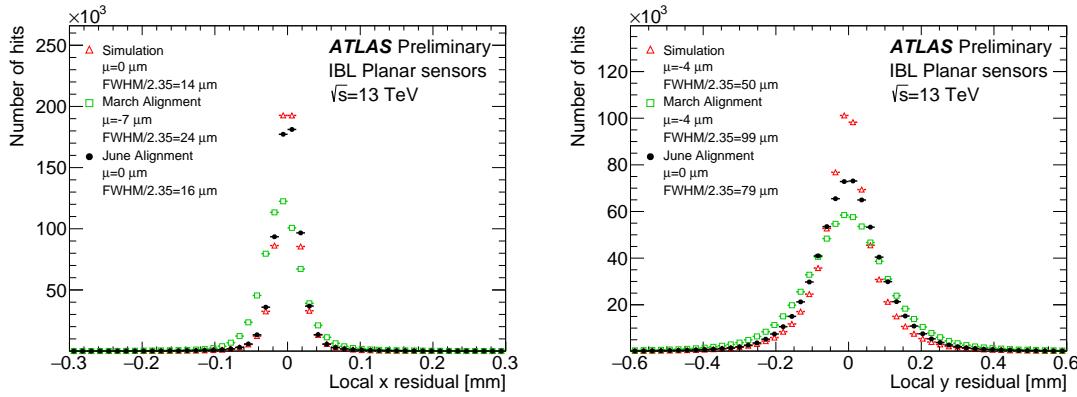


Figure 4.5: Local x (left) and local y (right) residual distributions of the IBL planar sensors using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions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

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

999 Similar distributions for the SCT and TRT barrel and end-caps are shown in Figures 4.8 and
 1000 4.9, respectively. Much like with the Pixel residuals, there is a reduction in the width of the TRT
 1001 residuals between the March and June alignments due to the alignment of the other subdetectors
 1002 improving the quality of the track fit. Even though neither subdetector was aligned at module-
 1003 level, the residuals indicate that the previous L3 alignment performed in Run 1 has not degraded

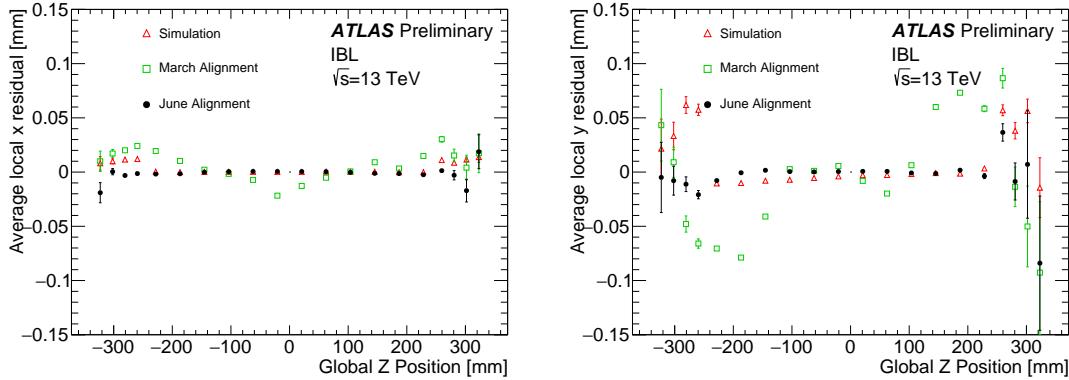


Figure 4.6: The mean of the local x (left) and local y (right) residual distributions as a function of the global z position of each IBL module using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation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

1004 significantly during the upgrade and maintenance period.

1005 4.2.2.2 Track parameter resolution from cosmic rays

1006 Cosmic ray data is very useful as an independent check on the alignment in the barrel of the
 1007 detector. While tracks from pp collisions originate within the detector and travel outwards, a cosmic
 1008 ray that passes through the center of the detector leaves a track in both halves of the detector.
 1009 If the cosmic ray is split in half, as in Figure 4.10, then it can be treated as two separate tracks
 1010 each with nearly identical track parameters (some differences arise due to energy loss as the particle
 1011 passes through the detector). The distribution of the difference in a given track parameter $\Delta\tau$ is
 1012 approximately Gaussian with a variance $\sigma^2(\Delta\tau)$. Since both tracks come from the same particle,
 1013 each track individually has a variance equal to $\sigma^2(\Delta\tau)/2$. The resolution of the track parameter is
 1014 then given by the root mean square of the distribution divided by $\sqrt{2}$.

1015 Cosmic rays whose split tracks each had transverse momentum $p_T > 2$ GeV and at least one,
 1016 eight, and 25 hits in the barrels of the Pixel, SCT, and TRT detectors, respectively, were selected to
 1017 measure a collection of track parameters. Figure 4.11 shows the difference in the impact parameter
 1018 Δd_0 and the charge divided by the transverse momentum $\Delta q/p_T$ of the selected split-track cosmic
 1019 rays for both the March and June alignments. Both distributions show a reduction in width in the
 1020 June alignment, corresponding to an improvement in the resolution of each track parameter. The
 1021 Δd_0 plot shows a significant improvement in the June alignment, further validating the removal of

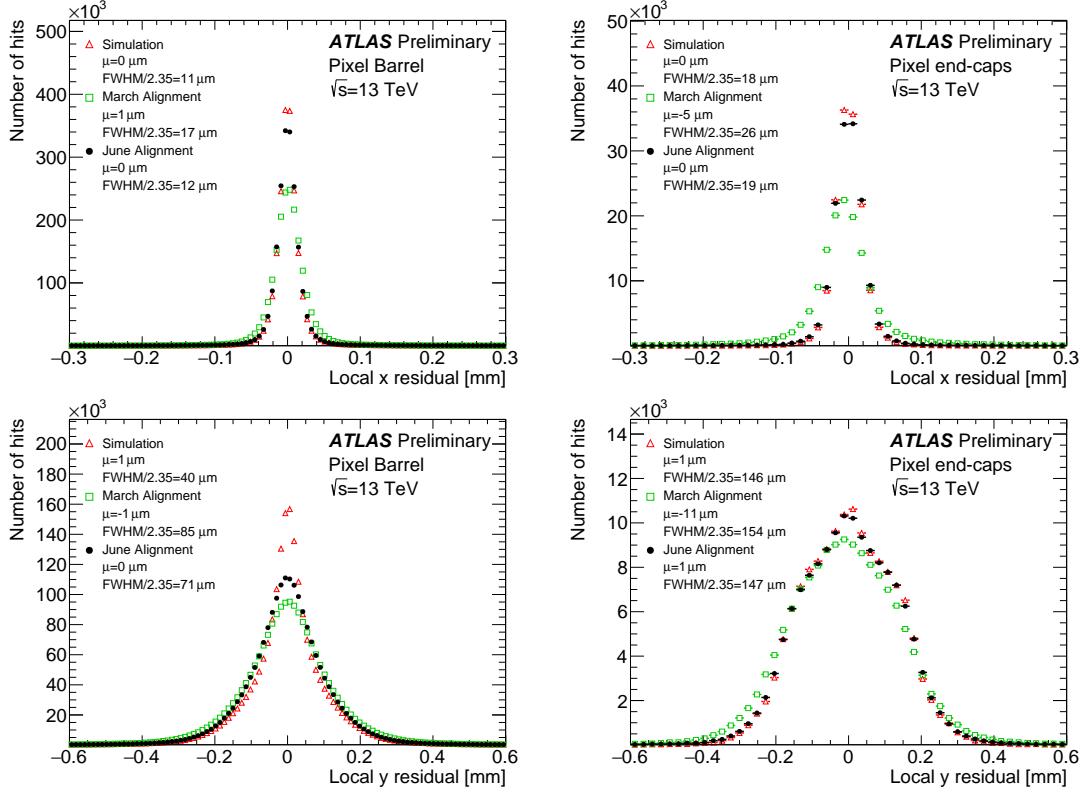


Figure 4.7: Local x (top) and local y (bottom) residual distributions for the Pixel barrel (excluding the IBL, left) and end-caps (right) using the $\sqrt{s} = 13$ TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using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

1022 the bias in the impact parameter.

1023 4.2.3 Error scaling

1024 The final step in preparing the new set of June alignment constants deals with the adjustment of
 1025 the hit errors, or *error scaling*. Knowledge of the exact position of a hit measurement on a track
 1026 is limited by the accuracy with which the sensors' positions are known. Let σ represent the hit
 1027 uncertainty used in track fitting, and σ_0 be the detector's intrinsic uncertainty. If $\sigma = \sigma_0$, the pull
 1028 of the track-hit residual distributions should form a Gaussian distribution centered at zero with a
 1029 standard deviation $\sigma = 1$ [32]. In the case of residual misalignment, the pull distributions' standard
 1030 deviations will stray from unity. The hit uncertainty can be written as:

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

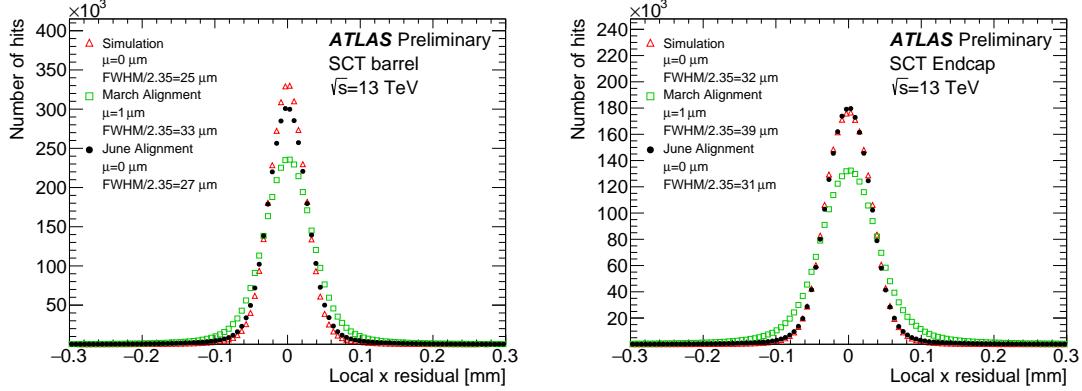


Figure 4.8: Local x residual distributions for the SCT barrel (left) and end-caps (right) using the $\sqrt{s} = 13 \text{ TeV}$ collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The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

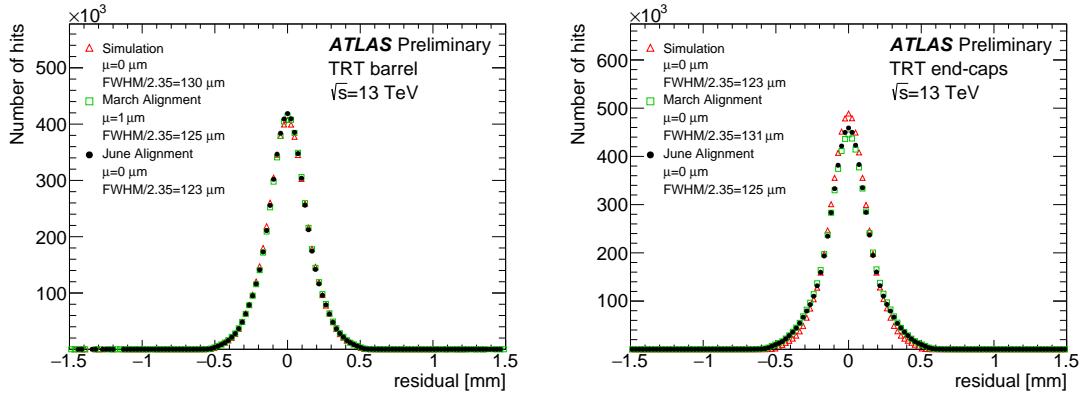


Figure 4.9: Residual distributions for the TRT barrel (left) and end-caps (right) using the $\sqrt{s} = 13 \text{ TeV}$ collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions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

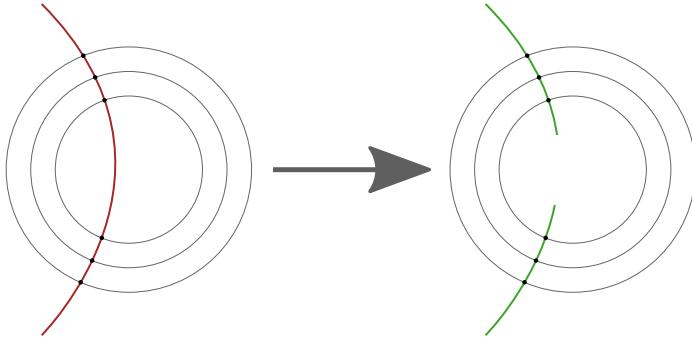


Figure 4.10: Representation of splitting a single cosmic ray track passing through the entire detector (left) into two separate tracks (right).

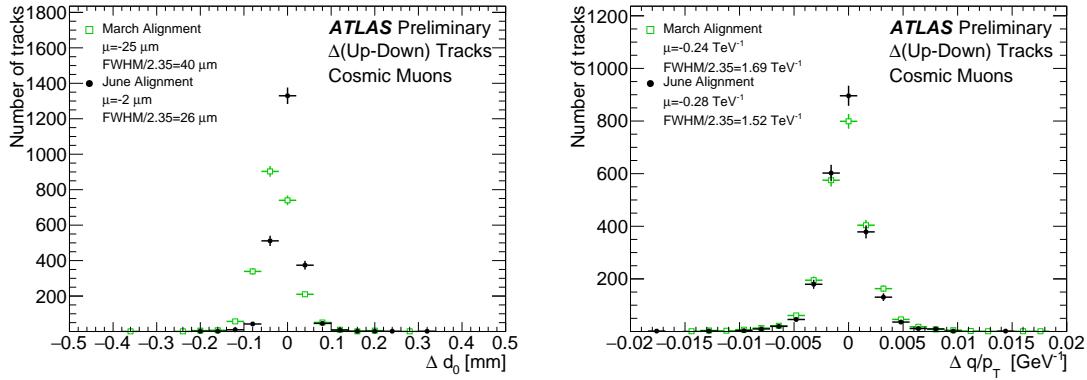


Figure 4.11: Distribution of the difference in the impact parameter Δd_0 (left) and charge over transverse momentum $\Delta q/p_T$ (right) between the two cosmic ray split tracks. The June (black) and March (green) alignments are compared. The distributions are normalized to the same number of entries.

1031 where a is a scaling factor, and b is a constant term which can be interpreted as a measure of any
 1032 remaining misalignment of the detector elements. In this alignment campaign, the value of a is fixed
 1033 at $a = 1$ and b is evaluated from the residual pull distributions for each subdetector in its sensitive
 1034 directions.

1035 Once the value of b is determined, pull distributions derived from the new value of σ should
 1036 have unit width. The error scaling values for each subdetector are listed in Table 4.3, and the pull
 1037 distributions for the IBL after error scaling are shown in Figure 4.12.

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

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

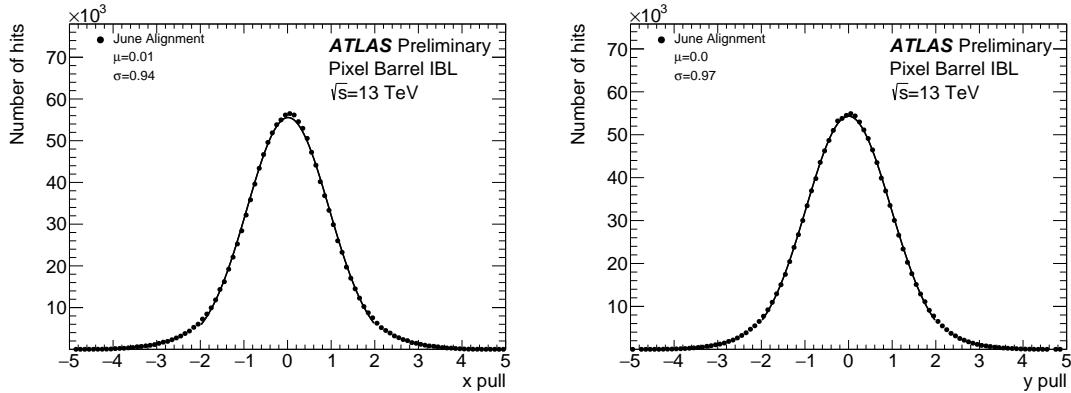


Figure 4.12: Pull distributions in local x (left) and y (right) for the IBL using the $\sqrt{s} = 13$ TeV collision data sample after applying the error scaling.

1038 4.3 Level 2 alignment of the TRT

1039 During validation of the final end-of-year reprocessing of the 2015 data, a misalignment was found in
 1040 the barrel of the TRT detector, as several modules (triangular clusters of straws) showed rotations in
 1041 the local y coordinate. The then-best available constants included a full L3 alignment of the silicon
 1042 detectors and a separate L2 alignment of the TRT. However, not all degrees of freedom were enabled
 1043 when the TRT was aligned. To correct for these tilts, an additional four iterations of L2 alignment
 1044 TRT was performed on the TRT enabling all available degrees of freedom (T_x , T_y , R_x , R_y , and R_z
 1045 in the barrel, and T_x , T_y , and R_z for the endcaps). Plots of the residual means from barrel ϕ sectors
 1046 containing modules affected by the tilt misalignment are shown in Figure 4.13 before and after the
 1047 L2 alignment.

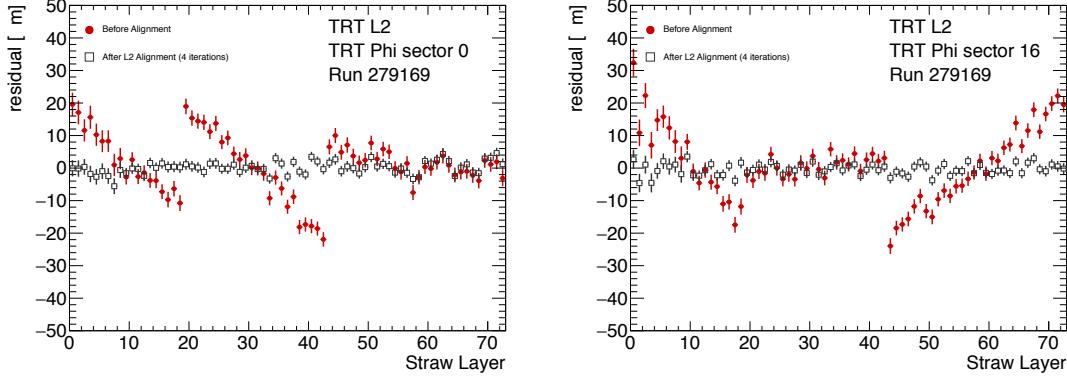


Figure 4.13: Residual means by straw layer in two TRT ϕ -sectors affected by a tilt misalignment. The tilts in each of the three modules are clearly visible in the red points representing the reconstructed data prior to alignment. After four iterations of L2 alignment, the residual means in the gray points are flat.

1048 Following the L2 alignment, some additional time was taken to determine if a full wire-by-wire
 1049 L3 alignment of the TRT was necessary. The TRT was last aligned at L3 during Run 1, but initial
 1050 alignment campaigns in Run 2 did not show signs of misalignment, as can be seen from the residual
 1051 distributions in Figure 4.9. In order to assess the alignment more carefully, two dimensional residual
 1052 maps in ϕ and z were constructed for each layer in the TRT barrel and endcaps using the current
 1053 alignment. These maps were compared to a similar set using the L3 alignment from 2010, from which
 1054 it was determined that the straw-level alignment indeed hadn't degraded and a new L3 alignment
 1055 was not needed. The maps for the first layer of the TRT barrel are shown in Figure 4.14 for both
 1056 sets of alignment constants.

1057 4.4 Momentum bias from sagitta deformations

1058 A variety of weak mode deformations can exist in the detector even after alignment. As mentioned
 1059 previously, these weak modes consist of misalignments which don't affect the χ^2 of the residuals
 1060 and thus are not handled by the basic alignment algorithm. In the presence of a weak mode, the
 1061 description of the detector geometry can still provide efficient and high quality track fits, but there
 1062 may also be systematic biases in one or more track parameters. Several weak modes, their impacts
 1063 on the reconstruction, and the steps taken to eliminate them are detailed in [35, 43]. This section
 1064 focuses specifically on sagitta distortions that result in a bias in the reconstructed track momentum.

1065 These *sagitta* distortions consist of detector movements orthogonal to the trajectory of the outgo-

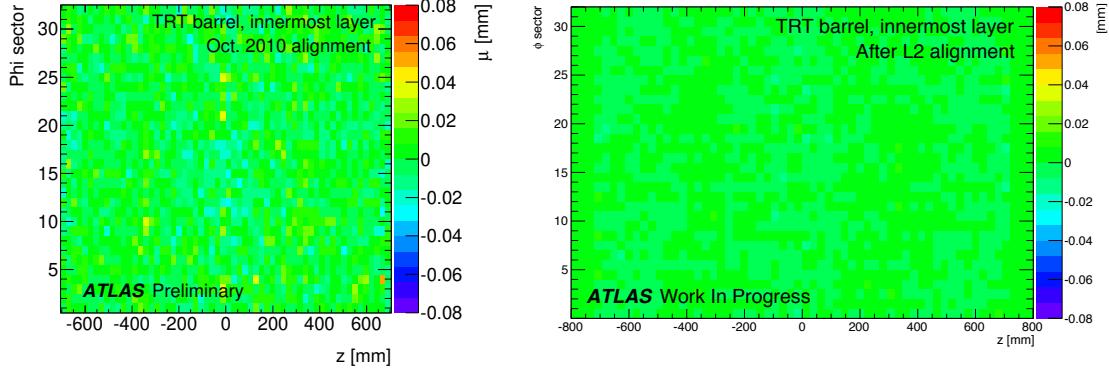


Figure 4.14: Two dimensional map of residuals in the first layer of the TRT barrel vs z and ϕ . Each bin represents the mean of a Gaussian fit to the TRT residuals in that bin. The map on the left is after the L3 (wire-by-wire) alignment of the TRT performed in 2010, and the map on the right is after the L2 alignment at the end of 2015. The z -axis for both plots use the same scale. Left figure taken from [32].

1066 ing particle. The effect on the reconstructed track curvature is different for positively and negatively
 1067 charged particles, resulting in a charge-antisymmetric bias. This effect is illustrated in the curl
 1068 deformation shown in Figure 4.15.

1069 In the plane transverse to ATLAS’s magnetic field, outgoing particle tracks form circular arcs.
 1070 The sagitta is defined as the distance from the center of this arc to the center of its base, as shown in
 1071 Figure 4.16, and it represents the “amount of bending” in the track. In the case where the sagitta s
 1072 is considerably smaller than the detector radius R_0 , which is a valid assumption when working with
 1073 high momentum tracks, the transverse momentum of a particle of charge q can be written as [44]:

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

1074 where B is the strength of the detector’s magnetic field. If a sagitta bias is present, the track’s
 1075 transverse momentum shifts by [43]:

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

1076 where δ_s is a universal bias parameter that uniquely defines the deformation. Finally, since the
 1077 reconstructed polar angle does not change under a sagitta deformation, the longitudinal component
 1078 of the momentum scales along with the transverse component, and an equivalent equation can be
 1079 written for the total momentum:

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

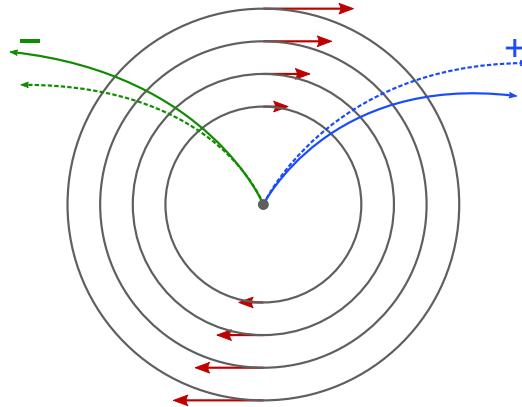


Figure 4.15: Representation of a curl distortion in the detector. The image shows a cutaway in the transverse plane. The deformation is represented by the red arrows, and the impact on the reconstructed positive (blue) and negative (green) tracks are shown. The dashed lines represent the true particle trajectories, and the solid lines represent the reconstructed trajectories.

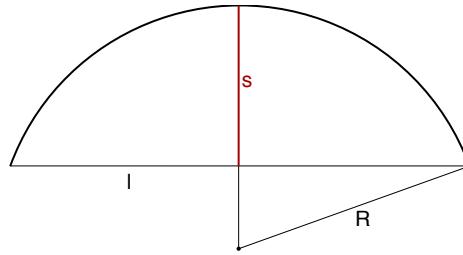


Figure 4.16: Geometric definition of the sagitta s in relation to the length of the chord l and the radius r of a circular arc.

1080 4.4.1 Sagitta bias monitoring with electron E/p

1081 Since a sagitta bias results in changes in the momentum of particles' tracks as measured by the ID,
 1082 they can be identified using independent measurements from other systems in the detector. One
 1083 such method involves using the energy-momentum ratio of electrons (E/p). Since the electron's
 1084 energy is measured in ATLAS's calorimeter systems, it is not sensitive to any sagitta bias that may
 1085 exist in the ID and the corresponding track momentum. Under the assumption that the calorimeter
 1086 response is independent of the charge of incoming particles, a charge-dependent momentum bias in
 1087 the ID will manifest as a difference in the E/p ratio for electrons and positrons.

1088 In the presence of a sagitta bias, the momentum will change according to Equation 4.15 and the
 1089 average measured $\langle E/p \rangle$ can be written as:

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

1090 where the approximation $p_T \approx E_T$ is used. Assuming that $\langle E/p \rangle^+ = \langle E/p \rangle^-$ in the absense of a
 1091 bias, the sagitta bias parameter can be written as:

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

1092 If the kinematic selections for electrons and positrons are identical, the energy scale of the calorimeter
 1093 will not factor into the $\langle E/p \rangle$ difference; however, it will affect $\langle E_T \rangle$ which would scale the measured
 1094 δ_s . This is expected to be a small effect, as the energy scale for electrons has been measured at
 1095 $\sqrt{s} = 13$ TeV with uncertainties on the per-mil level across the entire detector [45].

1096 4.4.1.1 Measuring $\langle E/p \rangle$

1097 The E/p ratio is measured using electrons and positrons from $Z \rightarrow e^\pm e^\mp$ events in order to obtain
 1098 a high purity sample of electron candidates. They are required to pass a basic selection criteria to
 1099 ensure they are well measured by both the ID and the calorimeters:

- 1100 • $E_T > 25$ GeV
- 1101 • $|\eta| < 2.47$, excluding the calorimeter’s barrel-to-endcap transition region in $1.37 < |\eta| < 1.52$
- 1102 • Pass MediumLH identification working point detailed in Section 3.2.4.3
- 1103 • Pass a selection of quality cuts, including a requirement that the electron be identified using
 1104 cluster information in the calorimeter
- 1105 • The associated track must have at least one hit in the IBL, three in the Pixel detector, and
 1106 five in the SCT detector.

