

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

3 William Kennedy DiClemente

7                   Presented to the Faculties of The University of Pennsylvania  
8       in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy  
9                   2019 Last compiled: March 7, 2019

---

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

14 Joshua Klein, Professor, Physics  
15 Graduate Group Chairperson

Dissertation Committee

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

22 MEASUREMENT OF ELECTROWEAK PRODUCTION OF SAME-SIGN W BOSON PAIRS  
23 WITH ATLAS

24 COPYRIGHT  
25 2019  
26 William Kennedy DiClemente

27 All rights reserved.

---

## Acknowledgements

---

29 It would be impossible to properly thank everyone who has helped me along this journey; nevertheless  
30 I will attempt to be as thorough as possible.

31 First and foremost, I would like to thank my family. My parents, Gwynne Kennedy and John  
32 DiClemente, for always believing in me and listening to me attempt to explain what it is I am  
33 working on. My many feline friends past and present—Stella, Lucky, Julia, Elise, Lucille, Tweedie,  
34 Ruby, and Sylvie—for keeping me warm during the winter holidays back home. My girlfriend Amber  
35 Wright, for tolerating me these past few months and doing your best to keep me relatively sane.

36 Thanks to my advisor Joe Kroll for guiding me through the past six years at Penn; your advice  
37 both in physics and in life has been invaluable to my growth as a physicist and a person. Additional  
38 thanks to the rest of the ATLAS faculty at Penn: Elliot Lipeles, Evelyn Thomson, and Brig Williams.  
39 The amount of open collaboration between students and faculty irrespective of who works for whom  
40 has helped me learn so much.

41 I would also like to extend thanks to two important figures from before my time at Penn. Firstly,  
42 to Gardner Friedlander, my high school physics teacher who first got me interested in the subject.  
43 You were the first to show me how I could use a pen and paper to predict events in real life, a  
44 fascination of mine that has continued into my work here, just with much harder math and on a more  
45 fundamental scale. Secondly, my undergraduate research advisor, Al Goshaw, at Duke University.  
46 You gave a college freshman who thought particle physics was “pretty neat” the opportunity to do  
47 meaningful research with one of the leading collaborations in the field. Without either of you, I  
48 likely would not be in this position today.

49 Thanks to the members of the Inner Detector Alignment group, including but not limited to  
50 Anthony Morley for his guidance on my qualification task, and to Shih-Chieh Hsu, Pierfrancesco  
51 Butti, Matthias Danninger, Salvador Marti, and Steffen Henkelmann for numerous collaborative

52 alignment efforts.

53 The entire  $W^\pm W^\pm jj$  13 TeV analysis group, and those with whom I worked most closely: Philip  
54 Sommer, Emily Duffield, Rustem Ospanov, Stefanie Todt, and Liqing Zhang. Special thanks to  
55 Rustem for pushing me to find my voice in the analysis. Thanks to my  $W^\pm W^\pm jj$  14 TeV prospects  
56 collaborators Claire Lee and Karolos Potamiamos.

57 Lastly, thanks to my fellow Penn ATLAS graduate students, Bijan Haney, Joey Reichert, Khilesh  
58 Mistry, Leigh Schaefer, Bill Balunas, Christian Herwig, Elodie Ressegue, and many more, for lis-  
59 tening to my ramblings, answering my many questions, and for countless entertaining lunchtime  
60 discussions.

# ABSTRACT

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

William Kennedy DiClemente

J. Kroll

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

---

# Contents

---

|    |   |      |
|----|---|------|
| 77 | Acknowledgements  | iii  |
| 78 | Abstract  | v    |
| 79 | Contents  | vi   |
| 80 | List of Tables  | x    |
| 81 | List of Figures   | xiii |
| 82 | Preface   | xx   |
| 83 | 1 Introduction  | 1    |
| 84 | 2 Theoretical Framework   | 3    |
| 85 | 2.1 Introduction to the Standard Model . . . . .                | 3    |
| 86 | 2.2 Electroweak symmetry breaking and the Higgs boson . . . . . | 6    |
| 87 | 2.3 Electroweak vector boson scattering . . . . .               | 9    |
| 88 | 3 LHC and the ATLAS Detector                                    | 12   |
| 89 | 3.1 The Large Hadron Collider . . . . .                         | 12   |
| 90 | 3.2 The ATLAS Detector . . . . .                                | 15   |
| 91 | 3.2.1 The Inner Detector . . . . .                              | 16   |
| 92 | 3.2.1.1 Pixel Detector . . . . .                                | 17   |
| 93 | 3.2.1.2 Semiconductor Tracker . . . . .                         | 18   |
| 94 | 3.2.1.3 Transition Radiation Tracker . . . . .                  | 18   |

|     |          |   |           |
|-----|----------|---|-----------|
| 95  | 3.2.2    | The Calorimeters . . . . .  | 19        |
| 96  | 3.2.2.1  | Liquid Argon Calorimeter . . . . .  | 20        |
| 97  | 3.2.2.2  | Tile Calorimeter . . . . .  | 21        |
| 98  | 3.2.3    | The Muon Spectrometer . . . . .   | 22        |
| 99  | 3.2.4    | Particle reconstruction . . . . .   | 22        |
| 100 | 3.2.4.1  | Track reconstruction . . . . .  | 23        |
| 101 | 3.2.4.2  | Electron reconstruction . . . . .   | 24        |
| 102 | 3.2.4.3  | Muon reconstruction . . . . .   | 27        |
| 103 | <b>4</b> | <b>Alignment of the ATLAS Inner Detector</b>  | <b>31</b> |
| 104 | 4.1      | The alignment method . . . . .  | 32        |
| 105 | 4.1.1    | Alignment levels . . . . .  | 36        |
| 106 | 4.1.2    | Alignment coordinate systems . . . . .  | 37        |
| 107 | 4.2      | Early 2015 alignment of the ATLAS detector . . . . .  | 38        |
| 108 | 4.2.1    | June alignment procedure . . . . .  | 39        |
| 109 | 4.2.2    | Alignment results . . . . .   | 41        |
| 110 | 4.2.2.1  | Residual distributions from collisions . . . . .  | 42        |
| 111 | 4.2.2.2  | Track parameter resolution from cosmic rays . . . . .   | 46        |
| 112 | 4.2.3    | Error scaling . . . . .   | 46        |
| 113 | 4.3      | Level 2 alignment of the TRT . . . . .  | 47        |
| 114 | 4.4      | Momentum bias from sagitta deformations . . . . .   | 50        |
| 115 | 4.4.1    | Sagitta bias monitoring with electron $E/p$ . . . . .   | 51        |
| 116 | 4.4.1.1  | Measuring $\langle E/p \rangle$ . . . . .   | 52        |
| 117 | 4.4.1.2  | Results in 13TeV data . . . . .   | 53        |
| 118 | <b>5</b> | <b>Measurement of same-sign <math>WW</math> production at <math>\sqrt{s} = 13</math> TeV with ATLAS</b> | <b>57</b> |
| 119 | 5.0.1    | Experimental overview of vector boson scattering . . . . .  | 57        |
| 120 | 5.0.2    | Same-sign $W^\pm W^\pm$ scattering . . . . .  | 58        |
| 121 | 5.0.3    | Overview of backgrounds . . . . .   | 60        |
| 122 | 5.1      | Data and Monte Carlo samples . . . . .  | 62        |
| 123 | 5.1.1    | Monte Carlo samples . . . . .   | 63        |
| 124 | 5.2      | Object and event selection . . . . .  | 65        |
| 125 | 5.2.1    | Object selection . . . . .  | 65        |

---

|     |          |  |            |
|-----|----------|--|------------|
| 126 | 5.2.1.1  | Muon candidate selection . . . . .   | 65         |
| 127 | 5.2.1.2  | Electron candidate selection . . . . .                                     | 66         |
| 128 | 5.2.1.3  | Jet candidate selection . . . . .  | 68         |
| 129 | 5.2.1.4  | Treatment of overlapping objects . . . . .                                 | 68         |
| 130 | 5.2.2    | Signal event selection . . . . .   | 69         |
| 131 | 5.3      | Background estimations . . . . .   | 70         |
| 132 | 5.3.1    | Estimation of the $WZ$ background . . . . .                                | 71         |
| 133 | 5.3.2    | Estimation of the $V\gamma$ background . . . . .                           | 72         |
| 134 | 5.3.3    | Estimation of backgrounds from charge misidentification . . . . .          | 74         |
| 135 | 5.3.3.1  | Validation of the charge misidentification estimate . . . . .              | 76         |
| 136 | 5.3.4    | Estimation of non-prompt backgrounds with the fake-factor method . . . . . | 77         |
| 137 | 5.3.4.1  | Overview of the default fake-factor method . . . . .                       | 78         |
| 138 | 5.3.4.2  | The fake-factor with $p_T^{\text{cone}}$ . . . . .                         | 80         |
| 139 | 5.3.4.3  | Application of the fake-factor . . . . .                                   | 81         |
| 140 | 5.3.4.4  | Systematic uncertainties . . . . .   | 85         |
| 141 | 5.3.4.5  | Results of the fake-factor . . . . .                                       | 86         |
| 142 | 5.3.4.6  | Validation of the fake-factor . . . . .                                    | 89         |
| 143 | 5.3.5    | Reduction of $WZ$ background using custom overlap removal . . . . .        | 89         |
| 144 | 5.4      | Cross section measurement . . . . .  | 94         |
| 145 | 5.4.1    | Maximum likelihood fit . . . . .   | 94         |
| 146 | 5.4.2    | Definition of the fiducial volume . . . . .                                | 96         |
| 147 | 5.4.3    | Cross section extraction . . . . .   | 97         |
| 148 | 5.5      | Summary of uncertainties . . . . .   | 98         |
| 149 | 5.5.1    | Experimental uncertainties . . . . .                                       | 98         |
| 150 | 5.5.2    | Theoretical uncertainties . . . . .  | 99         |
| 151 | 5.5.2.1  | Uncertainties from EWK-QCD interference . . . . .                          | 101        |
| 152 | 5.6      | Results . . . . .  | 102        |
| 153 | <b>6</b> | <b>Prospects for same-sign <math>WW</math> at the High Luminosity LHC</b>  | <b>106</b> |
| 154 | 6.0.1    | Analysis Overview . . . . .  | 107        |
| 155 | 6.1      | Theoretical motivation . . . . .   | 108        |
| 156 | 6.1.1    | Experimental sensitivity to longitudinal polarization . . . . .            | 108        |
| 157 | 6.2      | Monte Carlo samples . . . . .  | 109        |

|     |                     |   |            |
|-----|---------------------|---|------------|
| 158 | 6.3                 | Background estimations . . . . .  | 110        |
| 159 | 6.3.1               | Truth-based isolation . . . . .   | 111        |
| 160 | 6.4                 | Object and event selection . . . . .  | 112        |
| 161 | 6.4.1               | Object selection . . . . .  | 112        |
| 162 | 6.4.2               | Event selection . . . . .   | 112        |
| 163 | 6.5                 | Selection optimization . . . . .  | 113        |
| 164 | 6.5.1               | Random grid search algorithm . . . . .  | 114        |
| 165 | 6.5.2               | Inputs to the optimization . . . . .  | 115        |
| 166 | 6.5.3               | Results of the optimization . . . . .   | 116        |
| 167 | 6.6                 | Results . . . . .   | 117        |
| 168 | 6.6.1               | Event yields . . . . .  | 117        |
| 169 | 6.6.2               | Uncertainties . . . . .   | 121        |
| 170 | 6.6.3               | Cross section measurement . . . . .   | 122        |
| 171 | 6.6.4               | Longitudinal scattering significance . . . . .  | 122        |
| 172 | <b>7</b>            | <b>Conclusion</b>   | <b>126</b> |
| 173 | <b>A</b>            | <b>Additional material on <math>W^\pm W^\pm jj</math> measurement at <math>\sqrt{s} = 13\text{TeV}</math></b> | <b>127</b> |
| 174 | A.1                 | Impact of experimental uncertainty on MC background estimations . . . . .                                     | 127        |
| 175 | A.2                 | Pre-fit event yields . . . . .  | 129        |
| 176 | <b>B</b>            | <b>Additional material on <math>W^\pm W^\pm jj</math> prospects at the HL-LHC</b>                             | <b>130</b> |
| 177 | B.1                 | Truth isolation . . . . .   | 130        |
| 178 | B.1.1               | TRUTH1++ derivations . . . . .  | 131        |
| 179 | B.1.2               | Check of truth-based isolation . . . . .  | 132        |
| 180 | B.1.3               | Loose isolation working point . . . . .   | 132        |
| 181 | B.2                 | Plots of other optimization variables . . . . .   | 135        |
| 182 | <b>Bibliography</b> |   | <b>137</b> |

---

## List of Tables

---

|             |   |    |
|-------------|---|----|
| 184    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.  | 37 |
| 186    4.2  | Summary of the highest level of alignment applied to each ID subsystem when deriving the June alignment. . . . .  | 40 |
| 188    4.3  | Estimated value of the error scaling term $b$ for each subdetector component with the June alignment. . . . .   | 48 |
| 190    5.1  | Predicted cross sections for EQK and QCD production of diboson processes relevant to VBS at $\sqrt{s} = 13\text{TeV}$ using the <b>SHERPA</b> MC generator. The numbers for the $W^\pm W^\pm jj$ process are bolded. Leptons are required to have $p_T \geq 25\text{ GeV}$ and lie within $ \eta  \leq 2.5$ with $m_{ll} > 20\text{ GeV}$ , and at least two jets are required with $p_T \geq 30\text{ GeV}$ and $ \eta  < 4.5$ . The VBS contributions are enhanced by requiring the dijet invariant mass $m_{jj} > 500\text{ GeV}$ and dijet separation $\Delta y_{jj} > 2.4$ . . . . . | 60 |
| 196    5.2  | Summary of MC samples used in the analysis. . . . .   | 64 |
| 197    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. . . . .   | 66 |
| 199    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. . . . .   | 67 |
| 202    5.5  | Jet selection criteria. All jets are required to pass the above selection in order to be used in the analysis. . . . .  | 68 |
| 204    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. . . . .  | 69 |
| 207    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. . . . .  | 70 |
| 209    5.8  | The signal event selection. . . . .   | 71 |
| 210    5.9  | Event yields in the $WZ$ control region before normalization. All lepton flavor channels are combined. . . . .  | 72 |
| 212    5.10 | Selection criteria for the $V\gamma$ control region. . . . .  | 73 |
| 213    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. . . . .  | 74 |

|     |   |     |
|-----|---|-----|
| 216 | 5.12 Selection criteria for the same-sign inclusive validation region. . . . .  | 77  |
| 217 | 5.13 Event selection for the dijet region used for calculating the fake-factor. The selected                                  |     |
| 218 | lepton can pass either the nominal (signal) or loose selections. In the case of the nominal                                   |     |
| 219 | leptons, the $p_T > 27$ GeV requirement is replaced with $p_T > 15$ GeV. . . . .  | 83  |
| 220 | 5.14 Values of the fake-factor in each $p_T$ bin and for each individual systematic source. . . . .                           | 88  |
| 221 | 5.15 Estimated yields for the fake lepton background. The estimated yield is shown in the first                               |     |
| 222 | column together with the statistical uncertainty followed by the systematic uncertainties                                     |     |
| 223 | from variations of the the fake-factors within their statistical (stat.) and systematic                                       |     |
| 224 | (syst.) uncertainties. The labels $f_e$ and $f_\mu$ indicate the fake-factors for electrons and                               |     |
| 225 | muons, respectively. . . . .  | 88  |
| 226 | 5.16 Selection criteria for the same-sign top fakes validation region. . . . .  | 89  |
| 227 | 5.17 Custom OR definition. Leptons must pass this selection in order to be counted for the                                    |     |
| 228 | trilepton veto. . . . .   | 93  |
| 229 | 5.18 Definition of the fiducial volume. . . . .   | 96  |
| 230 | 5.19 Impact of various systematic effects on the fiducial cross section measurement. The                                      |     |
| 231 | impact of a given source of uncertainty is computed by performing the fit with the  |     |
| 232 | corresponding nuisance parameter varied up or down by one standard deviation from its   |     |
| 233 | nominal value. . . . .  | 99  |
| 234 | 5.20 List of sources of experimental uncertainties on the reconstruction of physics objects. . . . .                          | 100 |
| 235 | 5.21 Impact of experimental uncertainties for the $W^\pm W^\pm jj$ EWK processes in all channels.                             | 100 |
| 236 | 5.22 Impact of experimental uncertainties for the $WZ$ process in all channels. . . . .                                       | 100 |
| 237 | 5.23 The set of generator level cuts used for generating the interference samples with <code>MadGraph</code> . <sup>101</sup> |     |
| 238 | 5.24 Cross sections for each different $W^\pm W^\pm jj$ production mode (inclusive, EWK only, QCD                             |     |
| 239 | only, and interference only) generated using <code>MadGraph</code> . The cross sections are calculated                        |     |
| 240 | using a minimal set of generator level cuts from events where the $W$ decays to a muon.                                       | 102 |
| 241 | 5.25 Table of the data and prediction event yields in the signal region after the fit. Numbers                                |     |
| 242 | are shown for the six lepton flavor and charge channels and for all channels combined. The                                    |     |
| 243 | background estimations from the fake-factor are included in the “Non-prompt” category,  |     |
| 244 | and backgrounds from $V\gamma$ production and electron charge misidentification are combined                                  |     |
| 245 | in the “ $e/\gamma$ conversions” category. Finally, $ZZ$ , $VVV$ , and $t\bar{t}V$ backgrounds are combined                   |     |
| 246 | in the “Other prompt” category. . . . .   | 103 |
| 247 | 6.1 Summary of MC samples used in the analysis. . . . .   | 110 |
| 248 | 6.2 Truth-based isolation requirements for electrons and muons. . . . .   | 111 |
| 249 | 6.3 Summary of the signal event selection. . . . .  | 113 |
| 250 | 6.4 Updates to the $W^\pm W^\pm jj$ event selection criteria after optimization. Cuts not listed                              |     |
| 251 | remain unchanged from the default selection in Table 6.3. . . . .   | 117 |
| 252 | 6.5 Signal and background event yields using the default event selection for an integrated                                    |     |
| 253 | luminosity of $\mathcal{L} = 3000 \text{ fb}^{-1}$ . Events containing a fake or charge-flipped electron are                  |     |
| 254 | removed from their respective sources and combined into a single entry each. . . . .  | 118 |
| 255 | 6.6 Signal and background event yields using the optimized event selection for an integrated                                  |     |
| 256 | luminosity of $\mathcal{L} = 3000 \text{ fb}^{-1}$ . Events containing a fake or charge-flipped electron are                  |     |
| 257 | removed from their respective sources and combined into a single entry each. . . . .  | 119 |
| 258 | 6.7 Summary of estimated experimental and rate uncertainties. . . . .   | 121 |
| 259 | A.1 Impact of experimental uncertainties for the $W^\pm W^\pm jj$ QCD processes in all channels. .                            | 127 |
| 260 | A.2 Impact of experimental uncertainties for triboson process in all channels. . . . .  | 128 |
| 261 | A.3 Impact of experimental uncertainties for $t\bar{t}V$ processes in all channels. . . . .                                   | 128 |
| 262 | A.4 Impact of experimental uncertainties for the $W\gamma$ process in all channels. . . . .                                   | 128 |

|     |   |     |
|-----|---|-----|
| 263 | A.5 Impact of experimental uncertainties for the $Z\gamma$ process in all channels. . . . .   | 128 |
| 264 | A.6 Impact of experimental uncertainties for the $ZZ$ process in all channels. . . . .  | 129 |
| 265 | A.7 Table of the data and prediction event yields in the signal region before the fit. Numbers<br>266 are shown for the six lepton flavor and charge channels and for all channels combined.<br>267 Here the $WZ$ background yields are normalized to the data in the $WZ$ control region. The<br>268 background estimations from the fake-factor are included in the “Non-prompt” category,<br>269 and backgrounds from $V\gamma$ production and electron charge misidentification are combined<br>270 in the “ $e/\gamma$ conversions” category. Finally, $ZZ$ , $VVV$ , and $t\bar{t} + V$ backgrounds are<br>271 combined in the “Other prompt” category. . . . . | 129 |
| 272 | B.1 Event yields prior to applying any form of truth-based isolation criteria. . . . .  | 130 |
| 273 | B.2 Event yields after applying a test version of the truth-based isolation. . . . .  | 131 |
| 274 | B.3 Electron and muon isolation requirements for the loose working point. . . . .   | 132 |
| 275 | B.4 Event yields broken down by sample and by background type using the loose isolation<br>276 workingpoint. Events containing a fake or charge-flipped electron are removed from their<br>277 respective sample and added to the “fakes” and “charge flip” rows, respectively. Errors<br>278 include statistical uncertainty and estimated systematic rate uncertainty based on the<br>279 background process. . . . .   | 133 |
| 280 | B.5 Event yields broken down by background type using the tight isolation workingpoint.<br>281 Events containing a fake or charge-flipped electron are removed from their respective<br>282 sample and added to the “fakes” and “charge flip” rows, respectively. Errors include sta-<br>283 tistical uncertainty and estimated systematic rate uncertainty based on the background<br>284 process. . . . .   | 134 |

---

## List of Figures

---

|            |   |    |
|------------|---|----|
| 286    2.1 | Summary of several Standard Model total and fiducial production cross section measurements compared to the corresponding theoretical predictions calculated at NLO or higher. The dark colored error bar represents the statistical uncertainty, and the light colored error bar represents the full uncertainty (including systematic and luminosity uncertainties). The data/theory ratio, luminosity used and reference for each measurement are also shown. . . . . | 4  |
| 292    2.2 | An illustration of the potential term $V(\phi)$ in Equation 2.6 for the cases where $\mu^2 > 0$ (left) and $\mu^2 < 0$ (right). The right-hand plot shows the Higgs potential, or “Mexican hat potential”, with the minimum at $ \phi  = \sqrt{-\frac{\mu^2}{\lambda}}$ rather than at $ \phi  = 0$ as in the left-hand plot. . . . .   | 7  |
| 296    2.3 | Feynman diagram of a generic VBS process. The gray circle represents any interaction with two incoming and two outgoing vector bosons, including any of the diagrams shown in Figures 2.4 and 2.5. . . . .  | 9  |
| 299    2.4 | Leading order $VV \rightarrow VV$ Feynman diagrams involving EWK bosons. From left to right: $s$ -channel, $t$ -channel, $u$ -channel, and the quartic gauge coupling. . . . .  | 9  |
| 301    2.5 | Leading order $VV \rightarrow VV$ Feynman diagrams involving the exchange of a Higgs boson. From left to right: $s$ -channel, $t$ -channel, and $u$ -channel. . . . .   | 10 |
| 303    2.6 | Cross sections in nanobarns for five different longitudinally polarized VBS processes as a function of center of mass energy $\sqrt{s}$ . Without a Higgs boson (left), the cross sections grow unbounded with $\sqrt{s}$ . With a 120 GeV Higgs boson (right), the cross sections no longer diverge. . . . .   | 11 |
| 307    3.1 | The CERN accelerator complex. For LHC collisions, protons are accelerated by the Linac 2 (purple), the PSB (light purple), the PS (magenta), and the SPS (light blue) before entering the LHC ring (dark blue). . . . .   | 13 |
| 310    3.2 | Peak instantaneous luminosity delivered to ATLAS during 13TeV $pp$ data taking as a function of time. . . . .   | 14 |
| 312    3.3 | Integrated luminosity collected by ATLAS as a function of time at 13TeV from 2015-2018. . . . .   | 14 |
| 313    3.4 | Distribution of the mean number of interactions per bunch crossing for the 2015 and 2016 $pp$ collision data at 13TeV. . . . .  | 15 |
| 315    3.5 | Cut-away view of the ATLAS detector. . . . .  | 16 |
| 316    3.6 | The barrel layers of the Pixel, SCT, and TRT detectors making up the Inner Detector. . . . .  | 17 |

|     |      |  |    |
|-----|------|--|----|
| 317 | 3.7  | Cut-away view of the ATLAS calorimeter systems. . . . .  | 19 |
| 318 | 3.8  | Diagram of the cells within the LAr barrel. The accordion structure can be seen in the cut-away view. . . . .  | 21 |
| 320 | 3.9  | Measured LH electron ID efficiencies in $Z \rightarrow ee$ events for the <b>LooseLH</b> (blue), <b>MediumLH</b> (red), and <b>TightLH</b> (black) working points as a function of electron $E_T$ . The bottom panel shows data-to-simulation ratios. . . . .  | 25 |
| 323 | 3.10 | Measured isolation efficiencies for the <b>LooseTrackOnly</b> (black), <b>Loose</b> (red), <b>GradientLoose</b> (blue), and <b>Gradient</b> (yellow) working points as a function of electron $E_T$ . The bottom panel shows data-to-simulation ratios. . . . .  | 27 |
| 326 | 3.11 | Muon reconstruction efficiencies in $Z \rightarrow \mu\mu$ events for the <b>Loose</b> (yellow), <b>Medium</b> (red), and <b>Tight</b> (blue) ID working points as a function of muon $\eta$ . The drop in efficiency for <b>Medium</b> and <b>Tight</b> muons in the range $ \eta  < 0.1$ is due to the exclusion of CT and ME muons, which are used to recover acceptance in this region. Collision data (solid points) is compared to simulation (open points) and the ratio is in the lower panel. . . . . | 29 |
| 331 | 3.12 | Muon isolation efficiencies in $Z \rightarrow \mu\mu$ events for the <b>Loose</b> (left) and <b>GradientLoose</b> (right) working points as a function of muon $p_T$ . Collision data (black) is compared to simulation (red) and the ratio is in the lower panel. . . . .   | 30 |
| 334 | 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 a shift in the third detector element. The cyan lines represent the track-to-hit residuals. . . . .   | 32 |
| 338 | 4.2  | Graphical representation of the ID alignment chain. . . . .  | 35 |
| 339 | 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. . . . .  | 38 |
| 343 | 4.4  | The $d_0$ distributions with respect to the reconstructed primary vertex using 13TeV 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. . . . .   | 41 |
| 347 | 4.5  | Local $x$ (left) and local $y$ (right) residual distributions of the IBL planar sensors using 13TeV 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. . . . .  | 43 |
| 351 | 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 13TeV 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). . . . .  | 43 |
| 355 | 4.7  | Local $x$ (left) and local $y$ (right) residual distributions for the Pixel barrel (excluding the IBL) using 13TeV 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. . . . .   | 44 |
| 359 | 4.8  | Local $x$ (left) and local $y$ (right) residual distributions for the Pixel endcaps using 13TeV 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. . . . .  | 44 |

|     |      |  |    |
|-----|------|--|----|
| 363 | 4.9  | Local $x$ residual distributions for the SCT barrel (left) and end-caps (right) using 13TeV 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. . . . .  | 45 |
| 364 |      |  |    |
| 365 |      |  |    |
| 366 |      |  |    |
| 367 | 4.10 | Residual distributions for the TRT barrel (left) and end-caps (right) using 13TeV 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. . . . .  | 45 |
| 368 |      |  |    |
| 369 |      |  |    |
| 370 |      |  |    |
| 371 | 4.11 | Representation of splitting a single cosmic ray track passing through the entire detector (left) into two separate tracks (right). . . . .   | 46 |
| 372 |      |  |    |
| 373 | 4.12 | Distribution of the difference in the impact parameter $\Delta d_0$ (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. . . . .   | 47 |
| 374 |      |  |    |
| 375 |      |  |    |
| 376 |      |  |    |
| 377 | 4.13 | Pull distributions in local $x$ (left) and $y$ (right) for the IBL using 13TeV collision data sample after applying the error scaling. . . . .   | 48 |
| 378 |      |  |    |
| 379 | 4.14 | Residual means by straw layer in two TRT $\phi$ -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. . . . .  | 49 |
| 380 |      |  |    |
| 381 |      |  |    |
| 382 |      |  |    |
| 383 | 4.15 | Two dimensional map of residuals in the first layer of the TRT barrel vs $z$ and $\phi$ . 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. . . . .                | 49 |
| 384 |      |  |    |
| 385 |      |  |    |
| 386 |      |  |    |
| 387 |      |  |    |
| 388 | 4.16 | Representation of a curl distortion in the detector. The image represents a cutaway view of the transverse plane of the barrel region. 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. . . . . | 50 |
| 389 |      |  |    |
| 390 |      |  |    |
| 391 |      |  |    |
| 392 |      |  |    |
| 393 | 4.17 | Geometric definition of the sagitta $s$ in relation to the length of the chord $l$ and the radius $R$ of a circular arc. . . . .   | 51 |
| 394 |      |  |    |
| 395 | 4.18 | $E/p$ distributions of electrons and positrons in two different $\eta$ - $\phi$ bins of the detector. The left hand plot is taken from a region with no momentum bias where $\langle E/p \rangle^+ = \langle E/p \rangle^-$ , while the right hand plot shows an 8% disagreement in $\langle E/p \rangle$ between electrons and positrons. . . . .   | 53 |
| 396 |      |  |    |
| 397 |      |  |    |
| 398 |      |  |    |
| 399 | 4.19 | Sagitta bias in the $\sqrt{s} = 13\text{TeV}$ data collected by ATLAS in 2016 as a function of $\eta$ and $\phi$ for the prompt (left) and reprocessed (right) alignments using the $E/p$ method. . . . .  | 54 |
| 400 |      |  |    |
| 401 | 4.20 | Sagitta bias in the $\sqrt{s} = 13\text{TeV}$ data collected by ATLAS in 2016 projected along $\eta$ for the prompt (gray) and reprocessed (blue) alignments using the $E/p$ method. . . . .   | 55 |
| 402 |      |  |    |
| 403 | 4.21 | Sagitta bias in the $\sqrt{s} = 13\text{TeV}$ data collected by ATLAS in 2017 as a function of $\eta$ and $\phi$ in reconstructed electrons (left) and after two iterations of momentum corrections (right) from the $E/p$ method. . . . .   | 55 |
| 404 |      |  |    |
| 405 |      |  |    |
| 406 | 4.22 | Sagitta bias in the $\sqrt{s} = 13\text{TeV}$ data collected by ATLAS in 2017 projected along $\eta$ in reconstructed electrons (gray) and after one (red) and two (blue) iterations of momentum corrections from the $E/p$ method. . . . .  | 56 |
| 407 |      |  |    |
| 408 |      |  |    |

|     |      |  |    |
|-----|------|--|----|
| 409 | 5.1  | Tree-level Feynman diagrams for VBS EWK $VVjj$ production including triple gauge<br>410   couplings involving $W$ and/or $Z$ bosons (top left and top middle), quartic gauge coupling<br>411   (top right), or the exchange of a Higgs boson ( $s$ -channel bottom left and $t$ -channel bottom<br>412   right). The labels are quarks ( $q$ ), fermions ( $f$ ), and gauge bosons ( $V = W, Z$ ) . . . . .  | 59 |
| 413 | 5.2  | Tree-level Feynman diagrams for non-VBS EWK $VVjj$ production. The labels are quarks<br>414   ( $q$ ), fermions ( $f$ ), and gauge bosons ( $V = W, Z$ ) . . . . .   | 59 |
| 415 | 5.3  | Tree-level Feynman diagrams for QCD $VVjj$ production. The labels are quarks ( $q$ ),<br>416   fermions ( $f$ ), and gauge bosons ( $V = W, Z$ ) . . . . .   | 59 |
| 417 | 5.4  | Leading order Feynman diagrams for VBS EWK production of $W^\pm W^\pm jj$ events. The<br>418   leftmost diagram contains a quartic gauge coupling vertex, and the rightmost diagram<br>419   contains an exchange of a Higgs boson . . . . .   | 61 |
| 420 | 5.5  | $W^\pm W^\pm jj$ VBS event topology containing two leptons (1 and 2) with the same elec-<br>421   tric charge, two neutrinos, and two forward tagging jets (3 and 4) with large rapidity<br>422   separation $\Delta y$ . . . . .  | 61 |
| 423 | 5.6  | Generator level comparisons at $\sqrt{s} = 7\text{TeV}$ of dijet invariant mass ( $m_{jj}$ , left) and dijet<br>424   rapidity ( $\Delta y_{jj}$ , right) in EWK (red) and QCD (blue) $W^\pm W^\pm jj$ events with no selection<br>425   cuts applied . . . . .  | 62 |
| 426 | 5.7  | ATLAS event display of a $pp \rightarrow W^+W^+ \rightarrow \mu^+\nu_\mu\mu^+\nu_\mu jj$ event. The muons are rep-<br>427   resented by the red lines travelling from the ID through the MS, and the forward jets<br>428   are represented by the blue cones with yellow energy deposits in the calorimeters. The<br>429   direction of the $E_T^{\text{miss}}$ in the transverse plane is indicated by the gray dashed line in the<br>430   inset image . . . . . | 63 |
| 431 | 5.8  | Leading lepton $p_T$ (left) and $\eta$ (right) distributions in the $WZ$ control region before<br>432   normalization. All lepton channels are combined . . . . .  | 72 |
| 433 | 5.9  | Trilepton invariant mass $m_{lll}$ distribution in the $WZ$ control region before normalization.<br>434   All lepton channels are combined . . . . .   | 73 |
| 435 | 5.10 | Charge misidentification rates for electrons as a function of $ \eta $ and $p_T$ . Rates are calcu-<br>436   lated from $Z \rightarrow e^+e^-$ MC after applying scale factors to approximate the charge mis-ID<br>437   rates in data . . . . .   | 75 |
| 438 | 5.11 | Dilepton invariant mass distribution $m_{ll}$ for the $ee$ channel in the same-sign inclusive VR .   | 77 |
| 439 | 5.12 | $p_T$ distributions for the leading (left) and subleading (right) electron for the $ee$ channel<br>440   in the same-sign inclusive VR. In these plots, the cut requiring $m_{ee}$ to fall within the $Z$<br>441   mass window has been inverted in order to test the modelling away from the $Z$ peak . .   | 78 |
| 442 | 5.13 | Graphical representation of how the fake factor method is used to estimate the fake<br>443   background in a given $NN$ region . . . . .   | 79 |
| 444 | 5.14 | $\Delta p_T$ distributions for nominal (blue) and loose (red) muons in simulated $t\bar{t}$ events. Each<br>445   muon has been matched to a truth-level jet. Both distributions are normalized to unit<br>446   area . . . . .  | 81 |
| 447 | 5.15 | $\Delta p_T$ distributions for muons (top) and electrons (bottom) in simulated $t\bar{t}$ events. Each<br>448   lepton has been matched to a truth-level jet, and that truth jet has had its $p_T$ corrected<br>449   to include all truth muons within a cone of $\Delta R < 0.4$ . The nominal leptons are in black.<br>450 $\Delta p_T$ is calculated for the loose leptons using $p_T$ (red) and $p_T + p_T^{\text{cone}}$ (blue) . . . . .                    | 82 |
| 451 | 5.16 | Distributions of $p_T^{\text{cone}}/p_T$ for nominal (black) and loose (red) muons in simulated $t\bar{t}$ events.   | 83 |
| 452 | 5.17 | The measured fake-factor as a function of muon $p_T + p_T^{\text{cone}}$ . The error bars represent the<br>453   statistical uncertainty only . . . . .  | 84 |
| 454 | 5.18 | The measured fake-factor as a function of electron $p_T + p_T^{\text{cone}}$ in the central ( $ \eta  < 1.37$ ,<br>455   blue) and forward ( $ \eta  > 1.37$ , red) regions of the detector. The error bars represent the<br>456   statistical uncertainty only . . . . .  | 85 |

|     |  |     |
|-----|--|-----|
| 457 | 5.19 Systematic variations in the fake-factor as a function of muon $p_T + p_T^{\text{cone}}$ . The individual<br>458 fake-factors obtained for each systematic variation are displayed with their statistical<br>459 uncertainties. . . . .   | 86  |
| 460 | 5.20 Systematic variations in the fake-factor as a function of electron $p_T + p_T^{\text{cone}}$ in the central<br>461 ( $ \eta  < 1.37$ , top) and forward ( $ \eta  > 1.37$ , bottom) regions of the detector. The individual<br>462 fake-factors obtained for each systematic variation are displayed with their statistical<br>463 uncertainties. . . . .   | 87  |
| 464 | 5.21 Distributions of the subleading lepton $p_T$ in the same-sign top fakes VR for $\mu^\pm\mu^\pm$ events<br>465 (top right), $e^\pm e^\pm$ events (top left), $\mu^\pm e^\pm$ events (bottom left), and all events combined<br>466 (bottom right). All errors are statistical only. . . . .   | 90  |
| 467 | 5.22 Pseudorapidity ( $\eta$ ) distributions of truth muons (top) and electrons (bottom) for Sherpa<br>468 $W^\pm W^\pm jj$ and $WZ$ MC samples. The blue vertical lines represent the allowed $\eta$ range<br>469 for each lepton flavor. The numbers correspond to the number of raw MC events that<br>470 fall within and outside of the allowed $\eta$ range for each MC sample. . . . .   | 91  |
| 471 | 5.23 Distributions of $p_{T,\text{ratio}}(\mu, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and $WZ$ back-<br>472 ground (teal) for truth-matched third muons in events that pass the trilepton veto. Both<br>473 distributions are normalized to unit area. The associated efficiency curves are on the<br>474 right where efficiency is defined as the percentage of total events that would pass a cut<br>475 on $p_{T,\text{ratio}}(\mu, j)$ at a given value on the $x$ -axis. . . . .   | 91  |
| 476 | 5.24 Distributions of $\Delta R(\mu, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and $WZ$ back-<br>477 ground (teal) for truth-matched third muons in events that pass the trilepton veto. Both<br>478 distributions are normalized to unit area. The associated efficiency curves are on the<br>479 right where efficiency is defined as the percentage of total events that would pass a cut<br>480 on $\Delta R(\mu, j)$ at a given value on the $x$ -axis. . . . .   | 92  |
| 481 | 5.25 Distributions of $p_{T,\text{ratio}}(e, j)$ for EWK and QCD $W^\pm W^\pm jj$ signal (black) and $WZ$ back-<br>482 ground (teal) for truth-matched third electrons in events that pass the trilepton veto.<br>483 Both distributions are normalized to unit area. The associated efficiency curves are on the<br>484 right where efficiency is defined as the percentage of total events that would pass a cut<br>485 on $p_{T,\text{ratio}}(e, j)$ at a given value on the $x$ -axis. . . . .   | 92  |
| 486 | 5.26 Two-dimensional plots of $p_{T,\text{ratio}}(\mu, j)$ vs $\Delta R(\mu, j)$ for truth-matched third muons in<br>487 events that pass the trilepton veto for EWK and QCD $W^\pm W^\pm jj$ signal (left) and $WZ$<br>488 background (right). The blue overlay indicates the area in which the third leptons will<br>489 pass the custom OR and result in the event failing the trilepton veto. . . . .  | 93  |
| 490 | 5.27 Visual representation of the different kinematic regions relevant to the cross section mea-<br>491 surement. The acceptance factor $\mathcal{A}$ converts from the truth level total phase space to the<br>492 truth level fiducial region, and the efficiency correction $\mathcal{C}$ translates the fiducial region<br>493 in to the reconstruction level signal region. . . . .   | 97  |
| 494 | 5.28 The dijet invariant mass $m_{jj}$ distributions for data and predicted signal and background<br>495 in the signal region after the fit. The shaded band represents the statistical and systematic<br>496 uncertainties added in quadrature. Note that the bins have been scaled such that they<br>497 represent the number of events per 100 GeV in $m_{jj}$ . The background estimations from<br>498 the fake-factor are included in the “Non-prompt” category, and backgrounds from $V\gamma$<br>499 production and electron charge misidentification are combined in the “ $e/\gamma$ conversions”<br>500 category. Finally, $ZZ$ , $VVV$ , and $t\bar{t}+V$ backgrounds are combined in the “Other prompt”<br>501 category. . . . . | 103 |

|     |      |   |     |
|-----|------|---|-----|
| 502 | 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 “ $e/\gamma$ conversions” category. Finally, $ZZ$ , $VVV$ , and $t\bar{t}V$ backgrounds are combined in the “Other prompt” category. . . . . | 104 |
| 508 | 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. . . . .          | 105 |
| 515 | 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. . . . .  | 108 |
| 517 | 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. . . . .  | 109 |
| 519 | 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. . . . .  | 115 |
| 523 | 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). . . . .   | 118 |
| 527 | 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). . . . .  | 119 |
| 530 | 6.6  | $p_T$ distributions for the leading jet using the default (left) and optimized (right) event selections for all channels combined. . . . .  | 120 |
| 532 | 6.7  | $p_T$ distributions for the subleading jet using the default (left) and optimized (right) event selections for all channels combined. . . . .   | 120 |
| 534 | 6.8  | $p_T$ distributions for lepton-jet centrality $\zeta$ using the default (left) and optimized (right) event selections for all channels combined. . . . .  | 121 |
| 536 | 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. . . . .  | 123 |
| 539 | 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. . . . .   | 124 |
| 542 | 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). . . . .  | 125 |
| 545 | 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. . . . .   | 131 |

|     |     |  |     |
|-----|-----|--|-----|
| 549 | 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). . . . .    | 135 |
| 550 | 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). . . . . | 135 |
| 551 | 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). . . . .    | 136 |
| 552 |     |  |     |
| 553 |     |  |     |
| 554 |     |  |     |
| 555 |     |  |     |
| 556 |     |  |     |
| 557 |     |  |     |