1107 Events with exactly two opposite-charge electrons passing this selection with a dielectron invariant
 1108 mass within 30 GeV of the Z boson mass are then used for the E/p calculation.

1109 Since the size of the sagitta bias δ_s is not expected to be constant across the entire detector,
 1110 a two-dimensional rectangular grid binned in detector η and ϕ is constructed. From the selected
 1111 events, separate distributions of E/p are made for electrons and positrons lying in each bin. Each
 1112 distribution is fit with Crystal Ball function⁸, and the peak of the distribution is taken as the value
 1113 of $\langle E/p \rangle$. If there is no bias on the track momentum in the bin, the peaks for electrons and positrons
 1114 should match. Example E/p distributions including the Crystal Ball fits are shown in Figure 4.17.

⁸The Crystal Ball function is a probability density function consisting of a Gaussian core and a power-law tail.

1115 It is important to emphasize that deviations from one in the *ratio* of $\langle E/p \rangle$ for electrons and
 1116 positrons indicates that a momentum bias may be present. The value of $\langle E/p \rangle$ itself is not expected
 1117 to equal one exactly, as the track momentum on average tends to be slightly lower than the energy
 1118 measurement in the calorimeter. This is due to the fact that if the electron were to radiate a photon,
 1119 its momentum would change slightly, while it is likely that both the electron and the emitted photon
 1120 would leave energy deposits near each other in the calorimeter and be reconstructed into the same
 1121 object.

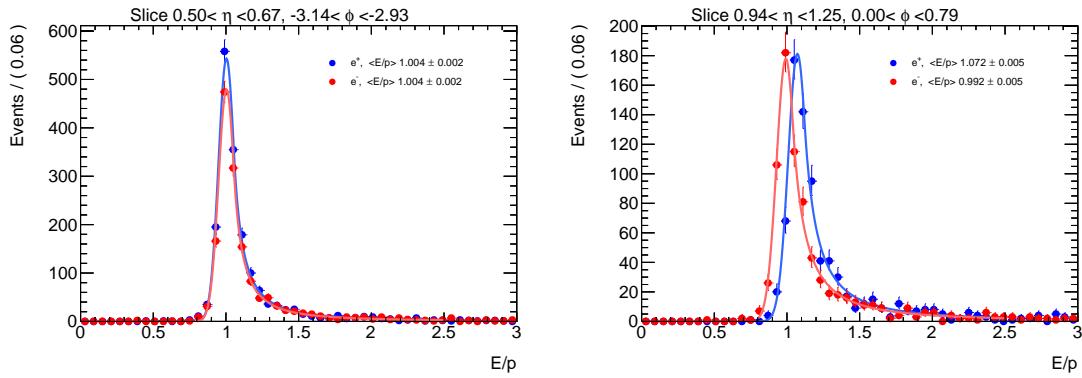


Figure 4.17: E/p distributions of electrons and positrons in two different $\eta\text{-}\phi$ bins of the detector. The left hand plot is taken from a region with no momentum bias where $\langle E/p \rangle^+ = \langle E/p \rangle^-$, while the right hand plot shows an 8% disagreement in $\langle E/p \rangle$ between electrons and positrons.

1122 Once the $\langle E/p \rangle^\pm$ distributions in each $\eta\text{-}\phi$ bin have been extracted from the fits, a two dimensional map of δ_s can be constructed using Equation 4.17. The map gives an overview of sagitta
 1123 biases that may be present in the detector, and can be used by the alignment algorithm to reduce
 1124 the bias in the next iteration. In this case, the tracks fed to the alignment have their momenta
 1125 corrected according to [43]:

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

1127 where p_{reco} is the reconstructed momentum of the track. The corrected momentum is then con-
 1128 strained in the alignment.

1129 4.4.1.2 Results in 13 TeV data

1130 The E/p method has been used to monitor sagitta biases in the detector several times over the
 1131 course of Run 2. During this time, it has primarily served as an independent cross-check to a
 1132 second method using $Z \rightarrow \mu^\pm \mu^\mp$ events [43]. The $Z \rightarrow \mu^\pm \mu^\mp$ method identifies individual track
 1133 momentum biases through shifts in the reconstructed Z mass, which leaves it relatively insensitive

1134 to global sagitta biases. For this reason, the sagitta bias maps produced using this technique are
 1135 normalized to those from the E/p method before being used to constrain the alignment.

1136 The results of two implementations of the E/p method are presented here.

- 1137 1. The first follows the end-of-year reprocessing of the entire ATLAS 2016 data set at $\sqrt{s} =$
 1138 13 TeV. Two sets of alignment constants are compared: the *prompt* alignment, which was
 1139 derived shortly after each run was recorded, and the *reprocessed* alignment. The maps of the
 1140 sagitta bias comparing the two alignments calculated using the E/p method are shown in
 1141 Figure 4.18, and the comparison of the η projection of each map is shown in Figure 4.19.
- 1142 2. The second uses the 2017 data after reprocessing, and compares the effects of multiple it-
 1143 erations of the method. In each iteration, the momenta of the electrons and positrons are
 1144 corrected based on Equation 4.15 using the value of δ_s computed in the previous iteration,
 1145 and a new sagitta bias map is calculated. If the method is indeed characterizing the sagitta
 1146 biases correctly, the corrections should converge quickly. The initial sagitta bias map is com-
 1147 pared to the map after two such iterations in Figure 4.20, and the sagitta bias projected along
 1148 η for each iteration is shown in Figure 4.21. Indeed, after just two iterations, δ_s is consistent
 1149 with zero in nearly all bins.

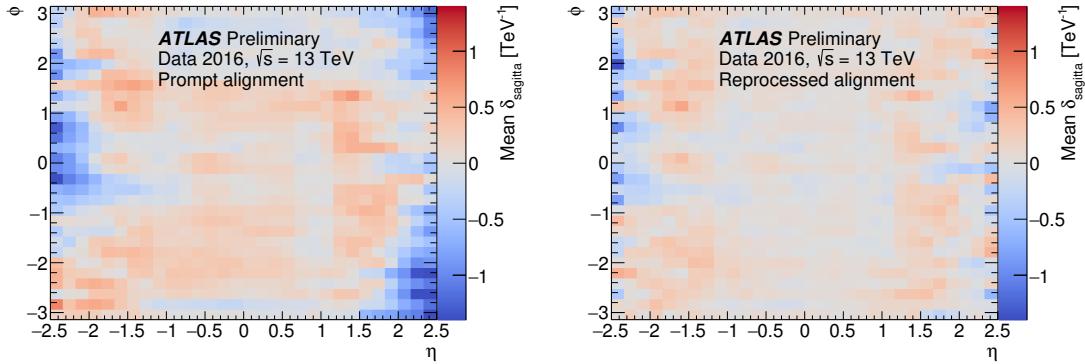


Figure 4.18: Sagitta bias in the $\sqrt{s} = 13$ TeV data collected by ATLAS in 2016 as a function of η and ϕ for the prompt (left) and reprocessed (right) alignments using the E/p method.

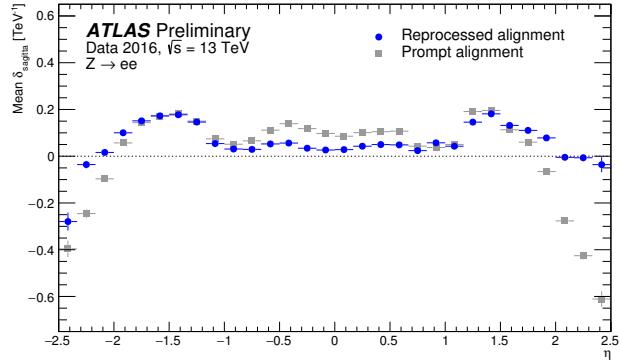


Figure 4.19: Sagitta bias in the $\sqrt{s} = 13 \text{ TeV}$ data collected by ATLAS in 2016 projected along η for the prompt (gray) and reprocessed (blue) alignments using the E/p method.

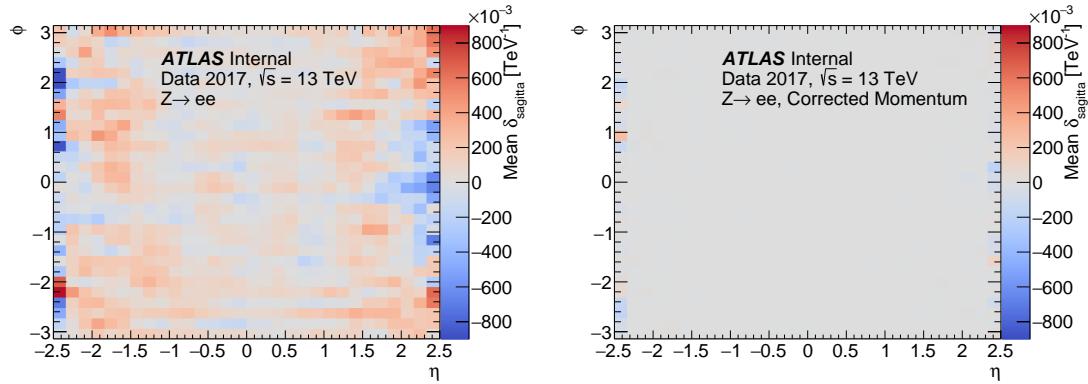


Figure 4.20: Sagitta bias in the $\sqrt{s} = 13 \text{ TeV}$ data collected by ATLAS in 2017 as a function of η and ϕ in reconstructed electrons (left) and after two iterations of momentum corrections (right) from the E/p method.

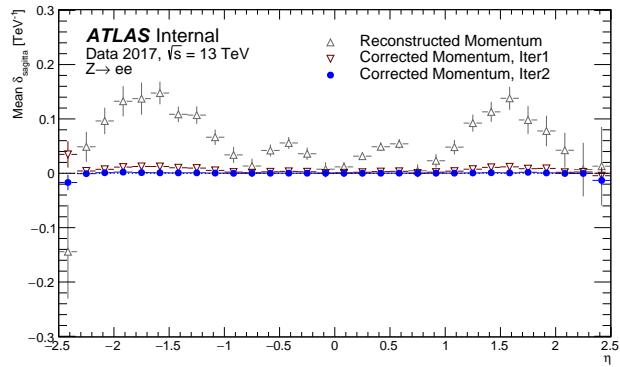


Figure 4.21: Sagitta bias in the $\sqrt{s} = 13$ TeV data collected by ATLAS in 2017 projected along η in reconstructed electrons (gray) and after one (red) and two (blue) iterations of momentum corrections from the E/p method.

1150

CHAPTER 5

1151

1152

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

1153 Production of same-sign W boson pairs is a particularly interesting SM process. When produced
1154 via vector boson scattering (VBS), $W^\pm W^\pm jj$ is particularly sensitive to the electroweak symmetry
1155 breaking (EWSB) mechanism as well as potential “beyond the Standard Model” (BSM) physics.
1156 $W^\pm W^\pm jj$ events can be produced via electroweak-mediated (EWK) diagrams, of which VBS is a
1157 subset, or QCD-mediated diagrams. The biggest advantage of same-sign $W^\pm W^\pm jj$ lies in its ratio
1158 of electroweak (EWK) to QCD production cross sections. Despite the opposite-sign $W^\pm W^\mp$ having
1159 a considerably larger total cross section, its EWK-mediated diagrams are considerably smaller than
1160 its QCD-mediated diagrams, while for same-sign $W^\pm W^\pm$ the ratio is approximately one to one.
1161 This makes $W^\pm W^\pm jj$ one of the best channels for studying VBS at the LHC.

1162 The first evidence of electroweak (EWK) $W^\pm W^\pm jj$ production was seen by the ATLAS and
1163 CMS experiments at $\sqrt{s} = 8$ TeV with excesses of 3.6σ [46] and 2.0σ [47] over backgrounds, respec-
1164 tively. More recently, ATLAS and CMS have both observed the EWK process at $\sqrt{s} = 13$ TeV
1165 with significances of 6.9σ [48] and 5.5σ [49], respectively. The analysis presented in this chap-
1166 ter is based off of the ATLAS $\sqrt{s} = 13$ TeV observation and cross section measurement of EWK
1167 $W^\pm W^\pm jj$ production [48, 50].

1168

5.0.2 Experimental overview of vector boson scattering

1169 VBS processes are very important to understand due to their sensitivity to the EWSB mechanism.
1170 As explained in Section 2.3, in the absence of a light SM Higgs boson, the scattering amplitude of
1171 longitudinally polarized vector bosons grows with center-of-mass energy. However, once the Higgs

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

With the discovery of the Higgs boson in 2012 [15, 16], the EWSB mechanism can now be directly studied. Due to the potential exchange of a Higgs boson in the VBS diagrams ($W^\pm W^\pm jj$ itself does not contain the s -channel diagram), VBS processes are directly sensitive to properties of the Higgs. For example, the high-mass tail in the VV scattering system allows an approximation of the effective coupling strength of the Higgs to vector bosons that is independent of any assumptions on the Higgs width [51]. Additionally, the center of mass energy dependence of the VV scattering can reveal whether the Higgs boson unitarizes the longitudinal scattering amplitude fully or only partially [52].

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

$VVjj$ events can be produced via two different physical processes. The first involves purely electroweak interactions in the tree-level diagrams, with $\mathcal{O}(\alpha_{\text{EWK}}) = 6$ and will be referred to as *EWK production*. This can be further broken down into VBS and non-VBS production. In the VBS EWK production, the scattering occurs via triple or quartic gauge couplings, as well as the 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 [53]; 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 $\mathcal{O}(\alpha_s) = 2 \otimes \mathcal{O}(\alpha_{\text{EWK}}) = 4$ 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 5.1, 5.2, and 5.3, respectively.

5.0.3 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 due to its favorable ratio of EWK to QCD production [51]. Since the VBS diagrams (which are a subset of the total EWK production) are the primary source of interest for an analysis, the QCD production would be considered a background in an analysis. Therefore a higher EWK-to-QCD

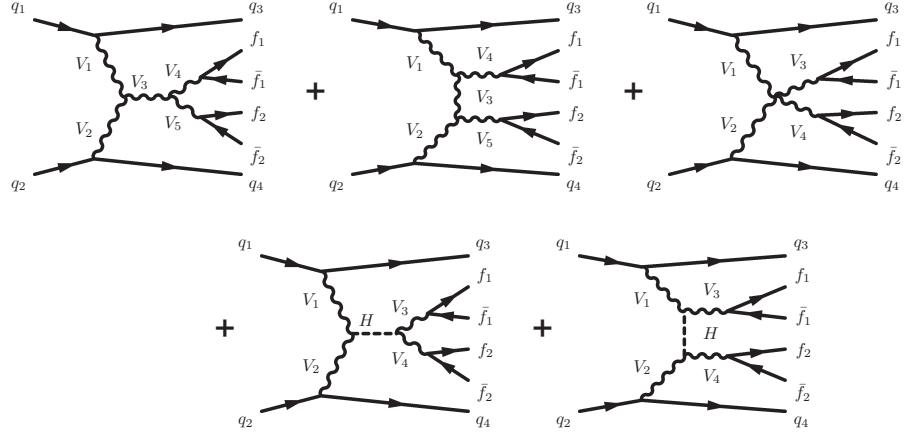


Figure 5.1: Tree-level Feynman diagrams for VBS EWK $VVjj$ production including triple gauge couplings involving W and/or Z bosons (top left and top middle), quartic gauge coupling (top right), or the exchange of a Higgs boson (s -channel bottom left and t -channel bottom right). The labels are quarks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

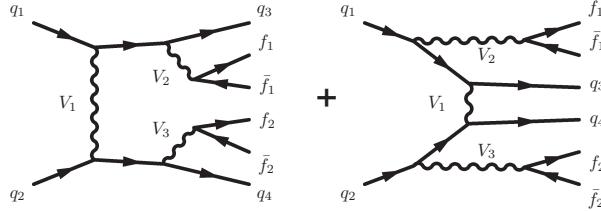


Figure 5.2: Tree-level Feynman diagrams for non-VBS EWK $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).

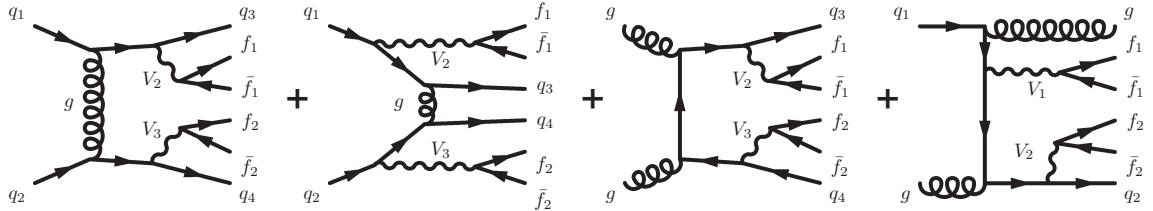


Figure 5.3: Tree-level Feynman diagrams for QCD $VVjj$ production. The labels are quarks (q), fermions (f), and gauge bosons ($V = W, Z$).

ratio results in increased sensitivity to VBS. A study at $\sqrt{s} = 8$ TeV [54] was done using the SHERPA Monte Carlo (MC) generator to calculate EWK and QCD production cross sections at leading order for a variety of $VVjj$ processes decaying to leptons and can be found in Table 5.1. Despite its lower cross section compared to other $VVjj$ processes, the EWK to QCD ratio for $W^\pm W^\pm jj$ is approximately one-to-one, whereas for opposite-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 [54].

This analysis studies $W^\pm W^\pm jj$ scattering where both W bosons decay leptonically to $e\nu$ or $\mu\nu$ ⁹. The $W^\pm W^\pm jj$ VBS final state consists of two leptons with the same electric charge, two neutrinos, and two high energy forward jets with a large invariant mass. Tree-level Feynman diagrams of VBS $W^\pm W^\pm jj$ production can be found in Figure 5.4 and a visual representation of the VBS topology can be found in Figure 5.5. The two forward jets also serve as a powerful tool to suppress the QCD production mode. In EWK events, the two jets tend to have much higher separation and a larger combined invariant mass than the two leading jets in a QCD event. The two plots shown in Figure 5.6 highlight the differences in these dijet quantities between the two production modes. An ATLAS event display of a real $W^\pm W^\pm jj$ candidate event is shown in Figure 5.7.

5.0.4 Overview of backgrounds

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

⁹Throughout the rest of this chapter, unless stated otherwise, l denotes either electrons (e) or muons (μ), and ν denotes a neutrino. Additionally, e , μ , and ν with no charge or anti-particle designation refer interchangeably to either the particle or anti-particle.

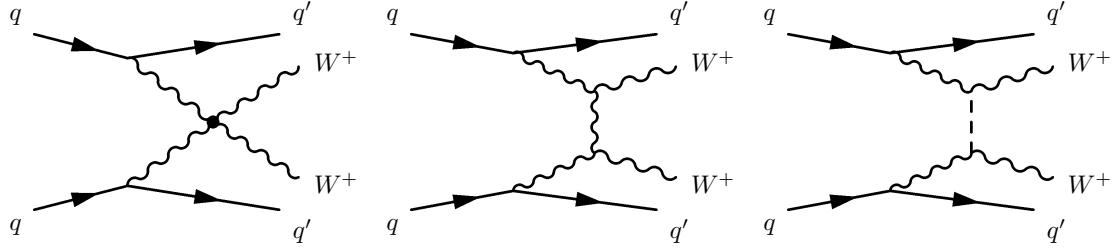


Figure 5.4: Leading order Feynman diagrams for VBS EWK production of $W^\pm W^\pm jj$ events. The leftmost diagram contains a quartic gauge coupling vertex, and the rightmost diagram contains an exchange of a Higgs boson.

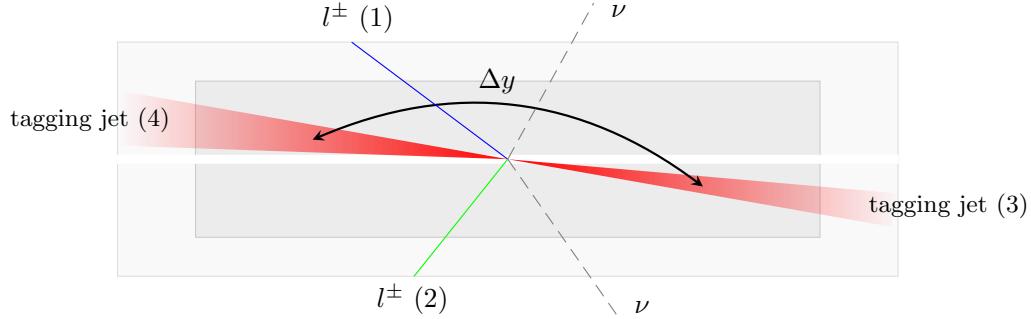


Figure 5.5: $W^\pm W^\pm jj$ VBS event topology containing two leptons (1 and 2) with the same electric charge, two neutrinos, and two forward tagging jets (3 and 4) with large rapidity separation Δy .

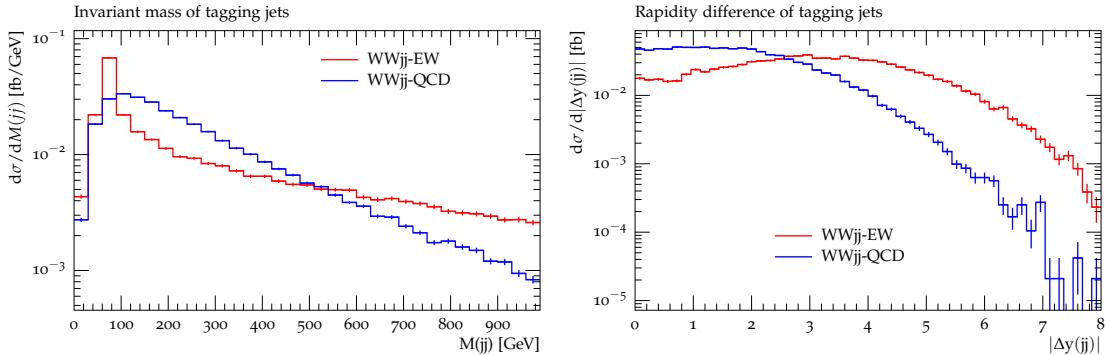


Figure 5.6: Generator level comparisons at $\sqrt{s} = 8$ TeV of dijet invariant mass (m_{jj} , left) and dijet rapidity (Δy_{jj} , right) in EWK (red) and QCD (blue) $W^\pm W^\pm jj$ events. Both data sets have been normalized to the same area. Plots taken from [54].

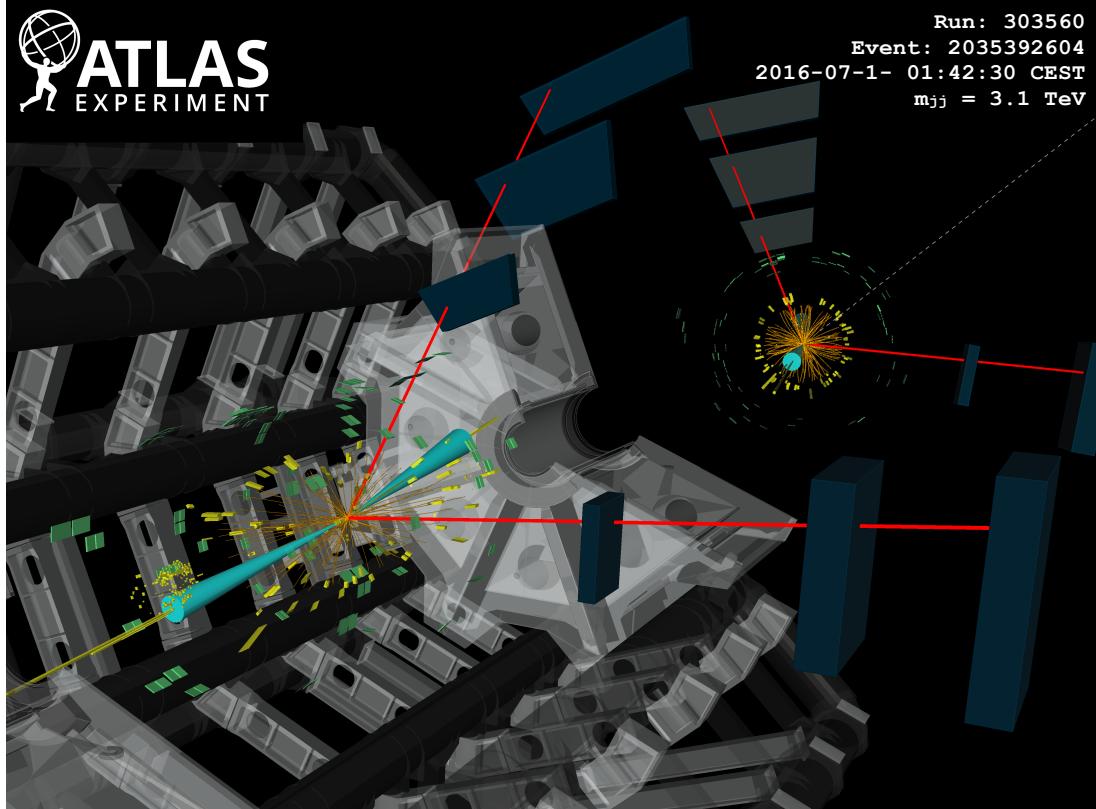


Figure 5.7: ATLAS event display of a $pp \rightarrow W^+W^+ \rightarrow \mu^+\nu_\mu\mu^+\nu_\mu jj$ event. The muons are represented by the red lines travelling from the ID through the MS, and the forward jets are represented by the blue cones with yellow energy deposits in the calorimeters. The direction of the E_T^{miss} in the transverse plane is indicated by the gray dashed line in the inset image. Event display taken from [48].

One of the largest sources of background involves processes with prompt leptons¹⁰. These are events that contain two leptons with the same electric charge and one or more additional leptons that are “lost”, either by failing the selection criteria or falling outside of the detector’s acceptance. The number of processes that can contribute is limited by the requirement of same-sign leptons, and as a result this background is dominated by processes involving two or more vector bosons, with the largest contribution coming from WZ events and smaller contributions from ZZ and $t\bar{t}V$ events. Triboson events where one boson decays hadronically also contribute to this background; however, the jets are generally softer and more central than in a typical VBS event, and the cuts applied on

¹⁰Prompt 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.