---

## Preface

---

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

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

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

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

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

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

612

Will K. DiClemente

Philadelphia, February 2019

# CHAPTER 1

---

## Introduction

---

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

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

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

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

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

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

## CHAPTER 2

# Theoretical Framework

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

### 662 2.1 Introduction to the Standard Model

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

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

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

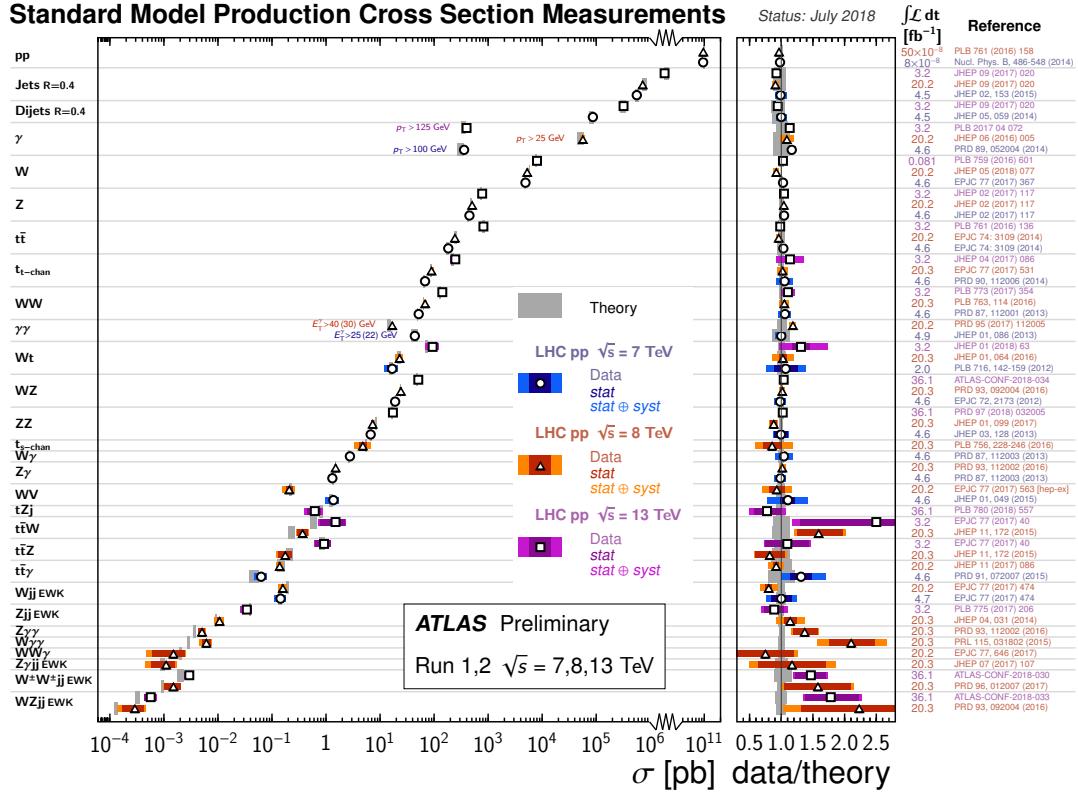


Figure 2.1: Summary of several Standard Model total and fiducial production cross section measurements compared to the corresponding theoretical predictions calculated at NLO or higher. The dark colored error bar represents the statistical uncertainty, and the light colored error bar represents the full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

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

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

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

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

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

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

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

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

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

<sup>717</sup> **2.2 Electroweak symmetry breaking and the Higgs boson**

<sup>718</sup> The results of electroweak mixing and the implications of the Higgs field have been introduced  
<sup>719</sup> in the previous section. If the EWK theory were an unbroken symmetry, the associated  $W^\pm$  and  
<sup>720</sup>  $Z$  bosons would be massless; however, when observed experimentally, they were found to be quite  
<sup>721</sup> heavy [18, 19], at around 80 GeV and 91 GeV, respectively [20]. Here, a more detailed explanation  
<sup>722</sup> of the Higgs mechanism and how it “spontaneously breaks” the EWK symmetry, resulting in the  
<sup>723</sup> three massive bosons ( $W^\pm$  and  $Z$ ) and one massless boson (photon), is presented.

<sup>724</sup> To see how the Higgs mechanism results in the massive vector bosons and a massless photon,  
<sup>725</sup> consider the following. Beginning with a complex scalar doublet  $\phi$  defined as:

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

<sup>726</sup> a Lagrangian  $\mathcal{L}$  can be written:

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

<sup>727</sup> where  $\lambda > 0$  and  $\mathcal{D}_\mu$  is the covariant derivative defined such that  $\mathcal{L}$  is invariant under a local  
<sup>728</sup>  $SU(2) \times U(1)$  gauge transformation:

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

<sup>729</sup> Here  $W_\mu^a$  ( $a = 1, 2, 3$ ) are the  $SU(2)$  fields with generators  $\tau_a$  and coupling constant  $g$ , and  $B_\mu$  is the  
<sup>730</sup>  $U(1)$  field with coupling constant  $g'$ .

<sup>731</sup> Isolating the potential term of the Lagrangian:

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

<sup>732</sup> a choice must be made on the sign of  $\mu^2$ , and the case of interest is for  $\mu^2 < 0$ . This results in  
<sup>733</sup> the famous “Mexican hat potential” shown in Figure 2.2, which is minimized along the collection of  
<sup>734</sup> points:

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

<sup>735</sup> This means that the minimum of the potential is not at  $\phi = 0$  (as it would be in the case where  
<sup>736</sup>  $\mu^2 > 0$ ), but rather at a value:

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

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

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

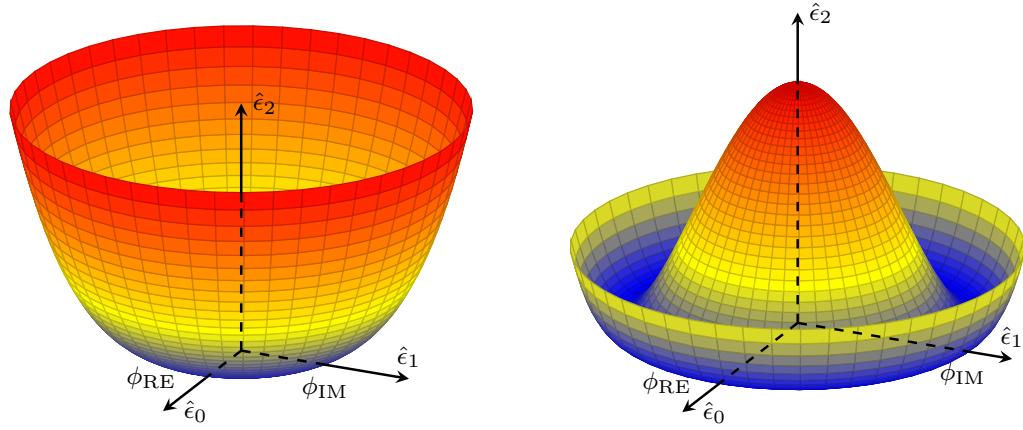


Figure 2.2: An illustration of the potential term  $V(\phi)$  in Equation 2.6 for the cases where  $\mu^2 > 0$  (left) and  $\mu^2 < 0$  (right). The right-hand plot shows the Higgs potential, or ‘Mexican hat potential’, with the minimum at  $|\phi| = \sqrt{-\frac{\mu^2}{\lambda}}$  rather than at  $|\phi|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

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

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

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

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

744

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

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

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

<sup>746</sup> where  $Z_\mu^2$  and  $A_\mu^2$  represent the physical  $Z$  boson and photon, respectively, and are defined as:

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

<sup>747</sup>

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

<sup>748</sup> From this, it can be seen that the photon is massless ( $M_A = 0$  in Equation 2.13), and the mass of  
<sup>749</sup> the  $Z$  boson is identified as:

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

<sup>750</sup> Lastly, the Higgs field can couple directly to the fermions. Taking the electron as an example,  
<sup>751</sup> an additional Lagrangian term can be written:

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

<sup>752</sup> where  $e_L$  and  $e_R$  are the left-handed doublet and right-handed singlet, respectively, and  $\phi$  is as in  
<sup>753</sup> Equation 2.3. The symmetry can be spontaneously broken by a perturbation about the VEV:

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

<sup>754</sup> which, when substituted into  $\mathcal{L}_e$  gives:

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

<sup>755</sup> 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  
<sup>756</sup> coupling to the electron is proportional to the mass of the electron. The rest of the fermion couplings  
<sup>757</sup> follow from this example.

<sup>758</sup> What is accomplished here is quite remarkable. The weak and electromagnetic interactions have  
<sup>759</sup> been unified into a single  $SU(2) \times U(1)$  interaction, and the physical bosons observed in nature  
<sup>760</sup> arise as mixtures of the four gauge fields. Three of the four degrees of freedom in the scalar field  
<sup>761</sup>  $\phi$  of Equation 2.3, are absorbed (or “eaten”) by the  $W^\pm$  and  $Z$  bosons, and the fourth generates  
<sup>762</sup> the Higgs boson. Additionally, it is shown that the Higgs couples to fermions in proportion to  
<sup>763</sup> their mass. From experimental measurements, the value of the VEV has been determined to be  
<sup>764</sup>  $v \approx 246$  GeV [20]. However, it should be noted that the theory does not predict the mass of the  
<sup>765</sup> Higgs boson or of the fermions; these must all be determined from experiment.

766 **2.3 Electroweak vector boson scattering**

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

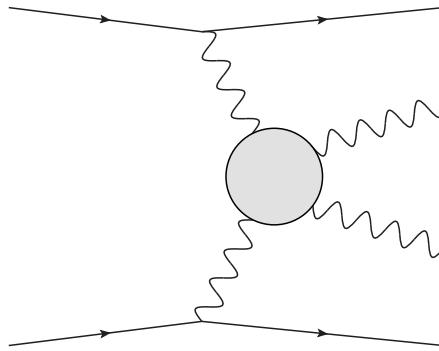


Figure 2.3: Feynman diagram of a generic VBS process. The gray circle represents any interaction with two incoming and two outgoing vector bosons, including any of the diagrams shown in Figures 2.4 and 2.5.

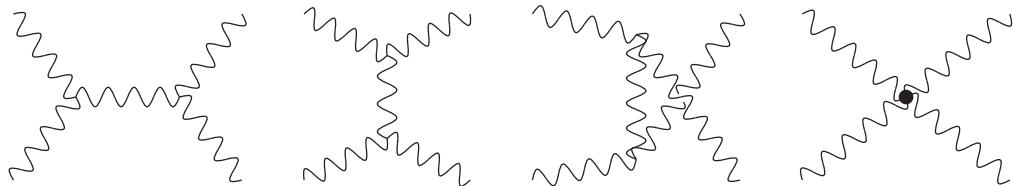


Figure 2.4: Leading order  $VV \rightarrow VV$  Feynman diagrams involving EWK bosons. From left to right:  $s$ -channel,  $t$ -channel,  $u$ -channel, and the quartic gauge coupling.

---

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

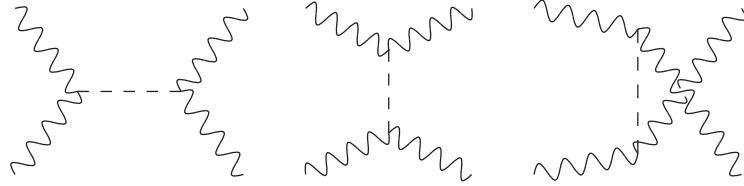


Figure 2.5: Leading order  $VV \rightarrow VV$  Feynman diagrams involving the exchange of a Higgs boson. From left to right:  $s$ -channel,  $t$ -channel, and  $u$ -channel.

777 As detailed in the previous section, the Higgs mechanism produces three Goldstone bosons and a  
 778 Higgs boson. The Goldstone bosons are then “eaten” by the physical gauge bosons, giving them mass  
 779 and consequently a longitudinal polarization<sup>2</sup>. In fact, according to the Electroweak Equivalence  
 780 Theorem, the high-energy interactions of longitudinal gauge bosons can be accurately described by  
 781 the Goldstone bosons of the EWSB mechanism [23]. Thus, the scattering of the massive gauge  
 782 bosons are inextricably linked to EWSB.

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

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

787  
 788 where  $v^{\mu}$  is of the order  $M_V/E$  and becomes small in the high energy limit, it can be seen that  
 789  $\epsilon_L^{\mu}$  grows with the momentum of the boson  $p^{\mu}$ . Therefore, the dominant contribution to the VBS  
 790 process at high energy comes from the longitudinally polarized gauge bosons [27].

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

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

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

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

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

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

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

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

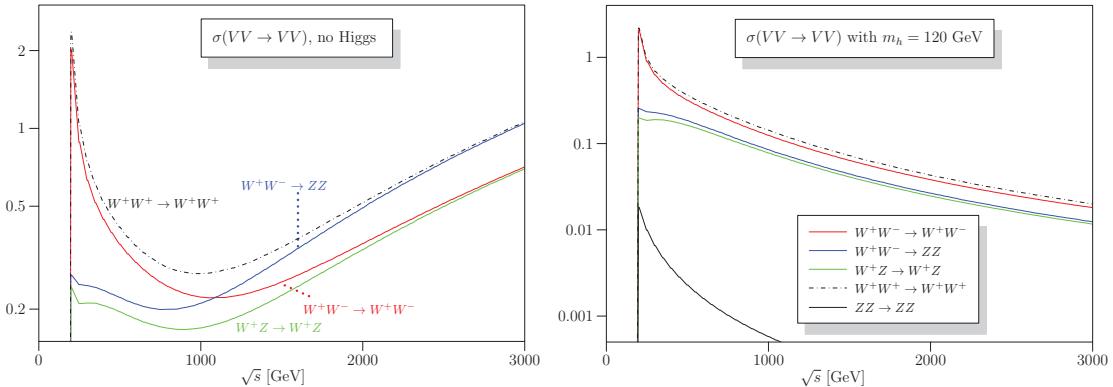


Figure 2.6: Cross sections in nanobarns for five different longitudinally polarized VBS processes as a function of center of mass energy  $\sqrt{s}$ . Without a Higgs boson (left), the cross sections grow unbounded with  $\sqrt{s}$ . With a 120 GeV Higgs boson (right), the cross sections no longer diverge.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

## CHAPTER 3

---

# LHC and the ATLAS Detector

---

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

810 **3.1 The Large Hadron Collider**

811 The Large Hadron Collider (LHC) [29] is the most powerful particle accelerator in the world, colliding  
 812 two beams of protons at a center of mass energy of  $\sqrt{s} = 13$  TeV. It is operated by the European  
 813 Organization for Nuclear Research (CERN) and consists of a 27 km ring located beneath the France–  
 814 Switzerland border. A chain of smaller accelerators incrementally boost the protons<sup>3</sup> up to higher  
 815 and higher energies before they reach the final collision energy within the main LHC ring. Collisions  
 816 occur at each of four detector experiments situated around the ring: ATLAS [30], ALICE [31],  
 817 CMS [32], and LHCb [33].

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

---

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

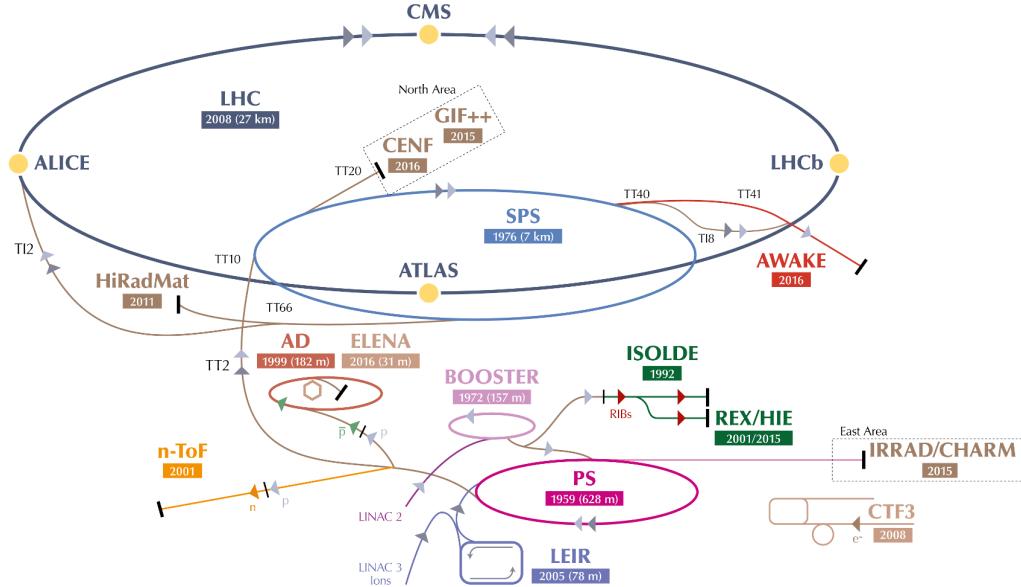


Figure 3.1: The CERN accelerator complex. For LHC collisions, protons are accelerated by the Linac 2 (purple), the PSB (light purple), the PS (magenta), and the SPS (light blue) before entering the LHC ring (dark blue) [35].

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

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

829 The calculation itself can be quite tricky, as it depends on a number of factors including the number  
830 of particles per bunch, the spread of the beam, and the crossing angle of the beams [36].

The LHC was originally designed to operate at an instantaneous luminosity of  $1.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ ; however, this number was exceeded by the end of the 2016 data taking period, with a peak luminosity of  $1.38 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . By the end of Run 2 in December 2018, the LHC was running at more than twice the design luminosity [37]. The instantaneous luminosity of proton-proton collisions as a function of time in 2015 and 2016 are shown in Figure 3.2.

The total amount of data collected is reported in terms of *integrated* luminosity, which is simply the time integral of the instantaneous luminosity. By the end of Run 2 (2015-2018), approximately  $140 \text{ fb}^{-1}$  of 13 TeV data collected by the ATLAS detector is available for physics, as shown in Figure 3.3. The  $36.1 \text{ fb}^{-1}$  collected during the first two years (2015 and 2016) is used for the

840 analysis later in this thesis.

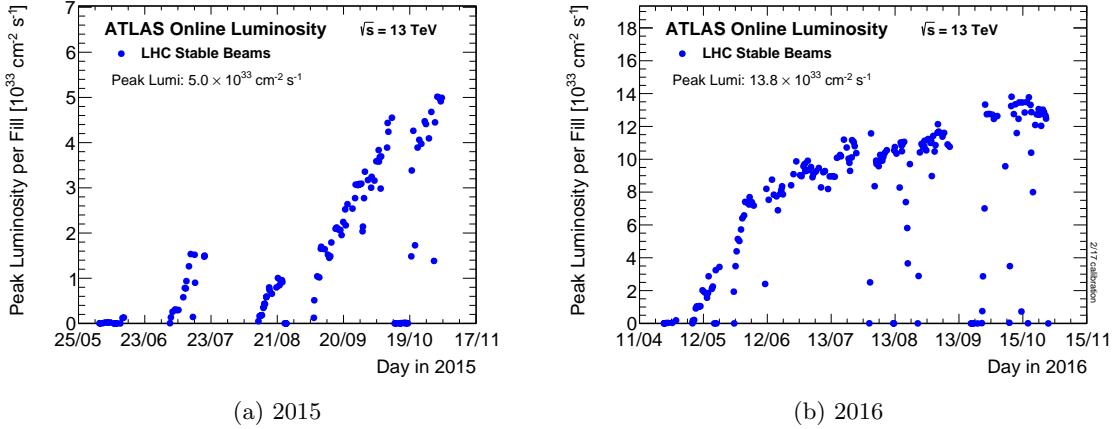


Figure 3.2: Peak instantaneous luminosity delivered to ATLAS during 13 TeV  $pp$  data taking as a function of time [37].

841 Due to the high instantaneous luminosity, more than one  $pp$  interaction occurs in a single bunch  
 842 crossing, referred to as *pileup*. During the 2016 data taking campaign, the average number of  
 843 interactions per bunch crossing  $\langle\mu\rangle$  was approximately 24 but has increased to upwards of 37 in  
 844 2017 and 2018 [37]. Figure 3.4 contains the average  $\mu$  for the 2015-2016 data set used for analysis  
 845 in this thesis. The high pileup is a challenge for accurately reconstructing an individual collision.

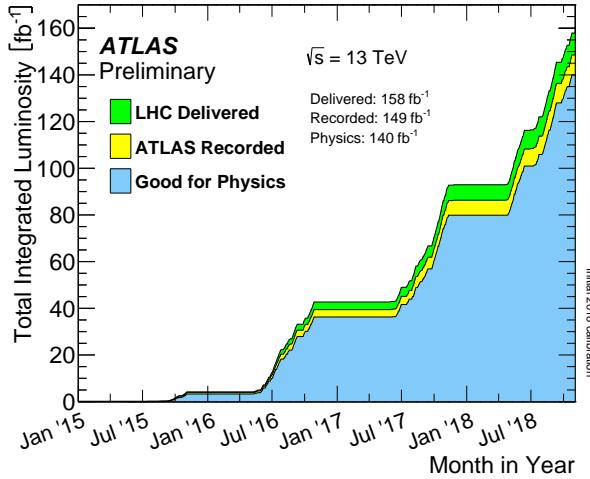


Figure 3.3: Integrated luminosity collected by ATLAS as a function of time at 13 TeV from 2015-2018 [37].

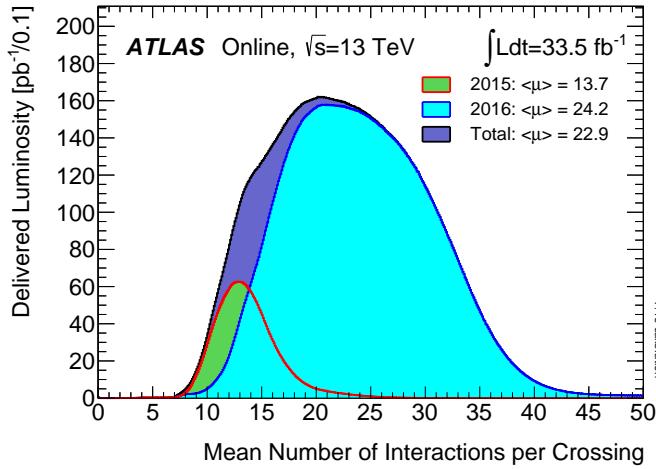


Figure 3.4: Distribution of the mean number of interactions per bunch crossing for the 2015 and 2016  $pp$  collision data at 13 TeV [37].

### 846 3.2 The ATLAS Detector

847 ATLAS (A Toroidal LHC ApparatuS) is a general-purpose particle detector. It is made up of  
 848 several different subdetector systems designed to measure different types of particles. Starting from  
 849 the beam line and working outwards, the Pixel Detector (PIX), Semiconductor Tracker (SCT),  
 850 and Transition Radiation Tracker (TRT) make up the Inner Detector (ID) and are responsible for  
 851 measuring the trajectories and momenta of charged particles. Next are two calorimeters, the Liquid  
 852 Argon Calorimeter (LAr) and the Tile Calorimeter (TileCal), which stop electromagnetic and hadronic  
 853 objects and measure their energies. Finally, the outermost Muon Spectrometer (MS) measures muon  
 854 tracks as they leave the detector, as they are too heavy to be stopped by the calorimeters. The  
 855 ATLAS detector and its subsystems are shown in Figure 3.5.

856 ATLAS uses a global, right-handed coordinate system with the origin at the center of the detector  
 857 (the nominal interaction point). The  $x$ -axis points from the origin inwards to the center of the LHC  
 858 ring, the  $y$ -axis points upwards, and the  $z$ -axis points along the beam line. Due to the azimuthal  
 859 symmetry of the detector, it is useful to use cylindrical coordinates  $(r, \phi)$  in the plane transverse to  
 860 the  $z$ -axis, where  $\phi$  is the azimuthal angle. Instead of using the polar angle  $\theta$  to describe particle  
 861 trajectories, pseudorapidity  $\eta$  is used instead, defined in terms of  $\theta$ :

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

862 Pseudorapidity has the useful property that differences in  $\eta$  are invariant under Lorentz boosts along

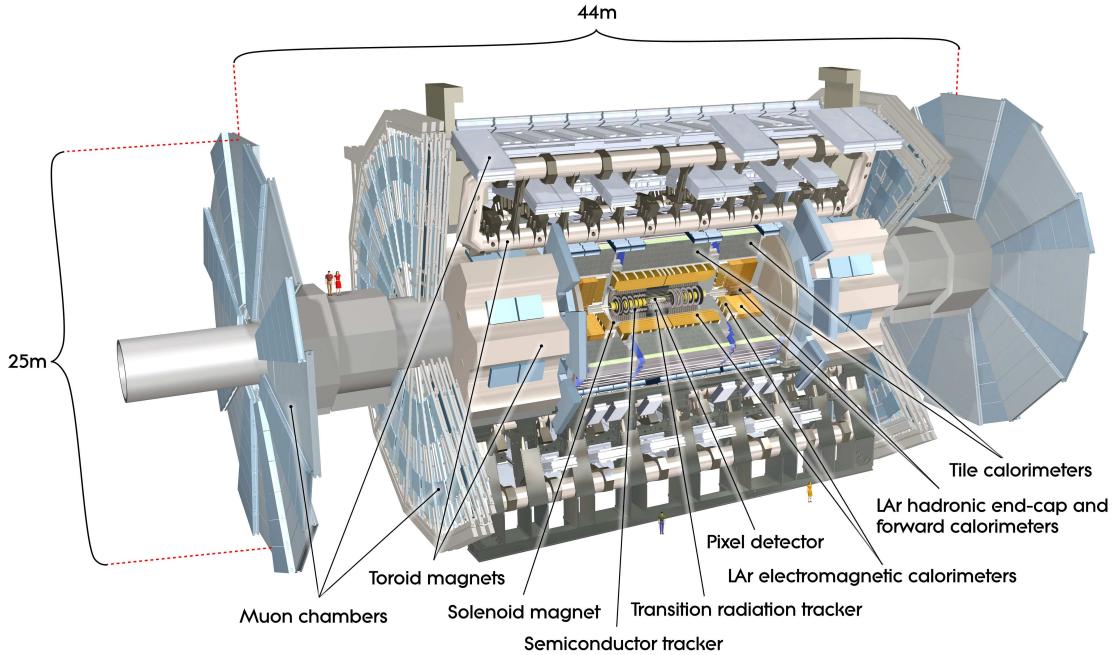


Figure 3.5: Cut-away view of the ATLAS detector [30].

863 the  $z$ -axis. The separation between two particles  $p_i$  and  $p_j$  is often expressed in terms of the quantity  
 864  $\Delta R$ , defined as:

$$\Delta R(p_i, p_j) = \sqrt{\Delta\eta_{i,j}^2 + \Delta\phi_{i,j}^2} \quad (3.3)$$

865 where  $\Delta\phi_{i,j} \in [-\pi, \pi]$  since  $\phi$  is periodic in  $2\pi$  and “wraps around” the detector in the azimuthal  
 866 direction.

### 867 3.2.1 The Inner Detector

868 The ID [38, 39] is a tracking system that reconstructs the trajectories of charged particles. It spans  
 869 just over a meter in radius, with the innermost layer of sensors at a radius of 33.25 cm from the  
 870 beam line. Charged particles traveling through the ID leave *hits* in each sensor they pass through,  
 871 and a track is fit to the hits to reconstruct the path of the particle according to the techniques that  
 872 will be outlined in Section 3.2.4.1. The ID’s pseudorapidity coverage extends out to  $|\eta| < 2.5$ . A  
 873 solenoid magnet outside the ID produces a 2 T magnetic field that bends the particles, allowing for  
 874 their momenta in the direction transverse to the field to be measured according to:

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

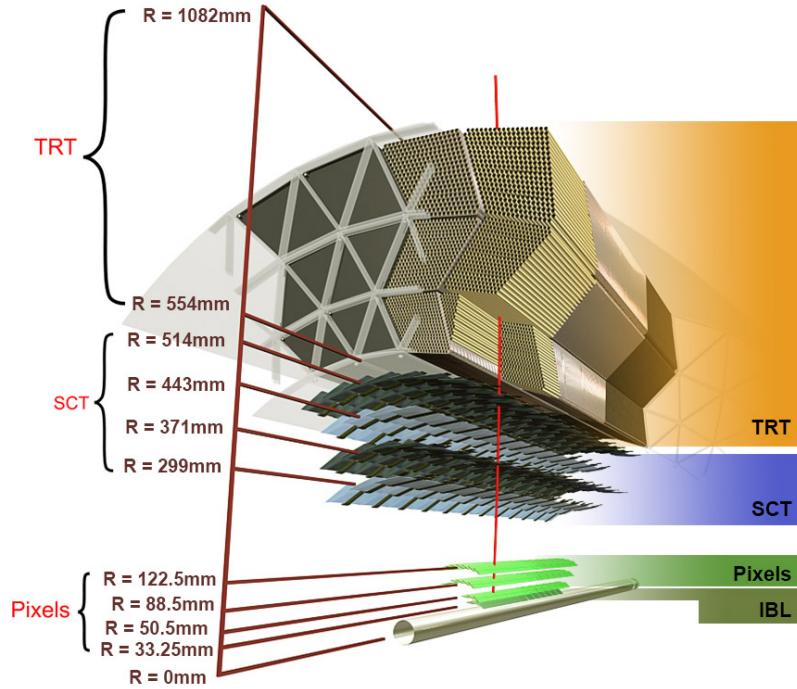


Figure 3.6: The barrel layers of the Pixel, SCT, and TRT detectors making up the Inner Detector.

875 where  $q$  is the charge of the particle ( $\pm 1$ ),  $B$  is the strength of the magnetic field, and  $r$  is the radius  
 876 of the track's curvature. A cut-away view of the barrel region of the ID is shown in Figure 3.6.

#### 877 3.2.1.1 Pixel Detector

878 The Pixel Detector consists of four cylindrical barrel layers<sup>4</sup> and three endcap disks on either side.  
 879 It is the innermost subdetector of the ID with coverage up to  $|\eta| < 2.5$ . The individual sensors  
 880 measure  $50 \mu\text{m} \times 400 \mu\text{m}$  and are installed on silicon wafers that make up the layers. All in all, there  
 881 are 1744 wafers with 80 million readout channels. The sensors themselves are silicon semiconducting  
 882 diodes that provide a signal when a charged particle passes through. The Pixel Detector has the  
 883 finest resolution of all the ID subdetectors, at  $10 \mu\text{m}$  in the  $r\text{-}\phi$  plane and  $40 \mu\text{m}$  in the  $z$  direction.

884 During the upgrade period between Run 1 and Run 2, a new innermost layer was added to the  
 885 Pixel detector barrel: the Insertable B-Layer (IBL) [40]. The IBL lies closest to the interaction  
 886 point, at a radius of 33.25 cm from the beam line, and it is relied upon to provide high-precision

---

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

887 measurements close to the interaction point. Its addition allows better precision in detecting dis-  
888 placed vertices from  $b$ -jets, for example. It consists of 280 silicon pixel modules arranged on 14  
889 staves that run parallel to the beam line. Each stave consists of 12 two-chip planar modules in the  
890 middle ( $|\eta| < 2.7$ ) with four 3D sensors [41] on either side ( $2.7 < |\eta| < 3.0$ ). The IBL's pixel sensors  
891 are  $50 \mu\text{m} \times 250 \mu\text{m}$  in size and have a resolution of  $10 \mu\text{m}$  in  $r\text{-}\phi$  and  $75 \mu\text{m}$  in  $z$  [42].

892 **3.2.1.2 Semiconductor Tracker**

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

900 **3.2.1.3 Transition Radiation Tracker**

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

909 Between the straws are polyethelene fibers in the barrel and polypropylene foil in the endcaps  
910 in order to encourage particles to emit transition radiation photons. These photons also ionize the  
911 gas within the straws, leading to a higher signal. The TRT takes advantage of the fact that lighter  
912 particles are more likely to emit transition radiation by using a ternary output: zero, low-threshold,  
913 and high-threshold. High-threshold hits are generally caused by electrons due to their low mass,  
914 and this can help in identifying electron tracks from backgrounds.

915 There are over 100,000 straws in the barrel of the TRT, and nearly 250,000 in the endcaps. The  
916 TRT provides pseudorapidity coverage up to  $|\eta| < 2.0$  with a resolution in the  $r\text{-}\phi$  plane of  $130 \mu\text{m}$ .

917 Since the drift tubes are insensitive along the direction of the wire, the TRT does not provide a  
 918 measurement along the  $z$  direction.

### 919 3.2.2 The Calorimeters

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

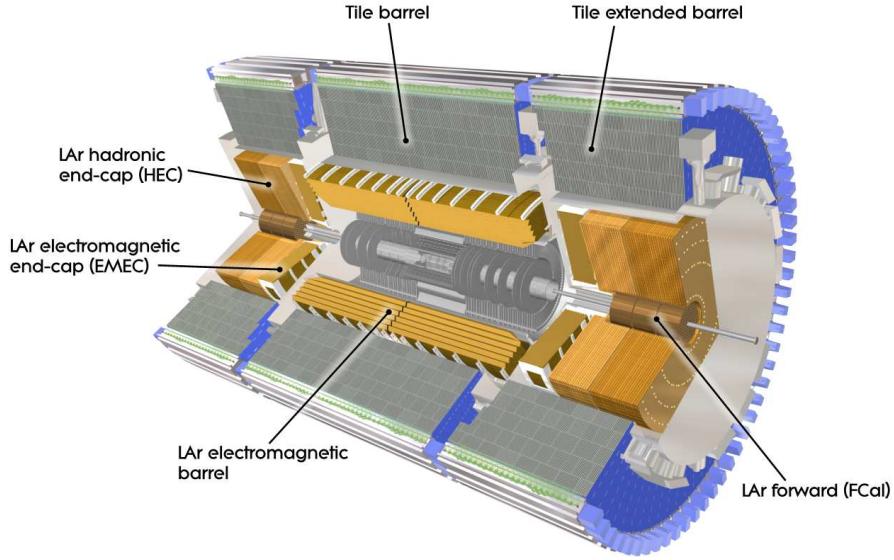


Figure 3.7: Cut-away view of the ATLAS calorimeter systems [48].

930 Electromagnetic objects, such as electrons and photons, shower via cascades of bremsstrahlung  
 931 photons and  $e^+e^-$  pairs. The radiation length  $X_0$  is defined as the mean distance over which an  
 932 electron's energy is reduced to  $1/e$  of its original value, or  $E(x) = E_0 e^{-x/X_0}$ . The majority of the

shower energy is deposited in the first few radiation lengths. The longitudinal shower depth scales logarithmically with particle energy, and the transverse shower width is described by the Molière radius<sup>5</sup> of the material.

Hadronic showers (referred to as *jets*) are the result of quarks or gluons which hadronize and shower primarily via the strong interaction. Hadronic showers are generally wider than the electromagnetic showers described above. The longitudinal depth of the hadronic shower scales with the nuclear interaction length of the material  $\lambda$ , defined as the mean distance for the number of particles in a hadronic jet to be reduced to  $1/e$  of the initial number. In addition, about 1/3 of the shower products are neutral pions  $\pi^0$  which decay electromagnetically via the process described above.