1230 the forward jets suppress these contributions.

1231 The other dominant background comes from non-prompt, or “fake”, leptons. Here one or more
 1232 leptons originate from the decay of another particle unrelated to the signal process, such as a heavy-
 1233 flavor decay or photon conversion, or come from a jet that is misidentified as a lepton. This back-
 1234 ground is mostly made up of events from $t\bar{t}$ and $W+jets$ processes, with a much smaller contribution
 1235 from conversions in $V\gamma$ events.

1236 Finally, opposite-sign lepton pairs can enter the signal region if one of the leptons is reconstructed
 1237 with the wrong charge (called *charge misidentification*¹¹). In practice, this only affects events with
 1238 electrons, as the charge misidentification rate for muons is negligible [55]. This is a major background
 1239 in events with two electrons, but is a much smaller contribution for events with one electron and
 1240 one muon.

1241 5.1 Data and Monte Carlo samples

1242 This analysis uses 36.1 fb^{-1} of $\sqrt{s} = 13$ TeV proton-proton collision data recorded by ATLAS
 1243 during 2015 and 2016. The uncertainty in the combined integrated luminosity is 2.1%. It is derived
 1244 following a methodology similar to that detailed in [56] and using the LUCID-2 detector for the
 1245 baseline luminosity measurements [57] from calibration of the luminosity scale using x - y beam-
 1246 separation scans.

1247 5.1.1 Monte Carlo samples

1248 A number of Monte Carlo (MC) simulations are employed to model signal and background pro-
 1249 cesses. In order to model the real collision data as closely as possible, each MC has been run through
 1250 a full simulation of the ATLAS detector [58] in GEANT4 [59], and events have been reconstructed
 1251 using the same algorithms as the data. The simulation reproduces as closely as possible the momen-
 1252 tum resolutions and calorimeter responses of the detector, and also includes the effects of pileup by
 1253 including soft QCD interactions using PYTHIA v8.1 [60]. The MC samples used in this analysis are
 1254 detailed in this section and summarized in Table 5.2.

1255 The $W^\pm W^\pm jj$ samples are modeled using SHERPA v2.2.2 [61, 62, 63] with the NNPDF3.0 PDF
 1256 set [64]. The EWK signal samples are generated by fixing the electroweak coupling constant to
 1257 $\mathcal{O}(\alpha_W) = 6$, and a QCD background sample was also generated with $\mathcal{O}(\alpha_W) = 4$. SHERPA includes
 1258 up to one parton at next-to-leading order (NLO) and up to three at leading order (LO) in the

¹¹Charge misidentification is also referred to interchangeably as *charge mis-ID* and *charge flip*.

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

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

1259 strong coupling constant α_s . A second $W^\pm W^\pm jj$ EWK sample is generated using **POWHEG-BOX**
 1260 v2 [65] with the **NNPDF3.0** PDF set and at NLO accuracy. This sample is only used for systematic
 1261 studies, as **POWHEG-BOX** does not include resonant triboson contributions in its matrix element, which
 1262 are non-negligible at NLO [66].

1263 Diboson processes (VV where $V = W, Z$) are simulated with **SHERPA v2.2.2** for mixed hadronic
 1264 and leptonic decays and **SHERPA v2.2.1** for fully leptonic decays of the bosons. Similarly, triboson
 1265 (VVV) and $V\gamma$ processes are simulated using **SHERPA v2.1.1** with up to one parton at NLO and up
 1266 to three at LO. $W+jets$ processes are simulated with **SHERPA2.2.1** with up to two partons at NLO
 1267 and four at LO. All the above **SHERPA** samples use the **NNPDF3.0** PDF set and **SHERPA**'s own parton
 1268 showering. The $Z+jets$ events are generated with **Madgraph5_aMC@NLO** [67] at LO and interfaced
 1269 with **PYTHIA v8.1** for parton showering.

1270 $t\bar{t}$ events are generated using **POWHEG-BOX v2** with the **CT10** PDF set [68]. $t\bar{t}V$ samples are
 1271 generated at NLO with **Madgraph5_aMC@NLO** and the **NNPDF3.0** PDF set interfaced with **PYTHIA v8**
 1272 for parton showering. Finally, single top events are generated with **POWHEG-BOX v1** and the **CT10f4**
 1273 PDF set interfaced with **PYTHIA v6** [69] for parton showering.

1274 5.2 Object and event selection

1275 This section details the selection criteria for objects used in the analysis as well as the selection for
 1276 signal events.

1277 **5.2.1 Object selection**

1278 Muons, electrons, and jets all must pass strict selection requirements to ensure that only high quality,
 1279 well measured objects are used. For leptons, a baseline selection is defined (called the *preselection*),
 1280 which all leptons must pass in order to be considered for the analysis. This preselection is an
 1281 intentionally loose set of criteria in order to have high acceptance for rejecting backgrounds with
 1282 additional leptons (i.e. $WZ \rightarrow 3l\nu jj$). Signal leptons are then required to satisfy a much tighter
 1283 *signal selection* aimed at suppressing backgrounds from non-prompt or fake leptons. A third set of
 1284 lepton selection criteria, the *loose selection*, defines a sample enriched in non-prompt leptons, and
 1285 it is used in the fake factor method for estimating the non-prompt background, discussed in detail
 1286 in Section 5.3.4. Jets are only required to pass one set of selection criteria. These selections are
 1287 detailed in the following sections and summarized in Table 5.3 for muons, Table 5.4 for electrons,
 1288 and Table 5.5 for jets.

1289 **5.2.1.1 Muon candidate selection**

1290 Cuts on muon p_T serve to reject low momentum leptons from background processes and additional
 1291 collisions from pileup events. Preselected muons must have transverse momentum $p_T > 6$ GeV, and
 1292 the signal muons must pass $p_T > 27$ GeV. The p_T requirement for loose muons is lower than for
 1293 signal muons, $p_T > 15$ GeV, for reasons that are discussed in Section 5.3.4. Muons are required
 1294 to fall within the detector's η acceptance: $|\eta| < 2.7$ for preselected muons, which is tightened to
 1295 $|\eta| < 2.5$ for the signal muons.

1296 Cuts on the transverse and longitudinal impact parameters are applied to ensure that the can-
 1297 didate muon originated from the primary particle interaction and not some other source, such as a
 1298 heavy flavor decay. The preselection and the loose selection both have looser requirements on the
 1299 transverse impact parameter significance (d_0/σ_{d_0}) than the signal selection; all three have the same
 1300 requirement on the transverse impact parameter ($|z_0 \times \sin \theta|$).

1301 Finally, the muon candidates are required to pass a particle identification and an isolation criteria
 1302 as defined in [70]. The methods used in constructing the identification and isolation workingpoints
 1303 are described in more detail in Section 3.2.4.2. The muon identification serves to select prompt muons
 1304 with high efficiency and well measured momenta. This analysis uses two different workingpoints,
 1305 **Loose** for preselected muons and **Medium** for loose and signal muons, where **Medium** muons are a
 1306 tighter subset of those that pass the **Loose** requirement. Muon isolation is a measurement of detector
 1307 activity around the muon candidate, and it is measured with both track-based and calorimeter-

1308 based variables. The isolation workingpoint used for the signal muons, **Gradient**, is defined such
 1309 that there is 90% or better background rejection efficiency for 25 GeV muons, and 99% efficiency at
 1310 60 GeV. There is no minimum isolation requirement for preselected or loose muons. Loose muons
 1311 are additionally required to fail one or both of the signal transverse impact parameter cut and signal
 1312 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.

1313 **5.2.1.2 Electron candidate selection**

1314 The electron candidate selections are very similar to those for muons. The p_T cut starts at $p_T >$
 1315 6 GeV for the preselection, increases to $p_T > 20$ GeV for loose electrons, and finally to $p_T > 27$ GeV
 1316 for signal electrons. The $|\eta|$ cut for electrons requires $|\eta| < 2.47$ for all electrons, with the region
 1317 $1.37 \leq |\eta| \leq 1.52$ removed from loose and signal electrons. This region is where the electromagnetic
 1318 calorimeter transitions from the barrel to the endcaps and is not fully instrumented. Both the
 1319 transverse and longitudinal impact parameter cuts are the same for all electron selections.

1320 The electron particle identification uses a multivariate likelihood technique (LH) [71] detailed
 1321 in Section 3.2.4.3. Preselected electrons must pass the loosest LH workingpoint `LooseLH` with
 1322 an additional requirement that there be a reconstructed track hit in the first layer of the pixel
 1323 detector (a so-called *B*-layer hit). The LH requirement for the loose and signal electrons the tightness
 1324 of the identification using `MediumLH` and `TightLH`, respectively. As for isolation, the `Gradient`
 1325 workingpoint is required for signal electrons only. The loose electrons must fail one or both of the
 1326 signal identification and isolation requirements.

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

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

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

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

1327 **5.2.1.3 Jet candidate selection**

1328 The final objects that need to pass selection are jets. Jets are clustered using the anti- k_t algo-
 1329 rithm [72] within a radius of $\Delta R = 0.4$. The jets are then calibrated using E_T - and η -dependent
 1330 correction factors that are trained using MC simulations [73]. These calibrated jets are then re-
 1331 quired to have $p_T > 30$ GeV if they lie in the forward regions of the detector ($2.4 < |\eta| < 4.5$) and

1332 $p_T > 25$ GeV in the central region ($|\eta| \leq 2.4$). In order to suppress pileup jets, the so-called jet-
1333 vertex-tagger (JVT) discriminant associates a jet with the primary interaction vertex [74]; central
1334 jets with $p_T > 60$ GeV are required to pass the **Medium** JVT workingpoint, which corresponds to
1335 an average efficiency of over 92%. Finally, the jets are required to be separated by selected prompt
1336 leptons by at least $\Delta R(j, l) > 0.3$.

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

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

1337 5.2.1.4 Treatment of overlapping objects

1338 In the event that one or more objects are reconstructed very close to each other, there is the possibility for double-counting if both originated from the same object. The procedure by which 1339 this ambiguity is resolved is called *overlap removal* (OR). The standard ATLAS recommendation 1340 for OR is implemented in this analysis [75, 76] and is summarized in Table 5.6.

1342 Since electrons leave a shower in the EM calorimeter, every electron has a jet associated with it. Therefore, any jets close to an electron (within $\Delta R(e, j) < 0.2$) are rejected due to the high 1343 probability that they are the same object. On the other hand, when jets and electrons overlap 1344 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 1345 a heavy-flavor decay, and the electron is rejected.

1347 High energy muons can produce photons via bremsstrahlung radiation or collinear final state 1348 radiation which results in a nearby energy deposit in the calorimeters. Non-prompt muons from 1349 hadronic decays produce a similar signature; however, in this case the jet has a higher track multiplicity 1350 in the ID. It is possible to address both cases by rejecting the jet when the ID track multiplicity 1351 is less than three and otherwise rejecting the muon for jets and muons within $\Delta R(\mu, j) < 0.4$.

1352 In addition to the case above where muon bremsstrahlung results in a nearby reconstructed jet, 1353 the ID track from the muon and the calorimeter energy deposit can lead to it being reconstructed 1354 as an electron. In this case, if both a muon and an electron share a track in the ID, the muon is 1355 kept and the electron is rejected, unless the muon is calorimeter-tagged¹², in which case the muon

¹²A calorimeter-tagged (CT) muon is a muon that is identified by matching an ID track to a calorimeter energy

1356 is removed in favor of the electron.

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

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

1357 5.2.2 Signal event selection

1358 After the objects have been selected, cuts are applied on a per-event level to select $W^\pm W^\pm jj$ signal
 1359 events. The event selection is summarized in Table 5.8 and is detailed in this section. It includes
 1360 the results of an optimization performed using a multidimensional grid scan.

1361 The initial event selection begins by choosing events that pass one or more of the trigger re-
 1362 quirements listed in Table 5.7. At least one signal lepton is “matched” to a passed trigger in order
 1363 to ensure that it was indeed a signal lepton that fired the trigger. A collection of *event cleaning*
 1364 cuts must also be passed in order to remove events collected during periods in which one or more
 1365 components of the detector was not operating optimally. Finally, the events are required to contain
 1366 at least one interaction vertex. An event can have multiple reconstructed vertices from additional
 1367 proton-proton collisions that occurred in the same bunch crossing. In this case, the *primary vertex*
 1368 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	$p_T > 26$ GeV and Medium isolation
	$p_T > 50$ GeV	$p_T > 50$ 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.

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 [70].

Events are then required to contain exactly two signal leptons with the same electric charge. The dilepton pair must have a combined invariant mass of $m_{ll} \geq 20$ GeV in order to suppress low mass Drell-Yan backgrounds. Two additional selections are applied to events in the ee -channel: both electrons are required to have $|\eta| < 1.37$ with an invariant mass at least 15 GeV away from the Z -boson mass to reduce events where one electron is reconstructed with the wrong charge (this background will be discussed in more detail in Section 5.3.3). To suppress backgrounds from events with more than two leptons, events with more than two leptons passing the preselection are vetoed.

Missing transverse energy (E_T^{miss}) represents any particles that escape the detector without being measured, such as neutrinos, and is defined as the magnitude of the vector sum of transverse momenta of all reconstructed objects. It can be difficult to calculate accurately, as it involves measurements from all subsystems within the detector, and it is sensitive to any corrections that may be applied to the reconstructed physics objects [77]. These corrections, including the momentum smearing for muons, energy scale and smearing for electrons, and jet calibrations, are propagated to the E_T^{miss} calculation. Events are required to contain $E_T^{\text{miss}} > 30$ GeV in order to account for the two neutrinos from the W boson decays.

At least two jets are required. The leading and subleading jets must have $p_T > 65$ GeV and $p_T > 35$ GeV, respectively, and are referred to as the *tagging jets*. Events are vetoed if they contain one or more jets that have been tagged as a b -jet to suppress backgrounds from heavy flavor decays (especially top quark events). The b -tagging algorithm used by ATLAS is a boosted decision tree (BDT) called MV2c10, and this analysis uses a workingpoint with 85% efficiency [78].

Finally, cuts are applied on the VBS signature outlined in Section 5.0.3. The tagging jets are required to have a dijet invariant mass $m_{jj} > 200$ GeV and be separated in rapidity by $|\Delta y_{jj}| > 2.0$. This preferentially selects the VBS EWK events over the QCD-produced $W^\pm W^\pm jj$ events.

5.3 Background estimations

The major sources of background events are summarized in Section 5.0.4, and the methods used to estimate them are detailed in this section. Prompt backgrounds from ZZ and $t\bar{t}V$ are estimated directly from MC simulations. The shape of the WZ and $V\gamma$ backgrounds are taken from MC, and the predicted yeilds are normalized to the data predictions in dedicated control regions, as outlined in Sections 5.3.1 and 5.3.2, respectively. Opposite sign events with a charge misidentified electron are estimated by a data-driven background method which is summarized in Section 5.3.3. Finally, a *fake factor* method is used to estimate the contributions from non-prompt backgrounds and is the

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.

1400 subject of Section 5.3.4.

1401 5.3.1 Estimation of the WZ background

1402 The dominant background involving prompt leptons comes from $WZ + \text{jets}$ events. The contribution
 1403 is estimated from MC simulation and normalized to data in a control region enriched in WZ events
 1404 defined by the same event selection as Table 5.8 for the signal region, with the following changes
 1405 applied to increase the purity of the WZ process:

- 1406 • The third lepton veto is inverted, requiring a third lepton with $p_T > 15$ GeV
- 1407 • Two of the leptons must make a same-flavor opposite-sign pair. If more than one pair exists,
 1408 the one with m_{ll} closest to the Z boson mass is chosen.
- 1409 • The trilepton invariant mass is required to be $m_{lll} > 106$ GeV to reduce contributions from
 1410 $Z\gamma$ and $Z + \text{jets}$

1411 Once the event yields in the control region are calculated, they are propagated to the final signal
 1412 region fit, detailed in Section 5.4.1, in a single bin combining all the lepton channels. The systematic
 1413 uncertainties of the WZ background are also calculated at this time. The event yields for the WZ
 1414 control region are listed in Table 5.9, and distributions of the leading lepton p_T and η as well as
 1415 trilepton invariant mass m_{lll} are found in Figures 5.9 and 5.8, respectively.

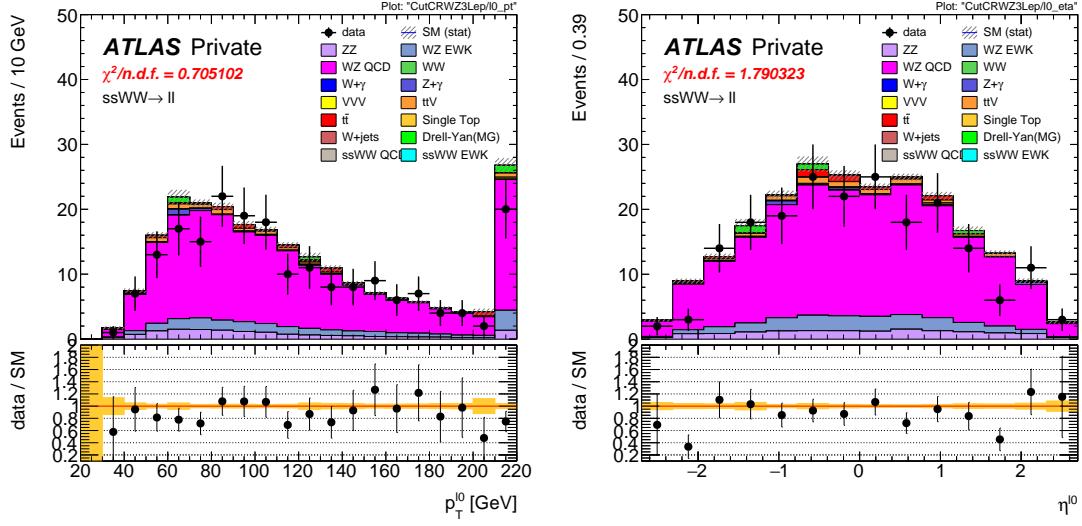


Figure 5.8: Leading lepton p_T (left) and η (right) distributions in the WZ control region before normalization. All lepton channels are combined.

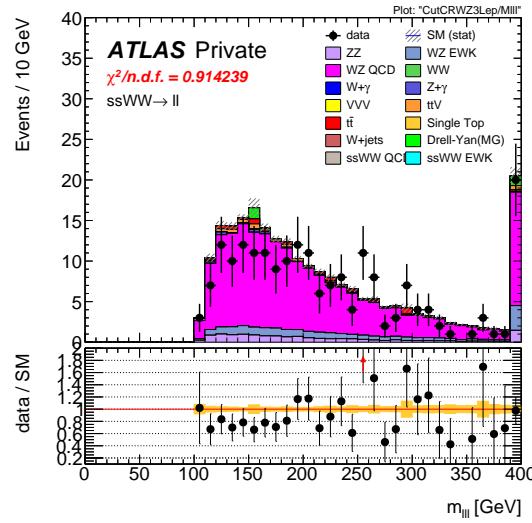


Figure 5.9: Trilepton invariant mass m_{lll} distribution in the WZ control region before normalization. All lepton channels are combined.

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.

¹⁴¹⁶ **5.3.2 Estimation of the $V\gamma$ background**

¹⁴¹⁷ Events from $V\gamma$ processes can pass selection if the photon converts into an e^+e^- pair and one of the
¹⁴¹⁸ electrons passes the selection criteria. The background is estimated from MC simulations which are
¹⁴¹⁹ then scaled by a normalization factor calculated from a control region enriched in $Z(\mu^+\mu^-)\gamma$ events.
¹⁴²⁰ This control region selects two opposite-sign muons and an additional electron that is assumed to
¹⁴²¹ come from the photon conversion. The full event selection is detailed in Table 5.10.

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

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

¹⁴²² The $Z\gamma$ MC samples available do not cover the full range of p_T^γ and $\Delta R(\gamma, l)$; thus, additional
¹⁴²³ Drell-Yan samples ($Z+jets$) are used to fill out the phase space. Overlap between the two samples
¹⁴²⁴ are removed based to avoid double counting. Events with final state photons at truth level are
¹⁴²⁵ checked to ensure that the photon did not originate from a hadronic decay. Cuts on $p_T^\gamma > 10$ GeV
¹⁴²⁶ and $\Delta R(\gamma, l) > 0.1$ are then applied at generator level, and $Z\gamma$ events that fail and $Z+jets$ events
¹⁴²⁷ that pass this additional selection are removed.

¹⁴²⁸ The normalization factor is calculated directly from the event yields in the $V\gamma$ control region
¹⁴²⁹ rather than in the signal fit, as is done for the WZ background. The event yields are listed in
¹⁴³⁰ Table 5.11, and the normalization factor is determined to be 1.77. No MC events from $Z\gamma$ processes
¹⁴³¹ survive the full event selection; thus, the scaling is only applied to the $W\gamma$ background in the signal

1432 region. A systematic uncertainty of 44% is assigned to the background based off of the uncertainties
1433 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.

1434 **5.3.3 Estimation of backgrounds from charge misidentification**

1435 If an electron's charge is mis-reconstructed, it can lead to a real, opposite-sign lepton pair passing
1436 the same-sign requirement in the event selection. There are two primary reasons this can occur:

- 1437 1. An electron emits a photon via bremsstrahlung which then converts into an electron-positron
1438 pair, and the conversion track with the wrong electric charge is matched to the original electron.
1439 This is the dominant process leading to charge flip, and it is highly dependent on the electron
1440 η due to the different amount of detector material the electron passes through.
- 1441 2. The curvature of the electron's track is mismeasured, resulting in the wrong charge being
1442 assigned. This process is dependent on the momentum of the electron, as its track becomes
1443 more straight as the momentum of the electron increases.

1444 In order to estimate this background, the rate at which an electron's charge is misidentified is
1445 calculated from $Z \rightarrow e^+e^-$ MC simulation. It is known that the MC does not perfectly model
1446 the material effects leading to charge flip; as a result, scale factors are applied to the MC in order
1447 for it to better reflect the real performance. These scale factors are obtained from the ratio of
1448 charge mis-ID rates in data and uncorrected MC in [50] following the method outlined in [79]. Once
1449 the scale factors are applied, the charge misidentification rate ε can be extracted by comparing the
1450 electron's reconstructed charge with the charge of its truth particle:

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

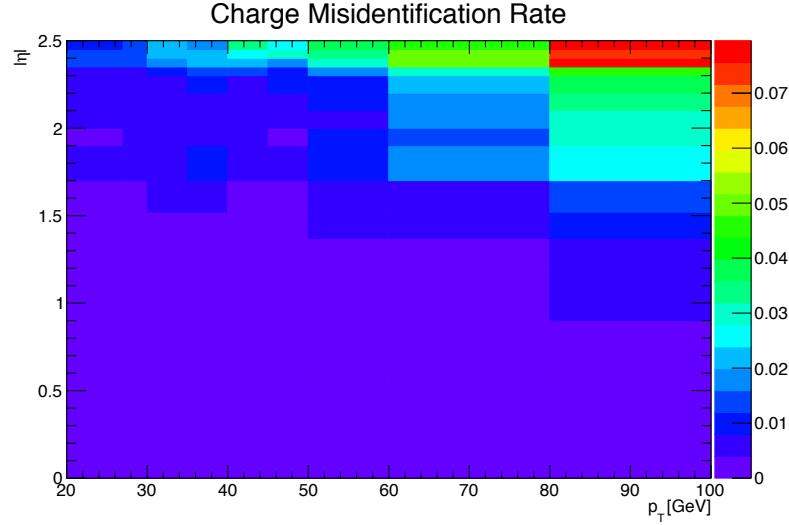


Figure 5.10: Charge misidentification rates for electrons as a function of $|\eta|$ and p_T . Rates are calculated from $Z \rightarrow e^+e^-$ MC after applying scale factors to approximate the charge mis-ID rates in data.

1451 The charge mis-ID rate is calculated in bins of electron $|\eta|$ and p_T and varies from below 0.1% in the
 1452 central region of the detector up to 8% in the forward regions for high p_T (above 90 GeV) electrons.
 1453 A two-dimensional plot of ε can be found in Figure 5.10.

1454 Given the charge flip rate $\varepsilon(\eta, p_T)$, the rate at which an electron has its charge correctly recon-
 1455 structed is $(1 - \varepsilon)$. Thus there are three possible combinations of charge identification, assuming a
 1456 two-electron event:

- 1457 1. Both electrons are reconstructed correctly: $(1 - \varepsilon)^2$
- 1458 2. Both electrons are mis-reconstructed: ε^2
- 1459 3. Only one electron is mis-reconstructed: $2\varepsilon(1 - \varepsilon)$

1460 In order to estimate the size of the background from charge misidentification, opposite-sign events
 1461 are selected using the default event selection for a given signal or control region with the same-sign
 1462 requirement inverted. These events are then weighted by the probability for one of the electrons to
 1463 be reconstructed with the wrong charge:

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

1464 where the subscripts 1 and 2 refer to the leading and subleading electrons, respectively, and ε_i is a
 1465 function of the η and p_T of the i^{th} electron. In the case of an event with only one electron and one

¹⁴⁶⁶ muon, Equation 5.2 simplifies:

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

¹⁴⁶⁷ This method assumes that there is little contamination from fake electrons in the opposite-sign
¹⁴⁶⁸ sample, and this has been verified with MC simulation.

¹⁴⁶⁹ Additionally, charge-flipped electrons tend to be reconstructed with lower energy when compared
¹⁴⁷⁰ to electrons with the correct charge. This is due to energy loss from the material interactions that
¹⁴⁷¹ can cause the charge to be misidentified. A correction factor is calculated from MC simulations,
¹⁴⁷² comparing the p_T of the truth electron to its reconstructed counterpart:

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

¹⁴⁷³ The correction is then applied to the p_T of the charge-flipped electron via

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

¹⁴⁷⁴ where p_T^0 is the uncorrected p_T of the electron and dE is a gaussian smearing factor centered at
¹⁴⁷⁵ zero with a width related to the energy resolution. Since which electron is misreconstructed is never
¹⁴⁷⁶ determined in this method, in the case of a two-electron event, the energy correction is applied
¹⁴⁷⁷ randomly to one of the two electrons based on the probabilities for them to be charge-flipped. This
¹⁴⁷⁸ also determines the overall sign of the event; the charge of the electron that does not receive the
¹⁴⁷⁹ correction is taken to be the charge for both.