### 3.2.2.1 Liquid Argon Calorimeter

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

Focusing on the electromagnetic components first, the EMB covers  $|\eta| < 1.475$  and the two EMECs cover  $1.375 < |\eta| < 3.2$ . They consist of alternating layers of lead absorber and liquid argon. The exact thickness of the lead depends on the location within the detector, ranging from 1.1-2.2 mm. The absorbers are folded into an accordion shape, where the folding angles are varied in order to keep the thickness of the liquid argon gap constant across the barrel (about 2.1 mm). The electromagnetic calorimeter is thick enough that the minimum number of radiation lengths a particle travels through is  $24 X_0$ , including the material from other subdetectors.

There are four layers within the EMB and EMEC including an innermost pre-sampler that helps correct for energy lost before the shower reaches the calorimeter. The next three layers consist of differently shaped cells successively reducing in granularity. The first layer consists of narrow strips for fine-grained  $\eta$  resolution, while the majority of the shower energy is deposited in the second layer. The accordion shape as well as the sizes of the cells in the EMB are shown in Figure 3.8.

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

The FCal provides coverage for hadronic jets over the range  $3.2 < |\eta| < 4.9$ . Each FCal endcap consists of three layers. The first is an electromagnetic calorimeter with a copper absorber, while the

---

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

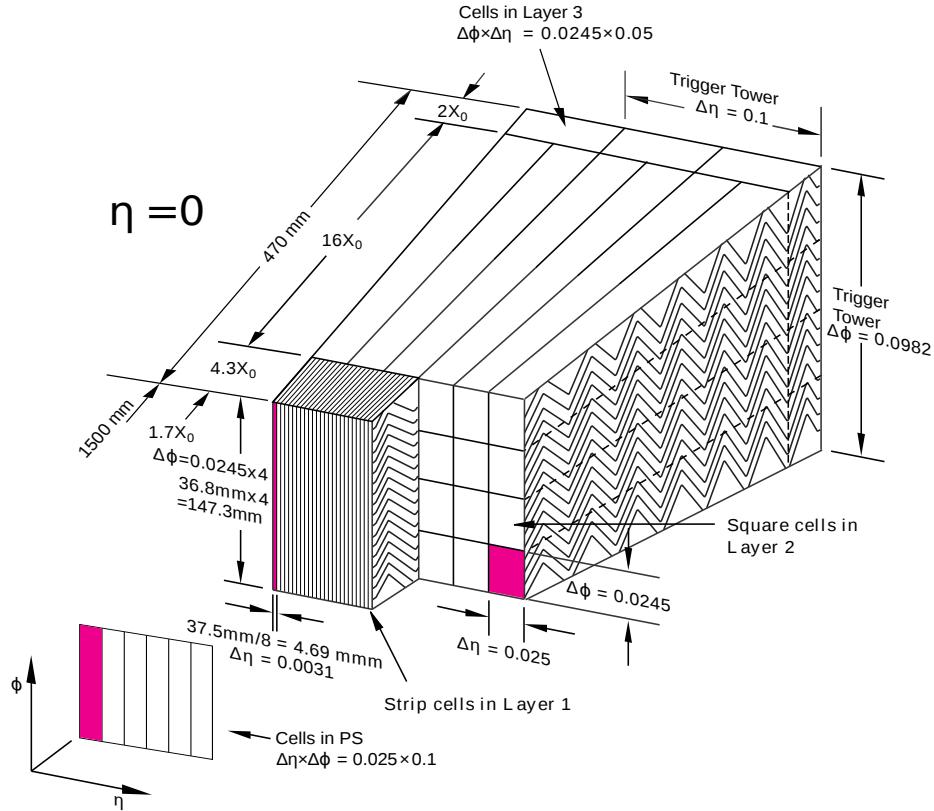


Figure 3.8: Diagram of the cells within the LAr barrel. The accordion structure can be seen in the cut-away view [46].

other two hadronic layers use a tungsten absorber. Due to the high particle flux entering the FCal, the liquid argon gaps are very narrow, and electrodes are embedded into the absorbers parallel to the beam line.

### 3.2.2.2 Tile Calorimeter

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

**972 3.2.3 The Muon Spectrometer**

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

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

**994 3.2.4 Particle reconstruction**

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

999    **3.2.4.1 Track reconstruction**

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

1003    The first step, clusterization, uses hits from the Pixel and SCT detectors. Neighboring pixels or  
1004    silicon strips that registered a hit in a sensor are grouped together into clusters using a connected  
1005    component analysis. Each cluster represents a *space-point*, or a three-dimensional measurement  
1006    corresponding to the point where the particle intersected the sensor. Since the SCT sensors consist  
1007    of two strip layers on top of each other (as described in Section 3.2.1.2), clusters from each layer  
1008    combine to form a single space-point. It is possible to have overlapping clusters from multiple  
1009    particles in a single sensor, and care is taken that these *merged clusters* are identified and handled  
1010    accordingly.

1011    Next, track seeds are formed using sets of three space-points. This number allows for a first  
1012    momentum estimate to be made while still allowing for as large a number of track combinations as  
1013    possible. The impact parameters of a track seed—the distance of closest approach to the collision—  
1014    are estimated by assuming a perfect helical trajectory in a uniform magnetic field. In order to ensure  
1015    the quality of a track seed, criteria on the momentum and impact parameters are imposed as well as  
1016    a requirement that at least one additional space-point lies along the preliminary trajectory. Finally,  
1017    a combinatorial Kalman filter [51] builds track candidates from the track seeds by incorporating  
1018    additional space-points lying along the preliminary trajectory. The filter allows for multiple track  
1019    candidates to be fit to the same track seed if more than one set of space-points is compatible.

1020    The final step of the reconstruction process is the ambiguity solving. Each collected track  
1021    candidate is processed individually before being sorted by its *track score*, a metric for quantifying  
1022    the likelihood that a given track candidate correctly represents the particle’s trajectory. The track  
1023    score is determined from a number of factors. Each cluster along the track candidate increases  
1024    the score by a weighted amount that incorporates the intrinsic resolution of the relevant detector’s  
1025    sensors in addition to other factors. Conversely, if a track candidate passes through a sensor but  
1026    there is no associated cluster (called a *hole*), the score is reduced. The  $\chi^2$  of the track fit contributes  
1027    as well in order to promote tracks with high quality fits. Finally, the logarithm of the momentum  
1028    adds to the score to suppress tracks with incorrectly assigned clusters, as these tracks typically have  
1029    low momenta. A track candidate is rejected by the ambiguity solver if its score is too low, or if it  
1030    fails to meet a basic set of quality criteria. If a cluster would be shared by more than one track, at

1031 most two tracks are allowed to pass through it. In this case, preference is given to tracks already  
 1032 passing through the ambiguity solver, which by construction results in the two highest scoring tracks  
 1033 using the shared cluster being kept.

1034 Following this procedure, TRT hits can be incorporated into the track fit through *TRT track*  
 1035 *extension* [52]. Compatible sets of TRT measurements are found for tracks found in the silicon  
 1036 detectors surviving the ambiguity solving. The algorithm requires that the original silicon-only  
 1037 track not be modified by the inclusion of the TRT hits; it is simply an extension of the existing  
 1038 track.

1039 What is described above is the *inside-out* reconstruction algorithm; there is also an *outside-in*  
 1040 reconstruction that begins in the TRT. This algorithm is not covered in detail here, as much of the  
 1041 process is similar to the above. The general workflow begins with finding track segments in the  
 1042 TRT, constructing the track candidates including the silicon hits, and finally ambiguity solving.

#### 1043 3.2.4.2 Electron reconstruction

1044 Electron reconstruction [53] uses information from both the ID and the electromagnetic calorimeters.  
 1045 The characteristic signature of an electron in ATLAS is a charged particle track in the ID that is  
 1046 matched in  $\eta\text{-}\phi$  to localized clusters of energy deposited in the calorimeter.

1047 Calorimeter cluster candidates are seeded from localized energy deposits according to a sliding-  
 1048 window algorithm [54]. The clusters are a  $3 \times 5$  rectangle of calorimeter towers in  $\eta \times \phi$  with a  
 1049 total transverse energy greater than 2.5 GeV. In the event that two clusters overlap, if the  $E_T$  of  
 1050 the clusters vary by more than 10%, the highest  $E_T$  cluster is kept, otherwise the candidate with  
 1051 the highest  $E_T$  in the central tower is kept. The ID tracks are those generated using the algorithm  
 1052 detailed above in Section 3.2.4.1, and tracks with a nearby calorimeter cluster are re-fit using a  
 1053 Gaussian-sum filter designed to take into account bremsstrahlung effects [55].

1054 To reconstruct the final electron candidate, the refit track and the cluster are subject to the final  
 1055 matching criteria:

$$|\eta_{\text{cluster}} - \eta_{\text{track}}| < 0.05 \quad \text{and} \quad (3.5)$$

$$-0.10 < q \times \Delta\phi_{\text{cluster, track}} < 0.05 \quad \text{or} \quad -0.10 < q \times \Delta\phi_{\text{res}} < 0.05$$

1056 where  $q$  is the charge of the track and  $\Delta\phi_{\text{res}}$  is the azimuthal separation between the cluster position  
 1057 and the track after rescaling its momentum to the energy of the cluster. If multiple tracks satisfy the  
 1058 above criteria, the primary track is selected by an algorithm that takes into account the center of

1059 each cluster relative to the parameters of the candidate track. Finally, the clusters are reconstructed  
 1060 about the seed cluster using a larger window size,  $3 \times 7$  in the barrel and  $5 \times 5$  in the endcaps, and  
 1061 the energy is calibrated to the original electron energy using techniques described in [56, 57].

1062 **Electron identification** To determine whether an electron candidate is a signal electron or back-  
 1063 ground object, an identification criteria (ID) is implemented, covered in more detail in [53, 58]. Elec-  
 1064 tron ID is performed using a multivariate likelihood technique (LH) that simultaneously evaluates  
 1065 a list of measurements of an electron candidate, including both tracking and calorimeter clustering  
 1066 information. To cover the different requirements of various physics and performance studies, four  
 1067 different likelihood working points are constructed corresponding to increasing thresholds for the  
 1068 LH discriminant: `VeryLooseLH`, `LooseLH`, `MediumLH`, and `TightLH`. Each successive working point is  
 1069 a subset of its predecessors. The efficiencies of the `LooseLH`, `MediumLH`, and `TightLH` working points  
 1070 as a function of electron  $E_T$  are shown in Figure 3.9.

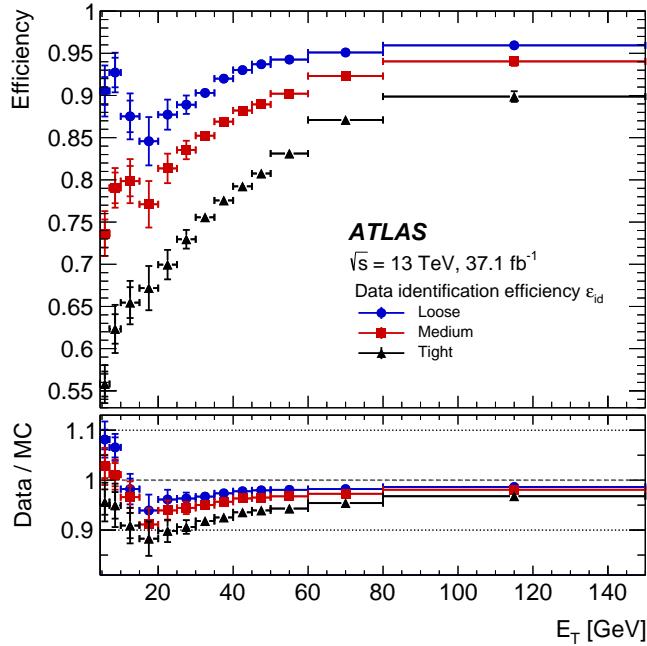


Figure 3.9: Measured LH electron ID efficiencies in  $Z \rightarrow ee$  events for the `LooseLH` (blue), `MediumLH` (red), and `TightLH` (black) working points as a function of electron  $E_T$ . The bottom plot shows data-to-simulation ratios. Plot taken from [53].

1071 **Electron isolation** Signal electrons, such as those from the decay of a  $W$  boson, tend to have  
 1072 little detector activity nearby in both the ID and the calorimeters. Background electrons, such as  
 1073 those from photon conversions or jets, are often produced in association with other particles. To  
 1074 take advantage of this, variables are constructed to quantify the amount of activity within a cone of  
 1075 a specified radius in  $\Delta R$  about an electron in both the tracking systems and the calorimeters.

1076 The track-based isolation consists of the sum of the transverse momentum of tracks within a cone  
 1077 of a specified radius about an electron (not including the electron itself). The tracks are required to  
 1078 have  $p_T > 1$  GeV, satisfy basic quality requirements, and be associated with the vertex from which  
 1079 the electron originated. Additionally, particles from bremsstrahlung radiation are considered part of  
 1080 the original electron and are subtracted from the isolation cone. A variable cone radius dependent  
 1081 on the  $p_T$  of the electron is used in order to compensate for busy detector environments:

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

1082 where  $R_{\max}$  is the largest allowed cone size, typically set at 0.2 for electrons.

1083 Calorimeter isolation is a bit more difficult due to the size of the energy deposits relative to the  
 1084 cone size, as parts of an energy cluster can lie outside of the cone. As such, topological clusters [59]  
 1085 (topo clusters) are seeded by calorimeter cells with deposited energy greater than four times the  
 1086 expected noise-level of that cell. The cluster is then expanded to incorporate electromagnetic and  
 1087 hadronic cells recording an energy greater than two times their expected noise-levels until no adjacent  
 1088 clusters remain satisfying the requirement. The isolation cone is then the sum of the  $E_T$  of all  
 1089 positive-energy topo clusters whose barycenters fall within a cone of radius  $\Delta R < 0.2$ . The electron's  
 1090 energy is subtracted by removing the cells within a rectangle around the electron.

1091 When applying the isolation selection, *relative isolation* is used, defined as the ratio of the track-  
 1092 or calorimeter-based isolation variable divided by the electron  $p_T$ . Four isolation working points are  
 1093 defined targeting specific values of efficiency. **Loose** and **LooseTrackOnly** target a fixed efficiency  
 1094 value across the  $p_T$  and  $\eta$  spectrum of the electrons, with the latter not applying a cut on calorimeter  
 1095 isolation. **Gradient** and **GradientLoose** target a  $p_T$ -dependent fixed efficiency that is uniform in  
 1096  $\eta$ . The efficiencies for these working points as a function of electron  $E_T$  are shown in Figure 3.10.  
 1097 Additional working points are also provided that instead use fixed values for the relative track and  
 1098 calorimeter isolation cuts.

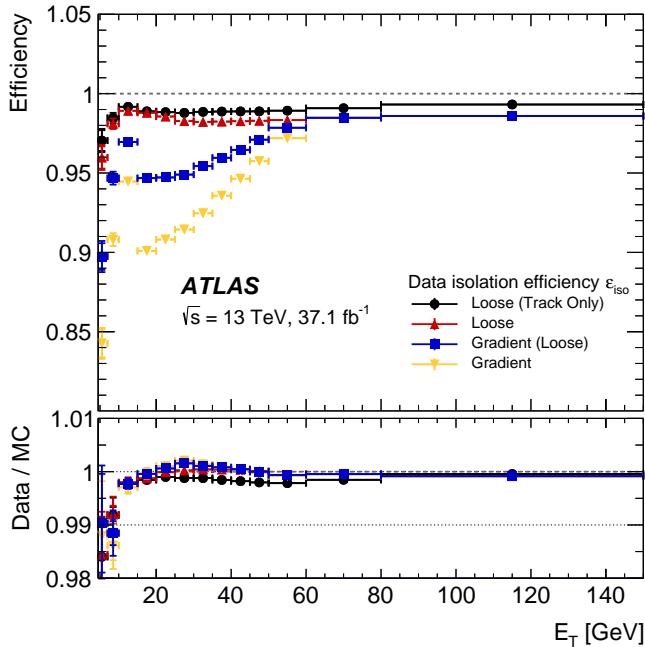


Figure 3.10: Measured isolation efficiencies for the `LooseTrackOnly` (black), `Loose` (red), `GradientLoose` (blue), and `Gradient` (yellow) working points as a function of electron  $E_T$ . The bottom panel shows data-to-simulation ratios. Plot taken from [53].

#### 1099 3.2.4.3 Muon reconstruction

1100 Muon reconstruction [60, 61] first occurs independently in the ID and the MS, and then the infor-  
 1101 mation from both is combined to form the final muon tracks used in analysis. Muons in the ID are  
 1102 reconstructed as a charged particle track following the standard procedure detailed in Section 3.2.4.1.

1103 In the MS, hits within each muon chamber are collected into segments, with separate algorithms  
 1104 for each of the four different detector components described in Section 3.2.3. Muon track candidates  
 1105 are then built by fitting together segments using a combinatorial search seeded by segments in the  
 1106 middle layers first, and then expanding to the outer and inner layers. A track must contain at least  
 1107 two matching segments, except in the transition region between the barrel and endcap where a single  
 1108 segment can be used. In the event that a segment is shared by multiple tracks, an overlap removal  
 1109 algorithm decides which track should keep the segment, or if it should remain shared. Finally, the  
 1110 hits within each track candidate are fit using a global  $\chi^2$ , and the track is accepted if the  $\chi^2$  satisfies  
 1111 a set of selection criteria.

1112 The ID and MS tracks are then combined according to several different reconstruction criteria

1113 determined by the available information from the ID, MS, and calorimeters. This results in four  
 1114 different muon “types”:

- 1115     • Combined (CB): Independent tracks in the ID and MS are combined with a global track refit  
 1116        using both sets of hits. MS hits may be added or removed if it improves the quality of the  
 1117        track fit. Muons are typically reconstructed outside-in, matching a MS track to one in the ID;  
 1118        however, an inside-out matching is also used as a complementary approach.
- 1119     • Segment-tagged (ST): An ID track is classified as a muon if it can be extrapolated to at least  
 1120        one track segment in the MDT or CSC chambers. These are used when a muon only crosses  
 1121        one layer of the MS, either due to low  $p_T$  or falling in a region of reduced acceptance.
- 1122     • Calorimeter-tagged (CT): An ID track is classified as a muon if it can be matched to a calorime-  
 1123        ter energy deposit compatible with a minimum ionizing particle. These muons are generally  
 1124        lower in purity than the other types, but they are useful for recovering acceptance in the region  
 1125         $|\eta| < 0.1$  where the MS is only partially instrumented.
- 1126     • Extrapolated (ME): The muon is reconstructed using a MS track that is loosely compatible  
 1127        with having originated from the interaction point. The MS track must transverse at least  
 1128        two layers of the MS in the central region and three in the forward region. These muons are  
 1129        generally used to extend the acceptance of muon reconstruction in the forward regions not  
 1130        covered by the ID ( $2.5 < |\eta| < 2.7$ ).

1131 **Muon identification** Muon identification serves to select signal muons with a high quality mo-  
 1132 mentum measurement from backgrounds (mainly from pions and kaons). For CB muons, three  
 1133 variables are used:

- 1134     •  $q/p$  significance: The absolute value of the difference in  $q/p$  of the muons (where  $q$  is the  
 1135        muon’s charge) as measured by the ID and the MS divided by the corresponding uncertainties  
 1136        added in quadrature.
- 1137     •  $\rho'$ : The absolute value of the difference between the  $p_T$  measurements in the ID and the MS  
 1138        divided by the  $p_T$  of the combined track.
- 1139     • The normalized  $\chi^2$  of the combined track fit.

1140 Additional requirements are imposed on the number of hits within the ID to ensure the tracks’  
 1141 momenta are well measured.

1142 There are three primary muon identification working points<sup>6</sup> of increasing background rejection:  
 1143 **Loose**, **Medium**, and **Tight**. **Loose** muons include all four types listed above, but CT and ST muons  
 1144 are restricted to the region  $|\eta| < 0.1$ . The default recommendation for analysis are **Medium** muons,  
 1145 which only include CB and ME tracks. Finally, **Tight** muons are made up of CB muons with hits in  
 1146 at least two components of the MS and that pass the **Medium** requirements. Each successive working  
 1147 point is a subset of the previous one, and the cuts on the three variables listed above are tightened  
 1148 in each step. The muon reconstruction efficiency for each of these three working points in  $Z \rightarrow \mu\mu$   
 1149 events is shown in Figure 3.11.

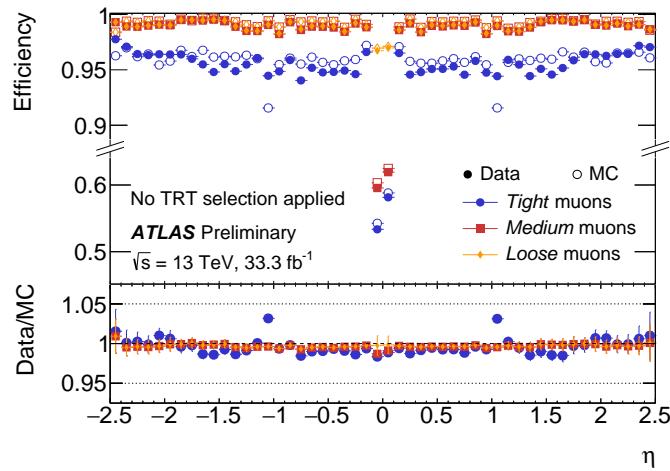


Figure 3.11: Muon reconstruction efficiencies in  $Z \rightarrow \mu\mu$  events for the **Loose** (yellow), **Medium** (red), and **Tight** (blue) ID working points as a function of muon  $\eta$ . The drop in efficiency for **Medium** and **Tight** muons in the range  $|\eta| < 0.1$  is due to the exclusion of CT and ME muons, which are used to recover acceptance in this region. Collision data (solid points) is compared to simulation (open points) and the ratio is in the lower panel. Plot taken from [62].

1150 **Muon isolation** Isolation for muons is handled in much the same way as for electrons (see Sec-  
 1151 tion 3.2.4.2). A track-based variable is computed by summing the transverse momenta of tracks with  
 1152  $p_T > 1$  GeV within a cone of variable radius as in Equation 3.6 with  $R_{\max} = 0.3$ . The calorimeter-  
 1153 based isolation again uses topo clusters of radius  $\Delta R < 0.2$  with the energy deposit corresponding  
 1154 to the muon removed. Similar isolation working points are constructed using the same criteria as  
 1155 for electrons, and the efficiency of the **Loose** and **GradientLoose** working points as a function of  
 1156 muon  $p_T$  are shown in Figure 3.12.

<sup>6</sup>A fourth working point, **Highpt**, is optimized for high mass searches, such as  $W'$  and  $Z'$  resonances, and is not covered here.

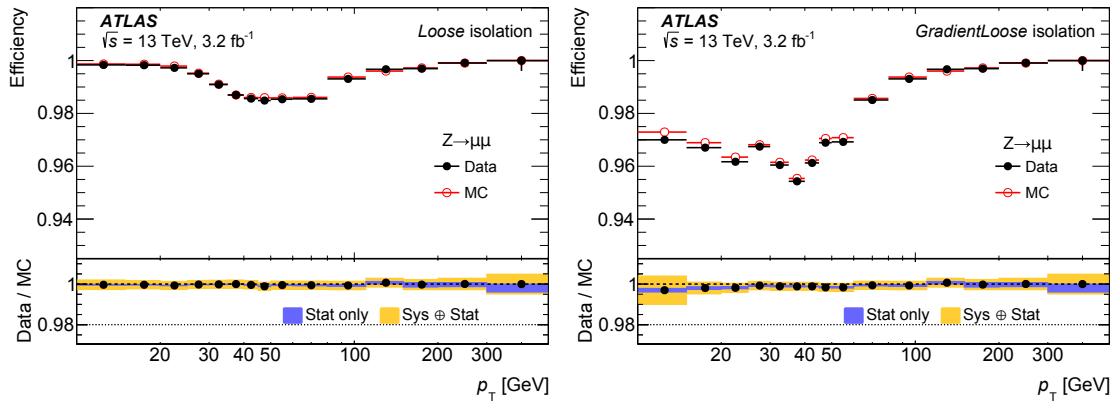


Figure 3.12: Muon isolation efficiencies in  $Z \rightarrow \mu\mu$  events for the Loose (left) and GradientLoose (right) working points as a function of muon  $p_T$ . Collision data (black) is compared to simulation (red) and the ratio is in the lower panel. Plots taken from [61].

## CHAPTER 4

# Alignment of the ATLAS Inner Detector

1159 When a charged particle passes through the ATLAS ID, it leaves hits in the sensors along its  
1160 path. In order to reconstruct an accurate particle track from these hits, it is necessary to know  
1161 where in space these hits occurred as precisely as possible, which in turn requires knowledge of the  
1162 physical location of the sensor that registered each hit. If one of the sensors is displaced relative  
1163 to its expected position in the known detector geometry, or *misaligned*, the assumed location of  
1164 the corresponding hit will not match its actual location, resulting in an incorrect track fit. These  
1165 misalignments can occur for any number of reasons, including but not limited to elements shifting  
1166 during maintenance periods or from cycles in ATLAS’s magnetic field, or small movements during  
1167 normal detector operations. A visualization of how a misaligned detector element can affect the  
1168 track reconstruction is shown in Figure 4.1.

1169 In order to correct the misalignments, the ID alignment procedure is applied to accurately  
1170 determine the physical position and orientation of each detector element. The baseline accuracy of  
1171 the alignment is required to be such that the track parameter resolutions are not degraded by more  
1172 than 20% with respect to those derived from a perfect detector geometry<sup>7</sup>. This corresponds to a  
1173 precision of better than  $10 \mu\text{m}$  in the positioning of the elements of the silicon detectors [63].

1174 This chapter outlines the ID alignment procedure, the alignment of the detector during the 2015  
1175 data taking period, and the steps taken to measure momentum biases in the alignment.

<sup>7</sup>The 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.

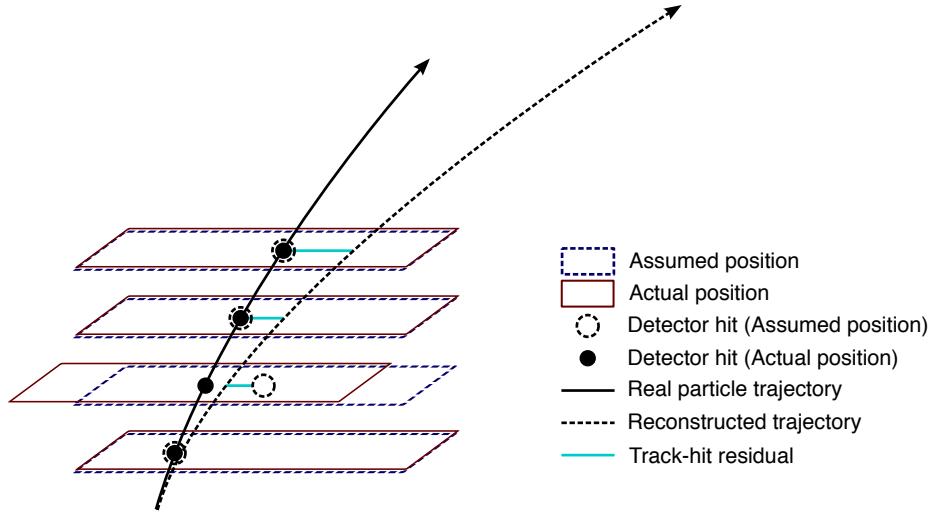


Figure 4.1: Graphical representation of the effect of a misaligned detector element. The reconstructed particle track (dashed arrow) differs from the actual trajectory of the particle (solid arrow) due to a shift in the third detector element. The cyan lines represent the track-to-hit residuals.

## 1176 4.1 The alignment method

1177 The alignment procedure uses a track-based algorithm that updates the locations of detector ele-  
 1178 ments in order to minimize the set of track-hit *residuals*. These residuals are defined as the distance  
 1179 between the where fitted track intersects a given detector element and the position of the actual hit  
 1180 recorded by the same element, shown by the cyan lines in Figure 4.1.

1181 Tracks in ATLAS are parameterized as five-dimensional vectors [64]:

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

1182 where  $d_0$  and  $z_0$  are the transverse and longitudinal impact parameters with respect to the origin,  
 1183  $\phi_0$  is the azimuthal angle of the track at the point of closest approach to the origin,  $\theta$  is the polar  
 1184 angle, and  $q/p$  is the charge of the track divided by its momentum. The residual for the  $i^{\text{th}}$  hit of a  
 1185 given track can then be written in terms of the track parameters  $\vec{\tau}$  and a set of alignment parameters  
 1186  $\vec{a}$  that describe the hit location [65]:

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

1187 where  $\vec{e}_i$  is the intersection point of the extrapolated track with the sensor,  $\vec{m}_i$  is the position of the  
 1188 associated hit within the sensor, and  $\hat{k}$  is the unit vector defining the direction of the measurement  
 1189 within the sensor.  $\vec{r}$  then is the vector of residuals for the track.

1190 A  $\chi^2$  function can be built from the residuals of all collected tracks:

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

1191 where  $V$  is the covariance matrix of the hit measurements. The  $\chi^2$  function is then minimized with  
 1192 respect to the alignment parameters  $\vec{a}$ , which contain all degrees of freedom being aligned. The  
 1193 minimization condition with respect to  $\vec{a}$  is:

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

1194 This equation can be difficult to solve exactly, so the residual is rewritten as a first order Taylor  
 1195 expansion:

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

1196 where  $\vec{r}_0$  is dependent on an initial set of track and alignment parameters  $\vec{r}_0$  and  $\vec{a}_0$ , respectively;  
 1197 the track parameter dependence has also been folded into the total derivative  $\frac{d\vec{r}}{d\vec{a}}$ . Equation 4.5 can  
 1198 then be inserted into the minimization condition from Equation 4.4 to give:

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

1199 From this equation, the alignment matrix  $\mathcal{M}_a$  and alignment vector  $\vec{\nu}_a$  can be defined:

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

1200

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

1201 Finally, the alignment corrections  $\delta\vec{a}$  can be solved for by inverting the alignment matrix:

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

1202 which is a linear system of equations with a number of equations equal to the number of alignment  
 1203 degrees of freedom [66].

1204 Inverting the full matrix and solving the resulting system of equations is referred to as *Global*  
 1205  $\chi^2$  alignment [65]. This can be useful, as  $\mathcal{M}_a$  contains all the correlations between the alignable  
 1206 structures. However, inverting the matrix is difficult when the number of degrees of freedom becomes  
 1207 large—as the number of alignable structures increases, so too does the size of the matrix  $\mathcal{M}_a$ .  
 1208 Eventually, inverting the matrix becomes too computationally intensive to be practical.

1209 This problem is solved by the *Local  $\chi^2$*  algorithm [67]. In this case, the alignment matrix is  
 1210 constructed to be block-diagonal, allowing for it to be easily inverted even for large numbers of  
 1211 degrees of freedom. This is achieved by replacing the full derivative in Equation 4.6 with the partial  
 1212 derivative  $\frac{\partial \vec{r}}{\partial \vec{a}}$ . The new alignment matrix  $\mathcal{M}'_a$  and alignment vector  $\vec{\nu}'_a$  become:

$$\mathcal{M}'_a = \sum_{\text{tracks}} \left( \frac{\partial \vec{r}}{\partial \vec{a}} \right)^T V^{-1} \left( \frac{\partial \vec{r}}{\partial \vec{a}} \right) \quad (4.10)$$

1213

$$\vec{\nu}'_a = \sum_{\text{tracks}} \left( \frac{\partial \vec{r}}{\partial \vec{a}} \right)^T V^{-1} \vec{r}_0 \quad (4.11)$$

1214 Inverting  $\mathcal{M}'_a$  is considerably faster and less memory intensive compared to  $\mathcal{M}_a$ , even for large  
 1215 numbers of degrees of freedom; however, the correlations between the alignable structures is lost.  
 1216 Due to the Taylor expansion used in Equation 4.6, several iterations of the alignment algorithm may  
 1217 be necessary to converge on a final set of alignment constants. The Local  $\chi^2$  alignment typically  
 1218 requires more iterations due to the loss of the correlation information [68].

1219 In practice, the ATLAS reconstruction is run over a set of events, and the resulting tracks are  
 1220 fed to the alignment algorithm. The residuals are calculated, the alignment matrix is built and  
 1221 inverted, and a new set of alignment constants is obtained. The convergence is checked in two ways:

- 1222 1. Measuring change in the  $\chi^2$  with respect to the previous iteration. If it is near zero, then the  
 1223  $\chi^2$  is approaching its minimum.
- 1224 2. Looking at the residual distributions for different alignable structures. A well aligned detector  
 1225 will have a residual distribution that is approximately Gaussian, with a mean of zero with a  
 1226 width approximating the intrinsic resolution of the detector.

1227 If the above checks are satisfied, the process is finished and the final alignment constants are read  
 1228 out; if not, another iteration is performed. A visual representation of the alignment chain is shown  
 1229 in Figure 4.2.

1230 Since a  $\chi^2$  minimization is used to align the detector, if there is a systematic misalignment in  
 1231 the detector that does not adversely affect the  $\chi^2$ , the algorithm will be insensitive to it. These  
 1232 misalignments are referred to as *weak modes*, and special care is taken to remove them [69]. One  
 1233 potential impact of weak modes is a bias in the track momentum of reconstructed particles. This  
 1234 particular effect is the subject of Section 4.4.

1235 The detector is aligned both in “real-time” as data is collected and during dedicated offline  
 1236 alignment campaigns. The real-time alignment is run in ATLAS’s *calibration loop*, which comprises

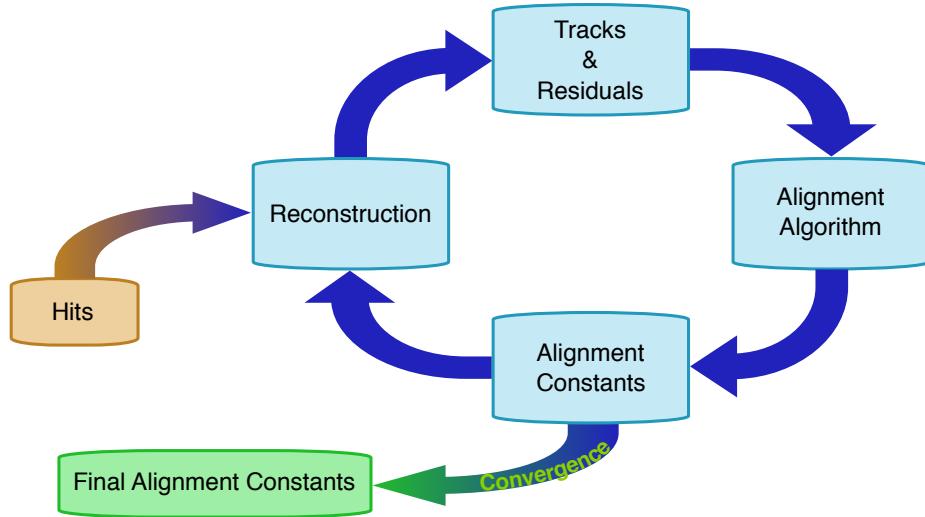


Figure 4.2: Graphical representation of the ID alignment chain.

1237 the first stage in the preparation of data for physics analysis. The calibration loop requires the  
 1238 alignment—as well as various other detector calibrations—to be available within 48 hours for initial  
 1239 data processing. A fast, coarse-grained alignment<sup>8</sup> is run on a subset of the available data containing  
 1240 full tracking information, and the results are propagated to the reconstruction of that particular  
 1241 run [70]. Due to the time constraints of the calibration loop, a full sensor-by-sensor alignment is not  
 1242 possible.

1243 The more thorough and finely tuned alignments are reserved for dedicated alignment campaigns,  
 1244 typically near the beginning and at the end of data taking campaigns. The former generally occurs  
 1245 once a sufficient amount of data is collected after a detector shutdown, in order to obtain a good  
 1246 baseline alignment for use in the remainder of the data collection period. One such alignment  
 1247 campaign, the initial offline alignment of the ATLAS detector at the beginning of Run 2, is the  
 1248 subject of Section 4.2. The latter occurs once data taking is complete. A new set of alignment  
 1249 constants is derived for the full set of available data, and it is typically divided into several “blocks”  
 1250 to account for potential run-by-run misalignments. The data is then reprocessed using the newly  
 1251 derived detector geometry.

---

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

---

1252   **4.1.1 Alignment levels**

1253   The alignment of the detector is performed at several levels of increasing granularity. This adds  
1254   flexibility in being able to align only as finely as needed, and it also allows for global, detector-level  
1255   misalignments to be corrected first before dealing with finer adjustments. The main alignment levels  
1256   are as follows:

- 1257   • Level 1 (L1) alignment involves moving entire subdetector components as a single unit, such  
1258   as the entire Pixel detector, or the SCT barrel. These often have the largest misalignments,  
1259   but they are easily corrected and do not require large volumes of data to do so.
- 1260   • Level 2 (L2) alignment treats individual layers in the silicon detectors (modules in the TRT)  
1261   and end cap disks as individual alignable objects.
- 1262   • Level 2.7 (L27) alignment was introduced with the addition of the IBL to the ID in Run 2. It  
1263   involves the stave-by-stave alignment of the IBL and Pixel barrel<sup>9</sup>.
- 1264   • Level 3 (L3) alignment treats each module in the silicon detectors and each straw in the TRT  
1265   as an individual alignable object. It is the finest grained alignment available but also the most  
1266   computationally intensive due to the large number of degrees of freedom. Due to the large  
1267   number of individual detector elements being aligned, high statistics are required.

1268   The different alignment levels are listed in more detail in Table 4.1, including the number of alignable  
1269   structures and associated degrees of freedom for each detector component.

1270   The implementation of the alignment algorithm in the software is flexible enough to allow each  
1271   subsystem to be aligned individually at a specified level. Each alignable structure has six degrees of  
1272   freedom: 3 translations ( $T_x, T_y, T_z$ ) and 3 rotations ( $R_x, R_y, R_z$ )<sup>10</sup>; however individual degrees of  
1273   freedom may be turned on and off as required. In a typical alignment job, L1 and L2 contain few  
1274   enough degrees of freedom that the Global  $\chi^2$  algorithm can be used, but L3 alignments (which can  
1275   contain over 36,000 degrees of freedom in the silicon detectors alone) require the Local  $\chi^2$  algorithm.

---

<sup>9</sup>Even though the IBL is considered a part of the Pixel Detector, for the purposes of this Chapter, “Pixel” will refer to the original three layers of the Pixel barrel and its endcaps, and the IBL will be referenced separately.

<sup>10</sup>The 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 ( $T_\phi$ ) and rotation with respect to the radial axis ( $R_r$  for the barrel and  $R_z$  for the end-caps) [71].

| Level  | Description of alignable structure       | Structures    | DoF     |
|--------|--|---------------|---------|
| 1      | IBL detector                             | 1             | 6       |
|        | Whole Pixel detector                     | 1             | 6       |
|        | SCT barrel and 2 end-caps                | 3             | 18      |
|        | TRT barrel and 2 end-caps ( $T_z$ fixed) | 3             | 17      |
| Total: |  | 8             | 47      |
| 2      | IBL detector                             | 1             | 6       |
|        | Pixel barrel layers                      | 3             | 18      |
|        | Pixel end-cap disks                      | $2 \times 3$  | 36      |
|        | SCT barrel layers                        | 4             | 24      |
|        | SCT end-cap disks                        | $2 \times 9$  | 108     |
|        | TRT barrel 32 modules ( $T_z$ fixed)     | $3 \times 32$ | 480     |
|        | TRT end-cap wheels                       | $2 \times 40$ | 480     |
| Total: |  | 208           | 792     |
| 2.7    | IBL staves                               | 14            | 84      |
|        | Pixel barrel staves                      | $22+38+52$    | 672     |
|        | Pixel end-cap disks                      | $2 \times 3$  | 18      |
|        | Total:                                   |               | 132     |
| 3      | IBL modules                              | 280           | 1,680   |
|        | Pixel modules                            | 1,744         | 10,464  |
|        | SCT modules                              | 4,088         | 24,528  |
|        | TRT barrel wires ( $T_\phi, R_r$ only)   | 105,088       | 210,176 |
|        | TRT end-cap wires ( $T_\phi, R_Z$ 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.

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

When considering the alignment degrees of freedom listed earlier in Section 4.1.1, grouped collections of modules, layers, or entire subdetectors use the global coordinate system; individual modules

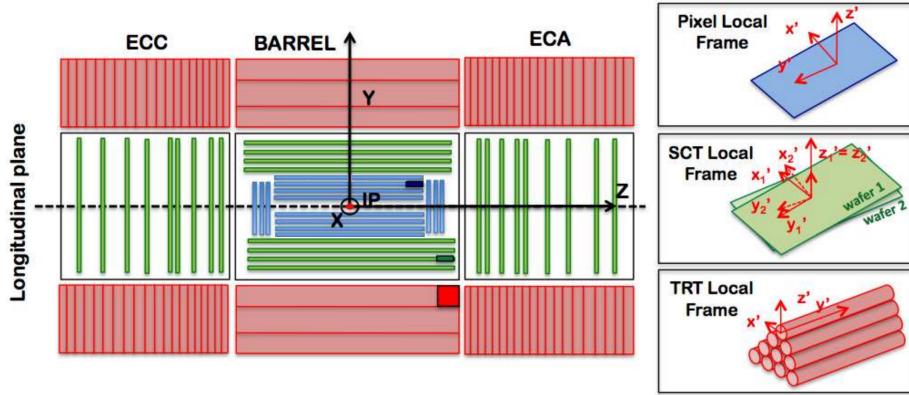


Figure 4.3: A schematic representation of the Inner Detector in the longitudinal plane with the global coordinate system overlaid on top. The Pixel detector and IBL are shown in blue, the SCT in green, and the TRT in red. The local coordinates for each subdetector module are inset on the right. Image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

1288 use their respective local coordinate systems. The translations  $T_i$  are with respect to the origin of  
 1289 the given reference frame, and the rotations  $R_i$  are taken about the Cartesian axes.

## 1290 4.2 Early 2015 alignment of the ATLAS detector

1291 At the end of Run 1, the LHC was shut down for upgrades and maintenance. During this time,  
 1292 a number of upgrades were performed on the ATLAS detector, including the installation of the  
 1293 Insertable B-Layer (IBL), mounted on a new beam pipe. These changes to the ID required some de-  
 1294 tector components to be removed temporarily, and many elements shifted relative to each other over  
 1295 the course of the maintenance process. In order to correct for these large detector movements prior to  
 1296 13 TeV data taking, an alignment was performed using cosmic ray data collected in early 2015 [72].  
 1297 This alignment was able to correct for the majority of the large detector-wide misalignments as well  
 1298 as determine the global position of the IBL at the micron level.

1299 In June of 2015, shortly after the data taking period began, the first track-based alignment of  
 1300 the refurbished ID was performed using the initial  $7.9 \text{ pb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$  proton-proton collision  
 1301 data [73]. Starting from the geometry determined by the cosmic ray alignment, referred to hereafter  
 1302 as the *March alignment*, an improved set of alignment constants (the *June alignment*) was derived  
 1303 from a data set of approximately 1.4 million selected tracks. A sample of Monte Carlo (MC) events  
 1304 containing approximately 2.7 million tracks from dijet events simulated using a perfect detector  
 1305 geometry is used as a comparison to the data; the MC events are reweighted to match the  $\eta$  and  $p_T$

1306 distributions found in the data. Additional validation of the alignment results uses a set of cosmic  
1307 ray data collected by the detector during the LHC collisions.

1308 **4.2.1 June alignment procedure**

1309 The data set used as the input for the alignment is made up of a subset of physics events used for  
1310 prompt reconstruction recorded at a rate of 10 Hz. To ensure that only high quality tracks are used  
1311 for the alignment, each track is required to have transverse momentum  $p_T > 3$  GeV, contain at least  
1312 one hit in the Pixel detector, at least seven hits in the combined silicon detectors (IBL, Pixel, and  
1313 SCT), and at least 25 hits in the TRT.

1314 A full L3 alignment of the IBL was included in the March alignment; however, a realignment was  
1315 still necessary. Since cosmic rays pass through the detector top-down, the staves on the sides of the  
1316 IBL recorded fewer hits and thus could not be aligned as precisely as those on the top and bottom.  
1317 Additionally, the IBL was operating at a temperature of  $-20^\circ\text{C}$  during the cosmic data taking, and  
1318 it was set to  $-10^\circ\text{C}$  for collision data taking. This proved to be significant, as it was observed that  
1319 the IBL staves experience a temperature-dependent, parabolic bowing in the local  $x$ -direction of  
1320 approximately  $-10\mu\text{m}/\text{K}$  [74]. As a result, a full L3 alignment of the IBL was essential in order to  
1321 correct for the bowing. Due to it being a brand new element of the detector as well as its importance  
1322 in vertexing and  $b$ -jet tagging, aligning the IBL sensors with a high degree of precision was one of  
1323 the main goals of the June alignment.

1324 The June alignment was performed in two stages, with the first pass focusing on relative move-  
1325 ments of the big structures and correcting for the bowing of the IBL. The March alignment corrected  
1326 for these larger movements as well; however, it was observed during Run 1 that these sort of mis-  
1327 alignments are introduced by changing conditions in the detector [69], such as adjustments in the  
1328 cooling system settings or magnet power cycling, which may have occurred between the early cos-  
1329 mic data taking and the first  $\sqrt{s} = 13$  TeV collisions. The silicon detectors were aligned at several  
1330 different levels and the IBL was aligned at the module level; the TRT detector was kept fixed to  
1331 act as a global reference frame. The full alignment chain for the first pass consisted of the following  
1332 steps:

- 1333 1. The IBL, Pixel, and SCT detectors were aligned at L1. The SCT barrel was not aligned in  
1334  $T_z$  in order to constrain global displacements along the  $z$ -axis, as the TRT is not sensitive to  
1335 that degree of freedom.

- 1336     2. The IBL, and Pixel barrel and end-caps, and SCT barrel were aligned at L2. The SCT end-caps  
 1337        were aligned at L1.
- 1338     3. The IBL and pixel barrel were aligned at L27, using all six degrees of freedom. The Pixel  
 1339        end-cap disks were only aligned in the plane ( $T_x$ ,  $T_y$ , and  $R_z$ ). The SCT was treated the same  
 1340        as in the previous step.
- 1341     4. The IBL was aligned at L3 using all six degrees of freedom for each module.

1342       The primary goal for the second pass was to remove a bias in the transverse impact parameter  
 1343        $d_0$  found in the March alignment. In addition to the bias, the resolution of  $d_0$  was also observed  
 1344       to be poorer than expected. In order to correct for this, an additional constraint was passed to  
 1345       the alignment which added the impact parameter with respect to the beam spot as a pseudo-  
 1346       measurement [75]. With this setup, when the alignment algorithm minimizes the  $\chi^2$ , it will take  
 1347       care of the impact parameter minimization as well. Only the IBL and Pixel detectors were aligned  
 1348       in the second pass. The different alignment stages are listed below, with the beam spot constraint  
 1349       being used in each:

- 1350       1. The IBL and Pixel detectors were aligned at L2 with the SCT fixed.  
 1351       2. The IBL was aligned at L27  
 1352       3. The IBL and Pixel barrel and end-caps were aligned at L3.

1353       The set of alignment constants obtained at the end of the second pass represents the June alignment.  
 1354       The highest level of alignment each subdetector received over the course of the two passes is listed  
 1355       in 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.

1356 **4.2.2 Alignment results**

1357 Alignment quality is primarily assessed by looking at the track-hit residual distributions. If the  
 1358 detector is well aligned, the residuals will be Gaussian-distributed with a mean of zero and a width  
 1359 approximating the detector's resolution. The residual distributions are constructed from the same  
 1360 selection of tracks that were used to perform the alignment, and are the focus of Section 4.2.2.1.  
 1361 A second check on the alignment involves observables sensitive to the track parameter resolution.  
 1362 In this case, cosmic rays are used, making use of a “split track” technique that takes advantage of  
 1363 the top-to-bottom cosmic ray trajectory (compared to the center-out trajectory of collision tracks).  
 1364 This method and the corresponding tests of the alignment are detailed in Section 4.2.2.2

1365 Additionally, the effect of the beam spot constrained alignment on the impact parameter  $d_0$   
 1366 needed to be checked. The  $d_0$  distributions for both the March and June alignments are compared  
 1367 to the MC simulation using a perfect geometry in Figure 4.4. In the March alignment, there is  
 1368 a clear bias of  $18 \mu\text{m}$  in the mean of the distribution and the width is nearly twice that of the  
 1369 perfect geometry. After the second pass of the June alignment, the mean has shifted to  $1 \mu\text{m}$  and  
 1370 the distribution has narrowed considerably. From this, it appears that the constrained alignment  
 1371 successfully removed the  $d_0$  bias.

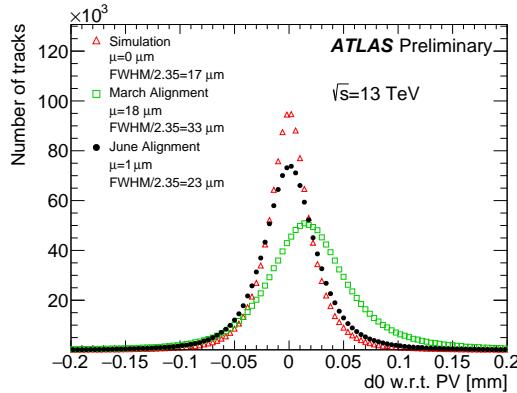


Figure 4.4: The  $d_0$  distributions with respect to the reconstructed primary vertex using 13 TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized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

1372 **4.2.2.1 Residual distributions from collisions**

1373 As mentioned previously, the primary focus of the June alignment campaign was on the IBL and the  
 1374 Pixel detectors. These subdetectors are the closest to the beam line and have the finest resolutions  
 1375 within the ID. The residual distributions in local  $x$  and  $y$  of the IBL planar sensors<sup>11</sup> are shown in  
 1376 Figure 4.5. These and subsequent figures in this section compare the June and March alignments to  
 1377 the perfectly-aligned MC simulation. Noticeable improvement in the distribution widths can be seen  
 1378 in both the local  $x$ - and  $y$ -directions, nearly matching the simulation in local  $x$ , the most sensitive  
 1379 direction.

1380 Due to the temperature-dependent bowing of the IBL, it is also interesting to look at the means of  
 1381 the residual distributions for each ring of IBL sensors along the beam line, as shown in Figure 4.6. A  
 1382 deformation is clearly visible in the March alignment in both measurement directions, and the shape  
 1383 in the local  $x$ -direction is consistent with an average stave bowing due to the different operating  
 1384 temperature of the IBL during the March alignment and the 13 TeV collisions. This feature was  
 1385 nearly eliminated in both directions through the L3 alignment of the IBL sensors.

1386 The local  $x$  and  $y$  residual distributions for the Pixel detector barrel and end-caps are shown  
 1387 in Figures 4.7 and 4.8. Even though the IBL is not included in the plots of the barrel, some of  
 1388 the noticeable improvement in the more sensitive local  $x$ -direction is an effect of the improved IBL  
 1389 alignment. Similarly, the relatively broad local  $y$  residual distribution in the barrel likely indicates  
 1390 that further refinement of the IBL alignment was needed along that direction. Even so, the June  
 1391 alignment outperforms the March alignment and rivals the simulation in most of the plots.

1392 Similar distributions for the SCT and TRT barrel and end-caps are shown in Figures 4.9 and  
 1393 4.10, respectively. Much like with the Pixel residuals, there is a reduction in the width of the TRT  
 1394 residuals between the March and June alignments due to the alignment of the other subdetectors  
 1395 improving the quality of the track fit. Even though neither subdetector was aligned at module-  
 1396 level, the residuals indicate that the previous L3 alignment performed in Run 1 did not degrade  
 1397 significantly during the upgrade and maintenance period.

---

<sup>11</sup>The 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.

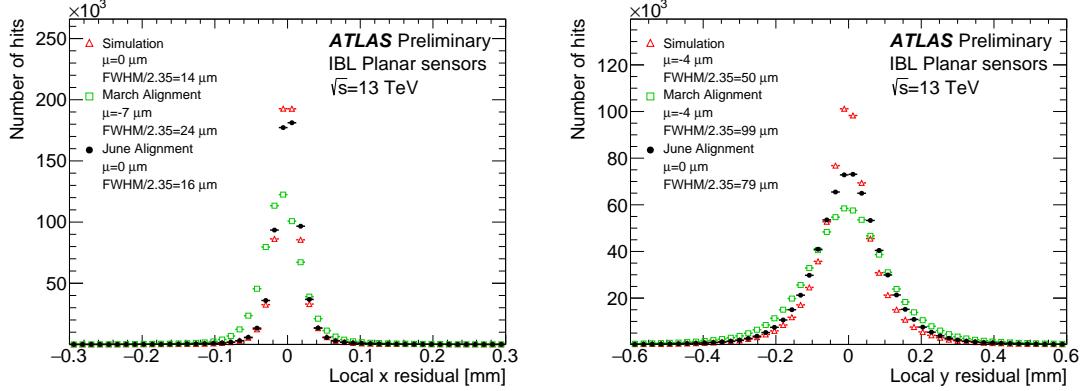


Figure 4.5: Local  $x$  (left) and local  $y$  (right) residual distributions of the IBL planar sensors using 13 TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions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

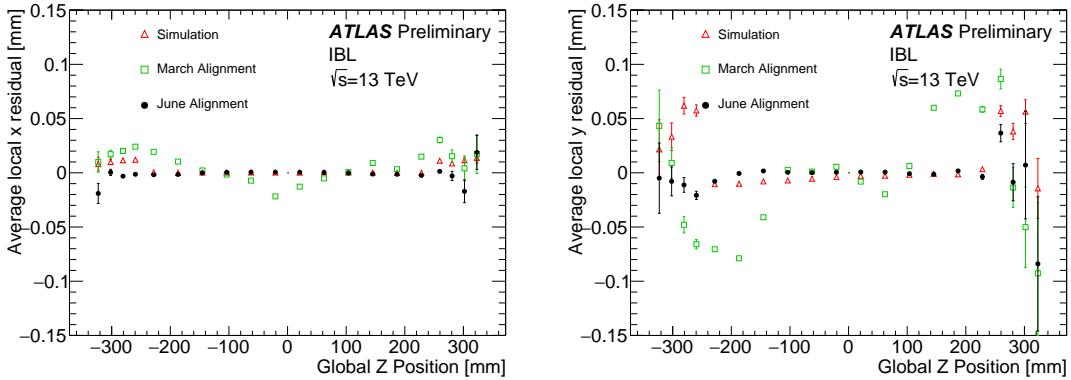


Figure 4.6: The mean of the local  $x$  (left) and local  $y$  (right) residual distributions as a function of the global  $z$  position of each IBL module using 13 TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using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

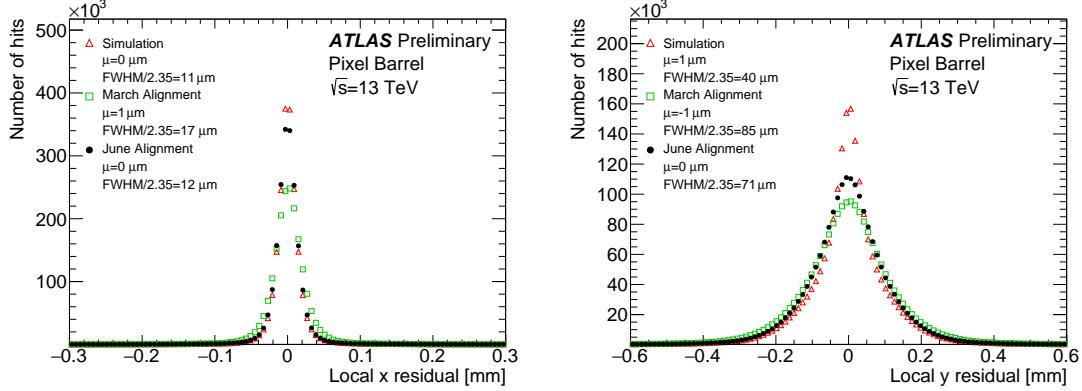


Figure 4.7: Local  $x$  (left) and local  $y$  (right) residual distributions for the Pixel barrel (excluding the IBL) using 13 TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red).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

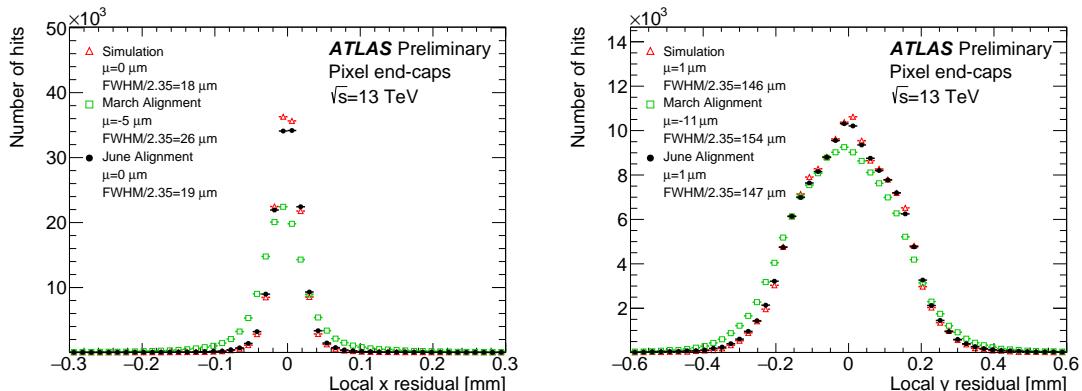


Figure 4.8: Local  $x$  (left) and local  $y$  (right) residual distributions for the Pixel end-caps using 13 TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions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

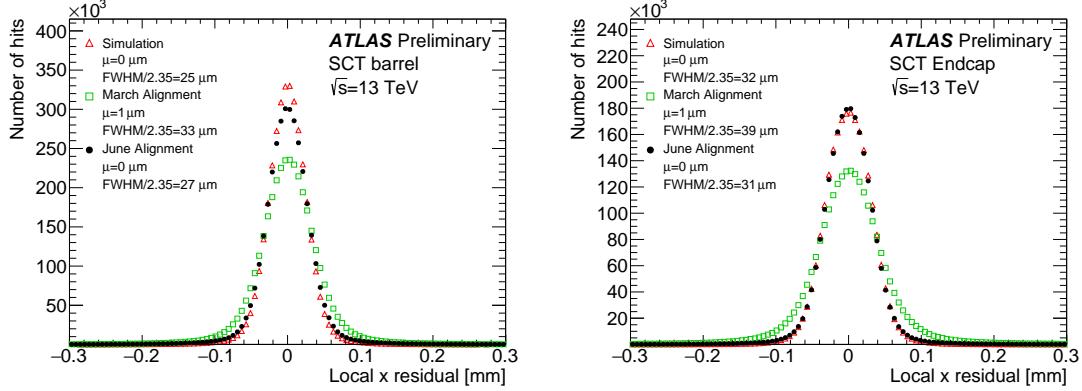


Figure 4.9: Local  $x$  residual distributions for the SCT barrel (left) and end-caps (right) using 13 TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized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

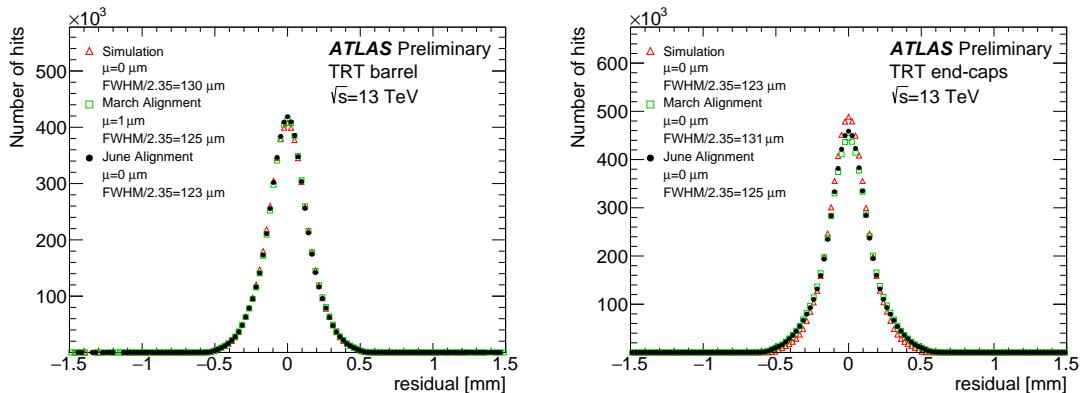


Figure 4.10: Residual distributions for the TRT barrel (left) and end-caps (right) using 13 TeV collision data sample reconstructed using the June (black) and March (green) alignments. The data is compared to a MC simulation using a perfect detector geometry (red). The distributions are normalized to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

1398 **4.2.2.2 Track parameter resolution from cosmic rays**

1399 Cosmic ray data is very useful as an independent check on the alignment in the barrel of the detector.  
 1400 While tracks from proton-proton collisions originate within the detector and travel outwards, a  
 1401 cosmic ray that passes through the center of the detector leaves a track in both halves of the  
 1402 detector. If the cosmic ray is split in half, as in Figure 4.11, then it can be treated as two separate  
 1403 tracks each with nearly identical track parameters (some differences arise due to energy loss as the  
 1404 particle passes through the detector). The distribution of the difference in a given track parameter  
 1405  $\Delta\tau$  is approximately Gaussian with a variance  $\sigma^2(\Delta\tau)$ . Since both tracks come from the same  
 1406 particle, each track individually has a variance equal to  $\sigma^2(\Delta\tau)/2$ . The resolution of the track  
 1407 parameter is then given by the root mean square of the distribution divided by  $\sqrt{2}$ .

1408 Cosmic rays whose split tracks each have transverse momentum  $p_T > 2$  GeV and at least one,  
 1409 eight, and 25 hits in the barrels of the Pixel, SCT, and TRT detectors, respectively, were selected to  
 1410 measure a collection of track parameters. Figure 4.12 shows the difference in the impact parameter  
 1411  $\Delta d_0$  and the charge divided by the transverse momentum  $\Delta q/p_T$  of the selected split-track cosmic  
 1412 rays for both the March and June alignments. Both distributions show a reduction in width in the  
 1413 June alignment, corresponding to an improvement in the resolution of each track parameter. The  
 1414  $\Delta d_0$  plot in particular shows significant improvement with the June alignment, further validating  
 1415 the removal of the bias in the impact parameter.

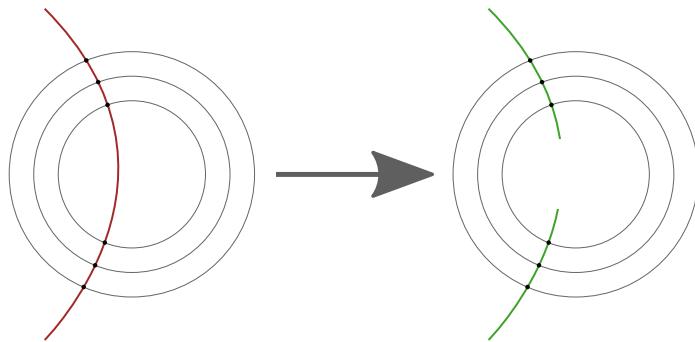


Figure 4.11: Representation of splitting a single cosmic ray track passing through the entire detector (left) into two separate tracks (right).

1416 **4.2.3 Error scaling**

1417 The final step in preparing the new set of June alignment constants deals with the adjustment of  
 1418 the hit errors, or *error scaling*. Knowledge of the exact position of a hit measurement on a track

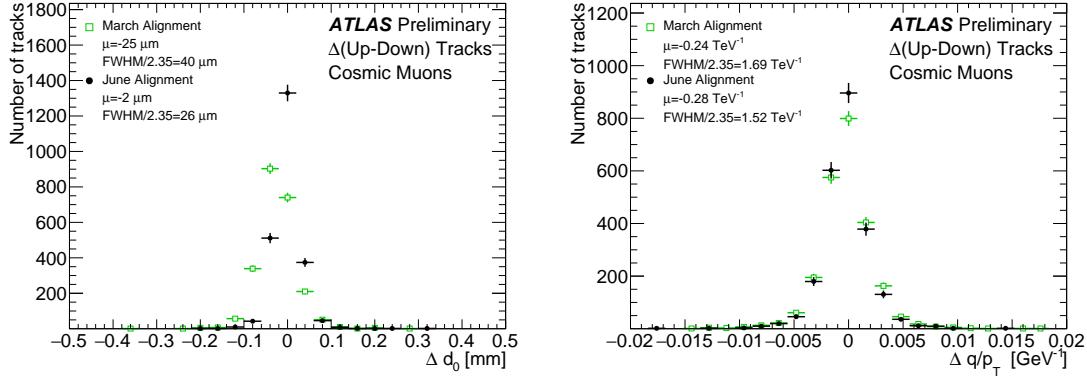


Figure 4.12: Distribution of the difference in the impact parameter  $\Delta d_0$  (left) and charge over transverse momentum  $\Delta q/p_T$  (right) between the two cosmic ray split tracks. The June (black) and March (green) alignments are compared. The distributions are normalized to the same number of entries.

is limited by the accuracy with which the sensors' positions are known. Let  $\sigma$  represent the hit uncertainty used in track fitting, and  $\sigma_0$  be the detector's intrinsic uncertainty. If  $\sigma = \sigma_0$ , the pull of the track-hit residual distributions should form a Gaussian distribution centered at zero with unit width [66]. In the case of residual misalignment, the pull distributions' standard deviations will stray from unity. The hit uncertainty can be written as:

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

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

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

### 4.3 Level 2 alignment of the TRT

During validation of the final end-of-year reprocessing of the 2015 data, a misalignment was found in the barrel of the TRT detector, as several modules (triangular clusters of straws) showed rotations in the local  $y$  coordinate. The then-best available constants included a full L3 alignment of the silicon detectors and a separate L2 alignment of the TRT. However, not all degrees of freedom were

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

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

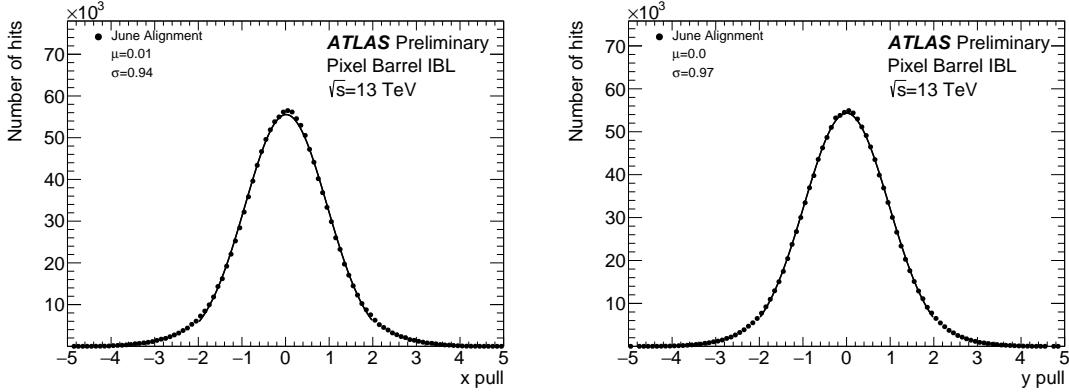


Figure 4.13: Pull distributions in local  $x$  (left) and  $y$  (right) for the IBL using 13 TeV collision data sample after applying the error scaling.

1436 enabled when the TRT was aligned. To correct for these tilts, an additional four iterations of L2  
 1437 alignment was performed on the TRT enabling all available degrees of freedom ( $T_x$ ,  $T_y$ ,  $R_x$ ,  $R_y$ , and  
 1438  $R_z$  in the barrel, and  $T_x$ ,  $T_y$ , and  $R_z$  for the endcaps). Plots of the residual means from TRT barrel  
 1439  $\phi$ -sectors containing modules affected by the tilt misalignment are shown in Figure 4.14 before and  
 1440 after the L2 alignment.

1441 Following the L2 alignment, some additional time was taken to determine if a full wire-by-wire  
 1442 L3 alignment of the TRT was necessary. The TRT was last aligned at L3 during Run 1, but  
 1443 initial alignment campaigns in Run 2 did not show signs of misalignment (see, for example, the  
 1444 residual distributions shown earlier in Figure 4.10). In order to assess the alignment more carefully,  
 1445 two dimensional residual maps in  $\phi$  and  $z$  were constructed for each layer in the TRT barrel and  
 1446 endcaps using the current alignment. These maps were compared to a similar set using the L3

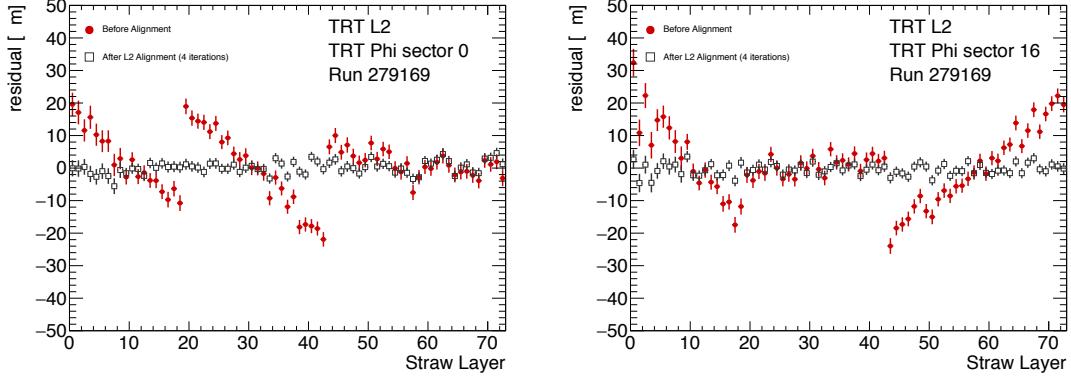


Figure 4.14: Residual means by straw layer in two TRT  $\phi$ -sectors affected by a tilt misalignment. The tilts in each of the three modules are clearly visible in the red points representing the reconstructed data prior to alignment. After four iterations of L2 alignment, the residual means in the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

1447 alignment from 2010, from which it was determined that the straw-level alignment indeed hadn't  
 1448 degraded, and a new L3 alignment was not needed. The maps for the first layer of the TRT barrel  
 1449 are shown in Figure 4.15 for both sets of alignment constants.

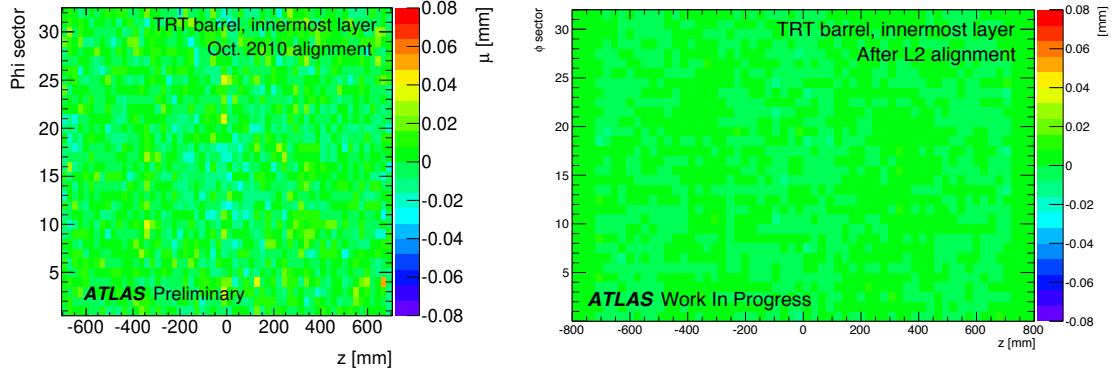


Figure 4.15: Two dimensional map of residuals in the first layer of the TRT barrel vs  $z$  and  $\phi$ . Each bin represents the mean of a Gaussian fit to the TRT residuals in that bin. The map on the left is after the L3 (wire-by-wire) alignment of the TRT performed in 2010, and the map on the right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

1450 **4.4 Momentum bias from sagitta deformations**

1451 A variety of weak mode deformations can exist in the detector even after alignment. As mentioned  
 1452 previously, these weak modes consist of misalignments which don't affect the  $\chi^2$  of the residuals and  
 1453 thus are not handled by the unconstrained alignment algorithm. In the presence of a weak mode,  
 1454 the description of the detector geometry can still provide efficient and high quality track fits, but  
 1455 there may also be systematic biases in one or more track parameters. Several weak modes, their  
 1456 impacts on the reconstruction, and the steps taken to eliminate them are detailed in [69, 76]. This  
 1457 section focuses specifically on *sagitta* deformations that result in a bias in the reconstructed track  
 1458 momentum.

1459 These sagitta distortions consist of detector movements orthogonal to the trajectory of the outgoing  
 1460 particle. The effect on the reconstructed track curvature is different for positively and negatively  
 1461 charged particles, resulting in a charge-antisymmetric bias. An example of this is illustrated by the  
 1462 curl deformation in Figure 4.16.

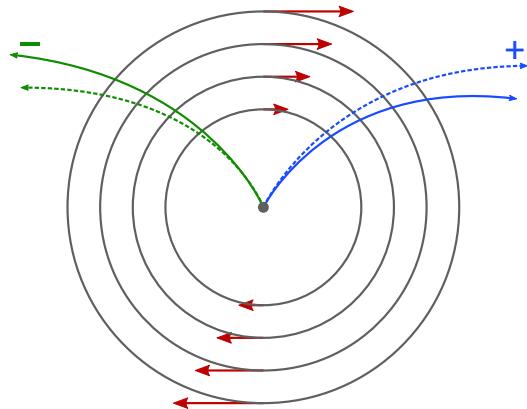


Figure 4.16: Representation of a curl distortion in the detector. The image represents a cutaway view of the transverse plane of the barrel region. The deformation is represented by the red arrows, and the impact on the reconstructed positive (blue) and negative (green) tracks are shown. The dashed lines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

1463 In the plane transverse to ATLAS's magnetic field, outgoing particle tracks form circular arcs.  
 1464 The sagitta is defined as the distance from the center of this arc to the center of its base, as shown in  
 1465 Figure 4.17, and it represents the "amount of bending" in the track. In the case where the sagitta  $s$   
 1466 is considerably smaller than the detector radius  $R_0$ , which is a valid assumption when working with

<sup>1467</sup> high momentum tracks, the transverse momentum of a particle of charge  $q$  can be written as [77]:

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

<sup>1468</sup> where  $B$  is the strength of the detector's magnetic field. If a sagitta bias is present, the track's  
<sup>1469</sup> transverse momentum shifts by [76]:

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

<sup>1470</sup> where  $\delta_s$  is a universal bias parameter that uniquely defines the deformation. Finally, since the  
<sup>1471</sup> reconstructed polar angle does not change under a sagitta deformation, the longitudinal component  
<sup>1472</sup> of the momentum scales along with the transverse component, and an equivalent equation can be  
<sup>1473</sup> written for the total momentum:

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

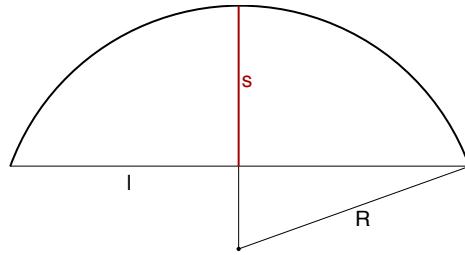


Figure 4.17: Geometric definition of the sagitta  $s$  in relation to the length of the chord  $l$  and the radius  $R$  of a circular arc.

#### <sup>1474</sup> 4.4.1 Sagitta bias monitoring with electron $E/p$

<sup>1475</sup> Since a sagitta bias results in changes in the momenta of particle tracks as measured by the ID, they  
<sup>1476</sup> can be identified using independent measurements from other systems in the detector. One such  
<sup>1477</sup> method involves using the energy-momentum ratio of electrons ( $E/p$ ). Since the electron's energy  
<sup>1478</sup> is measured in ATLAS's calorimeter systems, it is not sensitive to any sagitta bias that may exist  
<sup>1479</sup> in the ID and in the corresponding measurement of the track momentum. Under the assumption  
<sup>1480</sup> that the calorimeter response is independent of the charge of incoming particles, a charge-dependent  
<sup>1481</sup> momentum bias in the ID will manifest as a difference in the  $E/p$  ratio for electrons and positrons.