¹⁴⁸⁰ Systematic uncertainties on the charge mis-ID rates are calculated by generating two additional
¹⁴⁸¹ sets of rates with the uncertainties on the scale factors varied up and down. The size of the esti-
¹⁴⁸² mated charge flip background without the energy correction applied is also taken as a systematic
¹⁴⁸³ uncertainty. These systematic uncertainties are estimated to be approximately $\pm 15\%$.

¹⁴⁸⁴ 5.3.3.1 Validation of the charge misidentification estimate

¹⁴⁸⁵ The performance of the charge misidentification estimation is tested in the same-sign inclusive
¹⁴⁸⁶ validation region (VR), defined in Table 5.12. For ee events, the mass of the dilepton pair is required
¹⁴⁸⁷ to lie within 15 GeV of the Z boson mass to increase the purity of the charge flip background.
¹⁴⁸⁸ $t\bar{t}$ production, which can contribute to both the charge mis-ID and fake lepton backgrounds, is
¹⁴⁸⁹ suppressed by the b -jet veto. The di-electron invariant mass is shown in Figure 5.11, and distributions
¹⁴⁹⁰ of the leading and subleading electron p_T in the ee -channel are shown in Figure 5.12 with the Z

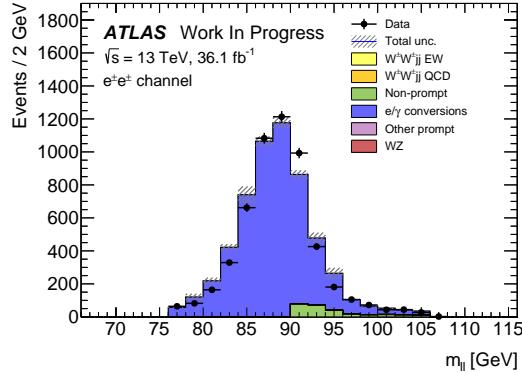


Figure 5.11: Dilepton invariant mass distribution m_{ll} for the ee channel in the same-sign inclusive VR.

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.

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

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

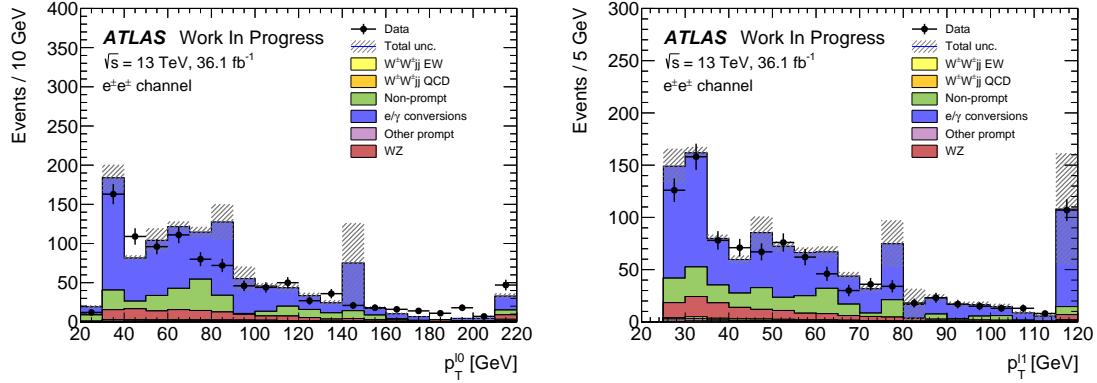


Figure 5.12: p_T distributions for the leading (left) and subleading (right) electron for the ee channel in the same-sign inclusive VR. In these plots, the cut requiring m_{ee} to fall within the Z mass window has been inverted in order to test the modelling away from the Z peak.

1504 5.3.4.1 Overview of the default fake factor method

1505 The goal of the fake factor method is to measure the fake rate from real collision events in a region
 1506 enriched in fake leptons and use it to estimate the size of the fake lepton background in a chosen
 1507 signal or control region. This is done by creating two samples using different lepton definitions:

- 1508 1. The *nominal* sample is made up of leptons passing the signal selection.
 1509 2. The *loose* sample is made up of leptons that fail the signal selection while still passing a
 1510 loosened set of criteria. This sample is enriched in fake leptons and is orthogonal to the set of
 1511 signal leptons.

1512 Using the sets of nominal and loose leptons, a fake factor f can be calculated in a region enriched
 1513 in processes that are prone to producing fake leptons:

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

1514 Since the fake rate is not expected to be constant over the entire phase space, the fake factor can
 1515 be divided into bins:

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

1516 where b represents the bin number. In this analysis, the fake factor is binned in lepton p_T .

1517 In order to estimate the fake background contribution in a given signal or control region, the
 1518 fake factor is applied to a second control region with a selection identical to the region of interest
 1519 with one of the leptons required to satisfy the loose criteria. The region for which the background

1520 is estimated contains two nominal leptons and is referred to as *nominal+nominal* (NN), and the
 1521 associated control region where the fake factor is applied contains one nominal and one loose lepton
 1522 and is referred to as *nominal+loose* (NL). The fake background in a NN region can then be
 1523 calculated as:

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

1524 Backgrounds containing two prompt leptons can also enter the NL region if one of the leptons
 1525 passes the nominal selection and the other passes the loose selection. Since the fake factor method
 1526 estimates the fake background by scaling the amount of non-prompt events in the NL region, if these
 1527 prompt contributions are not be removed, they will be included in the scaling and the background
 1528 will be overpredicted. The final estimate of the fake background becomes:

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

1529 **5.3.4.2 The fake factor with p_T^{cone}**

1530 When a jet produces a non-prompt lepton, that lepton only carries a fraction of the underlying jet's
 1531 total momentum. Due to the isolation cut applied to the nominal leptons, they typically carry a
 1532 much larger percentage of the underlying jet momentum¹³ than the loose leptons (which are allowed
 1533 to fail this criteria).

1534 This discrepancy in the underlying jet momentum fraction can cause problems in the calculation
 1535 of the fake factor f . Consider the case where two separate events have jets of identical momentum,
 1536 but one produces a non-prompt lepton that passes the nominal selection, and the other produces a
 1537 non-prompt lepton that passes the loose selection. The loose lepton on average will have lower p_T
 1538 than the nominal lepton despite both originating from jets with the same momentum. This can be
 1539 seen explicitly when comparing the p_T of a muon to its associated truth jet:

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

1540 Since muons are not included in the jet reconstruction algorithm, Δp_T approximates the momentum
 1541 of the muon compared to the rest of the jet. For muons that carry more than 50% of the jet's
 1542 momentum, Δp_T will be negative and vice-versa. The Δp_T distributions for nominal and loose
 1543 muons in $t\bar{t}$ MC events is shown Figure 5.13, where a 50 GeV jet on average corresponds to a
 1544 35 GeV nominal muon and a 20 GeV loose muon¹⁴.

¹³Since 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.

¹⁴To better illustrate the point, here the muon is added back into the jet p_T , and the corresponding muon p_T is

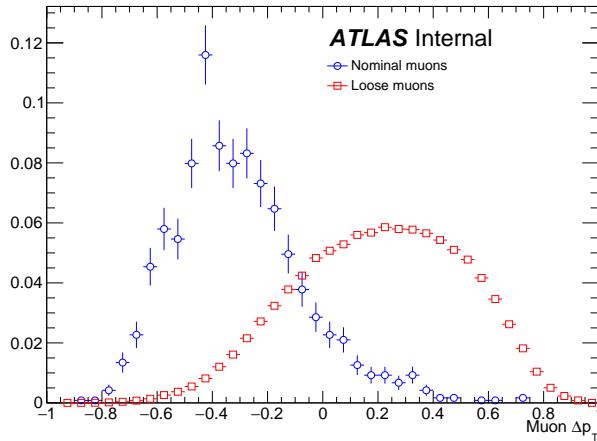


Figure 5.13: Δp_T distributions for nominal (blue) and loose (red) muons in simulated $t\bar{t}$ events. Each muon has been matched to a truth-level jet. Both distributions are normalized to unit area.

1545 Since the default fake factor defined in Equation 5.7 is binned in lepton p_T , within a given bin,
 1546 the underlying jet p_T spectrum can differ substantially between the numerator and the denominator.
 1547 Additionally, these differences can vary depending on the process producing the non-prompt leptons
 1548 or on the specific kinematic selections of the signal or control regions where the fake factor is applied.

1549 Fortunately, the majority of the jet momentum not carried by the non-prompt lepton (excluding
 1550 neutrinos) can be recovered using isolation variables. A track-based isolation is chosen, referred to
 1551 as p_T^{cone} , and it contains the sum of the p_T of all particle tracks originating from the primary vertex
 1552 within a cone of $\Delta R < 0.3$ around the lepton. Thus, the sample of loose leptons in the denominator
 1553 of the fake factor calculation is binned in $p_T + p_T^{\text{cone}}$ rather than simply lepton p_T . Adding the
 1554 isolation cone greatly reduces the difference in the fraction of the underlying jet momentum carried
 1555 by the nominal and loose leptons. To check this, a new Δp_T is calculated between a lepton and its
 1556 matched truth jet, where the truth jet p_T has been corrected to include all muons within a cone of
 1557 $\Delta R < 0.4$:

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

1558 The Δp_T distributions comparing p_T and $p_T + p_T^{\text{cone}}$ for nominal and loose leptons using the corrected
 1559 jet p_T are found in Figure 5.14, and better agreement is seen between the numerator (nominal) and
 1560 denominator (loose with $p_T + p_T^{\text{cone}}$) distributions.

obtained via $\Delta p_T(\mu, j) = \frac{(p_T(j) - p_T\mu) - p_T(\mu)}{(p_T(j) - p_T\mu) + p_T(\mu)} = \frac{p_T(j) - 2p_T(\mu)}{p_T(j)}$.

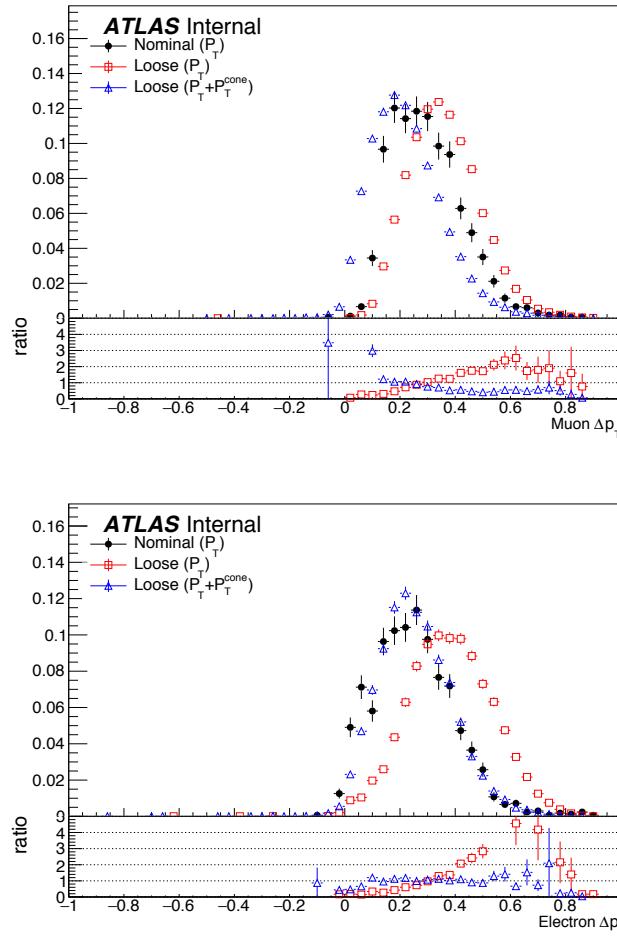


Figure 5.14: Δp_T distributions for muons (top) and electrons (bottom) in simulated $t\bar{t}$ events. Each lepton has been matched to a truth-level jet, and that truth jet has had its p_T corrected to include all truth muons within a cone of $\Delta R < 0.4$. The nominal leptons are in black. Δp_T is calculated for the loose leptons using p_T (red) and $p_T + p_T^{\text{cone}}$ (blue).

1561 The numerator remains binned in lepton p_T , due to the fact that it is meant to mirror the signal
 1562 region as closely as possible, and the signal lepton selection does not use $p_T + p_T^{\text{cone}}$. The impact of
 1563 this is expected to be negligible due to the p_T^{cone} isolation being small for signal leptons, as shown
 1564 for muons in Figure 5.15. Finally, the fake factor f becomes:

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

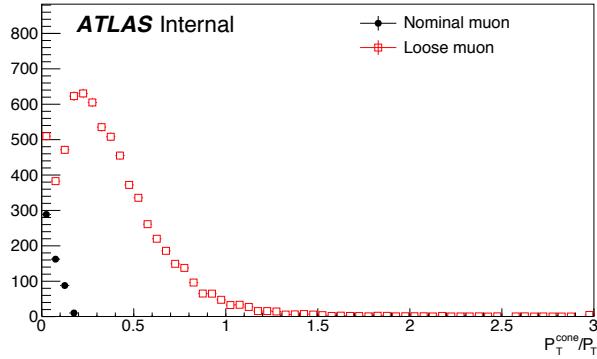


Figure 5.15: Distributions of p_T^{cone}/p_T for nominal (black) and loose (red) muons in simulated $t\bar{t}$ events.

1565 5.3.4.3 Application of the fake factor

1566 The fake factor itself is measured from a sample of events passing a dijet selection requiring
 1567 exactly one lepton (either passing the nominal or loose selections) and at least one jet. The leading
 1568 jet must also be b -tagged and approximately back-to-back with the lepton in order to enhance non-
 1569 prompt lepton contributions while reducing contributions from processes involving W and Z bosons.
 1570 W boson events are further suppressed by requiring the sum of the E_T^{miss} and the transverse mass
 1571 of the lepton and E_T^{miss} to be less than 50 GeV. The full event selection for the dijet region is
 1572 summarized in Table 5.13.

1573 The numerator sample is constructed from dijet events in which the lepton passes the nominal
 1574 (signal) selection and is binned in the lepton p_T . Similarly, the denominator sample is made up of
 1575 the remaining dijet events where the lepton passes the loose selection and is binned in the lepton
 1576 $p_T + p_T^{\text{cone}}$. The nominal and loose leptons pass the signal selection¹⁵ and loose selection, respectively,

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

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.

1577 defined earlier in Table 5.3 for muons and Table 5.4 for electrons. Backgrounds from $W+\text{jets}$, $Z+\text{jets}$,
 1578 $t\bar{t}$, and single top processes are estimated from MC simulations requiring one lepton to be prompt
 1579 using the truth information; these contributions are subtracted from the dijet data. The fake factor
 1580 is then calculated using Equation 5.12 for muons and for central and forward electrons separately.
 1581 The muon fake factor is shown in Figure 5.16, and the two electron fake factors are shown in
 1582 Figure 5.17. The numerical values of the fake factors, including their systematic uncertainties which
 1583 will be discussed in Section 5.3.4.4, are listed in Table 5.14.

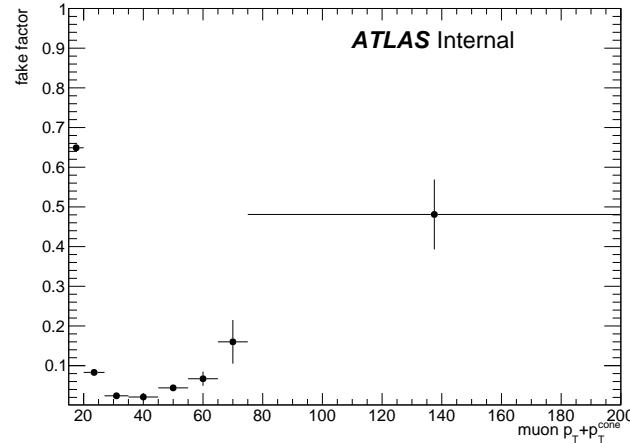


Figure 5.16: The measured fake factor as a function of muon $p_T + p_T^{\text{cone}}$. The error bars represent the statistical uncertainty only.

1584 In order to properly account for the denominator being binned in $p_T + p_T^{\text{cone}}$, special care needs
 1585 to be taken when estimating the fake background from the NL regions. For the purposes of the

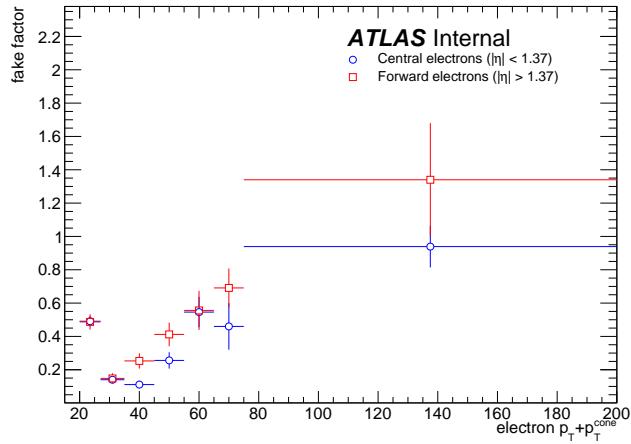


Figure 5.17: The measured fake factor as a function of electron $p_T + p_T^{\text{cone}}$ in the central ($|\eta| < 1.37$, blue) and forward ($|\eta| > 1.37$, red) regions of the detector. The error bars represent the statistical uncertainty only.

1586 fake factor calculation, it is perhaps more intuitive to consider a loose *object* with $p_T = p_T + p_T^{\text{cone}}$
 1587 instead of simply a loose *lepton*, as the lepton and the underlying jet are treated as a whole with this
 1588 method. When the lepton p_T cuts required by a particular signal or control region are applied to
 1589 nominal and loose leptons, the cut is applied to the p_T of the nominal lepton and to the $p_T + p_T^{\text{cone}}$
 1590 of the loose object. Similarly, when looking up the fake factor weight for a given *NL* event, the
 1591 value taken from the bin corresponding to the $p_T + p_T^{\text{cone}}$ of the loose object. Finally, when applying
 1592 the weight to the event, $p_T + p_T^{\text{cone}}$ is assigned as the p_T of the loose object. Figure 5.18 contains a
 1593 graphical representation of this procedure.

1594 Finally, it should be noted that the addition of p_T^{cone} to the loose object may cause the loose
 1595 leptons in the denominator sample to migrate into higher bins. This results in an overall decrease in
 1596 the number of loose objects in the lower $p_T + p_T^{\text{cone}}$ bins due to there not being additional leptons at
 1597 lower p_T to replace them. Since the fake factor is a ratio of the number of events in a bin, this effect
 1598 causes the first few bins of the fake factor to increase, as can be seen clearly in Figure 5.16. However,
 1599 the signal and control regions (and their corresponding *NL* regions) contain a $p_T > 27$ GeV cut that
 1600 prevents these migrations from negatively impacting the fake estimation.

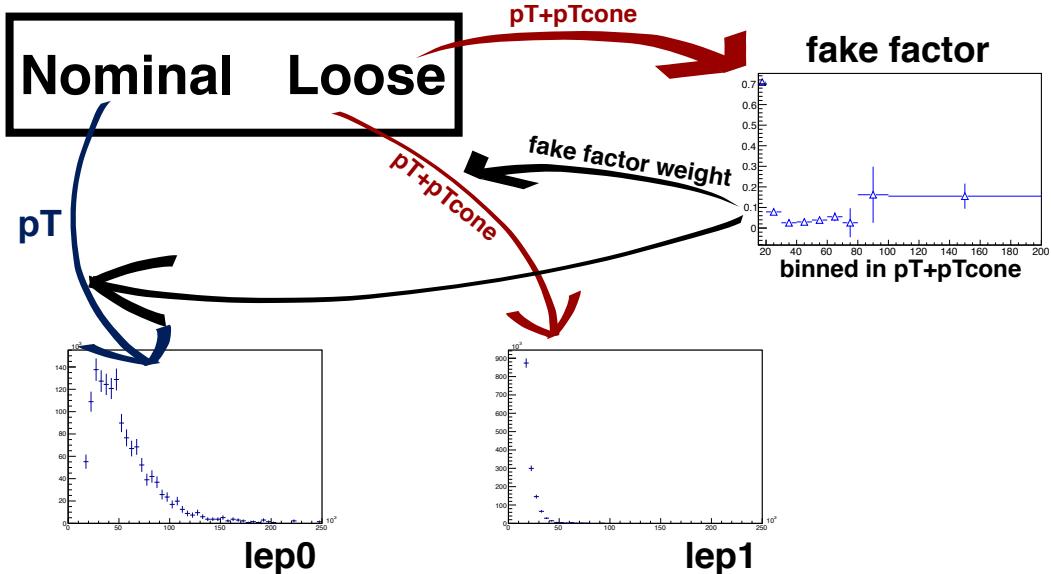


Figure 5.18: Graphical representation of the fake factor application using $p_T + p_{T\text{cone}}$. The value of $p_T + p_{T\text{cone}}$ for the loose lepton is used to “look up” the fake factor weight which is then applied to the event. The loose lepton’s p_T becomes $p_T + p_{T\text{cone}}$ for the purpose of the fake background estimation.

1601 5.3.4.4 Systematic uncertainties

1602 Four sources of systematic uncertainty are considered: the dijet event selection, the prompt back-
 1603 ground subtraction, the jet flavor composition, and residual dependence on the underlying jet p_T
 1604 spectrum. In order to measure the impact of these systematics, new fake factors are computed
 1605 with each of the systematic variations and the differences from the nominal values are taken as the
 1606 uncertainty.

- 1607 1. In order to estimate uncertainties due to the dijet selection, the cut on $M_T + E_T^{\text{miss}}$ is varied
 1608 by ± 5 GeV, $\Delta\phi(l, j)$ by ± 0.1 , and the jet p_T cut by $+5$ GeV.
- 1609 2. To estimate the systematic uncertainty on the prompt background subtraction, the MC pre-
 1610 diction in a $W+\text{jets}$ control region is compared to data. The discrepancy between data and
 1611 MC is found to be approximately 10% [50]. Therefore, the prompt background used for the
 1612 subtraction is scaled up and down by $\pm 10\%$.
- 1613 3. The difference in the jet flavor composition between the dijet events and the events in the
 1614 NL regions can affect the accuracy of the fake background estimation. The dijet sample is

1615 dominated by light jets, while the NL regions tend to be dominated by heavy flavor from $t\bar{t}$.
 1616 To account for this, the fake factor is computed with a b -jet veto.

1617 4. To measure any residual dependence on the underlying jet p_T spectrum, the leading jet p_T
 1618 distribution is reweighted to match the p_T spectrum of truth jets that produce fake leptons
 1619 in MC simulations. This results in an increase in the number of nominal and loose leptons at
 1620 high momentum [50].

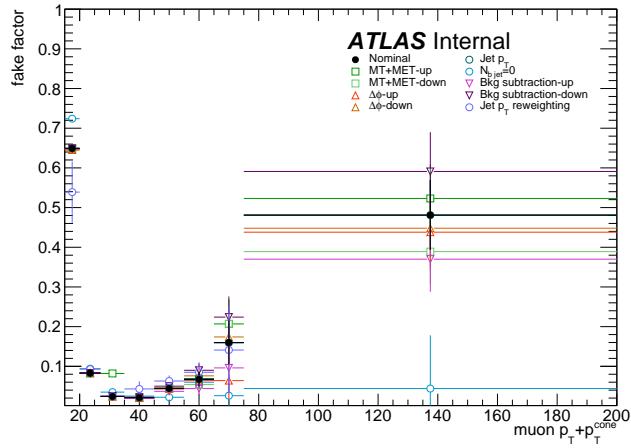


Figure 5.19: Systematic variations in the fake factor as a function of muon $p_T + p_T^{\text{cone}}$. The individual fake factors obtained for each systematic variation are displayed with their statistical uncertainties.

1621 5.3.4.5 Results of the fake factor

1622 The fake background contribution in the signal region is estimated by applying the fake factors
 1623 to the equivalent NL region using Equation 5.9, where the fake factor used corresponds to the
 1624 flavor of the loose lepton in the event. As usual, the prompt background is subtracted from the
 1625 NL events using MC simulation. Charge misidentification is handled using the same method as
 1626 in Section 5.3.3, with an additional set of charge flip rates calculated for loose leptons. The fake
 1627 background yields in the signal region are listed in Table 5.15. An overall uncertainty of 50% is
 1628 assigned to the fake background estimation in $\mu^\pm\mu^\pm$ events, and between 40% to 90% for $e^\pm e^\pm$ and
 1629 $\mu^\pm e^\pm$ events, including both statistical and systematic effects.

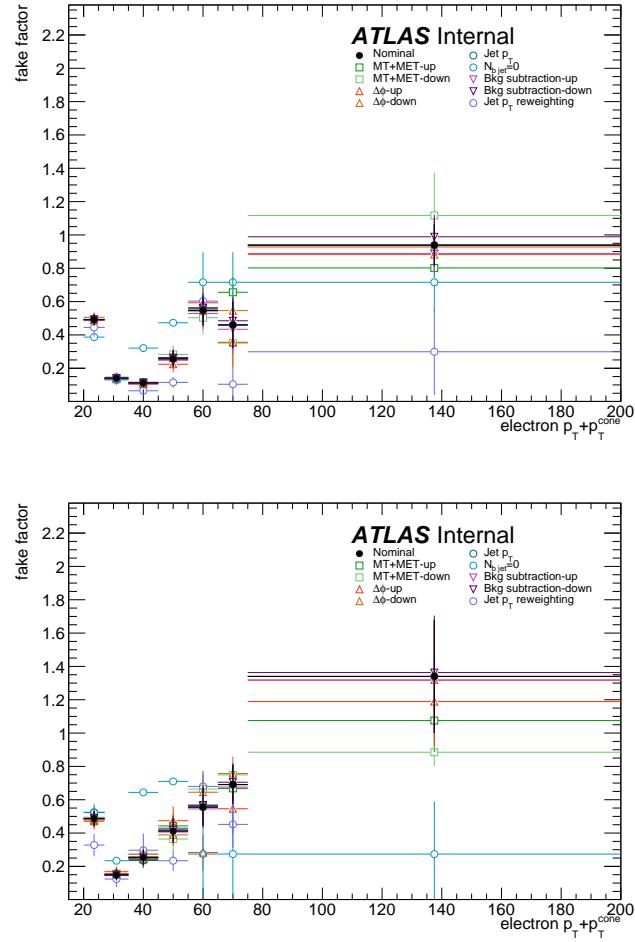


Figure 5.20: Systematic variations in the fake factor as a function of electron $p_T + p_T^{\text{cone}}$ in the central ($|\eta| < 1.37$, top) and forward ($|\eta| > 1.37$, bottom) regions of the detector. The individual fake factors obtained for each systematic variation are displayed with their statistical uncertainties.

1630 **5.3.4.6 Validation of the fake factor**

1631 The accuracy of the fake factor method is tested in several validation regions, the most sensitive
 1632 of which is the same-sign top fakes VR (SS top VR), defined in Table 5.16. This region inverts
 1633 the signal region's b -jet veto to accept events with exactly one b -jet. Due to this requirement, the
 1634 dominant source of events comes from the $t\bar{t}$ process where a b -jet fakes an isolated lepton. The
 1635 distribution of the subleading lepton p_T in this VR is shown in Figure 5.21 for all lepton flavor
 1636 combinations. There is good agreement between the data and the prediction, even when only taking
 1637 into account the statistical uncertainty and not the large systematic uncertainties assigned to the
 1638 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.

1639 **5.3.5 Reduction of WZ background using custom overlap removal**

1640 The dominant source of prompt background in this analysis comes from WZ events where both
 1641 bosons decay leptonically. Traditionally, the background is dealt with by imposing a veto on any
 1642 event with a third lepton passing some loose identification criteria (the so-called *trilepton veto*). In
 1643 the case of this analysis, if one or more leptons (in addition to the two signal leptons) passed the
 1644 preselection criteria, the event would be rejected. However, WZ events can still enter the signal
 1645 region if one of the leptons fails the veto selection or falls outside of the detector's acceptance.

1646 In order to understand the sources of WZ events that are not removed by the trilepton veto,
 1647 a study was performed on truth-level leptons¹⁶ on $W^\pm W^\pm jj$ and WZ MC samples. Events with
 1648 three truth leptons were selected, and each was matched to its reconstruction-level partner by finding
 1649 the closest $\Delta R(\text{truth}, \text{reco})$ and $\Delta p_{T,\text{truth},\text{reco}}$ match. For events surviving the trilepton veto, the
 1650 two signal leptons were removed, and the remaining leptons represent real leptons that failed to

¹⁶Truth 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.

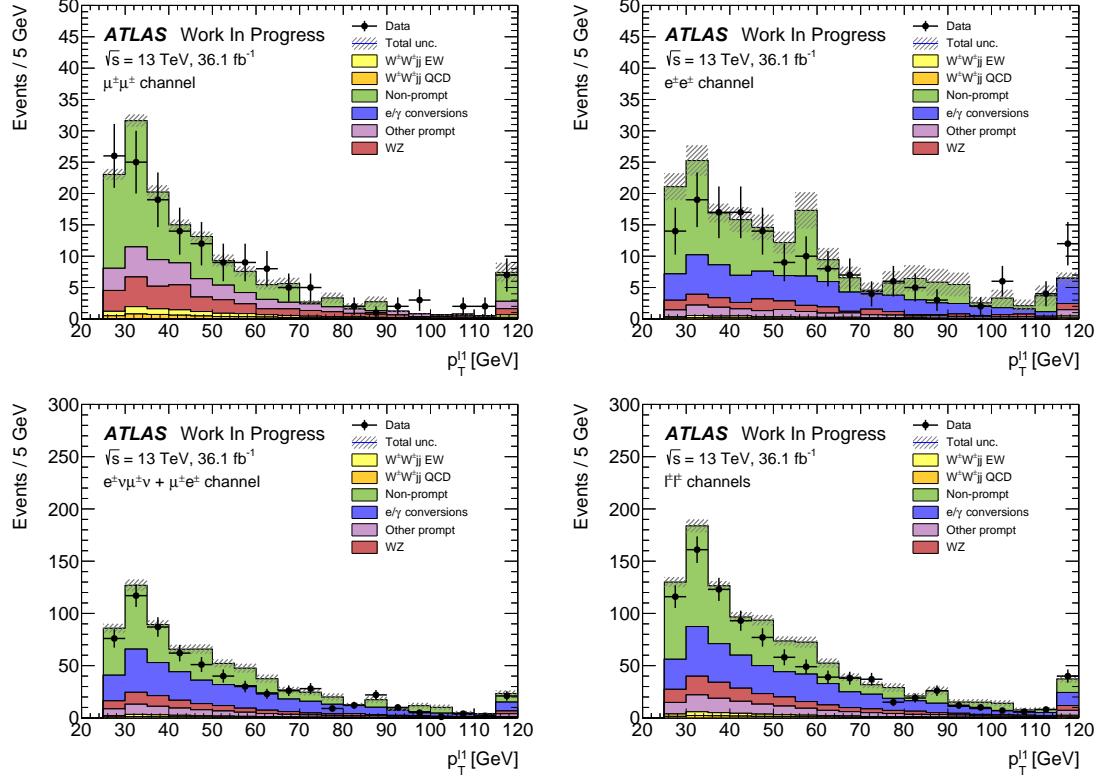


Figure 5.21: Distributions of the subleading lepton p_T in the same-sign top fakes VR for $\mu^\pm\mu^\pm$ events (top right), $e^\pm e^\pm$ events (top left), $\mu^\pm e^\pm$ events (bottom left), and all events combined (bottom right). All errors are statistical only.

be selected for the veto. Between 40-50% of these leptons fell outside of the eta acceptance of the analysis (see Figure 5.22) and were unrecoverable. The second largest source of leptons failing the preselection was the OR, defined in Section 5.2.1.4. The standard OR procedure appeared to be too aggressive in removing leptons in favor of jets, causing many three lepton events to “lose” their third lepton and pass the trilepton veto. Therefore a *custom OR* was investigated which would replace the standard OR in the preselection and allow for better WZ rejection by removing fewer third leptons.

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

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

which, along with $\Delta R(l, j)$, will allow for more third leptons to pass the preselection. The idea behind including $p_{T,\text{ratio}}$ is to be able to preferentially remove background leptons originating from

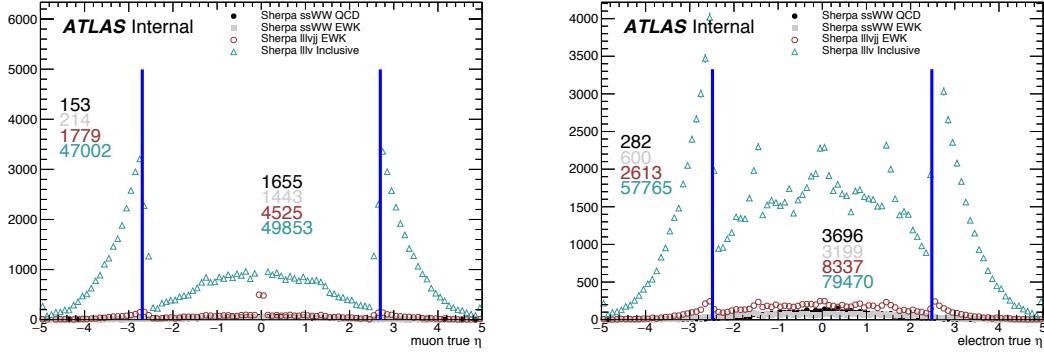


Figure 5.22: Pseudorapidity (η) distributions of truth muons (top) and electrons (bottom) for Sherpa $W^\pm W^\pm jj$ and WZ MC samples. The blue vertical lines represent the allowed η range for each lepton flavor. The numbers correspond to the number of raw MC events that fall within and outside of the allowed η range for each MC sample.

1662 jets (i.e. those that carry a low percentage of the total jet momentum) instead of removing *any*
 1663 lepton near a jet. The distributions of $p_{T,\text{ratio}}$ and the associated efficiency curves for muons and
 1664 electrons can be found in Figures 5.23 and 5.25, respectively, and the distributions for $\Delta R(\mu, j)$ for
 1665 muons can be found in Figure 5.24. Since all electrons have an associated jet in the calorimeters,
 1666 the $\Delta R(e, j)$ variable is not a good quantity to use for this custom OR.

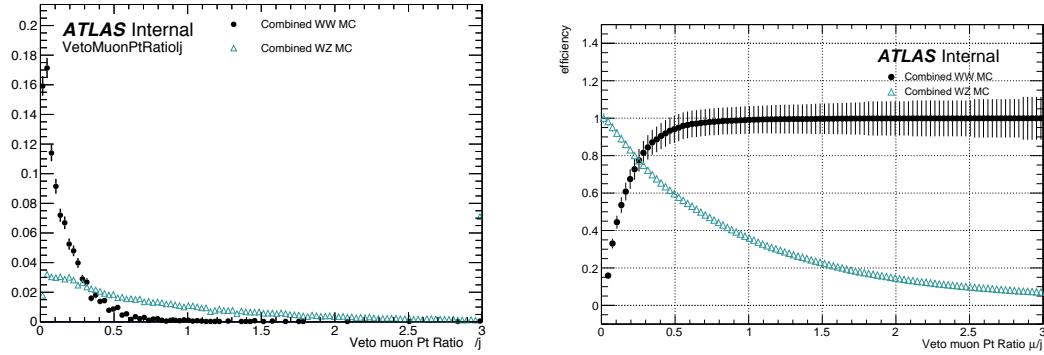


Figure 5.23: Distributions of $p_{T,\text{ratio}}(\mu, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and WZ background (teal) for truth-matched third muons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right where 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.

1667 A workingpoint for the Custom OR was chosen by requiring 90% signal retention for muons
 1668 and 90% background rejection for electrons. The cut on electrons was allowed to be much tighter

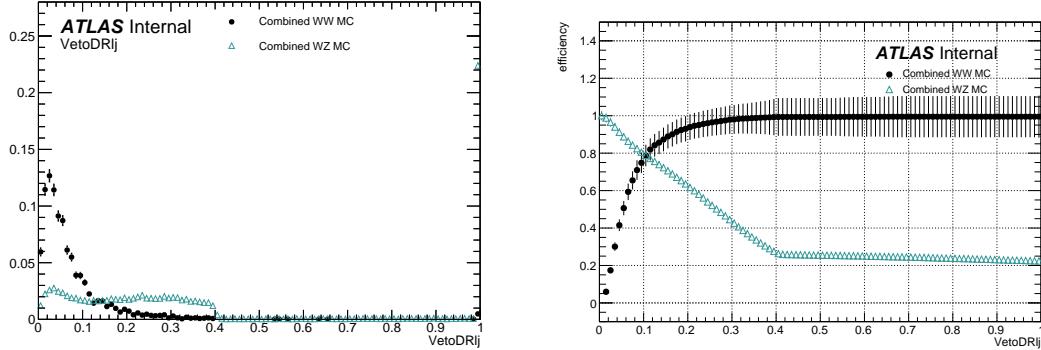


Figure 5.24: Distributions of $\Delta R(\mu, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and WZ background (teal) for truth-matched third muons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right where efficiency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

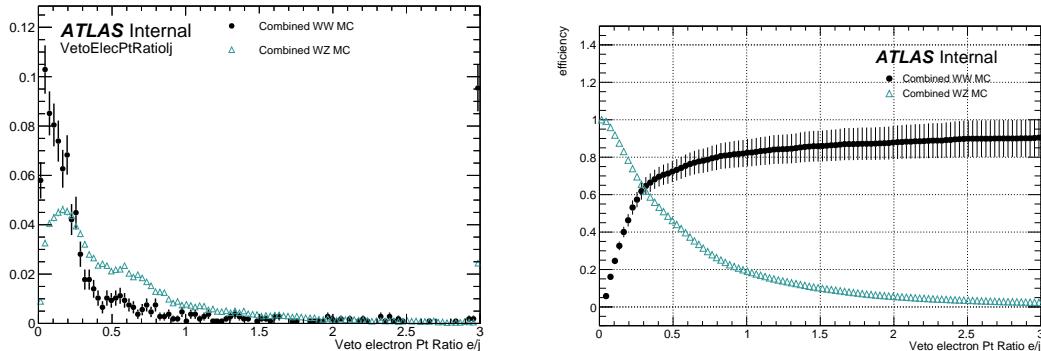


Figure 5.25: Distributions of $p_{T,\text{ratio}}(e, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and WZ background (teal) for truth-matched third electrons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right 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.

because the number of signal events with a third electron is considerably smaller than for muons. It should be emphasized that the signal events present in Figures 5.23-5.25 do not represent the full set of signal events, but only those with a real third lepton (which must come from some source other than the signal $W^\pm W^\pm jj$ process). For muons, a logical ‘or’ of $p_{T,\text{ratio}}(\mu, j)$ and $\Delta R(\mu, j)$ is used to maximize the third lepton acceptance due to correlations between the quantities, as shown in Figure 5.26; 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.

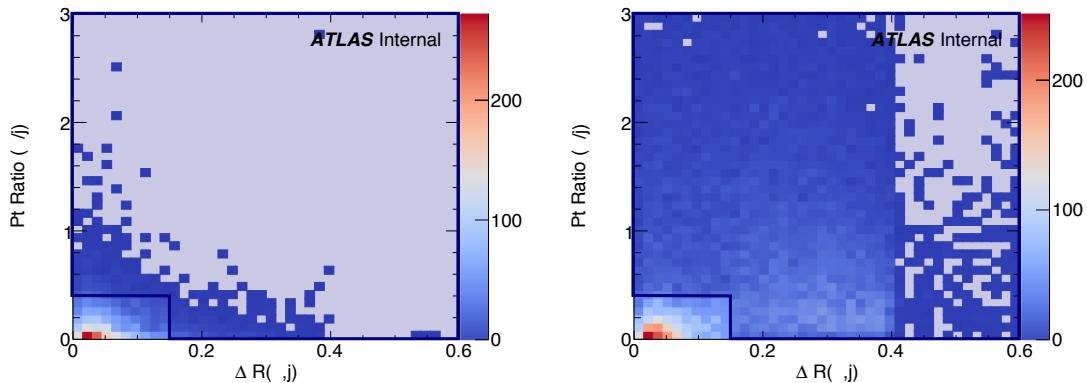


Figure 5.26: Two-dimensional plots of $p_{T,\text{ratio}}(\mu, j)$ vs $\Delta R(\mu, j)$ for truth-matched third muons in events that pass the trilepton veto for EWK and QCD $W^\pm W^\pm jj$ signal (left) and WZ background (right). The blue overlay indicates the area in which the third leptons will pass 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.

1682 **5.4 Cross section measurement**

1683 The $W^\pm W^\pm jj$ EWK cross section is extracted from the signal region using a maximum-likelihood
1684 fit applied simultaneously to four m_{jj} bins in the signal region as well as to the low- m_{jj} and WZ
1685 control regions. For the fit and cross section extraction, the signal region is defined as in Table 5.8
1686 with the dijet invariant mass requirement raised to $m_{jj} > 500$ GeV. The low- m_{jj} region is defined
1687 to mirror the signal region exactly with the dijet invariant mass inverted to $200 < m_{jj} < 500$ GeV,
1688 and the WZ control region is defined previously in Section 5.3.1.

1689 The signal and low- m_{jj} regions are split into six channels based on the flavor and charge of
1690 the dilepton pair: $\mu^+\mu^+$, $\mu^-\mu^-$, μ^+e^+ , μ^-e^- , e^+e^+ , and e^-e^- . This split by charge increases the
1691 sensitivity of the measurement due to the W^+/W^- charge asymmetry at hadron colliders favoring
1692 the production of W^+ bosons [80]. Since the signal events contain two W bosons, the signal strength
1693 compared to charge-symmetric backgrounds is much greater in the $++$ channels for both charges
1694 combined. The WZ control region is included in the fit as a single bin ($l^\pm l^\pm l^\pm$).

1695 The maximum likelihood fit and cross section extractions are outlined in Sections 5.4.1 and
1696 5.4.3, respectively. The results of the cross section measurement and of the analysis as a whole are
1697 presented in Section 5.6.

1698 **5.4.1 Maximum likelihood fit**

1699 **TODO:** This section is very similar to what is written in the support note... May need to put
1700 some work into flushing it out so it's not so close to copy-paste The number of predicted signal
1701 events in each channel c and m_{jj} bin b can be calculated from the SM predicted signal cross section
1702 $\sigma_{\text{theo}}^{\text{tot}}$, the total integrated luminosity \mathcal{L} , the signal acceptance \mathcal{A} , and the efficiency corrections $\mathcal{C}(\theta)$,
1703 where θ represents the set of nuisance parameters that parameterize the effects of each systematic
1704 uncertainty on the signal and background expectations. The acceptance and efficiency corrections
1705 will be covered in more detail in Section 5.4.2.

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

1706 A signal strength parameter μ is defined as the ratio of the measured cross section to the SM
1707 predicted cross section. The expected number of events in a given channel and bin can then be
1708 expressed as the sum of the estimated background ($N_{cb}^{\text{bkg}}(\theta)$) and the number of predicted signal

1709 events scaled by μ :

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

1710 The nuisance parameters are constrained by Gaussian probability distribution functions, and
 1711 the normalization of the WZ background mentioned in Section 5.3.1 is included in the fit as a free
 1712 parameter. The expected yields for signal and background processes are adjusted by the set of
 1713 nuisance parameters within the constraints of the systematic uncertainties. The yields after the fit
 1714 correspond to the value that best matches the observed data.

1715 The number of events per channel and bin after the fit can be written as a sum of the predicted
 1716 event yields for each sample s :

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

1717 In this equation, the fitted number of events in a given channel and bin is obtained by weighting
 1718 the histogram of predicted yields h_{cbs} by the product of a given luminosity λ and any normalization
 1719 factors ϕ_{cs} that may be given for each channel and sample. The input histogram and the normali-
 1720 zation factors may depend on the nuisance parameters θ taking into account sources of systematic
 1721 uncertainty. Uncertainties on the normalization factors $\eta_{cs}(\theta)$ are also included. Finally, bin-by-bin
 1722 scale factors γ_{cb} are included to parameterize the statistical uncertainties of the MC predictions.

1723 The binned likelihood function is given by a product of Gaussian functions for the luminosity
 1724 and for the background uncertainties and a product of Poisson functions for the number of observed
 1725 events in each bin and channel:

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

1726 where \mathcal{G} and \mathcal{P} are the Gaussian and Poisson functions, respectively. As before, \mathcal{L} represents the
 1727 integrated luminosity with uncertainty $\sigma_{\mathcal{L}}$ and associated nuisance parameter $\theta_{\mathcal{L}}$. The number of
 1728 measured events in a given bin and channel is represented by $N_{cb}^{\text{meas.}}$, and $\nu_{cb}(\mu)$ is the predicted
 1729 number of events defined in Equation 5.16 expressed as a function of the signal strength μ . Finally,
 1730 the set of nuisance parameters θ and any auxiliary measurements used to constrain them θ^0 are
 1731 multiplied for each parameter p .

1732 The profile likelihood ratio is defined as

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

1733 with $\hat{\mu}$ and $\hat{\theta}$ as the unconditional maximum likelihood estimates and $\hat{\hat{\theta}}$ as the conditional maximum
 1734 likelihood estimate for a given value of μ . The fitted signal strength $\hat{\mu}$ is obtained by maximizing
 1735 the likelihood function with respect to all parameters. The compatibility of the observed data
 1736 with the background-only hypothesis can then be calculated by setting $\mu = 0$. Observation of the
 1737 $W^\pm W^\pm jj$ EWK process is claimed if the data is found to be inconsistent with the background-only
 1738 hypothesis by more than 5σ .

1739 5.4.2 Definition of the fiducial volume

1740 Before extracting the cross section, it is necessary to define the fiducial volume, or the phase space
 1741 of measureable events. It is a subset of the total phase space defined by selection requirements
 1742 designed to mirror those applied in the analysis as closely as possible. The selection criteria for the
 1743 fiducial volume are listed in Table 5.18.

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

Table 5.18: Definition of the fiducial volume.

1744 In MC simulations, the total phase space is generated, providing the total theoretical cross section
 1745 $\sigma_{\text{theo}}^{\text{tot}}$ and the total number of signal events $\mathcal{N}_{\text{sig}}^{\text{tot}}$ ¹⁷. After applying the fiducial selection at truth
 1746 level, the total number of signal events in the fiducial region $\mathcal{N}_{\text{sig}}^{\text{fid}}$ is obtained. An acceptance factor
 1747 \mathcal{A} is used to represent the efficiency of events falling in the fiducial region at truth level:

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

¹⁷For the purpose of clarity, the number of events at truth level is represented by a script \mathcal{N} , and the number of events at reconstruction level uses a regular N .

1748 A correction factor \mathcal{C} is also necessary to translate from the truth level fiducial volume to the
 1749 reconstruction level signal region and is defined in terms of the number of reconstruction level MC
 1750 events in the signal region $N_{\text{sig},\text{MC}}^{\text{SR}}$:

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

1751 Since the fit is binned in m_{jj} , the acceptance and efficiency correction factors need to be as well.
 1752 Therefore, \mathcal{A}_i and \mathcal{C}_{ij} are written in terms of truth m_{jj} bins i and reconstruction m_{jj} bins j . A
 1753 graphical representation of these regions and the use of the acceptance and correction factors can
 1754 be seen in Figure 5.27.

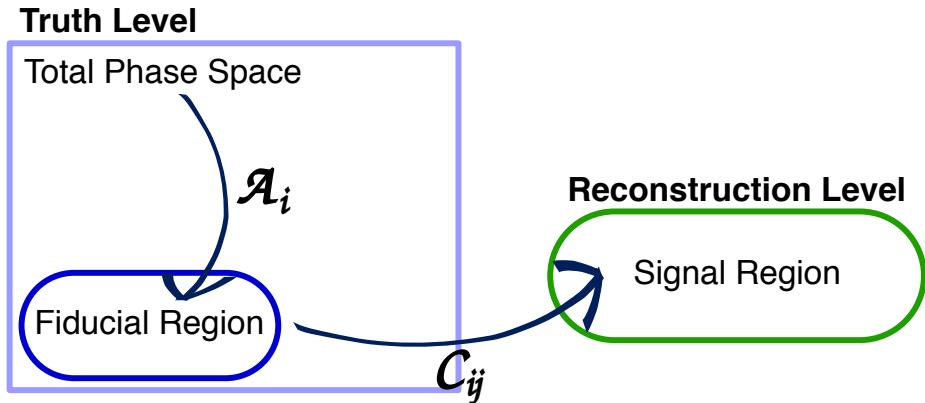


Figure 5.27: Visual representation of the different kinematic regions relevant to the cross section measurement. The acceptance factor \mathcal{A} converts from the truth level total phase space to the truth level fiducial region, and the efficiency correction \mathcal{C} translates the fiducial region into the reconstruction level signal region.

1755 5.4.3 Cross section extraction

1756 The $W^\pm W^\pm jj$ EWK fiducial cross section is measured using the signal strength parameter μ that is
 1757 determined by the maximum likelihood fit. This parameter is dependent on the nuisance parameters
 1758 θ and can be written explicitly in terms of the measured and theoretical cross sections as:

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

1759 In the simple case with only one bin, the equation for the total number of expected events in the
 1760 signal region first introduced in Equation 5.15 can be written as:

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

1761 with the non-binned versions of \mathcal{A} and \mathcal{C} defined in Equations 5.19 and 5.20, respectively.

1762 If the measured fiducial cross section is written as:

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

1763 then Equation 5.22 can be rearranged to read:

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

1764 The measured fiducial cross section can finally be rewritten in terms of $\hat{\mu}$, which is the best estimator
1765 of the signal strength as extracted from the fit:

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

1766 In practice, however, the cross section is not extracted from a single bin, and Equation 5.22
1767 becomes for a single channel in truth and reconstruction level m_{jj} bins i and j , respectively:

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

1768 where now the binned versions of \mathcal{A}_i and \mathcal{C}_{ij} are used. This equation can be extended to include all
1769 the analysis channels by increasing the number of bins i and j . Additionally, it can be shown that
1770 Equation 5.25 holds for this more complex case as well [50], provided care is taken to ensure that
1771 all the uncertainties are handled properly.

1772 5.5 Summary of uncertainties

1773 Systematic uncertainties enter the final fit as nuisance parameters which can impact the estimated
1774 signal and background yields and the shapes of the m_{jj} distributions. These uncertainties can arise
1775 from the experimental methods or from the theoretical calculations used in the analysis. This section
1776 summarizes the systematic uncertainties; the experimental uncertainties are detailed in Section 5.5.1,
1777 and the theoretical uncertainties are covered in Section 5.5.2. The impacts of the systematic uncer-
1778 tainties on the final cross section measurement are summarized in Table 5.19.

1779 5.5.1 Experimental uncertainties

1780 Experimental uncertainties include detector effects as well as uncertainties on the background es-
1781 timation methods. Sources of systematic uncertainty on the measurement of physics objects are

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

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

1782 listed in Table 5.20, grouped by the relevant object type. For backgrounds estimated from MC
 1783 simulations, variations in these sources of uncertainty are propagated through the analysis to obtain
 1784 the corresponding uncertainties on the event yields. Additional experimental uncertainties include
 1785 the integrated luminosity, the photon conversion rate from Section 5.3.2, and the data driven charge
 1786 misidentification and fake lepton background estimations from Sections 5.3.3 and 5.3.4.5, respec-
 1787 tively.

1788 The largest sources of experimental uncertainty on the MC estimations come from the jet-related
 1789 uncertainties and the b -tagging efficiency, while the largest uncertainty on the background estimation
 1790 comes from the fake factor. The effects of the uncertainties on the $W^\pm W^\pm jj$ EWK signal and the
 1791 dominant MC estimated background, WZ , are listed in Tables 5.21 and 5.22, respectively. Since
 1792 the overall contributions from other processes estimated with MC are small, the uncertainties on
 1793 these backgrounds have a lesser impact on the final measurement; these tables can be found in
 1794 Appendix A.1.

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

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

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

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

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

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

1795 **5.5.2 Theoretical uncertainties**

1796 It is also necessary to consider uncertainties on the theoretical predictions in the fiducial region. They
1797 include the choice of PDF set, the value of the strong coupling constant α_s , the renormalization
1798 scale μ_R , the factorization scale μ_F , and the parton showering. The size of these uncertainties are
1799 measured by generating new samples with variations in a chosen parameters and comparing them
1800 to samples using the nominal choice of the parameter. Internal variations on the PDF sets or using
1801 a different set entirely results in a relative uncertainty of up to 2.25% on the nominal sample. The
1802 impact from varying α_s is very small, on the order of < 0.01%. The factorization and renormalization
1803 scales are independently varied between 0.5-2.0 from their nominal values of 1.0. This results in
1804 relative uncertainties on the prediction of up to 15%. Finally, varying the parameters in the parton
1805 showering results in up to 8% uncertainty.

1806 **5.5.2.1 Uncertainties from EWK-QCD interference**

1807 As mentioned in Section 5.0.2, $W^\pm W^\pm jj$ production consists of both EWK processes. The two
1808 production modes cannot be naively separated due to cross terms in the matrix element calculation.
1809 These cross terms are referred to as *interference* terms. Since the $W^\pm W^\pm jj$ EWK production is
1810 the focus of the analysis, and the signal region is designed to preferentially select those events, it is
1811 important to measure the size of the EWK-QCD interference contributions.