<sup>1482</sup> In the presence of a sagitta bias, the momentum will change according to Equation 4.15 and the  
<sup>1483</sup> average measured  $\langle E/p \rangle$  can be written as:

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

1484 where the approximation  $p_T \approx E_T$  is used. Assuming that  $\langle E/p \rangle^+ = \langle E/p \rangle^-$  in the absence of a  
 1485 bias, the sagitta bias parameter can be written as:

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

1486 If the kinematic selections for electrons and positrons are identical, the energy scale of the calorimeter  
 1487 will not factor into the  $\langle E/p \rangle$  difference; however, it will affect  $\langle E_T \rangle$ , which would scale the measured  
 1488  $\delta_s$ . This is expected to be a small effect, as the energy scale for electrons has been measured at  
 1489 13 TeV with uncertainties on the per-mil level across the entire detector [78].

#### 1490 4.4.1.1 Measuring $\langle E/p \rangle$

1491 The  $E/p$  ratio is measured using electrons and positrons from  $Z \rightarrow ee$  events in order to obtain a  
 1492 high purity sample of candidate particles. They are required to pass a basic selection criteria to  
 1493 ensure they are well measured in both the ID and the calorimeters:

- 1494 •  $E_T > 25$  GeV
- 1495 •  $|\eta| < 2.47$ , excluding the calorimeter’s barrel-to-endcap transition region in  $1.37 < |\eta| < 1.52$
- 1496 • Pass the MediumLH identification working point detailed in Section 3.2.4.2
- 1497 • Pass a selection of quality cuts, including a requirement that the electron be identified using  
 1498 cluster information in the calorimeter
- 1499 • The associated track must have at least one hit in the IBL, three in the Pixel detector, and  
 1500 five in the SCT detector.

1501 Events containing exactly two opposite-charge electrons passing this selection with an invariant mass  
 1502 within 30 GeV of the  $Z$  boson mass are then used for the  $E/p$  calculation.

1503 Since the size of the sagitta bias  $\delta_s$  is not expected to be constant across the entire detector,  
 1504 a two-dimensional rectangular grid is constructed binned in detector  $\eta$  and  $\phi$ . From the selected  
 1505 events, separate distributions of  $E/p$  are made for electrons and positrons within each bin. Each  
 1506 distribution is fit with Crystal Ball function<sup>12</sup>, and the peak of the distribution is taken as the value  
 1507 of  $\langle E/p \rangle$ . If there is no bias on the track momentum in the bin, the peaks for electrons and positrons  
 1508 should agree. Example  $E/p$  distributions including the Crystal Ball fits are shown in Figure 4.18.

---

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

1509 It is important to emphasize that deviations from one in the *ratio* of  $\langle E/p \rangle^+$  to  $\langle E/p \rangle^-$  points  
 1510 to a potential momentum biases. The value of  $\langle E/p \rangle$  itself is not expected to equal one exactly,  
 1511 as the track momentum on average tends to be slightly lower than the energy measurement in the  
 1512 calorimeter. This is due to the fact that if the electron were to radiate a photon, its momentum  
 1513 would change slightly, while it is likely that both the electron and the emitted photon would leave  
 1514 energy deposits near each other in the calorimeter and be reconstructed into the same object.

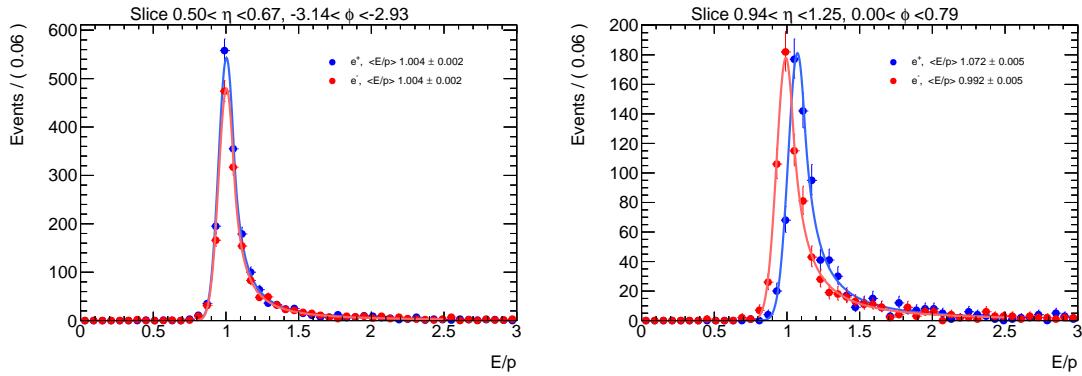


Figure 4.18:  $E/p$  distributions of electrons and positrons in two different  $\eta\text{-}\phi$  bins of the detector. The left hand plot is taken from a region with no momentum bias where  $\langle E/p \rangle^+ = \langle E/p \rangle^-$ , while the right hand plot shows an 8% disagreement in  $\langle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

1515 Once the  $\langle E/p \rangle^\pm$  distributions in each  $\eta\text{-}\phi$  bin have been extracted from the fits, a two dimensional  
 1516 map of  $\delta_s$  can be constructed using Equation 4.17. The map gives an overview of sagitta  
 1517 biases that may be present in the detector, and can be used by the alignment algorithm to reduce  
 1518 the bias in the next iteration. In this case, the tracks fed to the alignment have their momenta  
 1519 corrected according to [76]:

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

1520 where  $p_{\text{reco}}$  is the reconstructed momentum of the track. The corrected momentum is then con-  
 1521 strained in the alignment.

#### 1522 4.4.1.2 Results in 13 TeV data

1523 The  $E/p$  method has been used to monitor sagitta biases in the detector several times over the  
 1524 course of Run 2. During this time, it has primarily served as an independent cross-check to a second  
 1525 method using  $Z \rightarrow \mu\mu$  events [76]. The  $Z \rightarrow \mu\mu$  method identifies individual track momentum  
 1526 biases through shifts in the reconstructed  $Z$  mass, which leaves it relatively insensitive to global  
 1527 sagitta biases. For this reason, the sagitta bias maps produced using this technique are normalized

1528 to those from the  $E/p$  method before being used to constrain the alignment. The results of two  
 1529 implementations of the  $E/p$  method are presented here.

- 1530 1. The first follows the end-of-year reprocessing of the entire ATLAS 2016 data set. Two sets  
 1531 of alignment constants are compared: the *prompt* alignment, which was derived shortly after  
 1532 each run was recorded, and the *reprocessed* alignment. The maps of the sagitta bias in each  
 1533 alignment calculated using the  $E/p$  method are shown in Figure 4.19, and the comparison of  
 1534 the  $\eta$  projection of the maps is shown in Figure 4.20.  
 1535  
 1536 2. The second uses the 2017 data after reprocessing, and compares the effects of multiple iterations  
 1537 of the  $E/p$  method. In each iteration, the momenta of the electrons and positrons are corrected  
 1538 according to Equation 4.15 using the value of  $\delta_s$  computed in the previous iteration, and a  
 1539 new sagitta bias map is calculated. If the method is indeed characterizing the sagitta biases  
 1540 correctly, the corrections should converge quickly. The initial sagitta bias map is compared to  
 1541 the map after two such iterations in Figure 4.21, and the sagitta bias projected along  $\eta$  for  
 1542 each iteration is shown in Figure 4.22. Indeed, after just two iterations,  $\delta_s$  is consistent with  
 zero in nearly all bins.

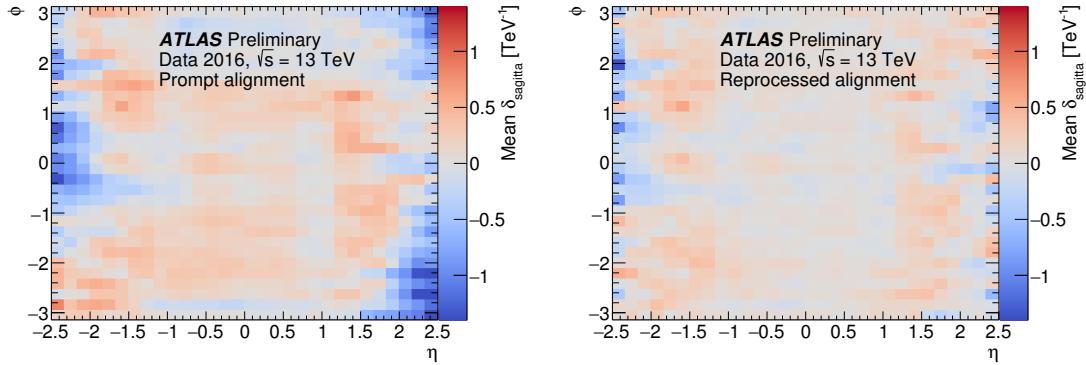


Figure 4.19: Sagitta bias in the  $\sqrt{s} = 13$  TeV data collected by ATLAS in 2016 as a function of  $\eta$  and  $\phi$  for the prompt (left) and reprocessed (right) alignments using the  $E/p$  method.

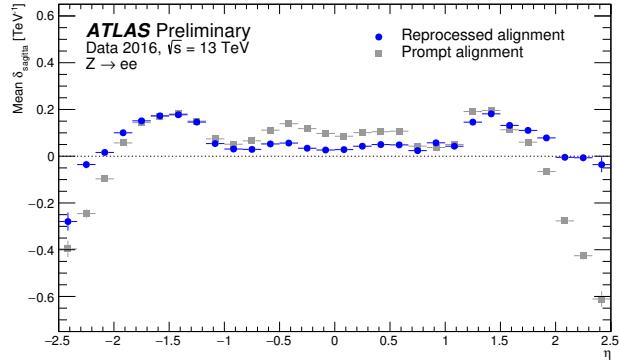


Figure 4.20: Sagitta bias in the  $\sqrt{s} = 13 \text{ TeV}$  data collected by ATLAS in 2016 projected along  $\eta$  for the prompt (gray) and reprocessed (blue) alignments using the  $E/p$  method.

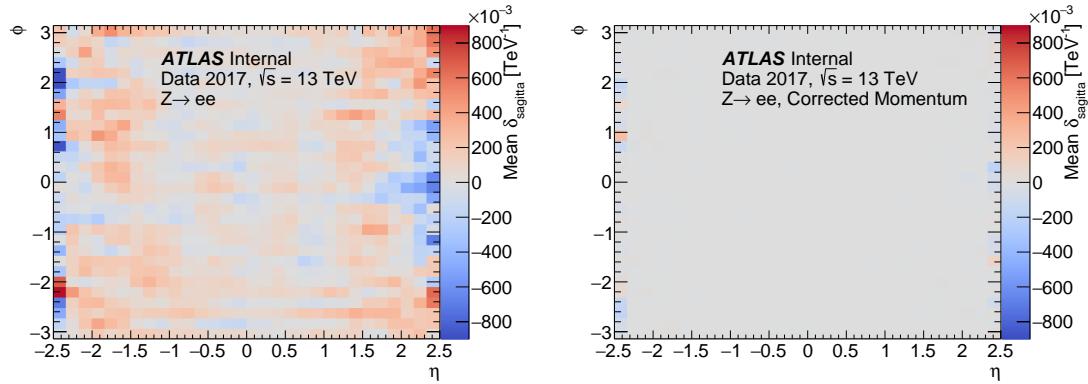


Figure 4.21: Sagitta bias in the  $\sqrt{s} = 13 \text{ TeV}$  data collected by ATLAS in 2017 as a function of  $\eta$  and  $\phi$  in reconstructed electrons (left) and after two iterations of momentum corrections (right) from the  $E/p$  method.

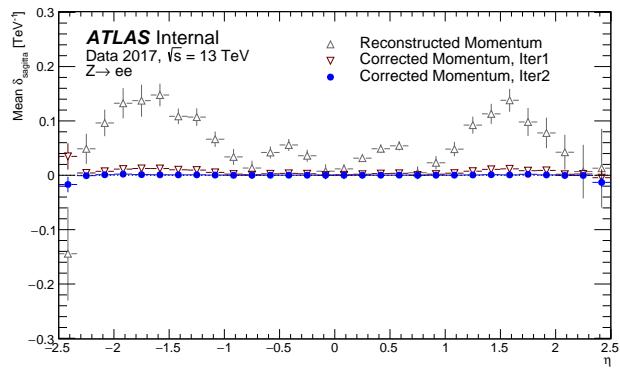


Figure 4.22: Sagitta bias in the  $\sqrt{s} = 13$  TeV data collected by ATLAS in 2017 projected along  $\eta$  in reconstructed electrons (gray) and after one (red) and two (blue) iterations of momentum corrections from the  $E/p$  method.

1543

## CHAPTER 5

1544

1545

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

1546 Production of same-sign  $W$  boson pairs is a particularly interesting SM process. When produced  
1547 via vector boson scattering (VBS),  $W^\pm W^\pm jj$  is sensitive to the electroweak symmetry breaking  
1548 (EWSB) mechanism as well as potential Beyond the Standard Model (BSM) physics processes.  
1549  $W^\pm W^\pm jj$  events can be produced via electroweak-mediated (EWK) diagrams, of which VBS is a  
1550 subset, or QCD-mediated diagrams. The biggest advantage of same-sign  $W^\pm W^\pm jj$  over other VBS  
1551 processes lies in its ratio of electroweak (EWK) to QCD production cross sections. Despite the  
1552 opposite-sign  $W^\pm W^\mp$  having a larger total cross section, its EWK-mediated diagrams are much  
1553 smaller than its QCD-mediated diagrams, while for same-sign  $W^\pm W^\pm$  the EWK production is  
1554 considerably larger. This makes  $W^\pm W^\pm jj$  one of the premier channels for studying VBS at the  
1555 LHC.

1556 The first evidence of electroweak (EWK)  $W^\pm W^\pm jj$  production was seen by the ATLAS and CMS  
1557 experiments at  $\sqrt{s} = 8$  TeV with excesses of  $3.6\sigma$  [79] and  $2.0\sigma$  [80] over backgrounds, respectively.  
1558 More recently, ATLAS and CMS have both observed the EWK process at  $\sqrt{s} = 13$  TeV with  
1559 significances of  $6.9\sigma$  [81] and  $5.5\sigma$  [82], respectively. The ATLAS  $\sqrt{s} = 13$  TeV observation and  
1560 cross section measurement of EWK-produced  $W^\pm W^\pm jj$  is presented in this chapter [81, 83].

### 1561 5.0.1 Experimental overview of vector boson scattering

1562 VBS processes are very important to understand due to their sensitivity to the EWSB mechanism.  
1563 As explained in Section 2.3, in the absence of a light SM Higgs boson, the scattering amplitude of  
1564 longitudinally polarized vector bosons grows with center-of-mass energy. However, once the Higgs

1565 is introduced, the divergences cancel and the cross section no longer grows unbounded.

1566 With the discovery of the Higgs boson in 2012 [16, 17], the EWSB mechanism can now be directly  
 1567 studied. Due to the potential exchange of a Higgs boson in the VBS diagrams ( $W^\pm W^\pm jj$  itself does  
 1568 not contain an  $s$ -channel Higgs exchange), VBS processes are directly sensitive to properties of the  
 1569 Higgs. For example, the high-mass tail in the  $VV$  scattering system allows an approximation of the  
 1570 effective coupling strength of the Higgs to vector bosons that is independent of any assumptions  
 1571 on the Higgs width [84]. Additionally, the center of mass energy dependence of the  $VV$  scattering  
 1572 can reveal whether the Higgs boson unitarizes the longitudinal scattering amplitude fully or only  
 1573 partially [85].

1574 VBS events are characterized by two quarks from the colliding protons each radiating a vector  
 1575 boson which then scatter and decay in the detector. The incoming quarks carry a large amount of  
 1576 momentum and only deflect a small amount upon emitting the vector boson; as a result, they often  
 1577 enter the calorimeters very close to the beam line. Ignoring the decay products of the scattered  
 1578 bosons for now, these VBS events result in a final state of two vector bosons ( $V$ ) and two jets ( $j$ )  
 1579 at high pseudorapidities (called *forward jets* or *tag jets*) from the outgoing quarks. The shorthand  
 1580  $VVjj$  is used to represent this final state.

1581  $VVjj$  events can be produced via two different physical processes. The first involves purely  
 1582 electroweak interactions in the tree-level diagrams, of order  $\mathcal{O}(\alpha_{\text{EWK}}) = 6$  in the electroweak coupling  
 1583 constant, and will be referred to as *EWK production*. This can be further broken down into VBS  
 1584 and non-VBS events. In the VBS EWK production, the scattering occurs via triple or quartic gauge  
 1585 couplings, as well as the exchange of a Higgs boson. The non-VBS EWK production contains the  
 1586 same final state of two vector bosons and two outgoing quarks, but the bosons do not scatter. Due to  
 1587 gauge invariance, it is not possible to separate the VBS from the non-VBS productions [86]; therefore,  
 1588 both are included in the signal generation and are indistinguishable from one another. The second  
 1589 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  
 1590 will be referred to as *QCD production*. The tree-level Feynman diagrams for VBS EWK, non-VBS  
 1591 EWK, and QCD  $VVjj$  production are found in Figures 5.1, 5.2, and 5.3, respectively.

### 1592 5.0.2 Same-sign $W^\pm W^\pm$ scattering

1593 Same-sign  $W^\pm W^\pm jj$  scattering is considered to be one of the best channels for studying VBS at  
 1594 the LHC due to its favorable ratio of EWK to QCD production [84]. Since the VBS diagrams are  
 1595 the primary interest for analysis, the QCD production is considered a background. Therefore a

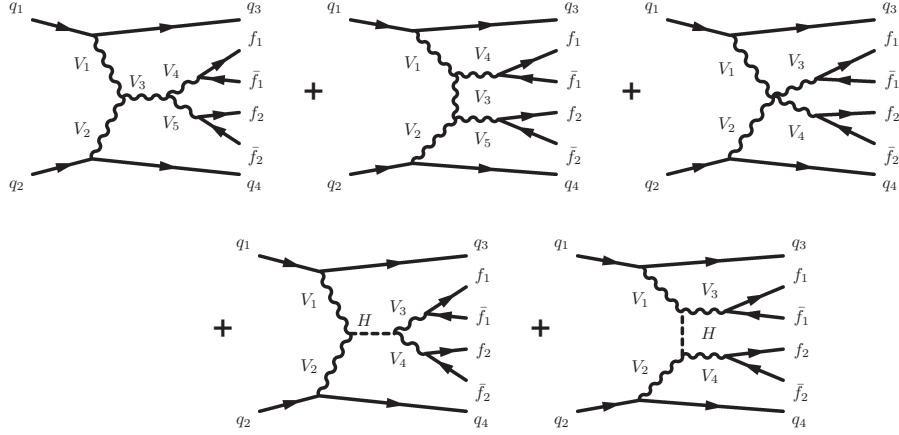


Figure 5.1: Tree-level Feynman diagrams for VBS EWK  $VVjj$  production including triple gauge couplings involving  $W$  and/or  $Z$  bosons (top left and top middle), quartic gauge coupling (top right), or the exchange of a Higgs boson ( $s$ -channel bottom left and  $t$ -channel bottom right). The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

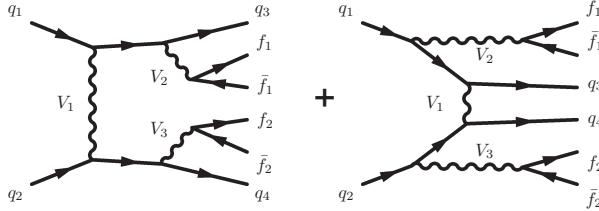


Figure 5.2: Tree-level Feynman diagrams for non-VBS EWK  $VVjj$  production. The labels are quarks ( $q$ ), fermions ( $f$ ), and gauge bosons ( $V = W, Z$ ).

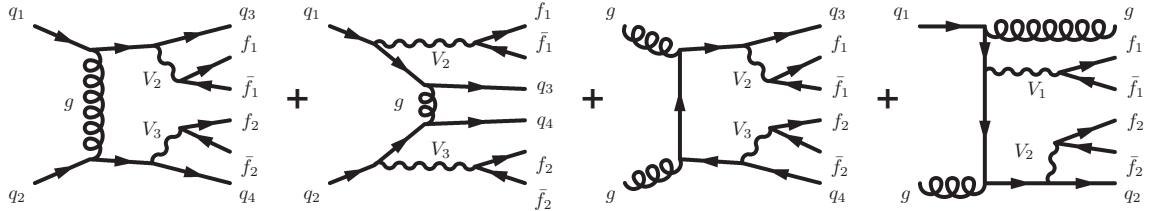


Figure 5.3: Tree-level Feynman diagrams for QCD  $VVjj$  production. The labels are quarks ( $q$ ), fermions ( $f$ ), and gauge bosons ( $V = W, Z$ ).

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

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

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

This analysis studies  $W^\pm W^\pm jj$  scattering where both  $W$  bosons decay leptonically to  $e\nu$  or  $\mu\nu$ <sup>13</sup>. 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 tag jets in the characteristic VBS signature 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. Finally, an ATLAS event display of a real  $W^\pm W^\pm jj$  candidate event is shown in Figure 5.7.

### 5.0.3 Overview of backgrounds

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

<sup>13</sup>Throughout the rest of this chapter, unless stated otherwise,  $l$  denotes either electrons ( $e$ ) or muons ( $\mu$ ), and  $\nu$  denotes a neutrino. Additionally,  $e$ ,  $\mu$ , and  $\nu$  with no charge or anti-particle designation refer interchangeably to either the particle or anti-particle.

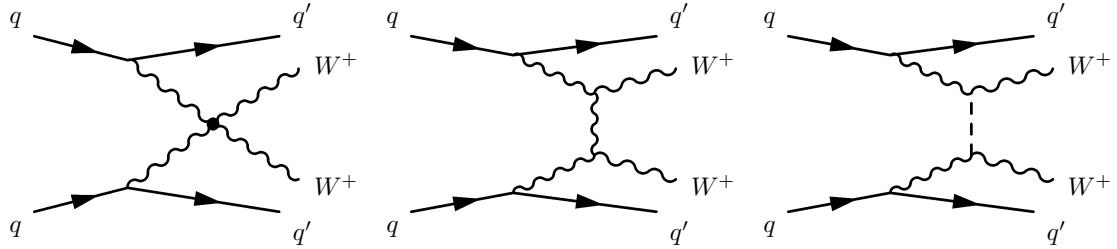


Figure 5.4: Leading order Feynman diagrams for VBS EWK production of  $W^\pm W^\pm jj$  events. The leftmost diagram contains a quartic gauge coupling vertex, and the rightmost diagram contains an exchange of a Higgs boson.

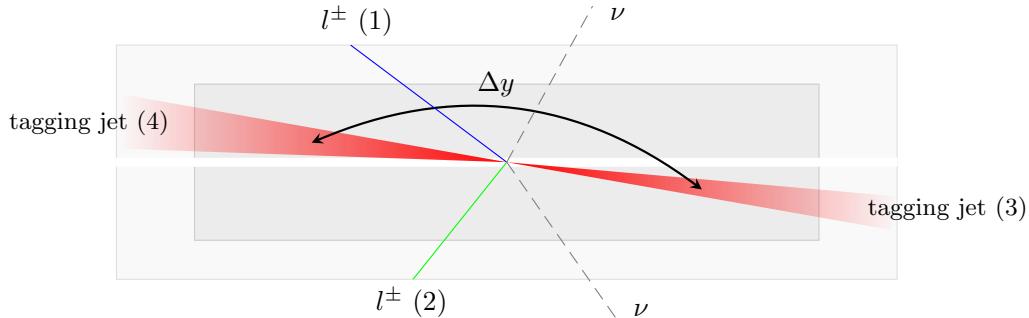


Figure 5.5:  $W^\pm W^\pm jj$  VBS event topology containing two leptons (1 and 2) with the same electric charge, two neutrinos, and two forward tagging jets (3 and 4) with large rapidity separation  $\Delta y$ .

1614 there is a considerable reduction in SM backgrounds (such as  $Z$  boson events) when compared to  
1615 an analysis like opposite-sign  $W^\pm W^\mp jj$ .

1616 One of the largest background sources involves processes with prompt leptons<sup>14</sup>. These are events  
1617 that contain two leptons with the same electric charge and one or more additional leptons that are  
1618 “lost”, either by failing the selection criteria or falling outside of the detector’s acceptance. The  
1619 number of processes that can contribute is limited by the requirement of same-sign leptons, and as a  
1620 result this background is dominated by multi-boson processes, with the largest contribution coming  
1621 from  $WZ$  events and smaller contributions from  $ZZ$  and  $t\bar{t} + V$  events. Triboson events where one  
1622 boson decays hadronically also contribute to this background; however, the jets are generally softer  
1623 and more central than in a typical VBS event, and the cuts applied on the forward jets suppress  
1624 these contributions.

---

<sup>14</sup>Prompt 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. Jets that are mis-reconstructed as a lepton are also considered non-prompt.

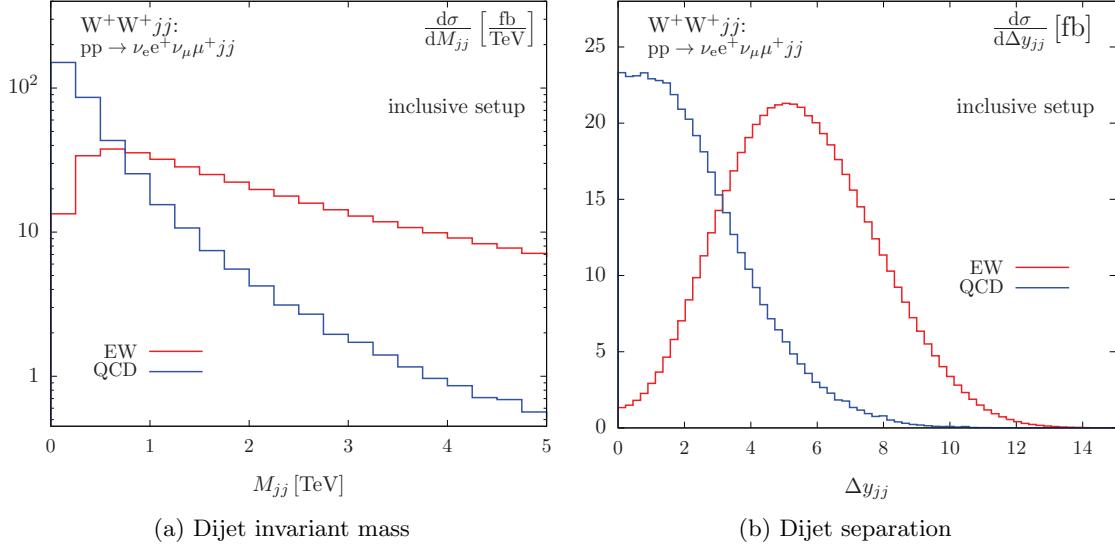


Figure 5.6: Generator level comparisons at  $\sqrt{s} = 7$  TeV of dijet invariant mass ( $M_{jj}$ , left) and dijet rapidity ( $\Delta y_{jj}$ , right) in EWK (red) and QCD (blue)  $W^\pm W^\pm jj$  events with no selection cuts applied. Plots taken from [88].

1625 The other dominant background comes from non-prompt, or “fake”, leptons. Here one or more  
 1626 leptons originate from the decay of another particle unrelated to the signal process, such as a heavy-  
 1627 flavor decay or photon conversion, or come from a jet that is misidentified as a lepton. This back-  
 1628 ground is mostly made up of events from  $t\bar{t}$  and  $W+jets$  processes, with a much smaller contribution  
 1629 from conversions in  $V\gamma$  events.

1630 Finally, opposite-sign lepton pairs can enter the signal region if one of the leptons is reconstructed  
 1631 with the wrong charge (called *charge misidentification*<sup>15</sup>). In practice, this only affects events with  
 1632 electrons, as the charge misidentification rate for muons is negligible [89]. This is a major background  
 1633 in events with two electrons, dominated by  $Z \rightarrow ee$  events; it is a much smaller contribution for  
 1634 events with one electron and one muon, where the primary contribution comes from  $t\bar{t}$  events.

## 1635 5.1 Data and Monte Carlo samples

1636 This analysis uses  $36.1 \text{ fb}^{-1}$  of  $\sqrt{s} = 13$  TeV proton-proton collisions recorded by ATLAS during  
 1637 the 2015 and 2016 data taking periods. The uncertainty in the combined integrated luminosity is  
 1638 2.1%. It is derived following a methodology similar to that detailed in [90] and using the LUCID-2

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

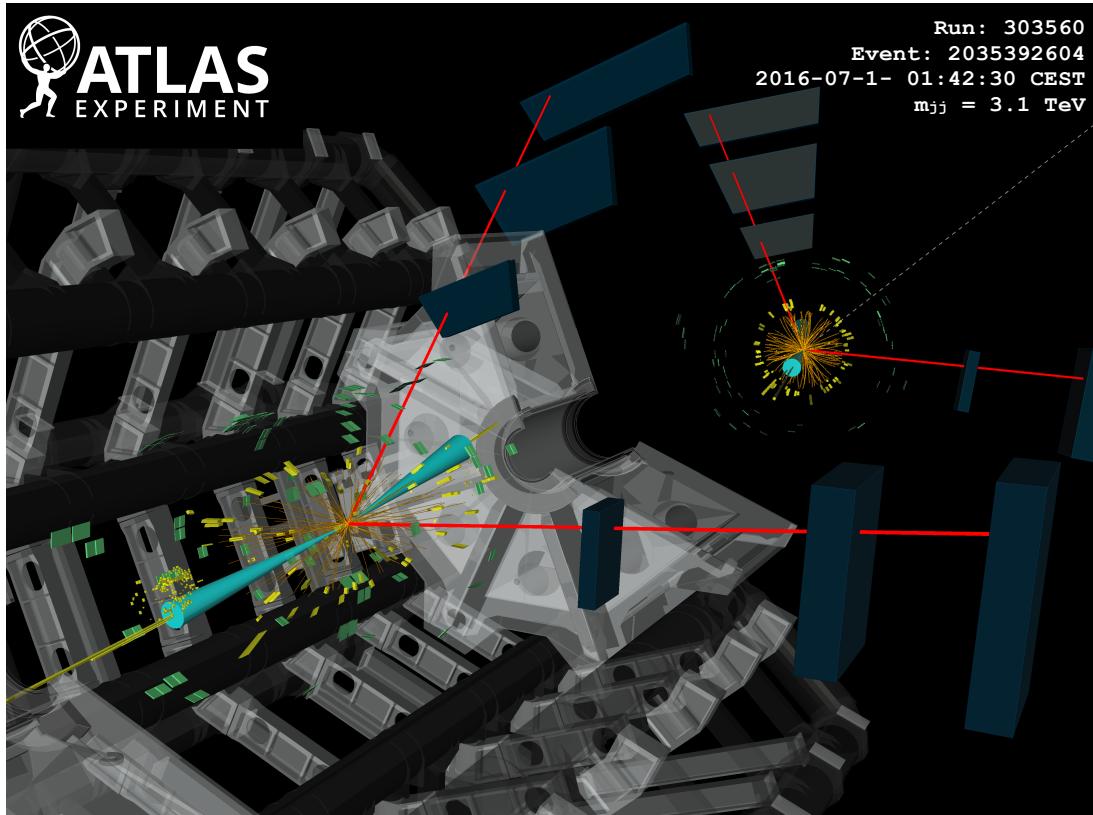


Figure 5.7: ATLAS event display of a  $pp \rightarrow W^+W^+ \rightarrow \mu^+\nu_\mu\mu^+\nu_\mu jj$  event. The muons are represented by the red lines travelling from the ID through the MS, and the forward jets are represented by the blue cones with yellow energy deposits in the calorimeters. The direction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

1639 detector for the baseline luminosity measurements [91] from calibration of the luminosity scale using  
 1640  $x$ - $y$  beam-separation scans.

### 1641 5.1.1 Monte Carlo samples

1642 A number of Monte Carlo (MC) simulations are employed to model signal and background processes.  
 1643 In order to model the real collision data as closely as possible, each MC sample has been passed  
 1644 through a full simulation of the ATLAS detector in GEANT4 [92, 93], and events have been recon-  
 1645 structed using the same algorithms as the data. The simulation reproduces as closely as possible  
 1646 the momentum resolutions and calorimeter responses of the detector, and also includes the effects  
 1647 of pileup by including soft QCD interactions using PYTHIA v8.1 [94]. The MC samples used in this

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

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

1648 analysis are detailed in this section and summarized in Table 5.2.

1649 The  $W^\pm W^\pm jj$  samples are modeled using SHERPA v2.2.2 [95, 96, 97] with the NNPDF3.0 PDF  
 1650 set [98]. The EWK signal samples were generated by fixing the electroweak coupling constant to  
 1651  $\mathcal{O}(\alpha_W) = 6$ , and a QCD background sample was also generated with  $\mathcal{O}(\alpha_W) = 4$ . SHERPA includes  
 1652 up to one parton at next-to-leading order (NLO) and up to three at leading order (LO) in the strong  
 1653 coupling constant  $\alpha_s$ . A second  $W^\pm W^\pm jj$  EWK sample was generated using POWHEG-BOX v2 [99]  
 1654 with the NNPDF3.0 PDF set and at NLO accuracy. This sample is only used for systematic studies,  
 1655 as POWHEG-BOX does not include resonant triboson contributions in its matrix element, which are  
 1656 non-negligible at NLO [100].

1657 Diboson processes ( $VV$  where  $V = W, Z$ ) are simulated with SHERPA v2.2.2 for mixed hadronic  
 1658 and leptonic decays and SHERPA v2.2.1 for fully leptonic decays of the bosons. Similarly, triboson  
 1659 ( $VVV$ ) and  $V\gamma$  processes are simulated using SHERPA v2.1.1 with up to one parton at NLO and up  
 1660 to three at LO.  $W+jets$  processes are simulated with SHERPA v2.2.1 with up to two partons at NLO  
 1661 and four at LO. All the above SHERPA samples use the NNPDF3.0 PDF set and SHERPA's own parton  
 1662 showering. The  $Z+jets$  events are generated with Madgraph5\_aMC@NLO [101] at LO and interfaced  
 1663 with PYTHIA v8.1 for parton showering.

1664  $t\bar{t}$  events are generated using POWHEG-BOX v2 with the CT10 PDF set [102].  $t\bar{t}V$  samples are  
 1665 generated at NLO with Madgraph5\_aMC@NLO and the NNPDF3.0 PDF set interfaced with PYTHIA v8  
 1666 for parton showering. Finally, single top events are generated with POWHEG-BOX v1 and the CT10f4  
 1667 PDF set interfaced with PYTHIA v6 [103] for parton showering.

**1668 5.2 Object and event selection**

1669 This section details the selection criteria for objects used in the analysis as well as the selection for  
1670 signal events.

**1671 5.2.1 Object selection**

1672 Muons, electrons, and jets all must pass strict selection requirements to ensure that only high quality,  
1673 well measured objects are used. For leptons, a baseline selection is defined (called the *preselection*),  
1674 which all leptons must pass in order to be considered for the analysis. This preselection is an  
1675 intentionally loose set of criteria designed to have high acceptance in order to reject backgrounds  
1676 with additional leptons (such as  $WZ \rightarrow 3l\nu jj$ ). Signal leptons are then required to satisfy a much  
1677 tighter *signal selection* aimed at suppressing backgrounds from non-prompt or fake leptons. A third  
1678 set of lepton selection criteria, the *loose selection*, defines a sample enriched in non-prompt leptons,  
1679 and it is used in the fake-factor method for estimating the non-prompt background, discussed in  
1680 detail in Section 5.3.4. Jets are only required to pass one set of selection criteria. These selections  
1681 are outlined in the following subsections and summarized in Table 5.3 for muons, Table 5.4 for  
1682 electrons, and Table 5.5 for jets.

**1683 5.2.1.1 Muon candidate selection**

1684 Cuts on muon momentum serve to reject low momentum leptons from background processes and from  
1685 additional collisions occurring in pileup events. Preselected muons must have transverse momentum  
1686  $p_T > 6$  GeV, and the signal muons must pass  $p_T > 27$  GeV. The  $p_T$  requirement for loose muons  
1687 is lower than for signal muons, at  $p_T > 15$  GeV, for reasons that are discussed in Section 5.3.4.3.  
1688 Muons are required to fall within the detector's  $\eta$  acceptance:  $|\eta| < 2.7$  for preselected muons, which  
1689 is tightened to  $|\eta| < 2.5$  for the signal muons.

1690 Cuts on the transverse and longitudinal impact parameters are applied to ensure that the can-  
1691 didate muon originated from the primary particle interaction and not some other source. The  
1692 preselection and the loose selection both have relaxed requirements on the transverse impact pa-  
1693 rameter significance ( $d_0/\sigma_{d_0}$ ) than the signal selection; all three have the same requirement on the  
1694 transverse impact parameter ( $|z_0 \times \sin \theta|$ ).

1695 Finally, the muon candidates are required to pass a particle identification and an isolation criteria  
1696 as defined in [61]. The methods used in constructing the identification and isolation working points  
1697 are described in more detail in Section 3.2.4.3. The muon identification serves to select prompt

1698 muons with high efficiency and well measured momenta. This analysis uses two different working  
 1699 points: **Loose** for preselected muons and **Medium** for loose and signal muons, where **Medium** muons  
 1700 are a tighter subset of those that pass the **Loose** requirement. Muon isolation is a measurement  
 1701 of detector activity around the muon candidate, and it is measured with both track-based and  
 1702 calorimeter-based variables. The isolation working point used for the signal muons, **Gradient**, is  
 1703 defined such that there is 90% or better background rejection efficiency for 25 GeV muons, and 99%  
 1704 efficiency at 60 GeV. There is no minimum isolation requirement for preselected or loose muons.  
 1705 Loose muons are additionally required to fail one or both of the signal transverse impact parameter  
 1706 cut and signal isolation requirement.

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

| 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       | <b>Medium</b>                       |
| Particle isolation            | <b>Gradient</b>                     |

| 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                                       | <b>Medium</b>                       |
| 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.

### 1707 5.2.1.2 Electron candidate selection

1708 The electron candidate selections are very similar to those for muons. The momentum cut starts  
 1709 at  $p_T > 6$  GeV for the preselection, increases to  $p_T > 20$  GeV for loose electrons, and finally to

<sup>1710</sup>  $p_T > 27$  GeV for signal electrons. The  $|\eta|$  cut for electrons requires  $|\eta| < 2.47$  for all electrons,  
<sup>1711</sup> with the region  $1.37 \leq |\eta| \leq 1.52$  removed from loose and signal electrons. This is where the  
<sup>1712</sup> electromagnetic calorimeter transitions from the barrel to the endcaps and is not fully instrumented.  
<sup>1713</sup> Both the transverse and longitudinal impact parameter cuts are the same for all electron selections.

<sup>1714</sup> The electron particle identification uses a multivariate likelihood technique (LH) detailed in  
<sup>1715</sup> Section 3.2.4.2. Preselected electrons must pass the `LooseLH` working point with an additional  
<sup>1716</sup> requirement that there be a reconstructed track hit in the first layer of the pixel detector (a so-  
<sup>1717</sup> called *B*-layer hit). The LH requirement for the loose and signal electrons increases in tightness  
<sup>1718</sup> using `MediumLH` and `TightLH` electrons, respectively. As for isolation, the `Gradient` working point is  
<sup>1719</sup> required for signal electrons only. The loose electrons must fail one or both of the signal identification  
<sup>1720</sup> 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.

1721 **5.2.1.3 Jet candidate selection**

1722 The final objects that need to pass selection are jets. Jets are clustered using the anti- $k_t$  algo-  
 1723 rithm [104] within a radius of  $\Delta R = 0.4$ . The jets are then calibrated using  $E_T$ - and  $\eta$ -dependent  
 1724 correction factors that are trained using MC simulations [105]. The calibrated jets are required  
 1725 to have  $p_T > 30$  GeV if they lie in the forward regions of the detector ( $2.4 < |\eta| < 4.5$ ) and  
 1726  $p_T > 25$  GeV in the central region ( $|\eta| \leq 2.4$ ). In order to suppress pileup jets, the so-called jet-  
 1727 vertex-tagger (JVT) discriminant associates a jet with the primary interaction vertex [106]; central  
 1728 jets with  $p_T > 60$  GeV are required to pass the **Medium** JVT working point, which corresponds to  
 1729 an average efficiency of over 92%. Finally, the jets are required to be separated from the selected  
 1730 leptons by at least  $\Delta R(j, l) > 0.3$ .

| Jet selection         |  |
|-----------------------|--|
| Momentum cut          | $p_T > 30$ GeV for $2.4 <  \eta  < 4.5$<br>$p_T > 60$ GeV for $ \eta  < 2.4$ |
| JVT cut               | <b>Medium</b>  |
| 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.

1731 **5.2.1.4 Treatment of overlapping objects**

1732 In the event that one or more objects are reconstructed very close to each other, there is the possibility  
 1733 for double-counting if both originated from the same object. The procedure by which this ambiguity  
 1734 is resolved is called *overlap removal* (OR). The standard ATLAS recommendation for OR [107, 108]  
 1735 is implemented in this analysis and is summarized in Table 5.6.

1736 Since electrons leave a shower in the EM calorimeter, every electron has a jet associated with  
 1737 it. Therefore, any jets close to an electron (within  $\Delta R(e, j) < 0.2$ ) are rejected due to the high  
 1738 probability that they are the same object. On the other hand, when jets and electrons overlap  
 1739 within a larger radius of  $0.2 < \Delta R(e, j) < 0.4$ , it is likely that the electron and jet both are part of  
 1740 a heavy-flavor decay, and the electron is rejected.

1741 High energy muons can produce photons via bremsstrahlung radiation or collinear final state  
 1742 radiation which result in nearby energy deposits in the calorimeters. Non-prompt muons from  
 1743 hadronic decays produce a similar signature; however, in this case the jet has a higher track multi-  
 1744 plicity in the ID. It is possible to address both cases simultaneously by rejecting the jet when the

1745 ID track multiplicity is less than three, and otherwise rejecting the muon, for jets and muons within  
 1746  $\Delta R(\mu, j) < 0.4$ .

1747 In addition to the case above where muon bremsstrahlung results in a nearby reconstructed  
 1748 jet, the ID track from the muon and the calorimeter energy deposit from the photon can lead to an  
 1749 electron being reconstructed. In this case, if both a muon and an electron share a track in the ID, the  
 1750 muon is kept and the electron is rejected, unless the muon is calorimeter-tagged (see Section 3.2.4.3),  
 1751 in which case the muon 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 $\geq 3$ | 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.

## 1752 5.2.2 Signal event selection

1753 After the objects have been selected, cuts are applied on a per-event level to select  $W^\pm W^\pm jj$  signal  
 1754 events. The event selection is summarized in Table 5.8.

1755 The initial event selection chooses events that pass one or more of the trigger requirements listed  
 1756 in Table 5.7. At least one signal lepton is “matched” to a passed trigger in order to ensure that  
 1757 it was indeed a signal lepton that fired the trigger. A collection of *event cleaning* cuts must also  
 1758 be passed in order to remove events collected during periods in which one or more components of  
 1759 the detector were not operating optimally. Finally, the events are required to contain at least one  
 1760 interaction vertex. An event can have multiple reconstructed vertices from additional proton-proton  
 1761 collisions that occurred in the same bunch crossing. In this case, the *primary vertex* is determined  
 1762 by choosing the vertex with the largest sum of the  $p_T^2$  of its associated tracks.

1763 Events are then required to contain exactly two signal leptons with the same electric charge.  
 1764 The dilepton pair must have a combined invariant mass of  $m_{ll} \geq 20$  GeV in order to suppress  
 1765 low mass Drell-Yan backgrounds. Two additional selections are applied to events containing two  
 1766 electrons: both are required to have  $|\eta| < 1.37$  with an invariant mass at least 15 GeV away from  
 1767 the  $Z$ -boson mass to reduce events where one electron is reconstructed with the wrong charge (this

|           | 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<br>$p_T > 50$ GeV | $p_T > 26$ GeV and Medium isolation<br>$p_T > 50$ 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.

background will be discussed in more detail in Section 5.3.3). To suppress backgrounds from final states with more than two leptons, such as  $WZ$  or  $ZZ$ , events with more than two leptons passing the preselection are vetoed.

Missing transverse energy ( $E_T^{\text{miss}}$ ) represents any particles that escape the detector without being measured, such as neutrinos, and it 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 [109]. These corrections, including the momentum smearing for muons, energy scale and smearing for electrons, and jet calibrations, are propagated to the  $E_T^{\text{miss}}$  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 working point with 85% efficiency [110].

Finally, cuts are applied on the VBS signature outlined in Section 5.0.2. 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 5.0.3, 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

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

Table 5.8: The signal event selection.

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 subject of Section 5.3.4.

### 5.3.1 Estimation of the $WZ$ background

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

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

Once the event yields in the control region are calculated, they are propagated to the final signal region fit, detailed in Section 5.4.1, in a single bin combining all the lepton channels. The systematic

1808 uncertainties of the  $WZ$  background are also calculated at this time. The event yields for the  $WZ$   
 1809 control region are listed in Table 5.9, and distributions of the leading lepton  $p_T$  and  $\eta$  as well as  
 1810 trilepton invariant mass  $m_{lll}$  are found in Figures 5.9 and 5.8, respectively.

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

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

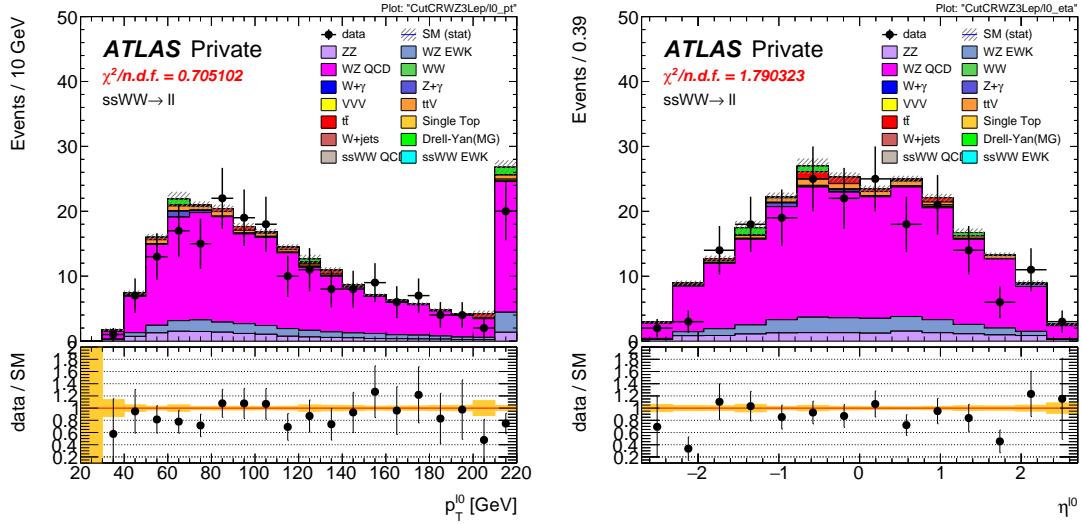


Figure 5.8: Leading lepton  $p_T$  (left) and  $\eta$  (right) distributions in the  $WZ$  control region before normalization. All lepton channels are combined.

### 1811 5.3.2 Estimation of the $V\gamma$ background

1812 Events from  $V\gamma$  processes can pass selection if the photon converts into an  $e^+e^-$  pair and one of the  
 1813 electrons passes the selection criteria. The background is estimated from MC simulations which are  
 1814 then scaled by a normalization factor calculated from a control region enriched in  $Z \rightarrow \mu\mu + \gamma$  events.

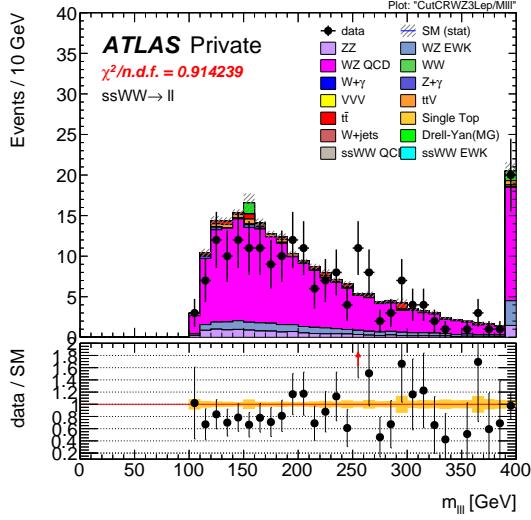


Figure 5.9: Trilepton invariant mass  $m_{lll}$  distribution in the  $WZ$  control region before normalization. All lepton channels are combined.

1815 This control region selects two opposite-sign muons and an additional electron that is assumed to  
 1816 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.

1817 The  $Z\gamma$  MC samples available do not cover the full range of  $p_T^\gamma$  and  $\Delta R(\gamma, l)$ ; thus, additional  
 1818 Drell-Yan samples ( $Z+jets$ ) are used to fill out the phase space. Overlap between the two samples  
 1819 are removed to avoid double counting. Events with final state photons are checked at truth level<sup>16</sup>  
 1820 to ensure that the photon did not originate from a hadronic decay. Cuts on  $p_T^\gamma > 10$  GeV and  
 1821  $\Delta R(\gamma, l) > 0.1$  are then applied at generator level, and  $Z\gamma$  events that fail this additional selection  
 1822 and  $Z+jets$  events that pass it are removed.

1823 The normalization factor is calculated directly from the event yields in the  $V\gamma$  control region  
 1824 rather than in the signal fit, as is done for the  $WZ$  background. The event yields are listed in

<sup>16</sup>Truth 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.

1825 Table 5.11, and the normalization factor is determined to be 1.77. No MC events from  $Z\gamma$  processes  
 1826 survive the full event selection; thus, the scaling is only applied to the  $W\gamma$  background in the signal  
 1827 region. A systematic uncertainty of 44% is assigned to the background based off of the uncertainties  
 1828 in the calculation of the normalization factor.

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

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.

### 1829 5.3.3 Estimation of backgrounds from charge misidentification

1830 If an electron's charge is mis-reconstructed, it can lead to a real opposite-sign lepton pair passing  
 1831 the same-sign requirement in the event selection. There are two primary reasons this can occur:

- 1832 1. An electron emits a photon via bremsstrahlung which then converts into an electron-positron  
 1833 pair, and the conversion track with the wrong electric charge is matched to the original electron.  
 1834 This is the dominant process leading to charge flip, and it is highly dependent on the electron  
 1835  $\eta$  due to the different amount of detector material the electron passes through.
- 1836 2. The curvature of the electron's track is mis-measured, resulting in the wrong charge being  
 1837 assigned. This process is dependent on the momentum of the electron, as its track becomes  
 1838 more straight as the momentum of the electron increases.

1839 In order to estimate this background, the rate at which an electron's charge is misidentified is  
 1840 calculated from  $Z \rightarrow ee$  MC simulation. It is known that the MC does not perfectly model the  
 1841 material effects leading to charge flip; as a result, scale factors are applied to the MC in order for it  
 1842 to better reflect the real performance. These scale factors are obtained from the ratio of charge  
 1843 mis-ID rates in data and uncorrected MC in [83] following the method outlined in [111]. Once the  
 1844 scale factors are applied, the charge misidentification rate  $\varepsilon$  can be extracted by comparing the

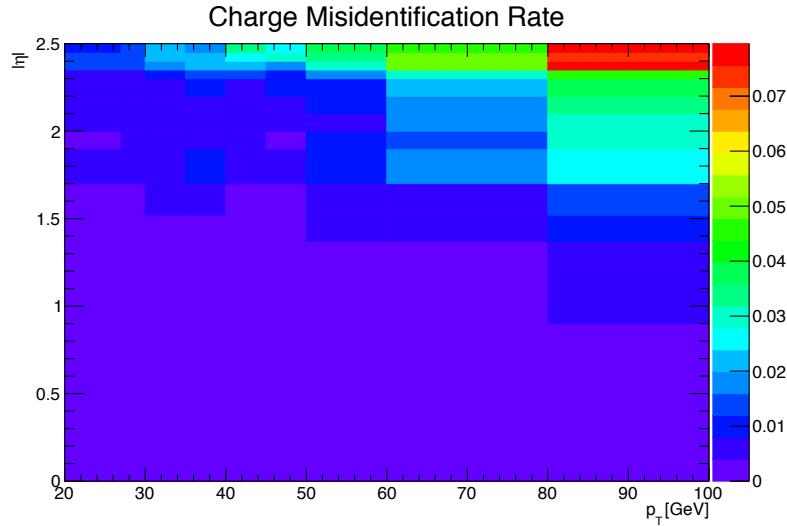


Figure 5.10: Charge misidentification rates for electrons as a function of  $|\eta|$  and  $p_{\text{T}}$ . Rates are calculated from  $Z \rightarrow e^+e^-$  MC after applying scale factors to approximate the charge mis-ID rates in data.

1845 electron's reconstructed charge with the charge of its truth particle:

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

1846 The charge mis-ID rate is calculated in bins of electron  $|\eta|$  and  $p_{\text{T}}$ , and it varies from below 0.1%  
 1847 in the central region of the detector up to 8% in the forward regions for high  $p_{\text{T}}$  (above 80 GeV)  
 1848 electrons. A two-dimensional plot of  $\varepsilon$  can be found in Figure 5.10.

1849 Given the charge flip rate  $\varepsilon(\eta, p_{\text{T}})$ , the rate at which an electron has its charge correctly recon-  
 1850 structed is  $(1 - \varepsilon)$ . Thus there are three possible combinations of charge identification, assuming a  
 1851 two-electron event:

- 1852 1. Both electrons are reconstructed correctly:  $(1 - \varepsilon)^2$
- 1853 2. Both electrons are mis-reconstructed:  $\varepsilon^2$
- 1854 3. Only one electron is mis-reconstructed:  $2\varepsilon(1 - \varepsilon)$

1855 In order to estimate the size of the background from charge misidentification, opposite-sign events  
 1856 are selected using the default event selection for a given signal or control region with the same-sign  
 1857 requirement inverted. These events are then weighted by the probability for one of the electrons to

1858 be reconstructed with the wrong charge:

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

1859 where the subscripts 1 and 2 refer to the leading and subleading electrons, respectively, and  $\varepsilon_i$  is a  
 1860 function of the  $\eta$  and  $p_T$  of the  $i^{\text{th}}$  electron. In the case of an event with one electron and one muon  
 1861 ( $\varepsilon_\mu = 0$ ), Equation 5.2 simplifies:

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

1862 This method assumes that there is little contamination from fake electrons in the opposite-sign  
 1863 sample, and this has been verified with MC simulation.

1864 Additionally, charge-flipped electrons tend to be reconstructed with lower energy when compared  
 1865 to electrons with the correct charge. This is due to energy loss from the material interactions that  
 1866 can cause the charge to be misidentified in the first place. A correction factor is calculated from  
 1867 MC simulations, comparing the  $p_T$  of the truth electron to its reconstructed counterpart:

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

1868 The correction is then applied to the  $p_T$  of the charge-flipped electron via

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

1869 where  $p_T^0$  is the uncorrected  $p_T$  of the electron and  $dE$  is a gaussian smearing factor centered at zero  
 1870 with a width related to the energy resolution. Since which electron is mis-reconstructed is never  
 1871 determined in this method, in the case of a two-electron event, the energy correction is applied  
 1872 randomly to one of the two electrons based on the probabilities for them to be charge-flipped. This  
 1873 also determines the overall sign of the event; the charge of the electron that does not receive the  
 1874 correction is taken to be the charge for both.

1875 Systematic uncertainties on the charge mis-ID rates are calculated by generating two additional  
 1876 sets of rates with the uncertainties on the scale factors varied up and down. The size of the esti-  
 1877 mated charge flip background without the energy correction applied is also taken as a systematic  
 1878 uncertainty. These systematic uncertainties are estimated to be approximately  $\pm 15\%$ .

### 1879 5.3.3.1 Validation of the charge misidentification estimate

1880 The performance of the charge misidentification estimation is tested in the same-sign inclusive  
 1881 validation region (VR), defined in Table 5.12. For  $ee$  events, the mass of the dilepton pair is required

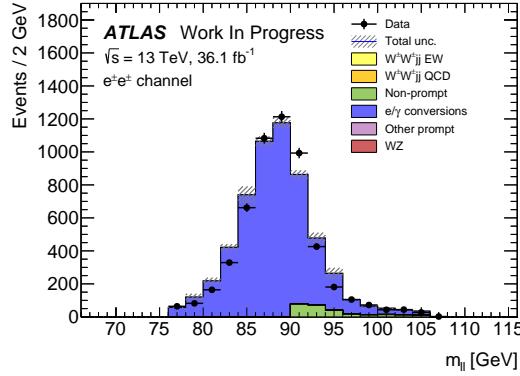


Figure 5.11: Dilepton invariant mass distribution  $m_{ll}$  for the  $ee$  channel in the same-sign inclusive VR.

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

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

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

### 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

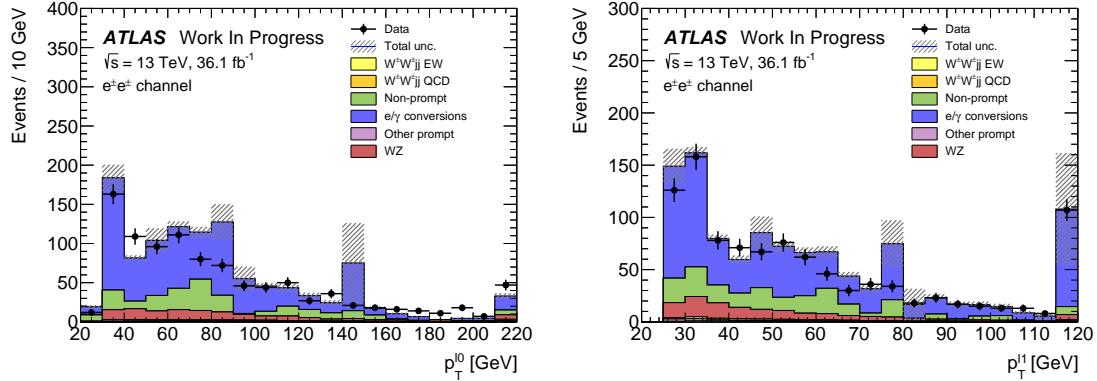


Figure 5.12:  $p_T$  distributions for the leading (left) and subleading (right) electron for the  $ee$  channel in the same-sign inclusive VR. In these plots, the cut requiring  $m_{ee}$  to fall within the  $Z$  mass window has been inverted in order to test the modelling away from the  $Z$  peak.

1895    *fake-factor* is used to estimate the size and shape of background processes from fake leptons. In this  
 1896    analysis, a new modification to the fake-factor is used involving the particle isolation variables; the  
 1897    method is outlined first in the context of the *default* fake-factor in Section 5.3.4.1, and the modified  
 1898    fake-factor is covered in Section 5.3.4.2.

#### 1899    5.3.4.1    Overview of the default fake-factor method

1900    The goal of the fake-factor method is to measure the fake rate from real collision events in a region  
 1901    enriched in fake leptons and use it to estimate the size of the fake lepton background in a chosen  
 1902    signal or control region. This is done by creating two samples using different lepton definitions:

- 1903    1. The *nominal* sample is made up of leptons passing the signal selection.  
 1904    2. The *loose* sample is made up of leptons that fail the signal selection while still passing a  
 1905    loosened set of criteria. This sample is enriched in fake leptons and is orthogonal to the set of  
 1906    nominal leptons.

1907    Using the sets of nominal and loose leptons, a fake-factor  $f$  can be calculated from a region enriched  
 1908    in processes that are prone to producing fake leptons:

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

1909    Since the fake rate is not expected to be constant over the entire phase space, the fake-factor can  
 1910    be divided into bins:

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

1911 where  $b$  represents the bin number. In this analysis, the fake-factor is binned in lepton  $p_T$ .

1912 In order to estimate the fake background contribution in a given signal or control region, the  
 1913 fake-factor is applied to a second control region with a selection identical to the region of interest  
 1914 except one of the leptons required to satisfy the loose criteria. The region for which the background  
 1915 is estimated contains two nominal leptons and is referred to as *nominal+nominal* (*NN*), and the  
 1916 associated control region where the fake-factor is applied contains one nominal and one loose lepton  
 1917 and is referred to as *nominal+loose* (*NL*). The fake background in a *NN* region can then be  
 1918 calculated as:

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

1919 Backgrounds containing two prompt leptons can also enter the *NL* region if one of the leptons  
 1920 passes the nominal selection and the other passes the loose selection. Since the fake-factor method  
 1921 estimates the fake background by scaling the amount of non-prompt events in the *NL* region, if these  
 1922 prompt contributions are not removed, they will be included in the scaling, and the background will  
 1923 be overpredicted. The final estimate of the fake background becomes:

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

1924 A visual representation of the fake background estimation process is shown in Figure 5.13.

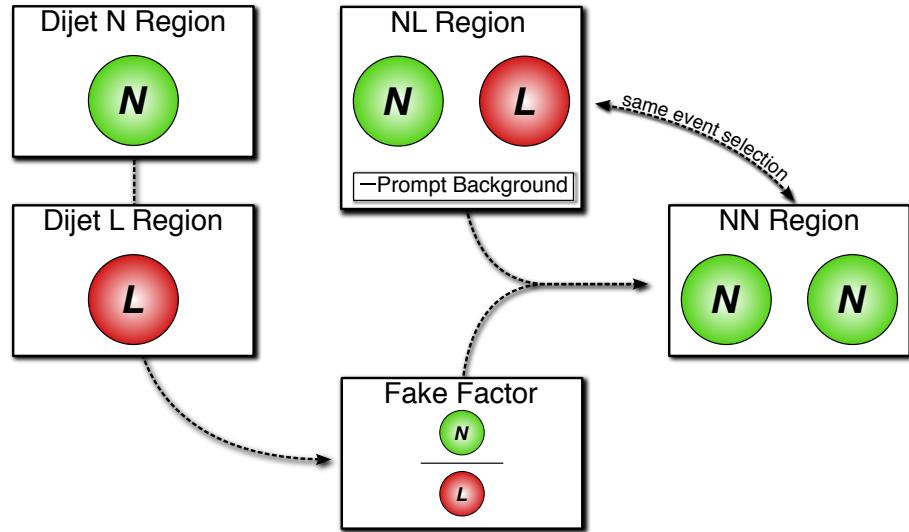


Figure 5.13: Graphical representation of how the fake factor method is used to estimate the fake background in a given *NN* region.

1925 **5.3.4.2 The fake-factor with  $p_T^{\text{cone}}$**

1926 When a jet produces a non-prompt lepton, that lepton only carries a fraction of the underlying jet's  
 1927 total momentum. Due to the isolation cut applied to the nominal leptons, they typically carry a  
 1928 much larger percentage of the underlying jet momentum than the loose leptons. Since the isolation  
 1929 essentially sets a limit on the amount of detector activity allowed around the lepton, if other nearby  
 1930 particles carried a significant amount of momentum, the lepton would likely fail this cut.

1931 This discrepancy in the underlying jet momentum fraction can cause problems in the calculation  
 1932 of the fake-factor  $f$ . Consider the case of two separate events with muons of identical momentum,  
 1933 but one passes the nominal selection, and the other passes the loose selection. The loose lepton on  
 1934 average will originate from a jet with higher  $p_T$  than the one corresponding to the nominal lepton  
 1935 despite both muons having the same momentum. This can be seen explicitly when comparing the  
 1936  $p_T$  of a muon to its associated truth jet:

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

1937 Since muons are not included in the jet reconstruction algorithm,  $\Delta p_T$  approximates the momentum  
 1938 of the muon compared to the rest of the jet. For muons that carry more than 50% of the jet's  
 1939 momentum,  $\Delta p_T$  will be negative and vice-versa. The  $\Delta p_T$  distributions for nominal and loose  
 1940 muons in  $t\bar{t}$  MC events is shown Figure 5.14, where a 25 GeV nominal muon on average corresponds  
 1941 to a 35 GeV jet, and a 25 GeV loose muon on average corresponds to a 62 GeV jet<sup>17</sup>.

1942 Since the default fake-factor defined in Equation 5.7 is binned in lepton  $p_T$ , the 25 GeV muons  
 1943 in the example above would occupy the same bin despite originating from very different jets. As  
 1944 a result, within a given bin, the underlying jet  $p_T$  spectrum can differ substantially between the  
 1945 numerator and the denominator. Additionally, these differences can vary depending on the process  
 1946 producing the non-prompt leptons or on the specific kinematic selections of the signal or control  
 1947 regions where the fake-factor is applied.

1948 Fortunately, the majority of the jet momentum not carried by the non-prompt lepton (excluding  
 1949 neutrinos) can be recovered using isolation variables. A track-based isolation is chosen, referred  
 1950 to as  $p_T^{\text{cone}}$ , and it contains the sum of the  $p_T$  of all particle tracks with  $p_T > 1$  GeV originating  
 1951 from the primary vertex within a cone of  $\Delta R < 0.3$  around the lepton. Thus, the sample of loose  
 1952 leptons in the denominator of the fake-factor calculation is binned in  $p_T + p_T^{\text{cone}}$  rather than simply

---

<sup>17</sup>To better illustrate the point, here the muon is added back into the jet  $p_T$ , and the corresponding muon  $p_T$  is obtained via  $\Delta p_T(\mu, j) = \frac{(p_T(j) - p_T\mu) - p_T(\mu)}{(p_T(j) - p_T\mu) + p_T(\mu)} = \frac{p_T(j) - 2p_T(\mu)}{p_T(j)}$ .

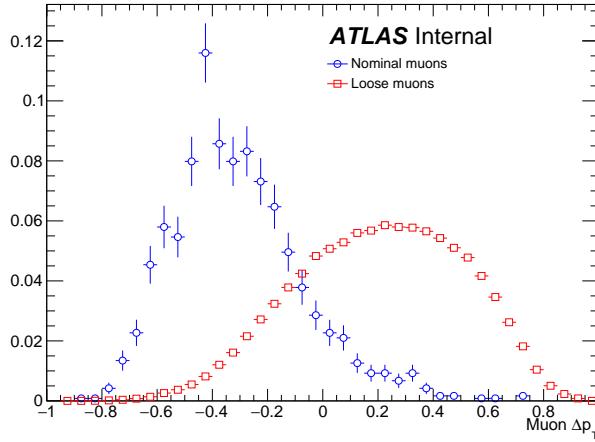


Figure 5.14:  $\Delta p_T$  distributions for nominal (blue) and loose (red) muons in simulated  $t\bar{t}$  events. Each muon has been matched to a truth-level jet. Both distributions are normalized to unit area.

lepton  $p_T$ . Adding the isolation cone greatly reduces the difference in the fraction of the underlying jet momentum carried by the nominal and loose leptons. To check this, a new  $\Delta p_T$  is calculated between a lepton and its matched truth jet, where the truth jet  $p_T$  has been corrected to include all muons within a cone of  $\Delta R < 0.4$ :

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

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

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

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

### 5.3.4.3 Application of the fake-factor

The fake-factor itself is measured from a sample of collision events passing a dijet selection that requires exactly one lepton (either passing the nominal or loose selections) and at least one jet.

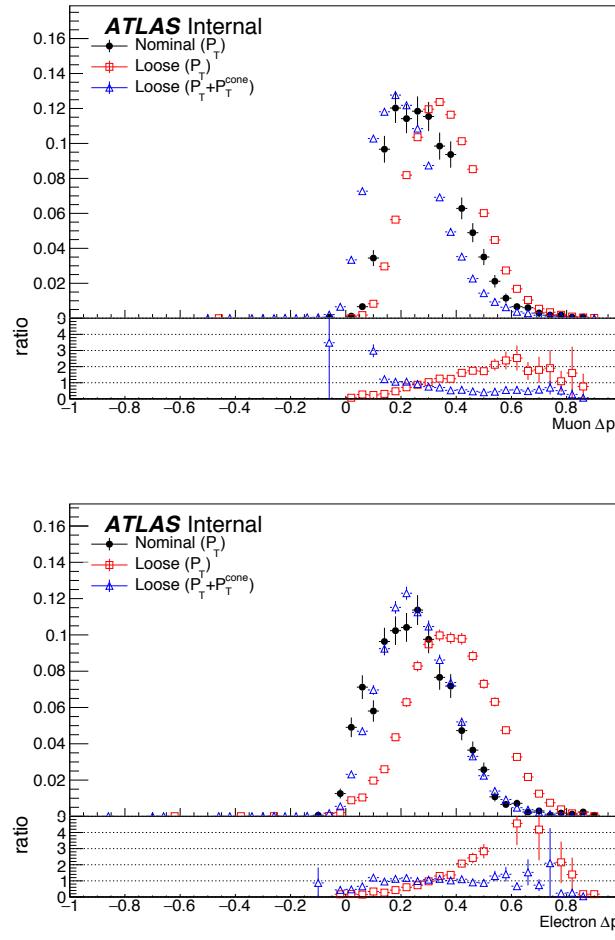


Figure 5.15:  $\Delta p_T$  distributions for muons (top) and electrons (bottom) in simulated  $t\bar{t}$  events. Each lepton has been matched to a truth-level jet, and that truth jet has had its  $p_T$  corrected to include all truth muons within a cone of  $\Delta R < 0.4$ . The nominal leptons are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

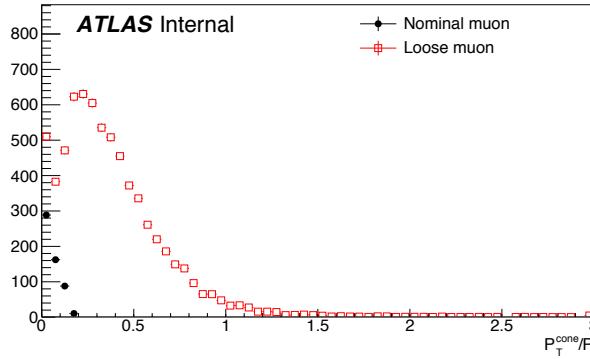


Figure 5.16: Distributions of  $p_T^{\text{cone}}/p_T$  for nominal (black) and loose (red) muons in simulated  $t\bar{t}$  events.

1967 The leading jet must also be  $b$ -tagged and approximately back-to-back with the lepton in order to  
 1968 enhance non-prompt lepton contributions while reducing contributions from processes involving  $W$   
 1969 and  $Z$  bosons.  $W$  boson events are further suppressed by requiring the sum of the  $E_T^{\text{miss}}$  and the  
 1970 transverse mass of the lepton to be less than 50 GeV. The full event selection for the dijet region is  
 1971 summarized in Table 5.13.

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

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

1972 The numerator sample is constructed from dijet events in which the lepton passes the nominal  
 1973 (signal) selection and is binned in the lepton  $p_T$ . Similarly, the denominator sample is made up of  
 1974 the remaining dijet events where the lepton passes the loose selection and is binned in the lepton  
 1975  $p_T + p_T^{\text{cone}}$ . The nominal and loose leptons pass the signal selection<sup>18</sup> and loose selection, respectively,  
 1976 defined earlier in Table 5.3 for muons and Table 5.4 for electrons. Backgrounds from  $W + \text{jets}$ ,  $Z + \text{jets}$ ,

<sup>18</sup>The  $p_T > 27$  GeV cut in the signal lepton selection is dropped in favor of the  $p_T > 15$  GeV requirement in the dijet selection.

1977  $t\bar{t}$ , and single top processes are estimated from MC simulations requiring one lepton to be prompt  
 1978 using the truth information; these contributions are subtracted from the dijet data. The fake-factor  
 1979 is then calculated using Equation 5.12 for muons and for central and forward electrons separately.  
 1980 The muon fake-factor is shown in Figure 5.17, and the two electron fake-factors (one each for central  
 1981 and forward electrons) are shown in Figure 5.18. The numerical values of the fake-factors, including  
 1982 their systematic uncertainties (which will be discussed in Section 5.3.4.4) are listed in Table 5.14.

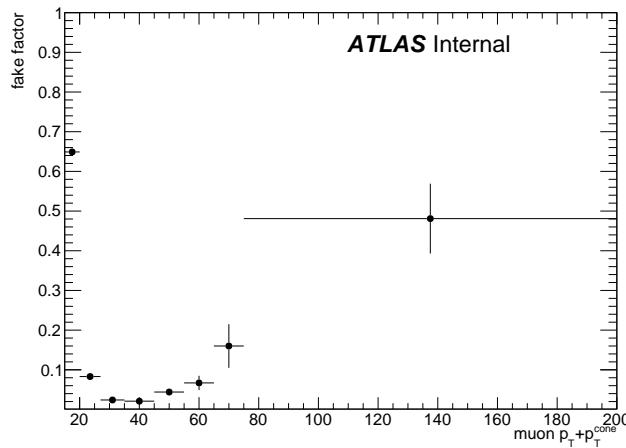


Figure 5.17: The measured fake-factor as a function of muon  $p_T + p_T^{\text{cone}}$ . The error bars represent the statistical uncertainty only.

1983 In order to properly account for the denominator being binned in  $p_T + p_T^{\text{cone}}$ , special care needs  
 1984 to be taken when estimating the fake background from the *NL* regions. For the purposes of the  
 1985 fake-factor calculation, it is perhaps more intuitive to consider a loose *object* with  $p_T = p_T + p_T^{\text{cone}}$   
 1986 instead of simply a loose lepton, as the lepton and the underlying jet are treated as a whole with this  
 1987 method. When the lepton  $p_T$  cuts required by a particular signal or control region are applied to  
 1988 nominal and loose leptons, the cut is applied to the  $p_T$  of the nominal lepton and to the  $p_T + p_T^{\text{cone}}$  of  
 1989 the loose object. Similarly, when looking up the fake-factor weight for a given *NL* event, the value  
 1990 is taken from the bin corresponding to the  $p_T + p_T^{\text{cone}}$  of the loose object. Finally, when applying the  
 1991 weight to the *NL* event,  $p_T + p_T^{\text{cone}}$  is assigned as the  $p_T$  of the loose object. This can be visualized  
 1992 by referring back to Figure 5.13; every time a loose lepton is used (the red circles in the Figure),  
 1993  $p_T + p_T^{\text{cone}}$  is used in place of  $p_T$ .

1994 Finally, it should be noted that the addition of  $p_T^{\text{cone}}$  to the loose object may cause the loose  
 1995 leptons in the denominator sample to migrate into higher bins. This results in an overall decrease in

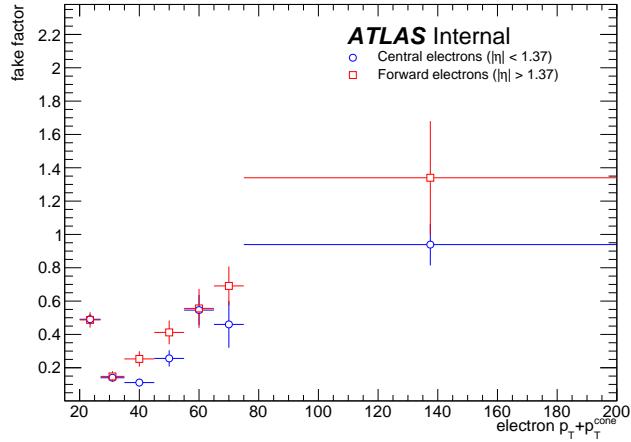


Figure 5.18: The measured fake-factor as a function of electron  $p_T + p_T^{\text{cone}}$  in the central ( $|\eta| < 1.37$ , blue) and forward ( $|\eta| > 1.37$ , red) regions of the detector. The error bars represent the statistical uncertainty only.

1996 the number of loose objects in the lower  $p_T + p_T^{\text{cone}}$  bins due to there not being additional leptons at  
 1997 lower  $p_T$  to replace them. Since the fake-factor is a ratio of the number of events in a bin, this effect  
 1998 causes the first few bins of the fake-factor to increase, as can be seen clearly in Figure 5.17. However,  
 1999 the signal and control regions (and their corresponding  $NL$  regions) contain a  $p_T > 27$  GeV cut that  
 2000 prevents these migrations from negatively impacting the fake estimation.