1812 The interference effects are estimated using the `MadGraph` MC generator, as it has a feature that
1813 allows direct modelling of the interference term. This allows four samples to be generated:

- 1814 1. Inclusive: All available diagrams are used in the matrix element calculation
1815 2. EWK only: Only EWK diagrams ($\mathcal{O}(\alpha_{\text{EWK}}) = 4$) are used
1816 3. QCD only: Only QCD diagrams ($\mathcal{O}(\alpha_s) = 2 \otimes \mathcal{O}(\alpha_{\text{EWK}}) = 2$) are used
1817 4. Interference: Only the interference terms are used

1818 A minimal set of generator level cuts, listed in Table 5.23, is applied in order to avoid biasing the
1819 sample towards either production mode. The cross sections for each of the four channels can be
1820 found in Table 5.24. The size of the interference is found to be approximately 6% of the total cross
1821 section and is taken as a systematic uncertainty.

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

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

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

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

1822 5.6 Results

1823 After running the full analysis chain, the event yields in the signal region, low- m_{jj} control region,
 1824 and WZ control region as well as associated nuisance parameters representing the uncertainties are
 1825 passed to the maximum likelihood fit. From this fit, the normalization factor for the WZ control
 1826 region μ_{WZ} and the signal strength parameter in the signal region μ_{obs} are determined, and the
 1827 predicted yields in each input bin have been shifted according to the process detailed in Section 5.4.1.

1828 The WZ normalization factor is measured to be:

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

1829 and is constrained primarily by the number of data events in the WZ control region. The observed
 1830 signal strength of $W^\pm W^\pm jj$ EWK production, defined in Equation 5.21, is extracted from the fit
 1831 and measured with respect to the prediction of the **SHERPA v2.2.2** MC generator:

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

1832 This corresponds to a rejection of the background-only hypothesis with a significance of 6.9σ .

1833 The observed number of data events are compared to the predicted signal and background yields
 1834 in the signal region in Table 5.25 before applying the fit and in Table 5.26 after the fit. 122 candidate
 1835 events are observed compared to a prediction of 60 signal and 69 background events.

1836 The m_{jj} distributions for data and prediction are shown in Figure 5.28 after the fit, and the
 1837 fitted event yields in the low- m_{jj} and WZ control regions are shown in Figure 5.29. Additional

1838 distributions can be found in Appendix A.

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

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

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

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

1839 The last ingredient necessary to measure the $W^\pm W^\pm jj$ EWK cross section is the theory predicted 1840 cross section in the fiducial region defined in Table 5.18. **SHERPA v2.2.2** is used for the calculation, 1841 and the cross section in the total generator phase space is 40.81 ± 0.05 fb, and the fiducial cross section 1842 is 2.01 ± 0.02 fb. This corresponds to an acceptance factor of $\mathcal{A} = 0.0493 \pm 0.0002$. Uncertainties on 1843 the simulation are estimated using variations of the scale, parton shower, and PDF set. The final 1844 prediction used in the cross section measurement including uncertainties from Section 5.5.2 is:

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

1845 Combining this **SHERPA** prediction with the measured signal strength μ_{obs} from Equation 5.28, 1846 the measured fiducial cross section $\sigma_{\text{meas}}^{\text{fid}}$ can be calculated using Equation 5.25:

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

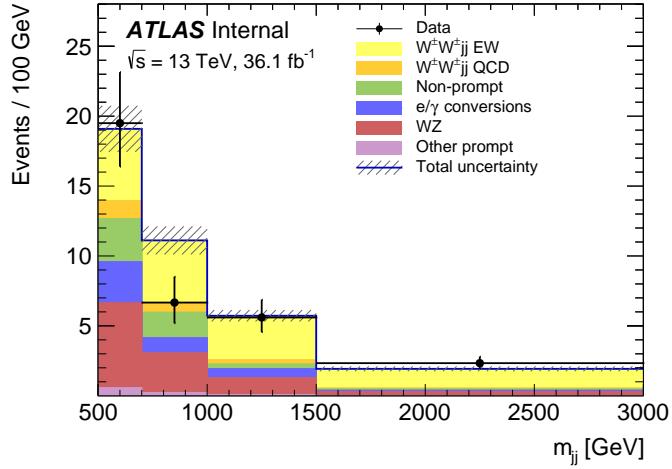


Figure 5.28: The dijet invariant mass m_{jj} distributions for data and predicted signal and background in the signal region after the fit. The shaded band represents the statistical and systematic uncertainties added in quadrature. Note that the bins have been scaled such that they represent the number of events per 100 GeV in m_{jj} . The background estimations from the fake factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t}V$ backgrounds are combined in the “Other prompt” category.

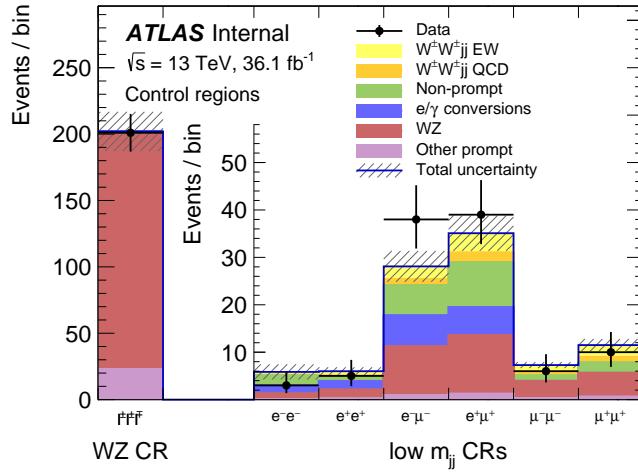


Figure 5.29: The event yields for data and predicted signal and background in the WZ and low- m_{jj} control regions after the fit. The shaded band represents the statistical and systematic uncertainties added in quadrature. The background estimations from the fake factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$ production and electron charge misidentification are combined in the “ e/γ conversions” category. Finally, ZZ , VVV , and $t\bar{t}V$ backgrounds are combined in the “Other prompt” category.

1847 A plot comparing the measured fiducial cross section to two theoretical calculations is shown in
 1848 Figure 5.30. The measured value is compared to the SHERPA v2.2.2 prediction used to calculate
 1849 μ_{obs} as well as to POWHEG-BOX v2. As mentioned in Section 5.1.1, this POWHEG sample does not
 1850 include the resonant triboson diagrams and is only used here for a visual comparison.

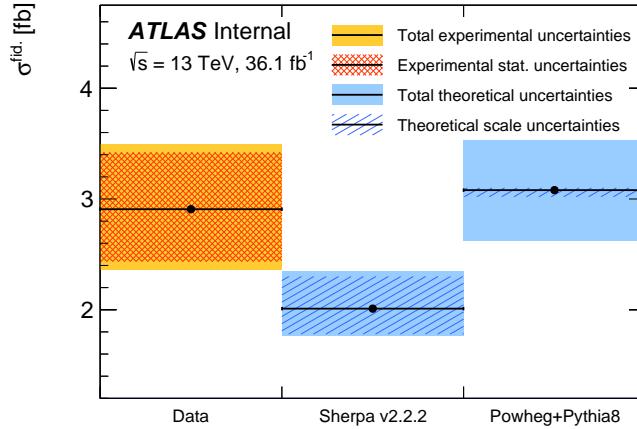


Figure 5.30: Comparison of the measured $W^\pm W^\pm jj$ EWK fiducial cross section with theoretical calculations from SHERPA v2.2.2 and POWHEG-BOX v2. The light orange band represents the total experimental uncertainty on the measured value, and the dark orange hashed band is the statistical uncertainty. For the simulations, the light blue band represents the total theoretical uncertainty, and the dark blue hashed band are the scale uncertainties. The theory predictions do not include the interference between the EWK and QCD production.

1851

CHAPTER 6

1852

Prospects for same-sign WW at the High 1853 Luminosity LHC

1854 On December 3, 2018, Run 2 of the LHC officially ended, and the collider was shut down to begin
1855 the first of two scheduled extended maintenance periods [81]. During these two long shutdowns,
1856 the Phase-I and Phase-II upgrades of the LHC and ATLAS will occur in order to prepare for the
1857 High-Luminosity LHC (HL-LHC) which is scheduled to begin operation in 2026 [82].

1858 The HL-LHC is planned to run at a center-of-mass energy of $\sqrt{s} = 14$ TeV with an instantaneous
1859 luminosity of $\mathcal{L} = 5 \times 10^{34}$ cm $^{-2}$ s $^{-1}$ with up to 200 collisions per beam-crossing. Over the course
1860 of operation, the HL-LHC is expected to collect a total integrated luminosity of $\mathcal{L} = 3000$ fb $^{-1}$ by
1861 2035 [83].

1862 These run conditions will be much harsher than what ATLAS has experienced so far, and there
1863 are several upgrades planned for the detector to operate in the high luminosity environment. Most
1864 notably, the entire ID will be replaced with an all-silicon tracker which will extend the coverage from
1865 $|\eta| \leq 2.7$ up to $|\eta| \leq 4.0$. This will allow for reconstruction of charged particle tracks which can
1866 in turn be matched to clusters in the calorimeters for electron identification or forward jet tagging
1867 [84].

1868 The upgraded detector, the higher beam energy, and the increased volume of data to be collected
1869 provides the opportunity to measure rarer processes with a much higher precision than what was
1870 possible in Run 1. Same-sign $W^\pm W^\pm jj$ production, is one such process. With greater statistics,
1871 the accuracy of the cross section measurement can be improved over the 13 TeV analysis detailed in
1872 Chapter 5, and it also will allow for more detailed physics studies, such as measuring the polarization
1873 of the W bosons. A measurement of the longitudinal polarization of the scattered W bosons has

not yet been possible, but it remains of great interest due to its sensitivity to electroweak symmetry breaking [85]. The analysis detailed in this chapter is based off of the 2018 ATLAS HL-LHC $W^\pm W^\pm jj$ prospects study [86] which extends upon the results of the previous year’s study [87].

6.0.1 Analysis Overview

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

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

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

6.1 Theoretical motivation

The motivation for studying the ssWW process as well as VBS in general has already been established previously in Sections 2.3 and 5.0.2. Since it is specifically the scattering of the longitudinally

1903 polarized vector bosons that is sensitive to the EWSB mechanism, a direct measurement of this cross
 1904 section will be very useful for understanding how the Higgs unitarizes the scattering amplitude [85].

1905 6.1.1 Experimental sensitivity to longitudinal polarization

1906 **TODO:** mention that since there are so many polarization possibilities, a large integrated luminosity
 1907 is needed to measure just one of them individually

1908 There are three possible polarization states for a massive vector boson: two transverse (+ or -)
 1909 and one longitudinal (0). Therefore, in a system with two W bosons, the overall polarization can be
 1910 purely longitudinal (00), purely transverse (++, --, and +-), or mixed (+0 and -0). The three
 1911 combinations will be referred to as *LL*, *TT*, and *LT* respectively.

1912 In order extract the longitudinal scattering component, it is necessary to find variables that can
 1913 help distinguish the LL from the TT and LT events. Several were studied, and those with the best
 1914 discriminating power between the polarizations are the leading and subleading lepton p_T as well as
 1915 the azimuthal separation ($|\Delta\phi_{jj}|$) of the two VBS jets. Both leptons in LL events tend to be softer
 1916 than the TT and LT events (see Figure 6.1), which motivates keeping cuts on these quantities as
 1917 low as possible in the event selection. In the case of $|\Delta\phi_{jj}|$, the LL events generally had a larger
 1918 dijet separation (see Figure 6.2), and this variable is used in a binned likelihood fit to extract the
 1919 longitudinal scattering significance.

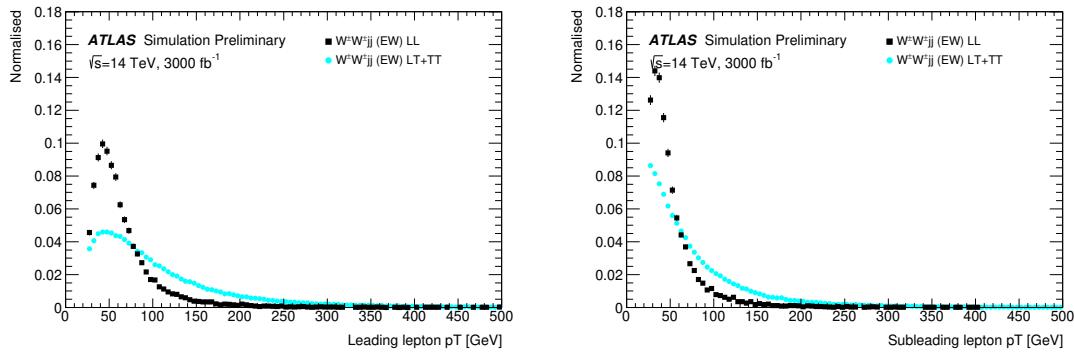


Figure 6.1: Comparison of the leading (left) and subleading (right) lepton p_T distributions for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan) $W^\pm W^\pm jj$ events.

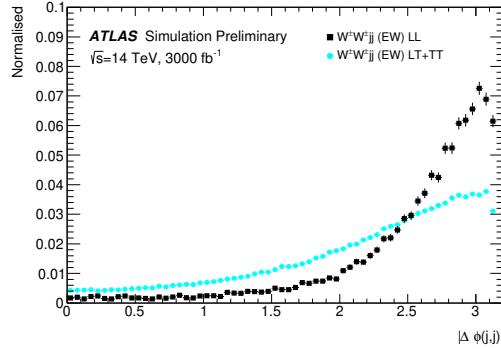


Figure 6.2: Comparison of the azimuthal dijet separation ($|\Delta\phi_{jj}|$) for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan) $W^\pm W^\pm jj$ events.

1920 6.2 Monte Carlo samples

1921 As no real HL-LHC data will be available for many years, all signal and background processes
 1922 are modeled using MC simulations generated at $\sqrt{s} = 14$ TeV, with the event yields scaled to the
 1923 anticipated HL-LHC integrated luminosity of $\mathcal{L} = 3000 \text{ fb}^{-1}$. The MC samples used in the analysis
 1924 are generated at particle-level and have not been run through the typical full simulation of the
 1925 ATLAS detector. Instead, smearing functions derived from a **GEANT4** simulation of the upgraded
 1926 ATLAS detector are used to estimate detector effects such as momentum resolution. In addition,
 1927 pileup events are fully simulated. The MC samples used in this analysis are summarized in Table 6.1.

1928 The signal sample consists of both VBS and non-VBS electroweak (EWK) $W^\pm W^\pm jj$ production,
 1929 and it is simulated with the **Madgraph5_aMC@NLO** generator using the **NNPDF3.0** PDF set and in-
 1930 terfaced with **PYTHIA v8** [88] for hadronization and parton showering. To study the longitudinal
 1931 polarization more directly, two additional **Madgraph5_aMC@NLO** $W^\pm W^\pm jj$ samples are used: one
 1932 containing only the longitudinal contribution (LL) and a second containing the transverse (TT) and
 1933 mixed (LT) contributions.

1934 There are many other processes that can produce the same final state as the $W^\pm W^\pm jj$ and
 1935 must also be accounted for using MC simulations. WZ events are generated using **SHERPA v2.2.0**,
 1936 which includes up to one parton at NLO in the strong coupling constant and up to three addi-
 1937 tional partons at LO. Both EWK and QCD production are included in these samples. ZZ and
 1938 triboson VVV ($V = W, Z$) events are generated using **SHERPA v2.2.2** with up to two additional
 1939 partons in the final state. For the triboson backgrounds, the bosons can decay leptonically or
 1940 hadronically. $W+jets$ backgrounds are generated for electron, muon, and tau final states at LO

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.

1941 with Madgraph5_aMC@NLO and the NNPDF3.0 set with showering from PYTHIA v8. $Z+jets$ events are
 1942 produced using POWHEG-BOX v2 and the CT10 PDF set interfaced with PYTHIA v8. Finally, $t\bar{t}$ and
 1943 single-top events are generated using POWHEG-BOX with showering from PYTHIA v6.

1944 6.3 Background estimations

1945 In this analysis, all background contributions are estimated using MC simulations. Backgrounds such
 1946 as electron charge misidentification and fake electrons from jets (which are traditionally estimated
 1947 using data-driven techniques) are estimated using a set of parameterization functions applied to the
 1948 MC. These functions calculate the probability that an electron is assigned the wrong charge or a
 1949 jet is mis-reconstructed as an electron parameterized by the p_T and η of the electron or jet. The
 1950 probabilities are derived from studies on expected electron performance with the upgraded ATLAS
 1951 detector [89].

1952 Processes involving two W and Z bosons are grouped together as *diboson* backgrounds, with the
 1953 exception of $W^\pm W^\pm jj$ events produced via QCD interactions, which are kept separate. Similarly,
 1954 all backgrounds with three vector bosons are combined and labeled as *triboson*. Any $W+jets$ or top
 1955 events that pass selection and do not contain a fake electron, as well as any $Z+jets$ events without an
 1956 electron identified as having its charge misidentified are combined as *other non-prompt* backgrounds.

1957 6.3.1 Truth-based isolation

1958 To properly calculate particle isolation, it requires information from several detector subsystems
 1959 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 B.1.

6.4 Object and event selection

6.4.1 Object selection

Electrons and muons are preselected to have $p_T > 7$ and 6 GeV, respectively, and $|\eta| \leq 4.0$. The likelihood of a given lepton to pass the trigger and identification requirements is estimated by calculating an efficiency dependent on the p_T and η of the lepton. The leptons are also required to pass the isolation criteria detailed in Table 6.2. Jets that have been tagged as a fake electron by the functions described in Section 6.3 are treated as electrons for the purpose of the object selection and

1985 are subject to the same criteria. In order to be considered a signal lepton, an additional requirement
 1986 of $p_T > 25$ GeV is applied on top of the preselection. The two highest p_T leptons passing this
 1987 selection are chosen to be the leading and subleading signal leptons.

1988 Jets are clustered using the anti- k_t algorithm [72] from final-state particles within a radius of
 1989 $\Delta R = 0.4$ (excluding muons and neutrinos). Jets are required to have $p_T > 30$ GeV and lie within
 1990 $|\eta| < 4.5$, with an additional cut of $p_T > 70$ GeV for jets above $|\eta| \geq 3.8$ in order to suppress jets
 1991 from pileup interactions. Jets overlapping with a preselected electron within $\Delta R(e, j) < 0.05$ are
 1992 removed in order to prevent double counting. The two highest p_T jets are defined as the leading
 1993 and subleading *tag jets*.

1994 6.4.2 Event selection

1995 The default event selection is summarized in Table 6.3 and described here. Exactly two signal
 1996 leptons are required with the same electric charge and separated from each other by $\Delta R(ll) > 0.3$.
 1997 In order to suppress contributions from Drell-Yan backgrounds, the two signal leptons must have
 1998 an invariant mass m_{ll} greater than 20 GeV. Additionally, if both signal leptons are electrons, their
 1999 mass must be at least 10 GeV from the Z -boson mass in order to reduce background from Z -boson
 2000 decays¹⁸. The event is required to have at least 40 GeV of missing transverse energy (E_T^{miss}) to
 2001 account for the two neutrinos from the W decays. Events with additional preselected leptons are
 2002 vetoed, which greatly reduces WZ and ZZ backgrounds.

2003 Each event must have at least two jets, and both tag jets are required to not overlap with the
 2004 signal leptons, and there is a veto on events with one or more b -jets. In order to preferentially select
 2005 EWK production, the tag jets are also required to have a large separation between them and a large
 2006 invariant mass. Finally, a cut on the lepton centrality¹⁹, ζ , defined in Equation 6.1 enhances the
 2007 EWK $W^\pm W^\pm jj$ signal.

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

¹⁸The 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.

¹⁹ 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.

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

Table 6.3: Summary of the signal event selection.

2008 6.5 Selection optimization

2009 An upgraded detector along with an increase in center of mass energy and integrated luminosity
 2010 provides an opportunity to study whether the event selection can be optimized to improve the signal
 2011 to background ratio.

2012 6.5.1 Random grid search algorithm

2013 The chosen method for optimizing the event selection is a cut-based algorithm known as the Random
 2014 Grid Search (RGS) [90]. Consider a simple case of two variables x and y chosen to differentiate signal
 2015 from background. In order to be considered a signal event, a given event would be required to pass
 2016 a set of selection criteria, called a *cut point*: $c = \{x > x_c, y > y_c\}$. A simple method to choose the
 2017 optimal cut point (i.e. the “best” values of the cuts x_c and y_c) would be to construct an $n \times m$
 2018 rectangular grid in x and y consisting of points $(x_0, y_0), (x_1, y_1), \dots, (x_n, y_m)$, as in the left plot of
 2019 Figure 6.3. One can then choose a cut point $c_k = \{x > x_i, y > y_j\}$ that maximizes the signal
 2020 significance as measured by a chosen metric. This would be considered a *rectangular grid search*.

2021 While effective in principle, a rectangular grid search comes with two major drawbacks:

- 2022 1. The algorithm scales exponentially as the number of variables to be optimized increases, as
 2023 this is effectively increasing the dimensionality of the grid. In the simple case of a square grid
 2024 with N bins per variable v , the number of cut points to be evaluated grows as N^v .

2025 2. Signal and background samples are rarely evenly distributed over the entire grid, resulting
 2026 in many cut points being sub-optimal and evaluating them would be a waste of computing
 2027 resources.

2028 To combat these limitations, the RGS algorithm constructs a grid of cut points directly from
 2029 the signal sample itself. In the two-dimensional example, this means that the variables x_i and y_j
 2030 making up the cut point $c_k = \{x > x_i, y > y_j\}$ take their values directly from a given signal event.
 2031 This has the benefit of creating a *random grid* of cut points that is biased towards regions of high
 2032 signal concentration by construction. This reduces the need for exponentially increasing numbers of
 2033 cut points while ensuring that computing resources are not wasted in regions with few to no signal
 2034 events. An example of a two-dimensional random grid is shown in the right-hand plot in Figure 6.3.

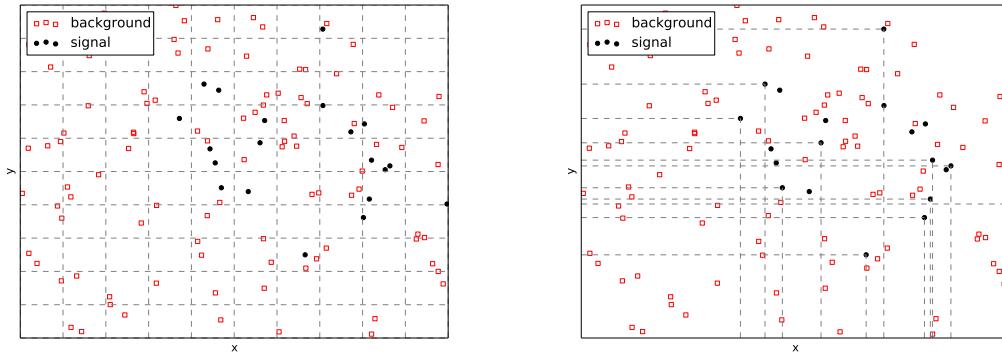


Figure 6.3: A visual representation of a two-dimensional rectangular grid (left) and a random grid (right) in variables x and y . The signal events are the black circles, and the red squares are the background events. Each intersection of gray dashed lines represents a cut point to be evaluated by the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

2035 Once the random grid of cut points is constructed, the optimal cut point can be chosen using any
 2036 number of metrics, such as signal to background ratio. For the purpose of the $W^\pm W^\pm jj$ upgrade
 2037 study, the optimal cut point is chosen to be the one that maximizes the signal significance Z as
 2038 defined in Equation 6.2 [91].

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

2039 where s and b are the number of signal and background events, respectively, σ_b is the total uncertainty
 2040 on the background, and b_0 is defined as:

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

2041 In the case where the background is known precisely (i.e. $\sigma_b = 0$), Equation 6.2 simplifies to

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

2042 which further reduces to the familiar $Z = s/\sqrt{b}$ for the case when $s \ll b$.

2043 6.5.2 Inputs to the optimization

2044 In order to train the RGS, signal and background samples are prepared from events passing the
 2045 event selection outlined in Table 6.3 up through the b -jet veto. The signal sample is chosen to be
 2046 the longitudinally polarized $W^\pm W^\pm jj$ EWK events, and the transverse and mixed polarizations
 2047 are treated as background along with $W^\pm W^\pm jj$ events from QCD interactions and the traditional
 2048 backgrounds listed in Section 6.3. Splitting the inclusive $W^\pm W^\pm jj$ EWK events by polarization
 2049 allows the optimization to favor the longitudinally polarized events as much as possible, even though
 2050 they both contribute to the EWK signal.

2051 The following variables are chosen for optimization:

- 2052 • Leading lepton p_T
- 2053 • Dilepton invariant mass (m_{ll})
- 2054 • Leading and subleading jet p_T
- 2055 • Dijet invariant mass (m_{jj})
- 2056 • Lepton-jet centrality (ζ)

2057 Subleading lepton p_T is omitted as it is desirable to keep the cut value as low as possible due to
 2058 its sensitivity to the longitudinal polarization (as discussed in Section 6.1.1). Additionally, the dijet
 2059 separation $\Delta\eta_{jj}$ was included in the optimization originally, however it was dropped from the list due
 2060 to the cut value being motivated by differences between EWK and QCD produced $W^\pm W^\pm jj$ events.

2061 Two additional constraints were imposed when selecting the optimal cut point:

- 2062 1. At least 1000 signal events must survive in order to prevent the optimization from being too
 2063 aggressive and unnecessarily reducing signal statistics.
- 2064 2. The dijet invariant mass may only vary within a 50 GeV range of the default value (from
 2065 450 – 550 GeV) due to the cut being physically motivated by the VBS event topology (see
 2066 Section 5.0.3).

2067 Lastly, the signal significance is calculated without taking into account the uncertainty of the
 2068 background using Equation 6.4. This is due to the fact that the statistical uncertainties of the fake
 2069 electron and charge misidentification backgrounds are quite large, owing to poor MC statistics in a
 2070 few of the samples. If Equation 6.2 were used instead, the optimization will cut unreasonably hard
 2071 against these backgrounds. Since Monte Carlo statistics is not expected to be a limiting factor when
 2072 this analysis is performed at the HL-LHC, it is more realistic to simply ignore these large statistical
 2073 uncertainties for the purpose of the optimization.