#### 2001 5.3.4.4 Systematic uncertainties

2002 Four sources of systematic uncertainty are considered: the dijet event selection, prompt background  
 2003 subtraction, jet flavor composition, and residual dependence on the underlying jet  $p_T$  spectrum. In  
 2004 order to measure the impact of these systematics, new fake-factors are computed with variations  
 2005 in each of the systematic sources and the differences from the nominal values are taken as the  
 2006 uncertainty.

- 2007 1. In order to estimate uncertainties due to the dijet selection, the cut on  $M_T + E_T^{\text{miss}}$  is varied  
 2008 by  $\pm 5$  GeV, the jet-lepton separation  $\Delta\phi(l, j)$  by  $\pm 0.1$ , and the jet  $p_T$  cut by  $\pm 5$  GeV.
- 2009 2. To estimate the systematic uncertainty on the prompt background subtraction, the MC pre-  
 2010 diction in a  $W+\text{jets}$  control region is compared to data. The discrepancy between data and  
 2011 MC is found to be approximately 10% [83]. Therefore, the prompt background used for the  
 2012 subtraction is scaled up and down by  $\pm 10\%$ .

- 2013    3. The difference in the jet flavor composition between the dijet events and the events in the  
 2014     $NL$  regions can affect the accuracy of the fake background estimation. The dijet sample is  
 2015    dominated by light jets, while the  $NL$  regions tend to be dominated by heavy flavor from  $t\bar{t}$ .  
 2016    To account for this, the fake-factor is computed with a  $b$ -jet veto.
- 2017    4. To measure any residual dependence on the underlying jet  $p_T$  spectrum, the leading jet  $p_T$   
 2018    distribution is reweighted to match the  $p_T$  spectrum of truth jets that produce fake leptons  
 2019    in MC simulations. This results in an increase in the number of nominal and loose leptons at  
 2020    high momentum [83].

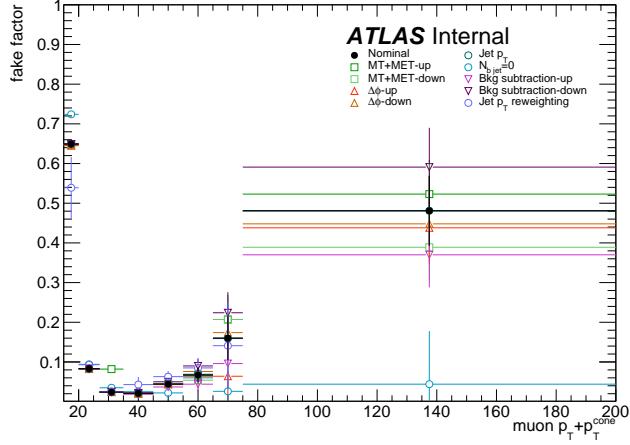


Figure 5.19: Systematic variations in the fake-factor as a function of muon  $p_T + p_T^{\text{cone}}$ . The individual fake-factors obtained for each systematic variation are displayed with their statistical uncertainties.

### 2021    5.3.4.5    Results of the fake-factor

- 2022    The fake background contribution in the signal region is estimated by applying the fake-factors  
 2023    to the equivalent  $NL$  region using Equation 5.9, where the fake-factor used corresponds to the  
 2024    flavor of the loose lepton in the event. As usual, the prompt background is subtracted from the  
 2025     $NL$  events using MC simulation. Charge misidentification is handled using the same method as  
 2026    in Section 5.3.3, with an additional set of charge flip rates calculated for loose leptons. The fake  
 2027    background yields in the signal region are listed in Table 5.15. An overall uncertainty of 50% is  
 2028    assigned to the fake background estimation in  $\mu^\pm\mu^\pm$  events, and between 40% to 90% for  $e^\pm e^\pm$  and  
 2029     $\mu^\pm e^\pm$  events, including both statistical and systematic effects.

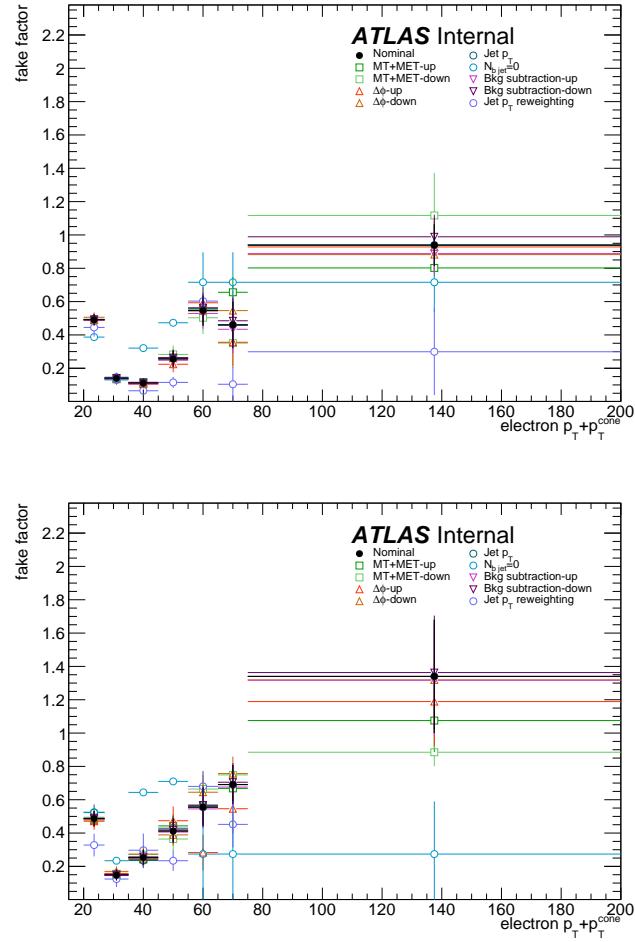


Figure 5.20: Systematic variations in the fake-factor as a function of electron  $p_T + p_T^{\text{cone}}$  in the central ( $|\eta| < 1.37$ , top) and forward ( $|\eta| > 1.37$ , bottom) regions of the detector. The individual fake-factors obtained for each systematic variation are displayed with their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

| fake-factor            | $p_T$ [15, 20] | $p_T$ [20, 27] | $p_T$ [27, 35] | $p_T$ [35, 45] | $p_T$ [45, 55] | $p_T$ [55, 65] | $p_T$ [65, 75] | $p_T$ [75, 200] |
|------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-----------------|
| nominal                | 0.649 ± 0.007  | 0.083 ± 0.002  | 0.024 ± 0.002  | 0.021 ± 0.003  | 0.044 ± 0.007  | 0.067 ± 0.018  | 0.160 ± 0.055  | 0.481 ± 0.088   |
| MT+MET                 | 0.649 ± 0.007  | 0.082 ± 0.002  | 0.082 ± 0.002  | 0.020 ± 0.003  | 0.045 ± 0.007  | 0.068 ± 0.018  | 0.207 ± 0.062  | 0.523 ± 0.086   |
| $\Delta\phi(\ell, j)$  | 0.648 ± 0.007  | 0.083 ± 0.003  | 0.024 ± 0.002  | 0.022 ± 0.004  | 0.044 ± 0.007  | 0.054 ± 0.020  | 0.207 ± 0.060  | 0.389 ± 0.081   |
| Jet $p_T$              | 0.645 ± 0.008  | 0.083 ± 0.003  | 0.024 ± 0.002  | 0.021 ± 0.004  | 0.045 ± 0.008  | 0.064 ± 0.021  | 0.064 ± 0.058  | 0.438 ± 0.092   |
| $N_{b\text{-jet}} = 0$ | 0.646 ± 0.006  | 0.083 ± 0.002  | 0.024 ± 0.002  | 0.020 ± 0.003  | 0.043 ± 0.006  | 0.076 ± 0.017  | 0.174 ± 0.050  | 0.448 ± 0.078   |
| Bkg. subtraction       | 0.648 ± 0.007  | 0.083 ± 0.002  | 0.024 ± 0.002  | 0.019 ± 0.003  | 0.037 ± 0.007  | 0.044 ± 0.019  | 0.096 ± 0.062  | 0.370 ± 0.082   |
| Jet $p_T$ Reweighting  | 0.649 ± 0.007  | 0.083 ± 0.002  | 0.025 ± 0.002  | 0.022 ± 0.003  | 0.050 ± 0.007  | 0.090 ± 0.017  | 0.224 ± 0.052  | 0.591 ± 0.099   |

(a) Fake-factor values for muons.

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

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

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

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

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

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

2030 **5.3.4.6 Validation of the fake-factor**

2031 The accuracy of the fake-factor method is tested in several validation regions, the most sensitive  
 2032 of which is the same-sign top fakes VR (SS top VR), defined in Table 5.16. This region inverts  
 2033 the signal region's  $b$ -jet veto to accept events with exactly one  $b$ -jet. Due to this requirement, the  
 2034 dominant source of events comes from the  $t\bar{t}$  process where a  $b$ -jet fakes an isolated lepton. The  
 2035 distribution of the subleading lepton  $p_T$  in this VR is shown in Figure 5.21 for all lepton flavor  
 2036 combinations. There is good agreement between the data and the prediction, even when only taking  
 2037 into account the statistical uncertainty and not the large systematic uncertainties assigned to the  
 2038 fake estimation.

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

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

2039 **5.3.5 Reduction of  $WZ$  background using custom overlap removal**

2040 The dominant source of prompt background in this analysis comes from  $WZ$  events where both  
 2041 bosons decay leptonically. Traditionally, the background is dealt with by imposing a veto on any  
 2042 event with a third lepton passing some loose identification criteria (the so-called *trilepton veto*).  
 2043 In the case of this analysis, if one or more leptons in addition to the two signal leptons pass the  
 2044 preselection criteria, the event is rejected. However,  $WZ$  events can still enter the signal region if  
 2045 one of the leptons fails the preselection or falls outside of the detector's acceptance.

2046 In order to understand the sources of  $WZ$  events that are not removed by the trilepton veto, a  
 2047 study was performed on truth-level leptons in  $W^\pm W^\pm jj$  and  $WZ$  MC samples. Events with three  
 2048 truth leptons were selected, and each was matched to its reconstruction-level partner by finding the  
 2049 closest  $\Delta R(\text{truth}, \text{reco})$  and  $\Delta p_T(\text{truth}, \text{reco})$  match. For events surviving the trilepton veto, the  
 2050 two signal leptons were removed, and the remaining leptons represent real leptons that failed to  
 2051 be selected for the veto. Between 40-50% of these leptons fall outside of the eta acceptance of the

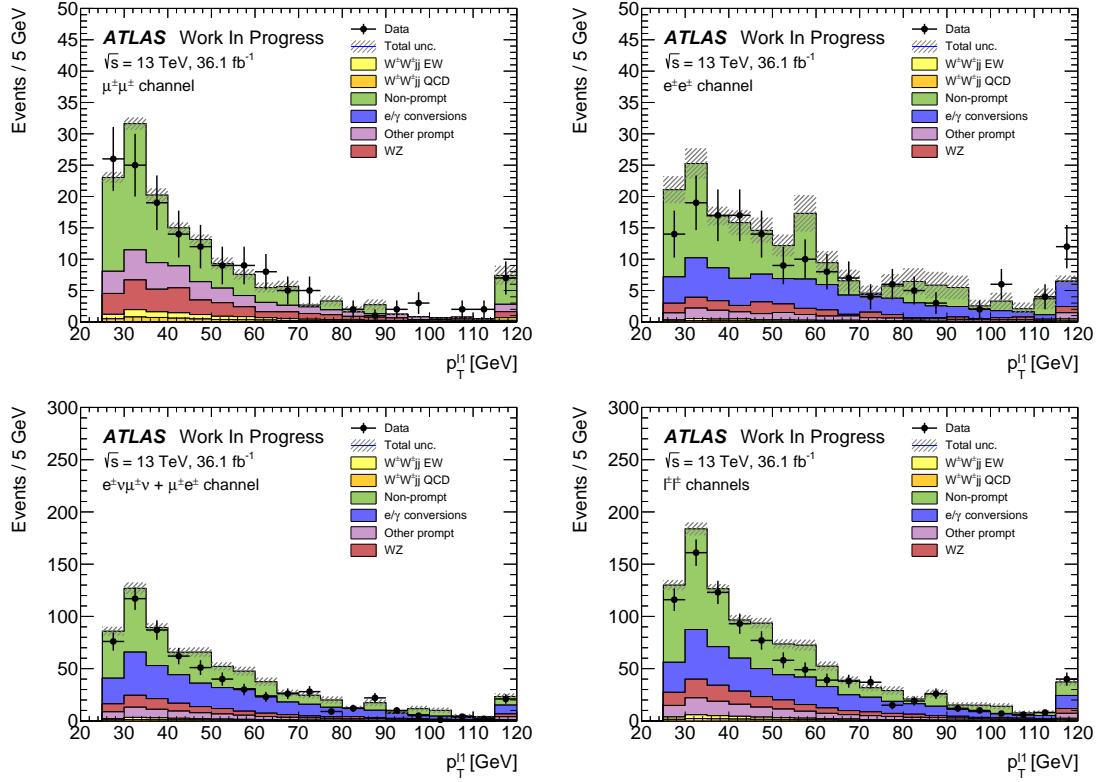


Figure 5.21: Distributions of the subleading lepton  $p_T$  in the same-sign top fakes VR for  $\mu^\pm\mu^\pm$  events (top right),  $e^\pm e^\pm$  events (top left),  $\mu^\pm e^\pm$  events (bottom left), and all events combined (bottom right). All errors are statistical only.

analysis (see Figure 5.22) and are unrecoverable. The second largest source of leptons failing the preselection is the OR, defined in Section 5.2.1.4. The standard OR procedure appears to be too aggressive in removing leptons in favor of jets, causing many three lepton events to “lose” their third lepton and pass the trilepton veto. Therefore a *custom OR* is investigated which would replace the standard OR in the preselection and allow for better  $WZ$  rejection by removing fewer third leptons.

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

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

which, along with  $\Delta R(l, j)$ , will make up the custom OR criteria. The idea behind including  $p_{T,\text{ratio}}$  is to be able to preferentially remove background leptons originating from jets (those that carry a low percentage of the total jet momentum) instead of removing *any* lepton near a jet. The distributions of  $p_{T,\text{ratio}}$  and the associated efficiency curves for muons and electrons can be found in Figures 5.23

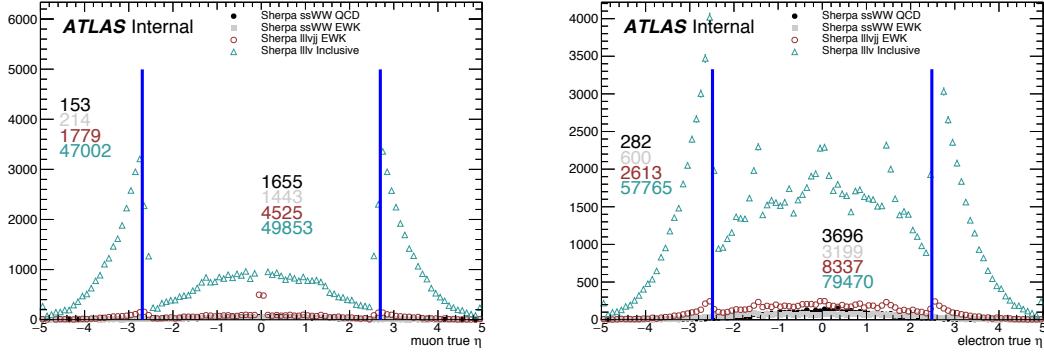


Figure 5.22: Pseudorapidity ( $\eta$ ) distributions of truth muons (top) and electrons (bottom) for Sherpa  $W^\pm W^\pm jj$  and  $WZ$  MC samples. The blue vertical lines represent the allowed  $\eta$  range for each lepton flavor. The numbers correspond to the number of raw MC events that fall within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

and 5.25, respectively, and the distributions for  $\Delta R(\mu, j)$  for muons can be found in Figure 5.24. Since all electrons have an associated jet in the calorimeters, the  $\Delta R(e, j)$  variable is not a good quantity to use for this custom OR.

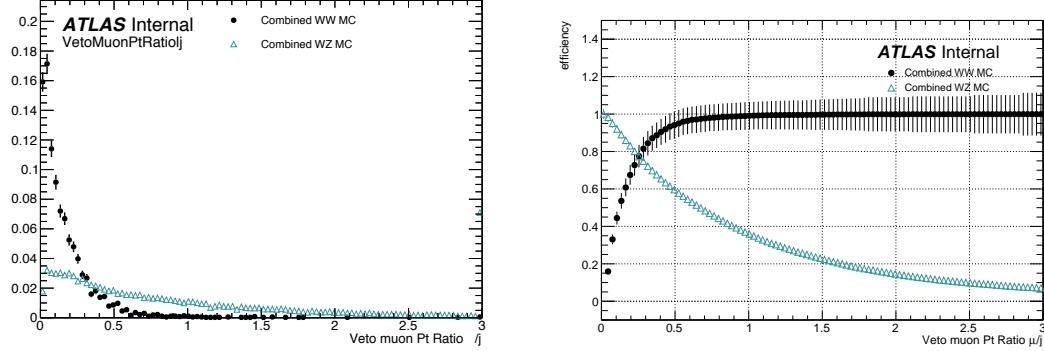


Figure 5.23: Distributions of  $p_{T,\text{ratio}}(\mu, j)$  for EWK and QCD  $W^\pm W^\pm jj$  signal (black) and  $WZ$  background (teal) for truth-matched third muons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the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

A working point for the Custom OR was chosen by requiring 90% signal retention for muons and 90% background rejection for electrons. The cut on electrons was allowed to be much tighter because the number of signal events with a third electron is considerably smaller than for muons. It should be emphasized that the signal events present in Figures 5.23-5.25 do not represent the full

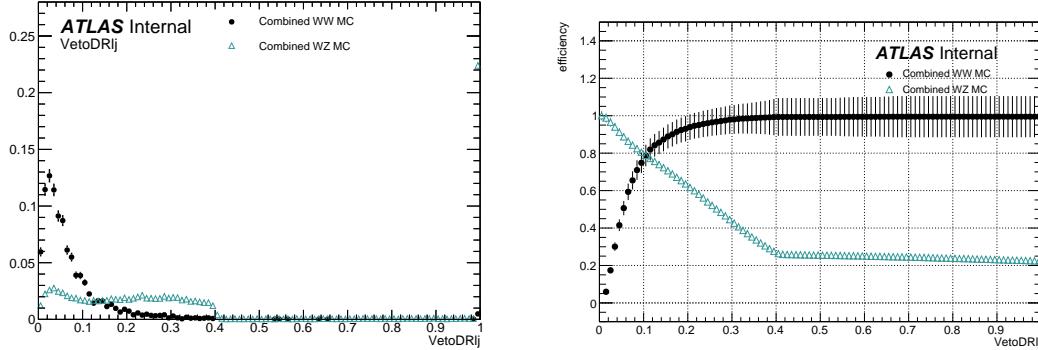


Figure 5.24: Distributions of  $\Delta R(\mu, j)$  for EWK and QCD  $W^\pm W^\pm jj$  signal (black) and  $WZ$  background (teal) for truth-matched third muons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the right where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

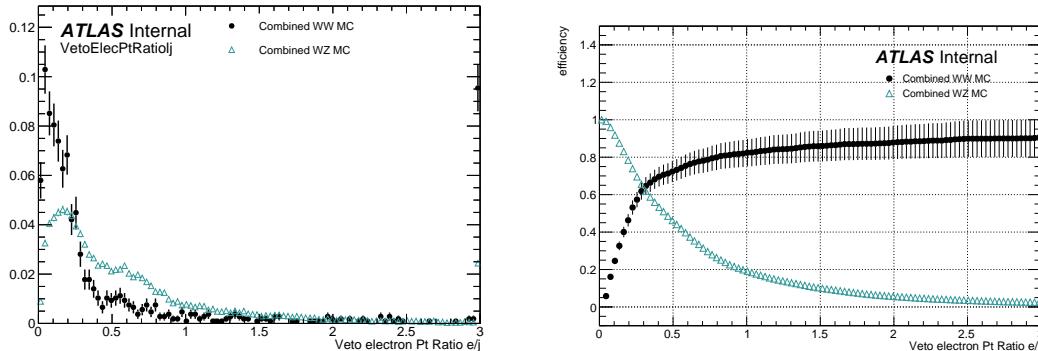


Figure 5.25: Distributions of  $p_{T,\text{ratio}}(e, j)$  for EWK and QCD  $W^\pm W^\pm jj$  signal (black) and  $WZ$  background (teal) for truth-matched third electrons in events that pass the trilepton veto. Both distributions are normalized to unit area. The associated efficiency curves are on the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

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 working point is defined in Table 5.17.

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

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

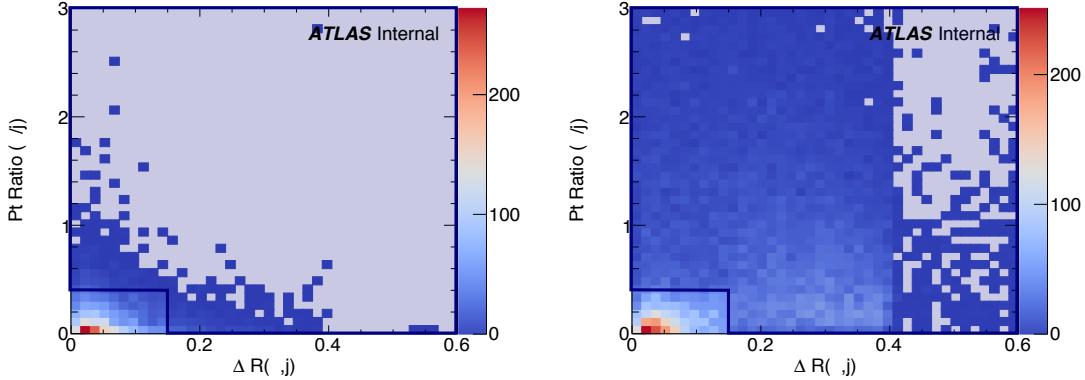


Figure 5.26: Two-dimensional plots of  $p_{T,\text{ratio}}(\mu, j)$  vs  $\Delta R(\mu, j)$  for truth-matched third muons in events that pass the trilepton veto for EWK and QCD  $W^\pm W^\pm jj$  signal (left) and  $WZ$  background (right). The blue overlay indicates the area in which the third leptons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

Initial tests of the performance of the Custom OR yielded 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 were not nearly as substantial, and ultimately the Custom OR was not included in the final analysis. However, it is still a potentially useful tool for improving background rejection based on lepton counting in analyses with overly aggressive OR procedures.

2081 **5.4 Cross section measurement**

2082 The  $W^\pm W^\pm jj$  EWK cross section is extracted from the signal region using a maximum-likelihood  
 2083 fit applied simultaneously to four  $m_{jj}$  bins in the signal region as well as to the low- $m_{jj}$  and  $WZ$   
 2084 control regions. For the fit and cross section extraction, the signal region is defined as in Table 5.8  
 2085 with the dijet invariant mass requirement raised to  $m_{jj} > 500$  GeV. The low- $m_{jj}$  region is defined  
 2086 to mirror the signal region exactly with the dijet invariant mass inverted to  $200 < m_{jj} < 500$  GeV,  
 2087 and the  $WZ$  control region is as defined previously in Section 5.3.1.

2088 The signal and low- $m_{jj}$  regions are split into six channels based on the flavor and charge of  
 2089 the dilepton pair:  $\mu^+\mu^+$ ,  $\mu^-\mu^-$ ,  $\mu^+e^+$ ,  $\mu^-e^-$ ,  $e^+e^+$ , and  $e^-e^-$ . This split by charge increases the  
 2090 sensitivity of the measurement due to the  $W^+/W^-$  charge asymmetry favoring the production of  
 2091  $W^+$  bosons [112]. Since the signal events contain two  $W$  bosons, the signal strength compared to  
 2092 charge-symmetric backgrounds is much greater in the  $++$  channels than for both charges combined.  
 2093 The  $WZ$  control region is included in the fit as a single bin ( $l^\pm l^\mp l^\pm$ ).

2094 The maximum likelihood fit and cross section extractions are outlined in Sections 5.4.1 and  
 2095 5.4.3, respectively. The results of the cross section measurement and of the analysis as a whole are  
 2096 presented in Section 5.6.

2097 **5.4.1 Maximum likelihood fit**

2098 The number of predicted signal events in each channel  $c$  and  $m_{jj}$  bin  $b$  can be calculated from the SM  
 2099 predicted total production cross section  $\sigma_{\text{theo}}^{\text{tot}}$  scaled by the total integrated luminosity  $\mathcal{L}$ , the signal  
 2100 acceptance  $\mathcal{A}$ , and the efficiency corrections  $\mathcal{C}(\theta)$ . Here  $\theta$  represents the set of nuisance parameters  
 2101 that parameterize the effects of each systematic uncertainty on the signal and background expec-  
 2102 tations. The acceptance and efficiency corrections will be covered in more detail in Section 5.4.2.  
 2103

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

2104 A signal strength parameter  $\mu$  is defined as the ratio of the measured cross section to the SM  
 2105 predicted cross section. The expected number of events in a given channel and bin can then be  
 2106 expressed as the sum of the estimated background ( $N_{cb}^{\text{bkg}}(\theta)$ ) and the number of predicted signal  
 2107 events scaled by  $\mu$ :

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

2108     The nuisance parameters are constrained by Gaussian probability distribution functions, and  
 2109     the normalization of the  $WZ$  background mentioned in Section 5.3.1 is included in the fit as a free  
 2110     parameter. The expected yields for signal and background processes are adjusted by the set of  
 2111     nuisance parameters within the constraints of the systematic uncertainties. The yields after the fit  
 2112     correspond to the value that best matches the observed data.

2113     The number of events per channel and bin after the fit can be written as a sum of the predicted  
 2114     event yields for each sample  $s$ :

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

2115     In this equation, the fitted number of events in a given channel and bin is obtained by weighting  
 2116     the histogram of predicted yields  $h_{cbs}$  by the product of a given luminosity  $\lambda$  and any normalization  
 2117     factors  $\phi_{cs}$  that may be given for each channel and sample. The input histogram and the normal-  
 2118     ization factors may depend on the nuisance parameters  $\theta$  taking into account sources of systematic  
 2119     uncertainty. Uncertainties on the normalization factors  $\eta_{cs}(\theta)$  are also included. Finally, bin-by-bin  
 2120     scale factors  $\gamma_{cb}$  are included to parameterize the statistical uncertainties of the MC predictions.

2121     The binned likelihood function is given by a product of Gaussian functions for the luminosity  
 2122     and for the background uncertainties and a product of Poisson functions for the number of observed  
 2123     events in each bin and channel:

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

2124     where  $\mathcal{G}$  and  $\mathcal{P}$  are the Gaussian and Poisson functions, respectively. As before,  $\mathcal{L}$  represents the  
 2125     integrated luminosity with uncertainty  $\sigma_{\mathcal{L}}$  and associated nuisance parameter  $\theta_{\mathcal{L}}$ . The number of  
 2126     measured events in a given bin and channel is represented by  $N_{cb}^{\text{meas.}}$ , and  $\nu_{cb}(\mu)$  is the predicted  
 2127     number of events defined in Equation 5.16 expressed as a function of the signal strength  $\mu$ . Finally,  
 2128     the set of nuisance parameters  $\theta$  and any auxiliary measurements used to constrain them ( $\theta^0$ ) are  
 2129     multiplied for each parameter  $p$ .

2130     The profile likelihood ratio is defined as

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

2131     where  $\hat{\mu}$  and  $\hat{\theta}$  are the unconditional maximum likelihood estimates, and  $\hat{\theta}$  is the conditional maxi-  
 2132     mum likelihood estimate for a given value of  $\mu$ . The fitted signal strength  $\hat{\mu}$  is obtained by maximiz-  
 2133     ing the likelihood function with respect to all parameters. The compatibility of the observed data

with the background-only hypothesis can then be calculated by setting  $\mu = 0$ . Observation of the  $W^\pm W^\pm jj$  EWK process is claimed if the data is found to be inconsistent with the background-only hypothesis by more than  $5\sigma$ .

### 5.4.2 Definition of the fiducial volume

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

| Fiducial region selection |  |
|---------------------------|--|
| Lepton selection          | Two prompt leptons ( $e, \mu$ )<br>$p_T > 27$ GeV and $ \eta  < 2.5$ for both leptons<br>Both leptons with the same electric charge<br>Dilepton invariant mass $m_{ll} > 20$ GeV<br>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<br>Leading jet $p_T > 65$ GeV<br>Subleading jet $p_T > 35$ GeV<br>Leading and subleading jet $ \eta  < 4.5$<br>Jet-lepton separation $\Delta R(l, j) > 0.3$<br>Dijet invariant mass $m_{jj} > 500$ GeV<br>Dijet separation $\Delta y_{jj} > 2.0$ |

Table 5.18: Definition of the fiducial volume.

The full phase space is generated in MC simulations, providing the total theoretical cross section  $\sigma_{\text{theo}}^{\text{tot}}$  and the total number of signal events  $\mathcal{N}_{\text{sig}}^{\text{tot}}$ <sup>19</sup>. After applying the fiducial selection at truth level, the total number of signal events in the fiducial region  $\mathcal{N}_{\text{sig}}^{\text{fid}}$  is obtained. An acceptance factor  $\mathcal{A}$  is used to represent the efficiency of events falling inside the fiducial region at truth level:

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

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

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

<sup>19</sup>For 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  $N$ .

2149 Since the fit is binned in  $m_{jj}$ , the acceptance and efficiency correction factors must be as well.  
 2150 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  
 2151 graphical representation of these regions and the use of the acceptance and correction factors can  
 2152 be seen in Figure 5.27.

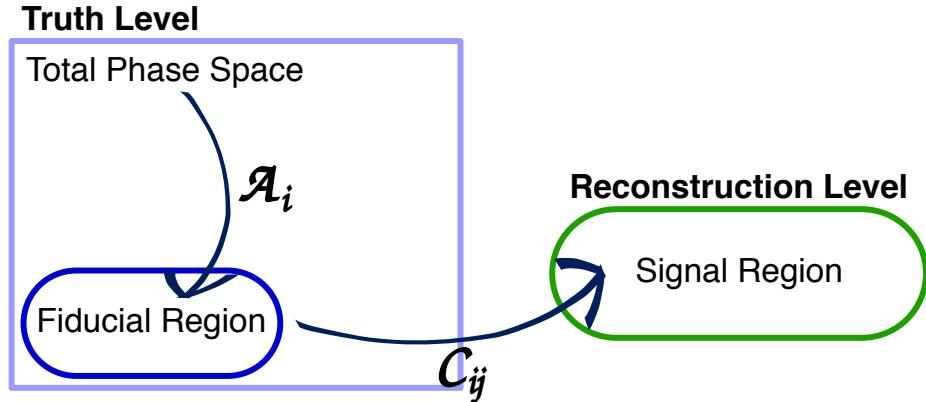


Figure 5.27: Visual representation of the different kinematic regions relevant to the cross section measurement. The acceptance factor  $\mathcal{A}$  converts from the truth level total phase space to the truth level fiducial region, and the efficiency correction  $\mathcal{C}$  translates the fiducial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

#### 2153 5.4.3 Cross section extraction

2154 The  $W^\pm W^\pm jj$  EWK fiducial cross section is measured using the signal strength parameter  $\mu$  that is  
 2155 determined by the maximum likelihood fit. This parameter is dependent on the nuisance parameters  
 2156  $\theta$  and can be written explicitly in terms of the measured and theoretical cross sections as:

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

2157 In the simple case with only one bin, the equation for the total number of expected events in the  
 2158 signal region first introduced in Equation 5.15 can be written as:

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

2159 with the unbinned versions of  $\mathcal{A}$  and  $\mathcal{C}$  defined in Equations 5.19 and 5.20, respectively.

2160 If the measured fiducial cross section is written as:

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

2161 then Equation 5.22 can be rearranged to read:

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

2162 The measured fiducial cross section can finally be rewritten in terms of  $\hat{\mu}$ , which is the best estimator  
2163 of the signal strength as extracted from the fit:

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

2164 In practice, however, the cross section is not extracted from a single bin, and Equation 5.22  
2165 becomes:

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

2166 for a single channel in truth and reconstruction level  $m_{jj}$  bins  $i$  and  $j$ , respectively, where the binned  
2167 versions of  $\mathcal{A}_i$  and  $\mathcal{C}_{ij}$  are used. This equation can be extended to include all the analysis channels  
2168 by increasing the number of bins  $i$  and  $j$ . Additionally, it can be shown that Equation 5.25 holds  
2169 for this more complex case as well [83], provided care is taken to ensure that all the uncertainties  
2170 are handled properly.

## 2171 5.5 Summary of uncertainties

2172 Systematic uncertainties enter the final fit as nuisance parameters which can impact the estimated  
2173 signal and background yields and the shapes of the  $m_{jj}$  distributions. These uncertainties can arise  
2174 from the experimental methods or from the theoretical calculations used in the analysis. This section  
2175 summarizes the systematic uncertainties; the experimental uncertainties are detailed in Section 5.5.1,  
2176 and the theoretical uncertainties are covered in Section 5.5.2. The impacts of the systematic uncer-  
2177 tainties on the final cross section measurement are summarized in Table 5.19.

### 2178 5.5.1 Experimental uncertainties

2179 Experimental uncertainties include detector effects as well as uncertainties on the background es-  
2180 timation methods. Sources of systematic uncertainty on the measurement of physics objects are  
2181 listed in Table 5.20, grouped by the relevant object type. For backgrounds estimated from MC  
2182 simulations, variations in these sources of uncertainty are propagated through the analysis to obtain  
2183 the corresponding uncertainties on the event yields. Additional experimental uncertainties include

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

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.

2184 the integrated luminosity, the photon conversion rate from Section 5.3.2, and the data driven charge  
 2185 misidentification and fake lepton background estimations from Sections 5.3.3 and 5.3.4.5, respec-  
 2186 tively.

2187 The largest sources of experimental uncertainty on the MC estimations come from the jet-related  
 2188 uncertainties and the  $b$ -tagging efficiency, while the largest uncertainty on the background estimation  
 2189 comes from the fake-factor. The effects of the uncertainties on the  $W^\pm W^\pm jj$  EWK signal and the  
 2190 dominant MC estimated background,  $WZ$ , are listed in Tables 5.21 and 5.22, respectively. Since  
 2191 the overall contributions from other processes estimated with MC are small, the uncertainties on  
 2192 these backgrounds have a lesser impact on the final measurement; these tables can be found in  
 2193 Appendix A.1.

### 2194 5.5.2 Theoretical uncertainties

2195 It is also necessary to consider uncertainties on the theoretical predictions in the fiducial region. They  
 2196 include the choice of PDF set, the value of the strong coupling constant  $\alpha_s$ , the renormalization  
 2197 scale  $\mu_R$ , the factorization scale  $\mu_F$ , and the parton showering. The size of these uncertainties are  
 2198 measured by generating new samples with variations in a chosen parameters and comparing them

| 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              |
| $E_T^{\text{miss}}$        | 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.

2199 to samples using the nominal choice of the parameter.

2200 For the signal sample, internal variations on the PDF sets as well as using a different set entirely  
 2201 results in a relative uncertainty of up to 2.25% on the nominal sample. The impact from varying  $\alpha_s$  is  
 2202 very small, on the order of < 0.01%. The factorization and renormalization scales are independently  
 2203 varied between 0.5-2.0 from their nominal values of 1.0. This results in relative uncertainties on the  
 2204 prediction of up to 15%. Finally, varying the parameters in the parton showering results in up to  
 2205 8% uncertainty.

### 2206 5.5.2.1 Uncertainties from EWK-QCD interference

2207 As mentioned in Section 5.0.1,  $W^\pm W^\pm jj$  production consists of both EWK processes. The two  
 2208 production modes cannot be naively separated due to cross terms in the matrix element calculation.  
 2209 These cross terms are referred to as *interference* terms. Since the  $W^\pm W^\pm jj$  EWK production is  
 2210 the focus of the analysis, and the signal region is designed to preferentially select those events, it is  
 2211 important to measure the size of the EWK-QCD interference contributions.

2212 The interference effects are estimated using the `MadGraph` MC generator, as it has a feature that  
 2213 allows direct modelling of the interference term. This allows four samples to be generated:

2214 1. Inclusive: All available diagrams are used in the matrix element calculation

2215 2. EWK only: Only EWK diagrams ( $\mathcal{O}(\alpha_{\text{EWK}}) = 6$ ) are used

2216 3. QCD only: Only QCD diagrams ( $\mathcal{O}(\alpha_s) = 2 \otimes \mathcal{O}(\alpha_{\text{EWK}}) = 4$ ) are used

2217 4. Interference: Only the interference terms are used

2218 A minimal set of generator level cuts, listed in Table 5.23, is applied in order to avoid biasing the  
 2219 sample towards either production mode. The cross sections for each of the four channels can be  
 2220 found in Table 5.24. The size of the interference is found to be approximately 6% of the total cross  
 2221 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       | $\sigma$ (fb)      |
|--------------|--------------------|
| Inclusive    | $3.646 \pm 0.0012$ |
| EWK only     | $2.132 \pm 0.0005$ |
| QCD only     | $1.371 \pm 0.0008$ |
| Interference | $0.227 \pm 0.0002$ |

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.

## 5.6 Results

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

The  $WZ$  normalization factor is measured to be:

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

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

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

This corresponds to a rejection of the background-only hypothesis with a significance of  $6.9\sigma$ .

The observed number of data events are compared to the predicted signal and background yields in the signal region after applying the fit in Table 5.25. The pre-fit event yields can be found in Appendix A.2. 122 candidate events are observed compared to a prediction of 60 signal and 69 background events. The  $m_{jj}$  distributions for data and prediction are shown in Figure 5.28 after the fit, and the fitted event yields in the low- $m_{jj}$  and  $WZ$  control regions are shown in Figure 5.29.

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

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

Table 5.25: 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 “ $e/\gamma$  conversions” category. Finally,  $ZZ$ ,  $VVV$ , and  $t\bar{t}V$  backgrounds are combined in the “Other prompt” category.