2074 6.5.3 Results of the optimization

2075 Ultimately, the random grid is constructed from over 38,000 LL-polarized $W^\pm W^\pm jj$ events in the
 2076 six variables listed above. After applying the constraints, the optimal cut point reduces the total
 2077 background from 9900 to 2310 while reducing the signal from 3489 to 2958. This corresponds to
 2078 an increase in signal significance from $Z = 33.26$ to $Z = 52.63$ as calculated by Equation 6.4. The
 2079 updates to the event selection are listed in Table 6.4.

2080 The large reduction in the background is primarily a result of the increase in the leading and
 2081 subleading jet p_T from 30 GeV to 90 GeV and 45 GeV, respectively. As can be seen in Figure 6.4,
 2082 this increase removes a significant portion of the backgrounds from jets faking electrons and charge
 2083 mis-ID. Additionally, the loosening of the lepton-jet centrality cut ζ allows more signal events to
 2084 survive the event selection (see Figure 6.5). Other changes to the event selection are minor and
 2085 do not individually have a large impact on the signal or background yields; similar distributions of
 2086 these variables are shown in Appendix B.2.

2087 The full event yields after optimization as well as the cross section measurement are detailed
 2088 alongside those using the default selection in Section 6.6.

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

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

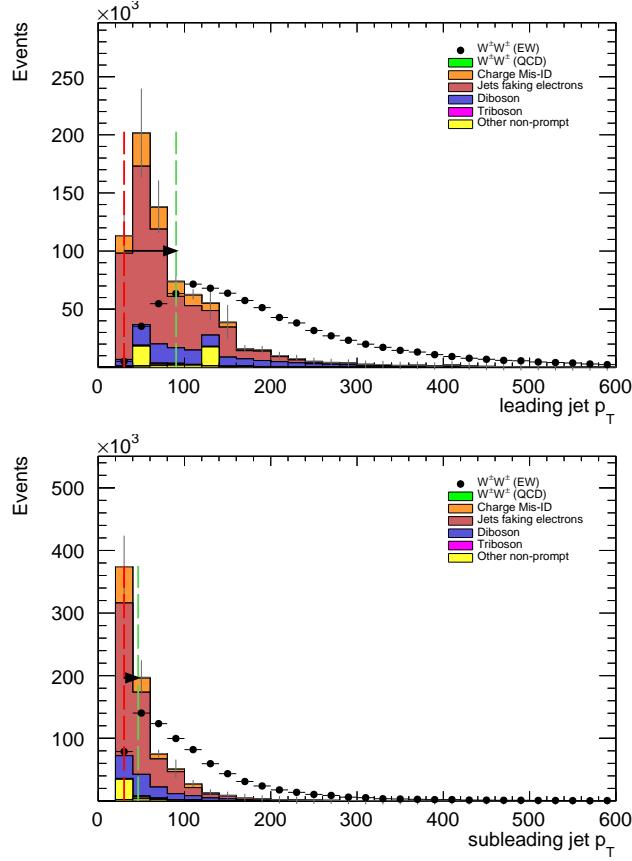


Figure 6.4: Leading (top) and subleading (bottom) jet p_T distributions. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

2089 6.6 Results

2090 6.6.1 Event yields

2091 After applying the full event selection, the analysis is broken down into four channels based off of
 2092 the flavor of the signal leptons: $\mu\mu$, ee , μe , and $e\mu$. The full signal and background event yields are
 2093 shown in Table 6.5 for each channel separately and combined using the default event selection. 3489
 2094 EWK $W^\pm W^\pm jj$ events are expected compared to 9900 background events. The dominant sources
 2095 of background are jets faking electrons followed by charge misidentification and diboson processes.
 2096 Triboson events, QCD $W^\pm W^\pm jj$, and other non-prompt sources make up approximately 5% of the
 2097 total background combined.

2098 The event yields for the optimized selection detailed in Section 6.5.3 are listed in Table 6.6. After

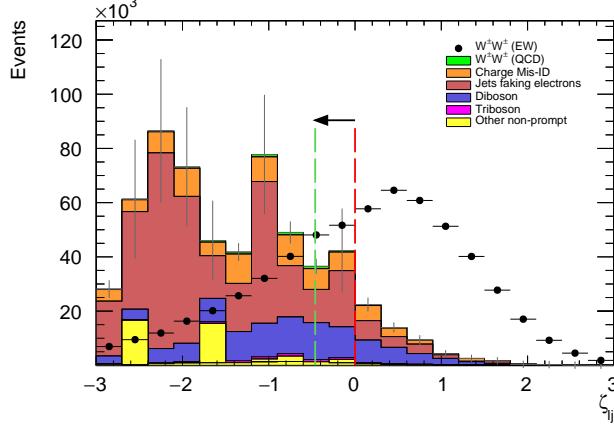


Figure 6.5: Lepton-jet centrality distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

	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.

optimization, 2958 signal events and just 2310 background events are expected. Diboson events are now the primary source of background, as the optimization greatly reduces the fake and charge misidentification backgrounds. As discussed earlier, the increase in the leading and subleading jet p_T cuts as well as the loosening of the centrality cut are most responsible for the changes in the signal and background yields; distributions of these quantities using the default and the optimized event selections can be found in Figures 6.6, 6.7, and 6.8, respectively.

It is important to note, however, that the MC sample used to estimate $Z+jets$ events suffers from poor statistics which results in large per-event weights once scaled to $\mathcal{L} = 3000 \text{ fb}^{-1}$. This sample contributes heavily to the fake and charge misidentification backgrounds, and a handful of these events being cut out by the optimization contributes has a large effect on the dramatic reduction

	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.

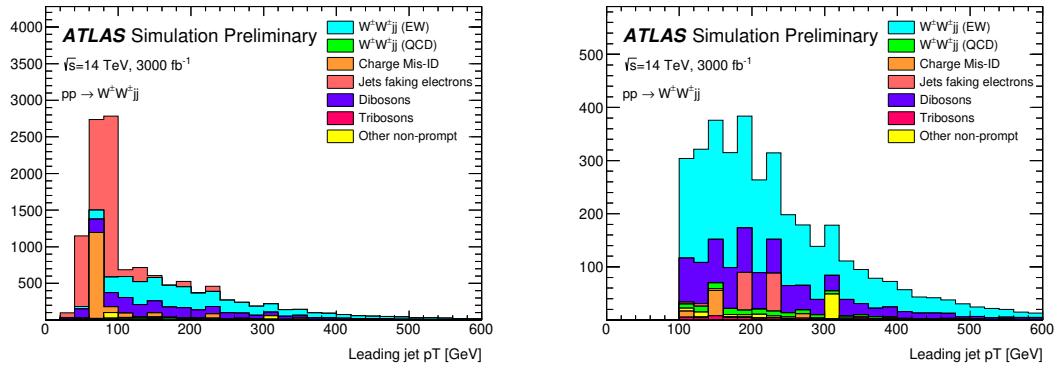


Figure 6.6: p_T distributions for the leading jet using the default (left) and optimized (right) event selections for all channels combined.

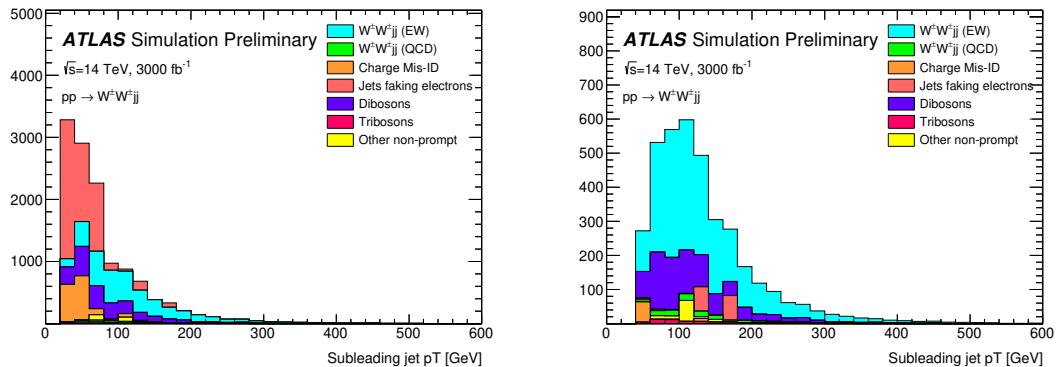


Figure 6.7: p_T distributions for the subleading jet using the default (left) and optimized (right) event selections for all channels combined.

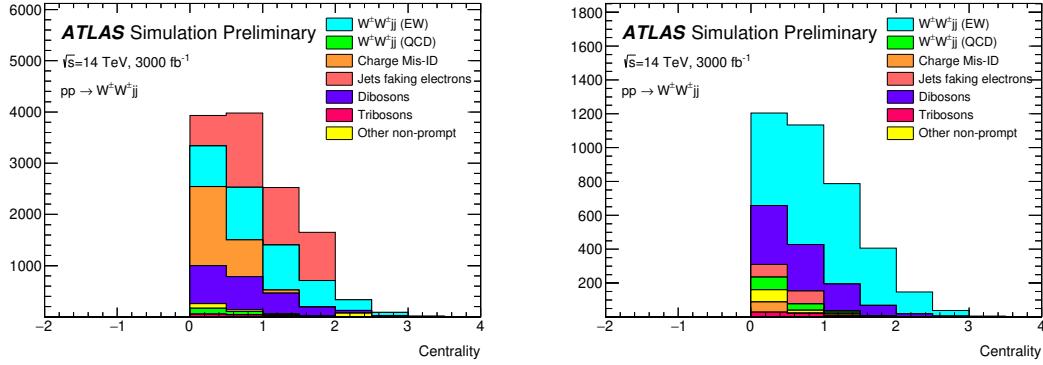


Figure 6.8: p_T distributions for lepton-jet centrality ζ using the default (left) and optimized (right) event selections for all channels combined.

of these backgrounds. As a result, these particular optimized results are likely overly optimistic. However, given proper MC statistics, it is still expected that the optimization will outperform the default selection.

6.6.2 Uncertainties

TODO: Ask for details on how some of these uncertainties were calculated – specifically the fakes and charge mis-ID The uncertainties considered for the analysis are summarized in Table 6.7. Values for experimental systematics on the trigger efficiency, lepton and jet reconstruction, and flavor tagging are taken directly from the 13 TeV analysis [48]. The rate uncertainties for the background processes are halved from the 13 TeV values according to ATLAS recommendations.

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.

2118 **6.6.3 Cross section measurement**

2119 The cross section is calculated using the same method as in the 13 TeV analysis, detailed in Sec-
 2120 tion 5.4. Unlike the previous analysis, however, eight lepton channels are used here instead of six.
 2121 The μe and $e\mu$ channels remain separated in addition to the $\mu\mu$ and ee channels, and each lepton
 2122 flavor channel is further split by charge (i.e. $\mu\mu \rightarrow \mu^+\mu^+ + \mu^-\mu^-$), as this increases the sensitivity
 2123 of the analysis. Each channel's m_{jj} distribution is combined in a profile likelihood fit to extract
 2124 the EWK $W^\pm W^\pm jj$ production cross section. Using the default event selection, the expected cross
 2125 section calculated to be:

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

2126 and with the optimized event selection:

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

2127 The optimized selection should not change the measured value of the cross section, and indeed both
 2128 are consistent with within uncertainties. The systematic uncertainty is reduced by approximately
 2129 7% with the optimized selection.

2130 Projections of the total uncertainty on the cross section as a function of integrated luminosity
 2131 made by **TODO: how was this made?** is shown in Figure 6.9. As the integrated luminosity increases
 2132 past $\mathcal{L} > 3000 \text{ fb}^{-1}$, the statistical uncertainty reduces faster than the systematic uncertainties.
 2133 However, the total uncertainty is expected to reduce by less than a percent with increased luminosity
 2134 past the planned 3000 fb^{-1} .

2135 **6.6.4 Longitudinal scattering significance**

2136 The longitudinal scattering significance is extracted in much the same way as the cross section, this
 2137 time using a binned likelihood fit on the $|\Delta\phi_{jj}|$ distribution. In order to increase sensitivity, the
 2138 $|\Delta\phi_{jj}|$ distribution is split into two bins in m_{jj} , and an additional cut on the pseudorapidity of the
 2139 subleading lepton is applied ($|\eta| < 2.5$) to reduce background from fake and charge misidentification.
 2140 The $|\Delta\phi_{jj}|$ distributions used in the fit are shown in Figure 6.10. Due to limited statistics, the four
 2141 lepton flavor channels are not split by charge. The expected significance of the $W_L^\pm W_L^\pm jj$ process
 2142 is 1.8σ with a precision of 47% on the measurement. Projections of the expected significance as a
 2143 function of integrated luminosity is shown in Figure 6.11.

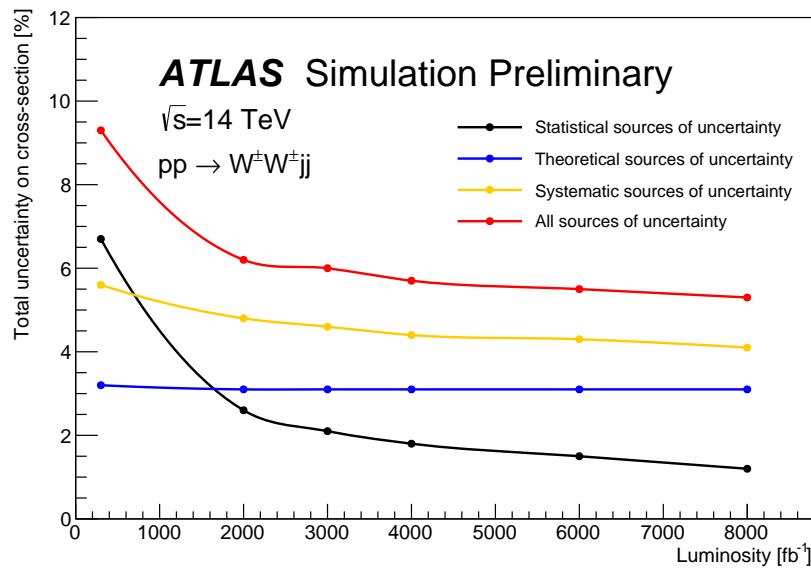


Figure 6.9: Projections of the statistical (black), theoretical (blue), systematic (yellow), and total (red) uncertainties on the measured cross section as a function of integrated luminosity using the optimized event selection.

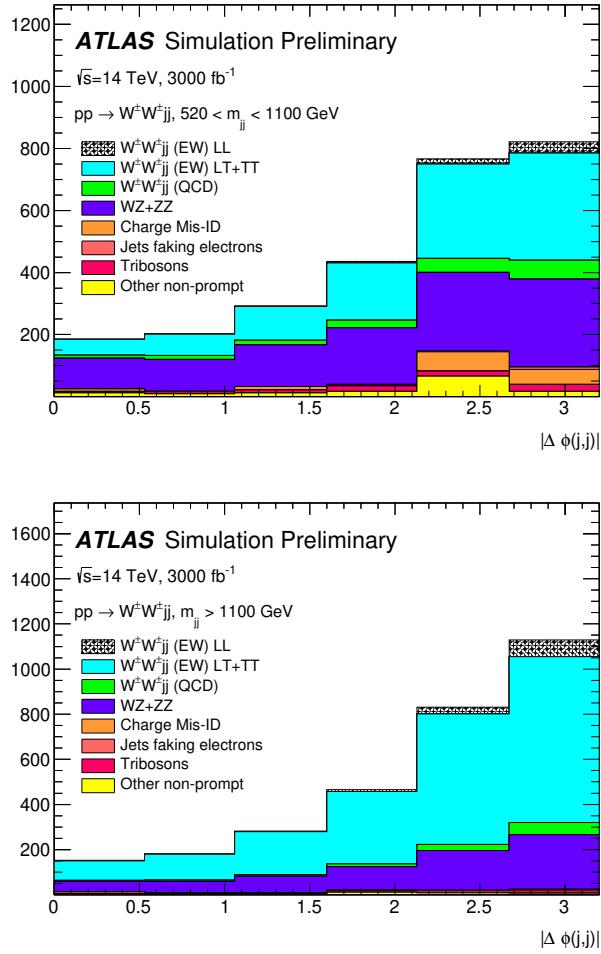


Figure 6.10: Dijet azimuthal separation ($|\Delta\phi_{jj}|$) for the low m_{jj} region ($520 < m_{jj} < 1100 \text{ GeV}$, top) and the high m_{jj} region ($m_{jj} > 1100 \text{ GeV}$, bottom). The purely longitudinal (LL, gray) is plotted separately from the mixed and transverse (LT+TT, cyan) polarizations.

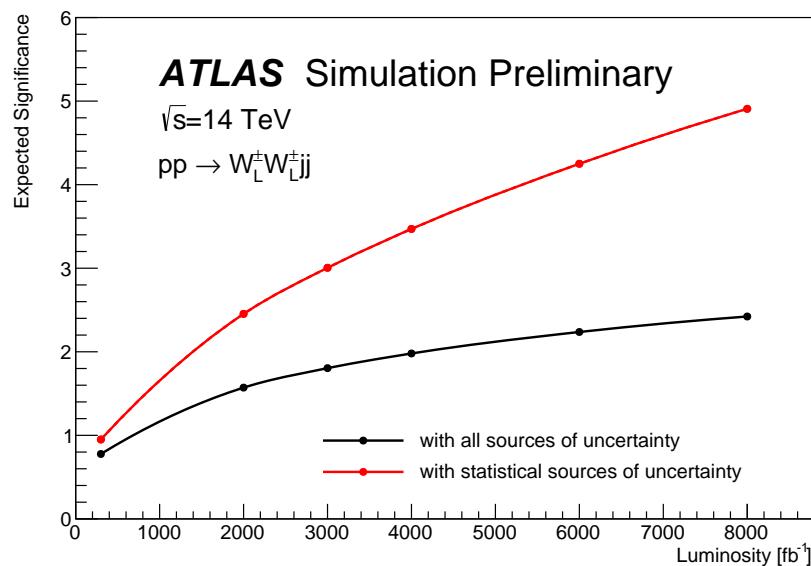


Figure 6.11: Projections of the expected longitudinal scattering significance as a function of integrated luminosity when considering all sources of uncertainties (black) or only statistical uncertainties (red).

2144

CHAPTER 7

2145

Conclusion

2146 Here's where you wrap it up.

2147 **Looking Ahead**

2148

2149 Here's an example of how to have an "informal subsection".

2150

APPENDIX A

2151

2152

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

2153

A.1 Impact of experimental uncertainty on MC background estimations

2154 Tables A.1-A.6 contain the impact of experimental systematic uncertainties for the remaining back-
 2155 grounds estimated from MC simulation. The $W^\pm W^\pm jj$ EWK signal and WZ background sys-
 2156 tematics are listed in the main body of the document, in Tables 5.21 and 5.22, respectively. While the
 2157 percentage of the contributions for some systematics appear large, the size of these backgrounds are
 2158 quite small compared to the total background.

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

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

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

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

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

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

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

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

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

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

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

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

2159 **A.2 Additional signal region plots**

2160

APPENDIX B

2161

2162

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

2163

B.1 Truth isolation

2164 As mentioned in Section 6.3.1, the size of the background contribution from top processes are much
 2165 larger than expected when no isolation is applied. The event yields using an earlier version of the
 2166 event selection with no truth-based isolation requirement are listed in Table B.1. Here, top events
 2167 make up nearly 90% of the total background, and the contributions from fake and charge-flipped
 2168 electrons are also large. The event yields using the same event selection with the truth-based isolation
 2169 included are shown in Figure B.2. When comparing the two tables, the considerable reduction in
 the top background can be clearly seen.

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

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

2170

2171

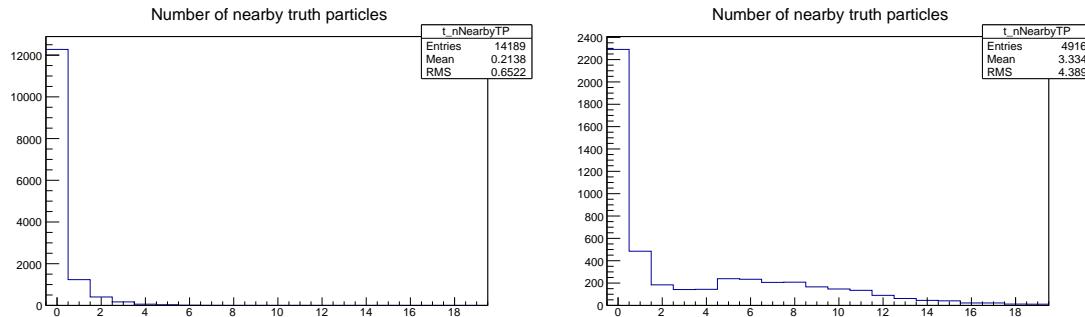
TODO: Add tables for tight vs loose working point, information on the necessity of TRUTH1++

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

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

2172 B.1.1 TRUTH1++ derivations

2173 The ATLAS standard TRUTH1 derivations used for this analysis contain a slimmed truth particle
 2174 container in order to reduce the file size. As a result, many of the truth particles that would be
 2175 included in the isolation variables are missing, and the truth-based isolation will not accurately
 2176 model the reconstruction-level isolation variables. In order to recover the performance of the truth-
 2177 based isolation in the top MC samples (where it is most needed), a custom derivation was produced
 2178 privately that duplicated the default TRUTH1 data structure but includes the full truth particle
 2179 record. The reduced size of the truth particle information in the TRUTH1 derivation compared to the
 2180 TRUTH1++ derivation is shown in Figure B.1.

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

2181 B.1.2 Check of truth-based isolation

2182 Since the isolation variables are constructed from truth particles, there is an expectation that the
 2183 efficiency of the isolation selection will be higher than what would be seen in the full simulation.
 2184 In order to test this, a truth-level 13 TeV $t\bar{t}$ MC sample was run through a selection altered to
 2185 mimic the 13 TeV $W^\pm W^\pm jj$ measurement as closely as possible. The results were compared to the
 2186 $t\bar{t}$ background in the 13 TeV analysis extrapolated to 14 TeV and 3000 fb^{-1} , and the truth-based
 2187 isolation reduces the expected events by a factor of approximately 4. However, the statistics in the
 2188 13 TeV truth-level sample are low, and it is therefore difficult to measure precisely how much the
 2189 truth-based isolation overperforms.

2190 B.1.3 Loose isolation working point

2191 As another check on the truth-based isolation, a second isolation working point was constructed
 2192 to match the official ATLAS Fixed Cut Loose isolation working point. The definition of this loose
 2193 isolation are found in Table B.3.

2194 The primary impact of loosening the isolation is a substantial increase in the non-prompt back-
 2195 round from top processes, and a moderate increase in the charge mis-ID and fake backgrounds.
 2196 Backgrounds from prompt leptons only did not see major changes. As a result, the tight working
 2197 point is chosen for the analysis. The event yields by sample and by background type using the
 2198 loose working point are in Table B.4, and Table B.5 has the numbers using the tight working point
 2199 (defined in Table 6.2) for comparison.

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

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

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

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

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

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

2200 B.2 Plots of other optimization variables

2201 Plots of the remaining optimization variables not shown in Section 6.5.3 are presented here for
 2202 reference. Figures B.2, B.3, and B.4 compare signal and background distributions for the default
 2203 and optimized cuts. None of these cuts change by much in the optimized selection and their impacts
 2204 on the overall event selection is minimal.

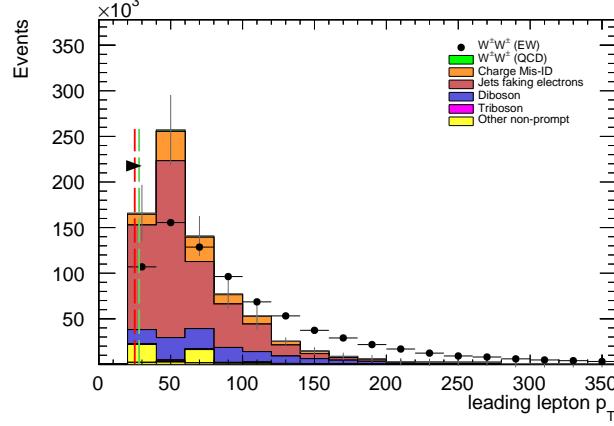


Figure B.2: Leading lepton p_T distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

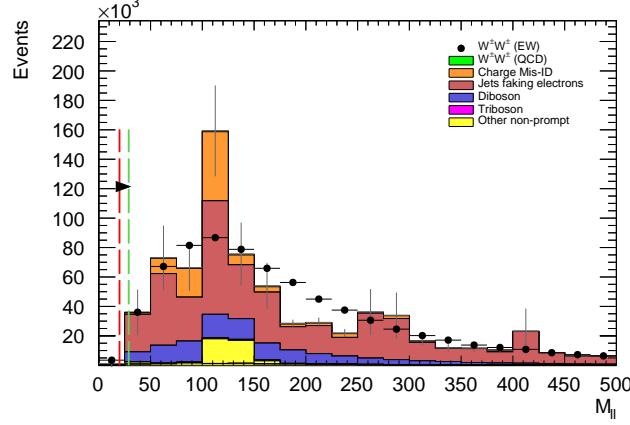


Figure B.3: Dilepton invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

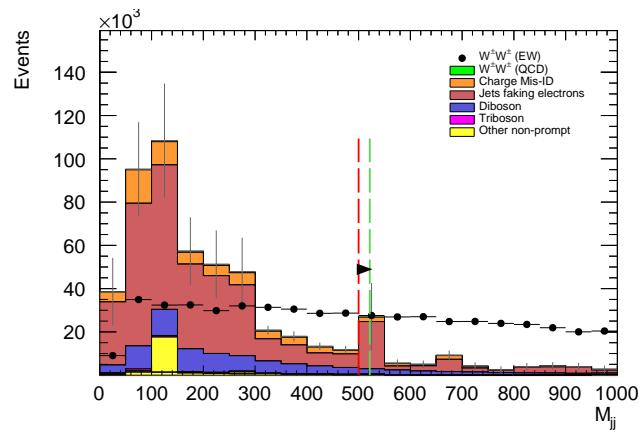


Figure B.4: Dijet invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The $W^\pm W^\pm jj$ EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

Bibliography

- 2206 [1] ATLAS Collaboration, M. Aaboud et al., *Measurement of the $W^\pm Z$ boson pair-production*
 2207 *cross section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector*, *Phys. Lett.* **B762**
 2208 (2016) 1–22, [arXiv:1606.04017 \[hep-ex\]](#). (document)
- 2209 [2] S. Weinberg, *The Quantum Theory of Fields, Volume 1: Foundations*. Cambridge University
 2210 Press, 1995. [2.1](#)
- 2211 [3] M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*.
 2212 Addison-Wesley, 1995. [2.1](#)
- 2213 [4] R. P. Feynman, *Mathematical formulation of the quantum theory of electromagnetic*
 2214 *interaction*, *Phys. Rev.* **80** (1950) 440–457. [2.1](#)
- 2215 [5] M. Y. Han and Y. Nambu, *Three-triplet model with double SU(3) symmetry*, *Phys. Rev.* **139**
 2216 (1965) B1006–B1010. [2.1](#)
- 2217 [6] D. J. Gross and F. Wilczek, *Asymptotically Free Gauge Theories - I*, *Phys. Rev.* **D8** (1973)
 2218 3633–3652. [2.1](#)
- 2219 [7] D. J. Gross and F. Wilczek, *ASYMPTOTICALLY FREE GAUGE THEORIES. 2.*, *Phys.*
 2220 *Rev.* **D9** (1974) 980–993. [2.1](#)
- 2221 [8] H. D. Politzer, *Reliable Perturbative Results for Strong Interactions?*, *Phys. Rev. Lett.* **30**
 2222 (1973) 1346–1349. [,274(1973)]. [2.1](#)
- 2223 [9] A. Salam and J. C. Ward, *Weak and Electromagnetic Interactions*, *Nuovo Cimento* **11** (1959)
 2224 568–577. [2.1](#)
- 2225 [10] S. L. Glashow, *The Renormalizability of Vector Meson Interactions*, *Nucl. Phys.* **10** (1959)
 2226 107–117. [2.1](#)
- 2227 [11] ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak
 2228 Group, SLD Heavy Flavour Group Collaboration, S. Schael et al., *Precision electroweak*
 2229 *measurements on the Z resonance*, *Phys. Rept.* **427** (2006) 257–454, [arXiv:hep-ex/0509008](#)
 2230 [hep-ex]. [2.1](#)
- 2231 [12] F. Englert and R. Brout, *Broken symmetry and the mass of gauge vector mesons*, *Phys. Rev.*
 2232 *Lett.* **13** (1964) 321–323. [2.1](#)

- 2233 [13] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, *Physics Letters* **12**
 2234 (1964) 132–133. 2.1
- 2235 [14] P. W. Higgs, *Broken symmetries and the masses of gauge bosons*, *Phys. Rev. Lett.* **13** (1964)
 2236 508–509. 2.1
- 2237 [15] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model*
 2238 *Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1,
 2239 [arXiv:1207.7214 \[hep-ex\]](https://arxiv.org/abs/1207.7214). 2.1, 5.0.2
- 2240 [16] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS*
 2241 *experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30, [arXiv:1207.7235 \[hep-ex\]](https://arxiv.org/abs/1207.7235). 2.1, 5.0.2
- 2242 [17] UA1 Collaboration, G. Arnison et al., *Experimental Observation of Isolated Large Transverse*
 2243 *Energy Electrons with Associated Missing Energy at $s^{**}(1/2) = 540\text{-GeV}$* , *Phys. Lett. B* **122**
 2244 (1983) 103–116. [,611(1983)]. 2.2
- 2245 [18] UA1 Collaboration, G. Arnison et al., *Experimental Observation of Lepton Pairs of Invariant*
 2246 *Mass Around $95\text{-GeV}/c^{**2}$ at the CERN SPS Collider*, *Phys. Lett. B* **126** (1983) 398–410.
 2247 [,7.55(1983)]. 2.2
- 2248 [19] Particle Data Group Collaboration, K. A. Olive et al., *Review of Particle Physics*, *Chin.*
 2249 *Phys. C* **38** (2014) 090001. 2.2, 2.2
- 2250 [20] D. R. Green, P. Meade, and M.-A. Pleier, *Multiboson interactions at the LHC*, *Rev. Mod.*
 2251 *Phys.* **89** (2017) no. 3, 035008, [arXiv:1610.07572 \[hep-ex\]](https://arxiv.org/abs/1610.07572). 2.3
- 2252 [21] H.-J. He and W. B. Kilgore, *The Equivalence theorem and its radiative correction - free*
 2253 *formulation for all $R(xi)$ gauges*, *Phys. Rev. D* **55** (1997) 1515–1532, [arXiv:hep-ph/9609326](https://arxiv.org/abs/hep-ph/9609326)
 2254 [hep-ph]. 2.3
- 2255 [22] B. W. Lee, C. Quigg, and H. B. Thacker, *The Strength of Weak Interactions at Very*
 2256 *High-Energies and the Higgs Boson Mass*, *Phys. Rev. Lett.* **38** (1977) 883–885. 2.3
- 2257 [23] S. D. Rindani, *Strong gauge boson scattering at the LHC*, in *Physics at the Large Hadron*
 2258 *Collider*, A. Datta, B. Mukhopadhyaya, A. Raychaudhuri, A. K. Gupta, C. L. Khetrapal,
 2259 T. Padmanabhan, and M. Vijayan, eds., pp. 145–155. 2009. [arXiv:0910.5068 \[hep-ph\]](https://arxiv.org/abs/0910.5068). 2.3, 2.3
- 2260 [24] V. D. Barger, K.-m. Cheung, T. Han, and R. J. N. Phillips, *Strong W^+W^+ scattering signals*
 2261 *at pp supercolliders*, *Phys. Rev. D* **42** (1990) 3052–3077. 2.3
- 2262 [25] G. van den Oord, *Recursion, Monte Carlo and Vector Boson Scattering at Hadron Colliders*.
 2263 PhD thesis, Nijmegen U., 2012.
 2264 http://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_G_v_d_Oord.pdf. 2.3,
 2265 2.3
- 2266 [26] A. Alboteanu, W. Kilian, and J. Reuter, *Resonances and Unitarity in Weak Boson Scattering*
 2267 *at the LHC*, *JHEP* **11** (2008) 010, [arXiv:0806.4145 \[hep-ph\]](https://arxiv.org/abs/0806.4145). 2.5
- 2268 [27] L. R. Evans and P. Bryant, *LHC Machine*, *JINST* **3** (2008) S08001.
 2269 <https://cds.cern.ch/record/1129806>. This report is an abridged version of the LHC
 2270 Design Report (CERN-2004-003). 3.1

- 2271 [28] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST
2272 **3** (2008) S08003. 3.1
- 2273 [29] ATLAS Collaboration, *ATLAS inner detector: Technical Design Report, Vol. 1*. CERN,
2274 Geneva, 1997. <https://cds.cern.ch/record/331063>. 4
- 2275 [30] P. F. Åkesson, T. Atkinson, M. J. Costa, M. Elsing, S. Fleischmann, A. N. Gaponenko,
2276 W. Liebig, E. Moyse, A. Salzburger, and M. Siebel, *ATLAS Tracking Event Data Model*,
2277 Tech. Rep. ATL-SOFT-PUB-2006-004. ATL-COM-SOFT-2006-005.
2278 CERN-ATL-COM-SOFT-2006-005, CERN, Geneva, Jul, 2006.
2279 <https://cds.cern.ch/record/973401>. 4.1
- 2280 [31] P. Brückman, A. Hicheur, and S. J. Haywood, *Global chi2 approach to the Alignment of the*
2281 *ATLAS Silicon Tracking Detectors*, Tech. Rep. ATL-INDET-PUB-2005-002.
2282 ATL-COM-INDET-2005-004. CERN-ATL-INDET-PUB-2005-002, CERN, Geneva, 2005.
2283 <https://cds.cern.ch/record/835270>. 4.1, 4.1
- 2284 [32] ATLAS Collaboration Collaboration, *Alignment of the ATLAS Inner Detector Tracking*
2285 *System with 2010 LHC proton-proton collisions at $\sqrt{s} = 7$ TeV*, Tech. Rep.
2286 ATLAS-CONF-2011-012, CERN, Geneva, Mar, 2011.
2287 <https://cds.cern.ch/record/1334582>. 4.1, 4.2.3, 4.14
- 2288 [33] R. Härtel and S. Bethke, *Iterative local Chi2 alignment approach for the ATLAS SCT*
2289 *detector*, Nov, 2005. <http://cds.cern.ch/record/1511044>. Presented 28 Nov 2005. 4.1
- 2290 [34] ATLAS Collaboration Collaboration, P. Brückman de Renstrom, *Alignment strategy for the*
2291 *Inner Detector of ATLAS*, . <https://cds.cern.ch/record/1047114>. 4.1
- 2292 [35] *Alignment of the ATLAS Inner Detector and its Performance in 2012*, Tech. Rep.
2293 ATLAS-CONF-2014-047, CERN, Geneva, Jul, 2014.
2294 <https://cds.cern.ch/record/1741021>. 4.1, 4.2.1, 4.4
- 2295 [36] J. J. Peña, *Alignment of the ATLAS Inner Detector Upgraded for the LHC Run II*, J. Phys.
2296 Conf. Ser. **664** (2015) no. 7, 072025. 4.1
- 2297 [37] J. Alison and I. J. Kroll, *The Road to Discovery: Detector Alignment, Electron Identification,*
2298 *Particle Misidentification, WW Physics, and the Discovery of the Higgs Boson*, Dec, 2015.
2299 <https://cds.cern.ch/record/1536507>. Presented 08 Nov 2012. 6
- 2300 [38] *ATLAS Inner Detector Alignment Performance with February 2015 Cosmic Rays Data*, Tech.
2301 Rep. ATL-PHYS-PUB-2015-009, CERN, Geneva, Apr, 2015.
2302 <https://cds.cern.ch/record/2008724>. 4.3, 4.2
- 2303 [39] ATLAS Collaboration Collaboration, M. Capeans, G. Darbo, K. Einsweiller, M. Elsing,
2304 T. Flick, M. Garcia-Sciveres, C. Gemme, H. Pernegger, O. Rohne, and R. Vuillermet, *ATLAS*
2305 *Insertable B-Layer Technical Design Report*, Tech. Rep. CERN-LHCC-2010-013.
2306 ATLAS-TDR-19, Sep, 2010. <https://cds.cern.ch/record/1291633>. 4.2
- 2307 [40] *Alignment of the ATLAS Inner Detector with the initial LHC data at $\sqrt{s} = 13$ TeV*, Tech.
2308 Rep. ATL-PHYS-PUB-2015-031, CERN, Geneva, Jul, 2015.
2309 <https://cds.cern.ch/record/2038139>. 4.2

- 2310 [41] *Study of the mechanical stability of the ATLAS Insertable B-Layer*, Tech. Rep.
2311 ATL-INDET-PUB-2015-001, CERN, Geneva, Jun, 2015.
2312 <https://cds.cern.ch/record/2022587>. 4.2.1
- 2313 [42] *Common Framework Implementation for the Track-Based Alignment of the ATLAS Detector*,
2314 Tech. Rep. ATL-SOFT-PUB-2014-003, CERN, Geneva, Mar, 2014.
2315 <https://cds.cern.ch/record/1670354>. 4.2.1
- 2316 [43] ATLAS Collaboration Collaboration, *Study of alignment-related systematic effects on the*
2317 *ATLAS Inner Detector track reconstruction*, Tech. Rep. ATLAS-CONF-2012-141, CERN,
2318 Geneva, Oct, 2012. <https://cds.cern.ch/record/1483518>. 4.4, 4.4, 4.4.1.1, 4.4.1.2
- 2319 [44] S. Marti-Garcia, S. Camarda, T. Golling, M. Danninger, N. A. Styles, J. Wollrath, W. K.
2320 Di Clemente, S. Henkelmann, J. Jimenez Peña, O. Estrada Pastor, A. K. Morley, H. Oide,
2321 A. T. Vermeulen, P. Butti, E. Ricci, F. M. Follega, and R. Iuppa, *Studies of radial distortions*
2322 *of the ATLAS Inner Detector*, Tech. Rep. ATL-COM-INDET-2018-010, CERN, Geneva, Mar,
2323 2018. <https://cds.cern.ch/record/2306724>. 4.4
- 2324 [45] ATLAS Collaboration Collaboration, *Electron and photon energy calibration with the ATLAS*
2325 *detector using data collected in 2015 at $\sqrt{s} = 13$ TeV*, Tech. Rep. ATL-PHYS-PUB-2016-015,
2326 CERN, Geneva, Aug, 2016. <https://cds.cern.ch/record/2203514>. 4.4.1
- 2327 [46] ATLAS Collaboration, ATLAS Collaboration, *Evidence for Electroweak Production*
2328 *of $W^\pm W^\pm jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector*, *Phys. Rev. Lett.* **113**
2329 (2014) no. 14, 141803, arXiv:1405.6241 [hep-ex]. 5
- 2330 [47] CMS Collaboration, V. Khachatryan et al., *Study of vector boson scattering and search for*
2331 *new physics in events with two same-sign leptons and two jets*, *Phys. Rev. Lett.* **114** (2015)
2332 no. 5, 051801, arXiv:1410.6315 [hep-ex]. 5
- 2333 [48] ATLAS Collaboration Collaboration, *Observation of electroweak production of a same-sign W*
2334 *boson pair in association with two jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS*
2335 *detector*, Tech. Rep. ATLAS-CONF-2018-030, CERN, Geneva, Jul, 2018.
2336 <https://cds.cern.ch/record/2629411>. 5, 5.7, 6.6.2
- 2337 [49] CMS Collaboration, CMS Collaboration, *Observation of electroweak production of same-sign*
2338 *W boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions*
2339 *at $\sqrt{s} = 13$ TeV*, arXiv:1709.05822 [hep-ex]. 5
- 2340 [50] C. Bittrich, W. K. Di Clemente, et al., *Support note for measurement of electroweak*
2341 *$W^\pm W^\pm jj$ production at $\sqrt{s} = 13$ TeV*, Tech. Rep. ATL-COM-PHYS-2018-252, CERN,
2342 Geneva, Mar, 2018. <https://cds.cern.ch/record/2309552>. 5, 5.3.3, 2, 4, 5.4.3
- 2343 [51] J. M. Campbell and R. K. Ellis, *Higgs Constraints from Vector Boson Fusion and Scattering*,
2344 *JHEP* **04** (2015) 030, arXiv:1502.02990 [hep-ph]. 5.0.2, 5.0.3
- 2345 [52] M. Szleper, *The Higgs boson and the physics of WW scattering before and after Higgs*
2346 *discovery*, arXiv:1412.8367 [hep-ph]. 5.0.2
- 2347 [53] E. Accomando, A. Ballestrero, A. Belhouari, and E. Maina, *Isolating Vector Boson Scattering*
2348 *at the LHC: Gauge cancellations and the Equivalent Vector Boson Approximation vs complete*
2349 *calculations*, *Phys. Rev.* **D74** (2006) 073010, arXiv:hep-ph/0608019 [hep-ph]. 5.0.2

- 2350 [54] P. Anger, B. Axen, et al., *Same Sign $W^\pm W^\pm$ Production and Limits on Anomalous Quartic
2351 Gauge Couplings*, Tech. Rep. ATL-COM-PHYS-2013-990, CERN, Geneva, Jul, 2013.
2352 <https://cds.cern.ch/record/1561731>. Internal note for approved paper **STDM-2013-06**.
2353 **5.0.3, 5.1, 5.6**
- 2354 [55] J. Almond, L. Bianchini, et al., *Search for heavy neutrino, W_R and Z_R gauge bosons in events
2355 with two high- P_T leptons and jets with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ TeV*,
2356 Tech. Rep. ATL-COM-PHYS-2013-810, CERN, Geneva, Jun, 2013.
2357 <https://cds.cern.ch/record/1555805>. Supporting note for EXOT-2012-24, published as
2358 JHEP07 (2015) 162. **5.0.4**
- 2359 [56] ATLAS Collaboration, M. Aaboud et al., *Luminosity determination in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector at the LHC*, Eur. Phys. J. **C76** (2016) no. 12, 653,
2360 [arXiv:1608.03953 \[hep-ex\]](https://arxiv.org/abs/1608.03953). **5.1**
- 2362 [57] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in
2363 ATLAS*, JINST **13** (2018) no. 07, P07017. **5.1**
- 2364 [58] ATLAS Collaboration, G. Aad et al., *The ATLAS Simulation Infrastructure*, Eur. Phys. J.
2365 **C70** (2010) 823–874, [arXiv:1005.4568 \[physics.ins-det\]](https://arxiv.org/abs/1005.4568). **5.1.1**
- 2366 [59] S. Agostinelli et al., *GEANT4 - a simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003)
2367 **250–303**. **5.1.1**
- 2368 [60] T. Sjostrand, S. Mrenna, and P. Skands, *A Brief Introduction to PYTHIA 8.1*, Comput.
2369 Phys. Commun. **178** (2008) 852–867, [arXiv:0710.3820 \[hep-ph\]](https://arxiv.org/abs/0710.3820). **5.1.1**
- 2370 [61] T. Gleisberg et al., *Event generation with SHERPA 1.1*, JHEP **02** (2009) 007,
2371 [arXiv:0811.4622 \[hep-ph\]](https://arxiv.org/abs/0811.4622). **5.1.1**
- 2372 [62] S. Schumann and F. Krauss, *A parton shower algorithm based on Catani-Seymour dipole
2373 factorization*, JHEP **03** (2008) 038, [arXiv:0709.1027 \[hep-ph\]](https://arxiv.org/abs/0709.1027). **5.1.1**
- 2374 [63] S. Höche, F. Krauss, S. Schumann, and F. Siegert, *QCD matrix elements and truncated
2375 showers*, JHEP **05** (2009) 053, [arXiv:0903.1219 \[hep-ph\]](https://arxiv.org/abs/0903.1219). **5.1.1**
- 2376 [64] R. D. Ball et al., *Parton distributions for the LHC Run II*, JHEP **04** (2015) 040,
2377 [arXiv:1410.8849 \[hep-ph\]](https://arxiv.org/abs/1410.8849). **5.1.1**
- 2378 [65] S. Alioli, P. Nason, C. Oleari, and E. Re, *A general framework for implementing NLO
2379 calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **06** (2010) 043,
2380 [arXiv:1002.2581 \[hep-ph\]](https://arxiv.org/abs/1002.2581). **5.1.1**
- 2381 [66] A. Ballestrero et al., *Precise predictions for same-sign W-boson scattering at the LHC*, Eur.
2382 Phys. J. **C78** (2018) no. 8, 671, [arXiv:1803.07943 \[hep-ph\]](https://arxiv.org/abs/1803.07943). **5.1.1**
- 2383 [67] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao,
2384 T. Stelzer, P. Torrielli, and M. Zaro, *The automated computation of tree-level and
2385 next-to-leading order differential cross sections, and their matching to parton shower
2386 simulations*, JHEP **07** (2014) 079, [arXiv:1405.0301 \[hep-ph\]](https://arxiv.org/abs/1405.0301). **5.1.1**
- 2387 [68] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin, and C. P. Yuan, *New
2388 parton distributions for collider physics*, Phys. Rev. D **82** (2010) 074024, [arXiv:1007.2241
2389 \[hep-ph\]](https://arxiv.org/abs/1007.2241). **5.1.1**

- 2390 [69] T. Sjostrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, JHEP **05** (2006)
 2391 026, [arXiv:0603175 \[hep-ph\]](https://arxiv.org/abs/0603175). 5.1.1
- 2392 [70] ATLAS Collaboration, G. Aad et al., *Muon reconstruction performance of the ATLAS*
 2393 *detector in protonproton collision data at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. **C76** (2016) no. 5, 292,
 2394 [arXiv:1603.05598 \[hep-ex\]](https://arxiv.org/abs/1603.05598). 5.2.1.1, 12
- 2395 [71] ATLAS Collaboration Collaboration, *Electron efficiency measurements with the ATLAS*
 2396 *detector using the 2015 LHC proton-proton collision data*, Tech. Rep.
 2397 ATLAS-CONF-2016-024, CERN, Geneva, Jun, 2016.
 2398 <https://cds.cern.ch/record/2157687>. 5.2.1.2
- 2399 [72] M. Cacciari, G. P. Salam, G. Soyez, *The anti- k_t jet clustering algorithm*, JHEP **04** (2008) 063,
 2400 [arXiv:0802.1189 \[hep-ph\]](https://arxiv.org/abs/0802.1189). 5.2.1.3, 6.4.1
- 2401 [73] ATLAS Collaboration, M. Aaboud et al., *Jet energy scale measurements and their systematic*
 2402 *uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys.
 2403 Rev. **D96** (2017) no. 7, 072002, [arXiv:1703.09665 \[hep-ex\]](https://arxiv.org/abs/1703.09665). 5.2.1.3
- 2404 [74] *Tagging and suppression of pileup jets with the ATLAS detector*, Tech. Rep.
 2405 ATLAS-CONF-2014-018, CERN, Geneva, May, 2014.
 2406 [http://cds.cern.ch/record/1700870](https://cds.cern.ch/record/1700870). 5.2.1.3
- 2407 [75] D. Adams, C. Anastopoulos, et al., *Recommendations of the Physics Objects and Analysis*
 2408 *Harmonisation Study Groups 2014*, Tech. Rep. ATL-PHYS-INT-2014-018, CERN, Geneva,
 2409 Jul, 2014. <https://cds.cern.ch/record/1743654>. 5.2.1.4
- 2410 [76] ATLAS Collaboration, M. Aaboud et al., *Measurement of the cross-section for producing a W*
 2411 *boson in association with a single top quark in pp collisions at $\sqrt{s} = 13$ TeV with ATLAS*,
 2412 JHEP **01** (2018) 063, [arXiv:1612.07231 \[hep-ex\]](https://arxiv.org/abs/1612.07231). 5.2.1.4
- 2413 [77] ATLAS Collaboration, M. Aaboud et al., *Performance of missing transverse momentum*
 2414 *reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV*, Eur.
 2415 Phys. J. **C78** (2018) no. 11, 903, [arXiv:1802.08168 \[hep-ex\]](https://arxiv.org/abs/1802.08168). 5.2.2
- 2416 [78] ATLAS Collaboration, M. Aaboud et al., *Measurements of b-jet tagging efficiency with the*
 2417 *ATLAS detector using $t\bar{t}$ events at $\sqrt{s} = 13$ TeV*, JHEP **08** (2018) 089, [arXiv:1805.01845](https://arxiv.org/abs/1805.01845)
 2418 [\[hep-ex\]](https://arxiv.org/abs/1805.01845). 5.2.2
- 2419 [79] J.-F. Arguin, J. Claude, G. Gonella, B. P. Kersevan, K. Koneke, K. Lohwasser, K. Mochizuki,
 2420 M. Muskinja, C. Piaulet, and P. Sommer, *Support Note for Electron ID: charge*
 2421 *mis-identification*, Tech. Rep. ATL-COM-PHYS-2017-1014, CERN, Geneva, Jul, 2017.
 2422 <https://cds.cern.ch/record/2273365>. 5.3.3
- 2423 [80] C.-H. Kom and W. J. Stirling, *Charge asymmetry in $W + \text{jets}$ production at the LHC*, Eur.
 2424 Phys. J. **C69** (2010) 67–73, [arXiv:1004.3404 \[hep-ph\]](https://arxiv.org/abs/1004.3404). 5.4
- 2425 [81] R. Steerenberg, *LHC Report: Another run is over and LS2 has just begun...*,
 2426 [https://home.cern/news/news/accelerators/](https://home.cern/news/news/accelerators/lhc-report-another-run-over-and-ls2-has-just-begun)
 2427 [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
- 2428 [82] *Letter of Intent for the Phase-I Upgrade of the ATLAS Experiment*, Tech. Rep.
 2429 CERN-LHCC-2011-012. LHCC-I-020, CERN, Geneva, Nov, 2011.
 2430 [http://cds.cern.ch/record/1402470](https://cds.cern.ch/record/1402470). 6

- 2431 [83] G. Apollinari, I. Bjar Alonso, O. Brning, M. Lamont, and L. Rossi, *High-Luminosity Large*
2432 *Hadron Collider (HL-LHC): Preliminary Design Report*. CERN Yellow Reports: Monographs.
2433 CERN, Geneva, 2015. <https://cds.cern.ch/record/2116337>. 6
- 2434 [84] ATLAS Collaboration Collaboration, ATLAS Collaboration, *ATLAS Phase-II Upgrade*
2435 *Scoping Document*, Cern-lhcc-2015-020, Geneva, Sep, 2015.
2436 <http://cds.cern.ch/record/2055248>. 6
- 2437 [85] D. Espriu and B. Yencho, *Longitudinal WW scattering in light of the “Higgs boson”*
2438 *discovery*, *Phys. Rev. D* **87** (2013) 055017, arXiv:1212.4158 [hep-ph]. 6, 6.1
- 2439 [86] ATLAS Collaboration Collaboration, *Prospects for the measurement of the $W^\pm W^\pm$ scattering*
2440 *cross section and extraction of the longitudinal scattering component in pp collisions at the*
2441 *High-Luminosity LHC with the ATLAS experiment*, Tech. Rep. ATL-PHYS-PUB-2018-052,
2442 CERN, Geneva, Dec, 2018. <http://cds.cern.ch/record/2652447>. 6
- 2443 [87] ATLAS Collaboration Collaboration, *Studies on the impact of an extended Inner Detector*
2444 *tracker and a forward muon tagger on $W^\pm W^\pm$ scattering in pp collisions at the*
2445 *High-Luminosity LHC with the ATLAS experiment*, Tech. Rep. ATL-PHYS-PUB-2017-023,
2446 CERN, Geneva, Dec, 2017. <https://cds.cern.ch/record/2298958>. 6
- 2447 [88] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel,
2448 C. O. Rasmussen, and P. Z. Skands, *An Introduction to PYTHIA 8.2*, *Comput. Phys.*
2449 *Commun.* **191** (2015) 159–177, arXiv:1410.3012 [hep-ph]. 6.2
- 2450 [89] ATLAS Collaboration Collaboration, *Expected performance for an upgraded ATLAS detector*
2451 *at High-Luminosity LHC*, Tech. Rep. ATL-PHYS-PUB-2016-026, CERN, Geneva, Oct, 2016.
2452 <http://cds.cern.ch/record/2223839>. 6.3
- 2453 [90] P. C. Bhat, H. B. Prosper, S. Sekmen, and C. Stewart, *Optimizing Event Selection with the*
2454 *Random Grid Search*, *Comput. Phys. Commun.* **228** (2018) 245–257, arXiv:1706.09907
2455 [hep-ph]. 6.5.1
- 2456 [91] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Asymptotic formulae for likelihood-based*
2457 *tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554, arXiv:1007.1727 [physics.data-an].
2458 [Erratum: Eur. Phys. J.C73,2501(2013)]. 6.5.1