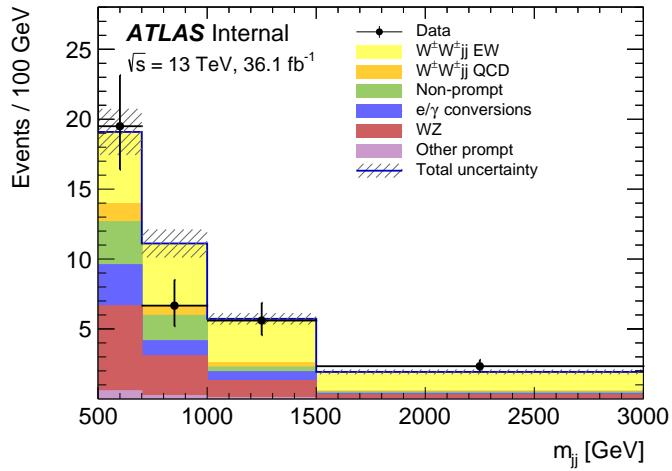


Figure 5.28: The dijet invariant mass  $m_{jj}$  distributions for data and predicted signal and background in the signal region after the fit. The shaded band represents the statistical and systematic uncertainties added in quadrature. Note that the bins have been scaled such that they represent the 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 “ $e/\gamma$  conversions” category. Finally,  $ZZ$ ,  $VVV$ , and  $t\bar{t} + V$  backgrounds are combined in the “Other prompt” category.

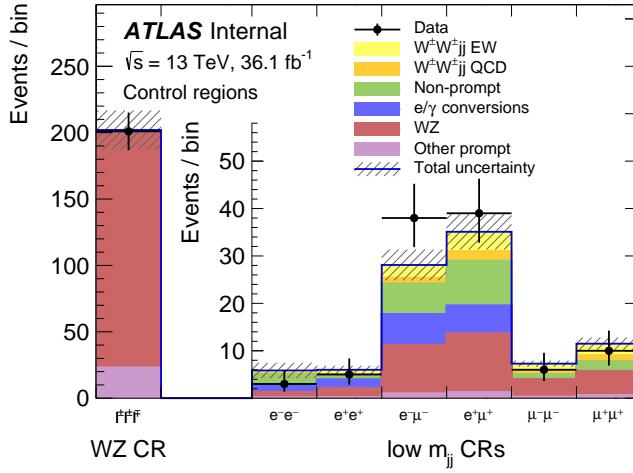


Figure 5.29: The event yields for data and predicted signal and background in the  $WZ$  and low- $m_{jj}$  control regions after the fit. The shaded band represents the statistical and systematic uncertainties added in quadrature. The background estimations from the fake-factor are included in the “Non-prompt”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

prediction used in the cross section measurement including uncertainties from Section 5.5.2 is:

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

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

$$\sigma_{\text{meas}}^{\text{fid}} = 2.91 \begin{array}{l} +0.51 \\ -0.47 \end{array} (\text{stat}) \begin{array}{l} +0.12 \\ -0.16 \end{array} (\text{model sys}) \begin{array}{l} +0.24 \\ -0.23 \end{array} (\text{experimental sys}) \begin{array}{l} +0.08 \\ -0.06 \end{array} (\text{luminosity}) \text{ fb} \quad (5.30)$$

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

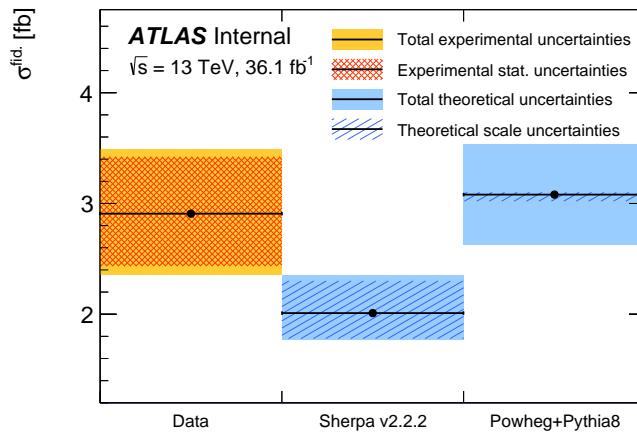


Figure 5.30: Comparison of the measured  $W^\pm W^\pm jj$  EWK fiducial cross section with theoretical calculations from **SHERPA v2.2.2** and **POWHEG-BOX v2**. The light orange band represents the total experimental uncertainty on the measured value, and the dark orange hashed band is the statistical 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.

## CHAPTER 6

---

2251     **Prospects for same-sign  $WW$  at the High**  
 2252         **Luminosity LHC**

---

2253     On December 3, 2018, Run 2 of the LHC officially ended, and the collider was shut down to begin  
 2254     the first of two scheduled extended maintenance periods [113]. During these two long shutdowns,  
 2255     the Phase-I and Phase-II upgrades of the LHC and ATLAS will occur in order to prepare for the  
 2256     High-Luminosity LHC (HL-LHC) which is scheduled to begin operation in 2026 [114].

2257         The HL-LHC is planned to run at a center-of-mass energy of  $\sqrt{s} = 14$  TeV with an instantaneous  
 2258     luminosity of  $\mathcal{L} = 5 \times 10^{34}$  cm $^{-2}$ s $^{-1}$  with up to 200 collisions per beam-crossing. Over the course  
 2259     of operation, the HL-LHC is expected to collect a total integrated luminosity of  $\mathcal{L} = 3000$  fb $^{-1}$  by  
 2260     2035 [115].

2261         These run conditions will be much harsher than what ATLAS has experienced so far, and there  
 2262     are several upgrades planned to adapt the detector to the high luminosity environment. Most  
 2263     notably, the entire ID will be replaced with an all-silicon tracker which will extend the coverage  
 2264     from  $|\eta| \leq 2.7$  up to  $|\eta| \leq 4.0$ . This will allow for forward particle tracks to be reconstructed, which  
 2265     can in turn be matched to clusters in the calorimeters for use in electron identification or forward  
 2266     jet tagging [116].

2267         The upgraded detector, the higher beam energy, and the increased volume of data to be col-  
 2268     lected provides the opportunity to measure rare processes to a much higher precision than what  
 2269     is possible with the current LCH dataset. Same-sign  $W^\pm W^\pm jj$  production is one such process.  
 2270     With greater statistics, the accuracy of the cross section measurement can be improved over the  
 2271     13 TeV analysis detailed in Chapter 5, and it also will allow for more detailed physics studies, such  
 2272     as measuring the polarization state of the scattered  $W$  bosons. A measurement of the cross section

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

### 6.0.1 Analysis Overview

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

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

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

2302 **6.1 Theoretical motivation**

2303 The motivation for studying the  $W^\pm W^\pm jj$  process as well as VBS in general has been established  
 2304 previously in Sections 2.3 and 5.0.1. Since only the longitudinally polarized vector bosons that is  
 2305 sensitive to the EWSB mechanism, a direct measurement of this cross section will be very useful for  
 2306 understanding how the Higgs unitarizes the scattering amplitude [117].

2307 **6.1.1 Experimental sensitivity to longitudinal polarization**

2308 There are three possible polarization states for a massive vector boson: two transverse (+ or -)  
 2309 and one longitudinal (0). Therefore, in a system with two  $W$  bosons, the overall polarization can be  
 2310 purely longitudinal (00), purely transverse (++, --, and +-), or mixed (+0 and -0). The three  
 2311 combinations will be referred to as *LL*, *TT*, and *LT* respectively.

2312 In order extract the longitudinal scattering component, it is necessary to find variables that can  
 2313 help distinguish the LL from the TT and LT events. Several were studied, and those with the best  
 2314 discriminating power between the different polarization states are the leading and subleading lepton  
 2315 transverse momenta as well as the azimuthal separation of the two VBS jets  $|\Delta\phi_{jj}|$ . Both leptons  
 2316 in LL events tend to be softer than the TT and LT events (see Figure 6.1), which motivates keeping  
 2317 cuts on the lepton  $p_T$  as low as possible in the event selection. In the case of the dijet separation,  
 2318 LL events prefer the tag jets to be back-to-back (see Figure 6.2). The  $|\Delta\phi_{jj}|$  distribution is chosen  
 2319 to be the discriminating variable between the polarizations, and it is ultimately passed to a binned  
 2320 likelihood fit to extract the longitudinal scattering significance.

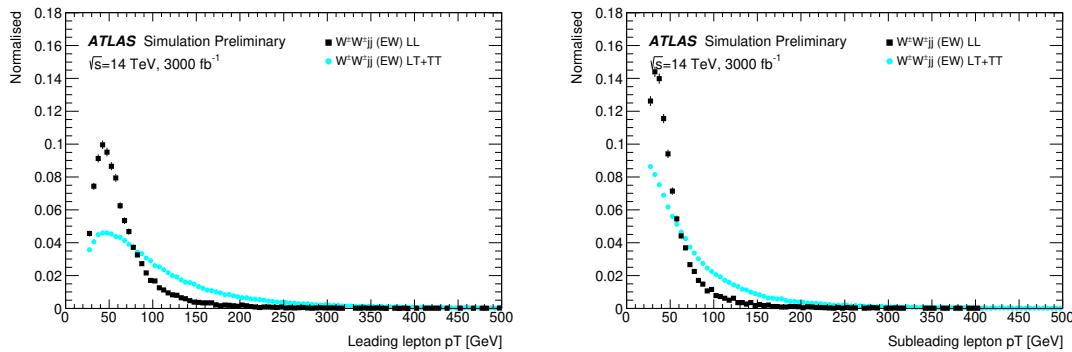


Figure 6.1: Comparison of the leading (left) and subleading (right) lepton  $p_T$  distributions for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan)  $W^\pm W^\pm jj$  events.

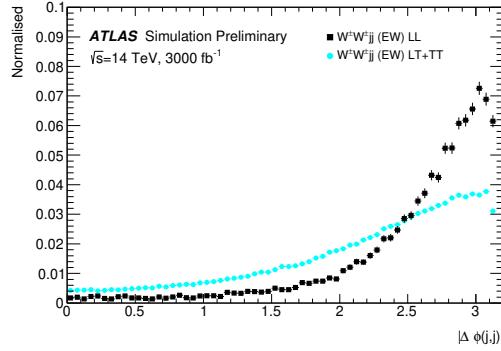


Figure 6.2: Comparison of the azimuthal dijet separation ( $|\Delta\phi_{jj}|$ ) for purely longitudinal (LL, black) and mixed polarization (LT+TT, cyan)  $W^\pm W^\pm jj$  events.

## 6.2 Monte Carlo samples

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

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

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

| 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.

2342 backgrounds are generated for electron, muon, and tau final states at LO with `Madgraph5_aMC@NLO`  
 2343 and the `NNPDF3.0` PDF set with showering from `PYTHIA v8`.  $Z+jets$  events are produced using  
 2344 `POWHEG-BOX v2` and the `CT10` PDF set interfaced with `PYTHIA v8`. Finally,  $t\bar{t}$  and single-top events  
 2345 are generated using `POWHEG-BOX` with showering from `PYTHIA v6`.

### 2346 6.3 Background estimations

2347 In this analysis, all background contributions are estimated using MC simulations. Backgrounds  
 2348 from electron charge misidentification and fake electrons from jets, which are traditionally estimated  
 2349 using data-driven techniques, are instead estimated using a set of parameterization functions applied  
 2350 to the MC. These functions calculate the probability that an electron is assigned the wrong charge or  
 2351 a jet is mis-reconstructed as an electron parameterized by the  $p_T$  and  $\eta$  of the respective electron or  
 2352 jet. The probabilities are derived from studies on expected electron performance with the upgraded  
 2353 ATLAS detector [121].

2354 Processes involving two  $W$  or  $Z$  bosons are grouped together as *diboson* backgrounds, with the  
 2355 exception of  $W^\pm W^\pm jj$  events produced via QCD interactions, which are kept separate. Similarly,  
 2356 all backgrounds with three vector bosons are combined and labeled as *triboson*. Any  $W+jets$  or top  
 2357 events that pass selection and do not contain a fake electron, as well as any  $Z+jets$  events without an  
 2358 electron identified as having its charge misidentified are combined as *other non-prompt* backgrounds.

2359 **6.3.1 Truth-based isolation**

2360 The canonical isolation variables used in ATLAS analyses require detailed information from several  
 2361 detector subsystems including particle tracks and calorimeter responses. Since the MC samples used  
 2362 in this analysis have not been run through a full detector simulation, it is not possible to reproduce  
 2363 the official isolation variables. For truth-level analysis, this is generally not a serious concern, as  
 2364 high- $p_T$  signal leptons tend to be well isolated to begin with. However, isolation is one of the  
 2365 most powerful tools for rejecting leptons from non-prompt sources, such as top events, which are  
 2366 produced in association with additional nearby particles from  $b$  and  $c$  hadron decays. It was seen in  
 2367 the early stages of this analysis that without any sort of isolation requirement, contributions from  
 2368 top backgrounds (including single top,  $t\bar{t}$ , and  $t\bar{t} + V$ ) were more than an order of magnitude higher  
 2369 than expected.

2370 As a result, it was necessary to find one or more quantities that are comparable to the isolation  
 2371 information that is available in fully-simulated samples. Analogues to track- and calorimeter-based  
 2372 isolation are constructed by summing the momentum and energy, respectively, of stable truth parti-  
 2373 cles with  $p_T > 1$  GeV within a specified radius of each signal lepton. For the track-based isolation,  
 2374 only charged truth particles are used; both charged and neutral particles (excluding neutrinos) are  
 2375 included for the calorimeter-based isolation. Ultimately, a set of isolation cuts are chosen that are  
 2376 similar to the fixed-cut recommendations for ATLAS Run 2 analyses. The truth-based isolation  
 2377 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.

2378 With no cut on truth-based isolation, 83% of the total background consisted of top events  
 2379 (without including top contributions to the fake electron background). The isolation requirement  
 2380 reduces the top background by over 99%, and the percentage of the total background from top  
 2381 events is reduced to 2%. Additional studies on the truth-based isolation as well as full event yields  
 2382 with and without the isolation requirement can be found in Appendix B.1.

---

2383 **6.4 Object and event selection**

2384 The majority of the default object and event selections were determined in the preceeding  $W^\pm W^\pm jj$   
 2385 HL-LHC prospects study [119], which focused on the impact of the upgraded detector's forward  
 2386 tracking capabilities. Several different combinations of lepton and jet  $\eta$  ranges were tested, and the  
 2387 results are used in this study.

2388 **6.4.1 Object selection**

2389 Electrons and muons are preselected to have  $p_T > 7$  and  $6$  GeV, respectively, and lie within  $|\eta| \leq 4.0$ .  
 2390 The likelihood of a given lepton to pass the trigger and identification requirements is estimated by  
 2391 calculating an efficiency dependent on the  $p_T$  and  $\eta$  of the lepton. The leptons are also required to  
 2392 pass the isolation criteria detailed in Table 6.2. Jets that have been tagged as a fake electron by the  
 2393 functions described in Section 6.3 are treated as electrons for the purpose of the object selection and  
 2394 are subject to the same criteria. In order to be considered a signal lepton, the transverse momentum  
 2395 requirement is raised to  $p_T > 25$  GeV. The two highest  $p_T$  leptons passing this selection are chosen  
 2396 to be the leading and subleading signal leptons.

2397 Jets are clustered using the anti- $k_t$  algorithm from final-state particles (excluding muons and  
 2398 neutrinos) within a radius of  $\Delta R = 0.4$ . All jets are required to have  $p_T > 30$  GeV and lie within  
 2399  $|\eta| < 4.5$ ; in order to suppress jets from pileup interactions, jets outside of  $|\eta| \geq 3.8$  must pass an  
 2400 higher momentum cut of  $p_T > 70$  GeV. Jets overlapping a preselected electron within  $\Delta R(e, j) <$   
 2401  $0.05$  are removed in order to prevent double counting. The two highest  $p_T$  jets are defined as the  
 2402 leading and subleading tag jets.

2403 **6.4.2 Event selection**

2404 The default event selection is summarized in Table 6.3 and described here. Exactly two signal  
 2405 leptons are required with the same electric charge and separated from each other by  $\Delta R(ll) > 0.3$ .  
 2406 In order to suppress contributions from Drell-Yan backgrounds, the two signal leptons must have  
 2407 an invariant mass  $m_{ll}$  greater than  $20$  GeV. Additionally, if both signal leptons are electrons, their  
 2408 mass must be at least  $10$  GeV away from the  $Z$ -boson mass in order to reduce background from  
 2409  $Z$ -boson decays<sup>20</sup>. The event is required to have at least  $40$  GeV of missing transverse energy ( $E_T^{\text{miss}}$ )

---

<sup>20</sup>The electron charge misidentification rate in the upgraded ATLAS detector is estimated to be high enough that contributions from  $Z \rightarrow ee$  backgrounds are non-negligible.

| Selection requirement | Selection value   |
|-----------------------|---|
| Lepton kinematics     | $p_T > 25 \text{ GeV}$<br>$ \eta  \leq 4.0$   |
| Jet kinematics        | $p_T > 30 \text{ GeV}$ for $ \eta  \leq 4.5$<br>$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)                                   |
| $E_T^{\text{miss}}$   | $E_T^{\text{miss}} > 40 \text{ GeV}$  |
| 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.

2410 to account for the two final-state neutrinos. Events with additional preselected leptons are vetoed,  
 2411 which greatly reduces  $WZ$  and  $ZZ$  backgrounds.

2412 Each event must have at least two jets, and both tag jets are required to not overlap with the  
 2413 signal leptons. Events with one or more  $b$ -jets are vetoed to suppress backgrounds from heavy-flavor  
 2414 decays. In order to preferentially select EWK production, the tag jets are required to have a large  
 2415 separation between them and a large invariant mass. Finally, a cut on the lepton centrality  $\zeta^{21}$ ,  
 2416 defined in Equation 6.1, further enhances the EWK  $W^\pm W^\pm jj$  signal.

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

2417

## 2418 6.5 Selection optimization

2419 The default event selection is optimized in order to improve the strength of the  $W^\pm W^\pm jj$  EWK  
 2420 signal. The expectation is that the increased detector acceptance from the forward tracking combined  
 2421 with an increase in center of mass energy and much higher integrated luminosity will allow tighter  
 2422 selection cuts without jeopardizing signal statistics.

---

<sup>21</sup> $\zeta$  is a measurement of whether the two signal leptons lie between the two tagging jets in  $\eta$ , as is preferred by the VBS topology.

2423 **6.5.1 Random grid search algorithm**

2424 The chosen method for optimizing the event selection is a cut-based algorithm known as the Random  
 2425 Grid Search (RGS) [122]. Consider a simple case of two variables  $x$  and  $y$  chosen to differentiate  
 2426 signal from background. In order to be considered a signal event, a given event would be required to  
 2427 pass a set of selection criteria, called a *cut point*:  $c = \{x > x_c, y > y_c\}$ . A simple method to choose  
 2428 the optimal cut point (the “best” values of the cuts  $x_c$  and  $y_c$ ) would be to construct an  $n \times m$   
 2429 rectangular grid in  $x$  and  $y$  consisting of points  $(x_0, y_0), (x_1, y_1), \dots, (x_n, y_m)$ , as in Figure 6.3a. One  
 2430 can then choose a cut point  $c_k = \{x > x_i, y > y_j\}$  that maximizes the signal significance as given  
 2431 by a chosen metric. This would be considered a *rectangular grid search*.

2432 While effective in principle, a rectangular grid search comes with two major drawbacks:

- 2433 1. The algorithm scales exponentially as the number of variables to be optimized increases, as  
 2434 this is effectively increasing the dimensionality of the grid. In the simple case of a square grid  
 2435 with  $N$  bins per variable  $v$ , the number of cut points to be evaluated grows as  $N^v$ .
- 2436 2. Signal and background samples are rarely evenly distributed over the entire grid, resulting  
 2437 in many cut points being sub-optimal, and evaluating them would be a waste of computing  
 2438 resources.

2439 To combat these limitations, the RGS algorithm constructs a grid of cut points directly from  
 2440 the signal sample itself. In the two-dimensional example, this means that the variables  $x_i$  and  $y_j$   
 2441 making up the cut point  $c_k = \{x > x_i, y > y_j\}$  take their values directly from a given signal event.  
 2442 This creates a *random grid* of cut points that has the benefit of being biased towards regions of high  
 2443 signal concentration by construction. This reduces the need for exponentially increasing numbers of  
 2444 cut points while ensuring that computing resources are not wasted in regions with few to no signal  
 2445 events. An example of a two-dimensional random grid is shown in Figure 6.3b.

2446 Once the random grid of cut points is constructed, the optimal cut point can be chosen using any  
 2447 number of metrics, such as signal to background ratio. For the purpose of the  $W^\pm W^\pm jj$  upgrade  
 2448 study, the optimal cut point is chosen to be the one that maximizes the signal significance  $Z$ , defined  
 2449 as [123]:

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

2450 where  $s$  and  $b$  are the number of signal and background events, respectively,  $\sigma_b$  is the total uncertainty

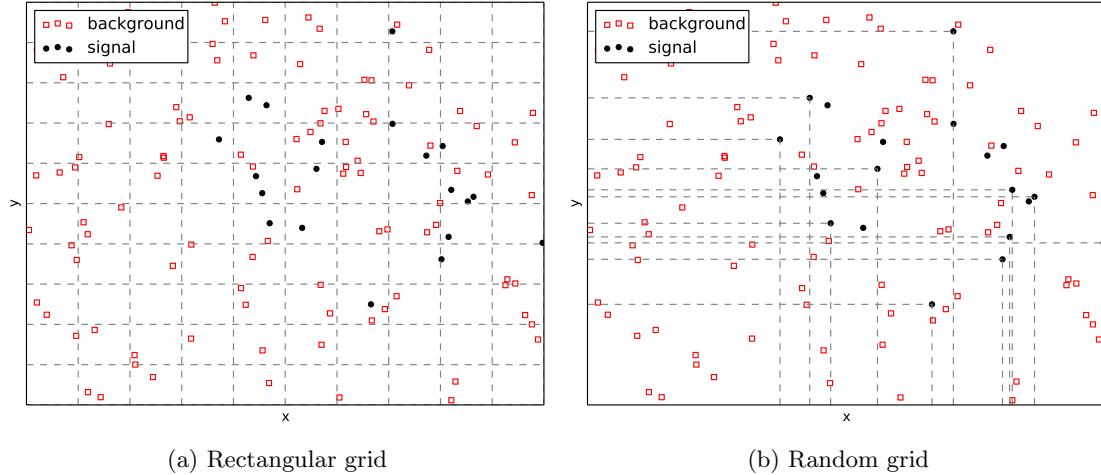


Figure 6.3: A visual representation of a two-dimensional rectangular grid (left) and a random grid (right) in variables  $x$  and  $y$ . The signal events are the black circles, and the red squares are the background events. Each intersection of gray dashed lines represents a cut point to be evaluated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

on the background, and  $b_0$  is defined as:

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

2452 In the case where the background is known precisely (i.e.  $\sigma_b = 0$ ), Equation 6.2 simplifies to

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

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

### 2454 6.5.2 Inputs to the optimization

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

2462 The following variables are chosen for optimization:

- Leading lepton  $p_T$

2464     • Dilepton invariant mass ( $m_{ll}$ )

2465     • Leading and subleading jet  $p_T$

2466     • Dijet invariant mass ( $m_{jj}$ )

2467     • Lepton-jet centrality ( $\zeta$ )

2468 Subleading lepton  $p_T$  is omitted as it is desirable to keep the cut value as low as possible due  
 2469 to its sensitivity to the longitudinal polarization (as discussed in Section 6.1.1); despite this, the  
 2470 leading lepton  $p_T$  is still allowed to be optimized as it can have strong background rejection power.  
 2471 Additionally, the dijet separation  $\Delta\eta_{jj}$  was included in early studies of the optimization, however it  
 2472 was dropped due to the cut value being motivated by well-studied differences between EWK- and  
 2473 QCD-produced  $W^\pm W^\pm jj$  events (as in Figure 5.6b).

2474 Two additional constraints are imposed on the optimal cut point:

- 2475 1. At least 1000 signal events must survive in order to prevent the optimization from being too  
 2476 aggressive and unnecessarily reducing signal statistics.
- 2477 2. The dijet invariant mass may only vary within a 50 GeV range of the default value (from  
 2478 450 – 550 GeV) due to the cut being physically motivated by the VBS event topology (as in  
 2479 Figure 5.6a).

2480 Lastly, the signal significance is calculated without taking into account the uncertainty of the  
 2481 background using Equation 6.4. This is due to the fact that the statistical uncertainties of the fake  
 2482 electron and charge misidentification backgrounds are quite large, owing to poor MC statisces in a  
 2483 few of the samples. If Equation 6.2 were used instead, the optimization would cut unreasonably  
 2484 hard against these backgrounds. Since Monte Carlo statistics is not expected to be a limiting factor  
 2485 when this analysis is performed at the HL-LHC, it is more realistic to simply ignore these large  
 2486 statistical uncertainties for the purpose of the optimization.

### 2487 6.5.3 Results of the optimization

2488 Ultimately, the random grid is constructed from over 38,000 LL-polarized  $W^\pm W^\pm jj$  events in the  
 2489 six variables listed above. After applying the constraints, the optimal cut point reduces the total  
 2490 background from 9900 to 2310 while reducing the signal from 3489 to 2958. This corresponds to  
 2491 an increase in signal significance from  $Z = 33.26$  to  $Z = 52.63$  as calculated by Equation 6.4. The  
 2492 updates to the event selection are listed in Table 6.4.

2493     The large reduction in the background is primarily a result of increasing the leading and sub-  
 2494     leading jet  $p_T$  from 30 GeV to 90 GeV and 45 GeV, respectively. As can be seen in Figure 6.4,  
 2495     this increase removes a significant portion of the backgrounds from jets faking electrons and charge  
 2496     mis-ID. Additionally, the loosening of the lepton-jet centrality cut  $\zeta$  allows more signal events to  
 2497     survive the event selection (see Figure 6.5). Other changes to the event selection are minor and  
 2498     do not individually have a large impact on the signal or background yields; similar distributions of  
 2499     these variables are shown in Appendix B.2.

2500     The full event yields after optimization as well as the cross section measurement are detailed  
 2501     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)<br>$p_T > 45$ 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.

## 2502     6.6 Results

### 2503     6.6.1 Event yields

2504     After applying the full event selection, the analysis is broken down into four channels based off of  
 2505     the flavor of the signal leptons:  $\mu\mu$ ,  $ee$ ,  $\mu e$ , and  $e\mu$ . The full signal and background event yields are  
 2506     shown in Table 6.5 for each channel separately and combined using the default event selection. 3489  
 2507     EWK  $W^\pm W^\pm jj$  events are expected compared to 9900 background events. The dominant sources  
 2508     of background are jets faking electrons followed by charge misidentification and diboson processes.  
 2509     Triboson events, QCD  $W^\pm W^\pm jj$ , and other non-prompt sources make up approximately 5% of the  
 2510     total background combined.

2511     The event yields for the optimized selection detailed in Section 6.5.3 are listed in Table 6.6. After  
 2512     optimization, 2958 signal events and just 2310 background events are expected. Diboson events are  
 2513     now the primary source of background, as the optimization greatly reduces the fake and charge  
 2514     mis-ID contributions. As discussed earlier, the increase in the leading and subleading jet  $p_T$  cuts  
 2515     as well as the loosening of the centrality cut are most responsible for the changes in the signal

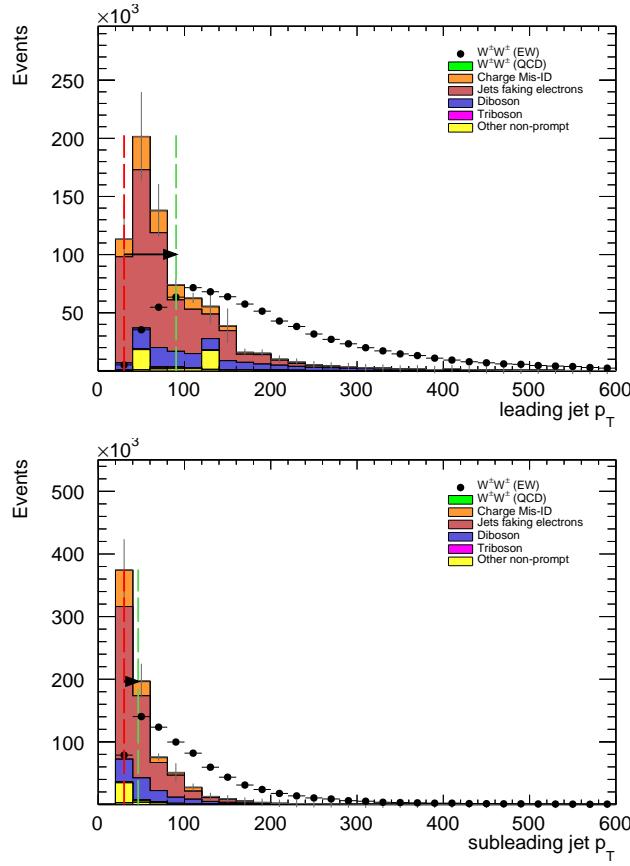


Figure 6.4: Leading (top) and subleading (bottom) jet  $p_T$  distributions. The default and optimized cuts are represented by the red and green dashed lines, respectively. The  $W^\pm W^\pm jj$  EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

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

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

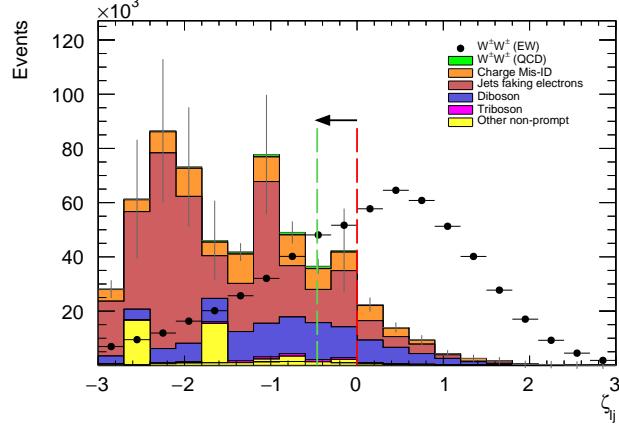


Figure 6.5: Lepton-jet centrality distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The  $W^\pm W^\pm jj$  EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

and background yields; distributions of these quantities using the default and the optimized event selections can be found in Figures 6.6, 6.7, and 6.8, respectively.

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

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

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

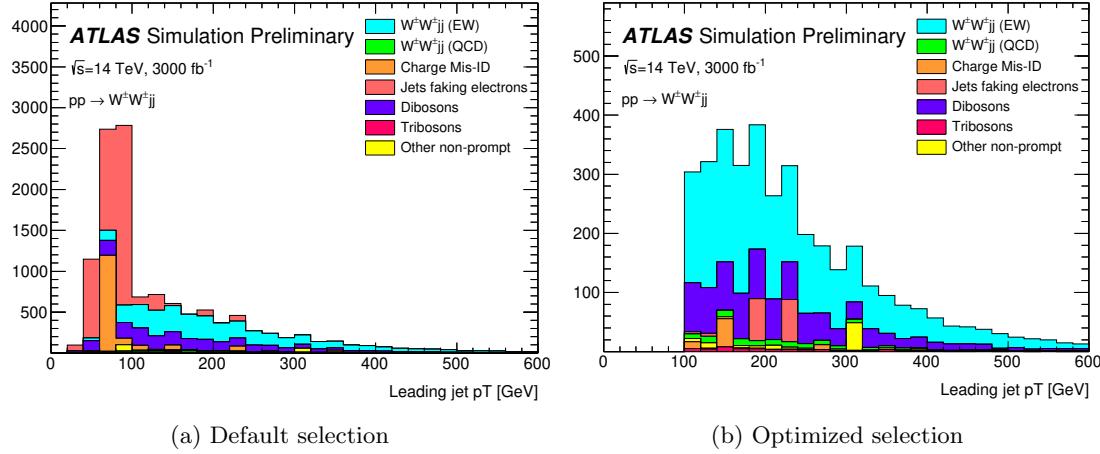


Figure 6.6:  $p_T$  distributions for the leading jet using the default (left) and optimized (right) event selections for all channels combined.

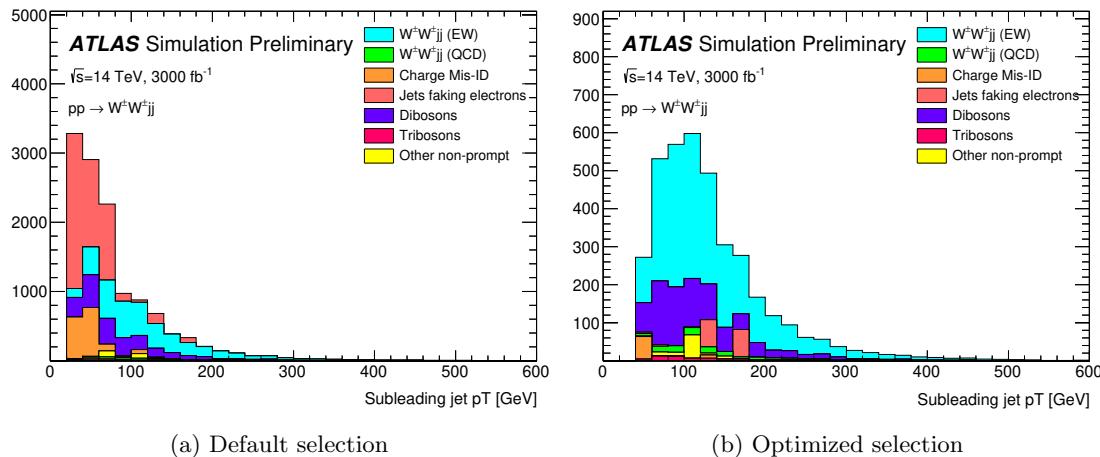


Figure 6.7:  $p_T$  distributions for the subleading jet using the default (left) and optimized (right) event selections for all channels combined.

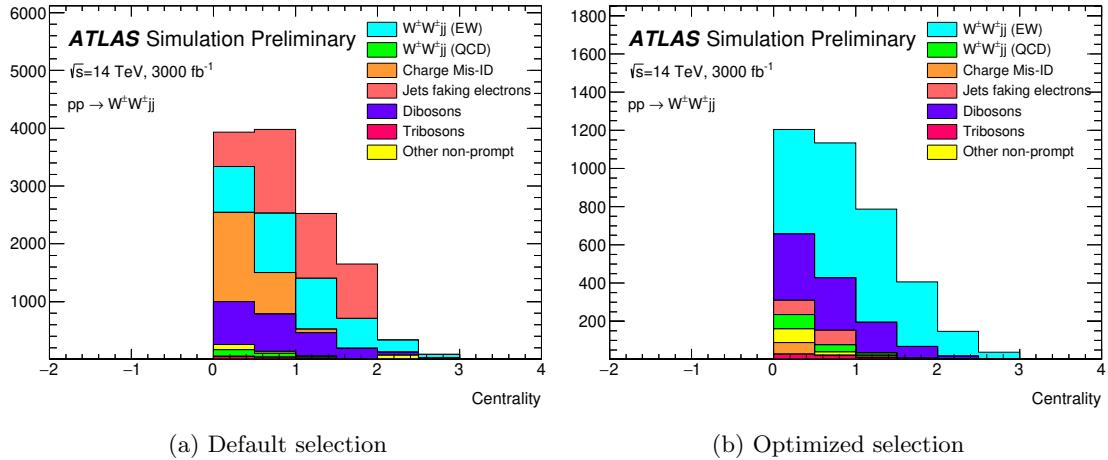


Figure 6.8:  $p_T$  distributions for lepton-jet centrality  $\zeta$  using the default (left) and optimized (right) event selections for all channels combined.

## 2525 6.6.2 Uncertainties

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 [81]. The rate uncertainties for the background processes are halved from the 13 TeV values according to ATLAS recommendations. The uncertainty on the fake electron estimation is also halved from the 13 TeV analysis. Finally, a conservative estimate of the uncertainty on the charge flip background is used as the electron charge mis-ID rate due to material interactions is difficult to predict at this stage.

| 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.

2533 **6.6.3 Cross section measurement**

2534 The cross section is calculated using the same method as in the 13 TeV analysis, detailed in Sec-  
 2535 tion 5.4. Unlike the previous analysis, however, eight lepton channels are used here instead of six.  
 2536 The  $\mu e$  and  $e\mu$  channels remain separated in addition to the  $\mu\mu$  and  $ee$  channels, and each lepton  
 2537 flavor channel is further split by charge (i.e.  $\mu\mu \rightarrow \mu^+\mu^+ + \mu^-\mu^-$ ), as this increases the sensitivity  
 2538 of the analysis. Each channel's  $m_{jj}$  distribution is combined in a profile likelihood fit to extract  
 2539 the EWK  $W^\pm W^\pm jj$  production cross section. Using the default event selection, the expected cross  
 2540 section calculated to be:

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

2541 and with the optimized event selection:

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

2542 The optimized selection should not change the measured value of the cross section, and indeed both  
 2543 are consistent with within uncertainties. The systematic uncertainty is reduced by approximately  
 2544 7% with the optimized selection. The total uncertainty on the cross section measurement is approx-  
 2545 imately 6%, compared to approximately 20% on the measured fiducial cross section of the 13 TeV  
 2546 analysis reported in Equation 5.30.

2547 Projections of each uncertainty type and the total uncertainty on the cross section as a function of  
 2548 integrated luminosity are shown in Figure 6.9. The predictions are made by scaling the event yields  
 2549 by different luminosity values and re-running the fitting procedure. As the integrated luminosity  
 2550 increases past  $\mathcal{L} > 3000 \text{ fb}^{-1}$ , the statistical uncertainty continues to reduce; however, the total  
 2551 uncertainty becomes limited by the systematics. Additionally, the total uncertainty is expected to  
 2552 reduce by less than a percent as the integrated luminosity increases past the planned  $3000 \text{ fb}^{-1}$ .

2553 **6.6.4 Longitudinal scattering significance**

2554 The longitudinal scattering significance is extracted in much the same way as the cross section, this  
 2555 time using a binned likelihood fit on the  $|\Delta\phi_{jj}|$  distribution. In order to increase sensitivity, the  
 2556  $|\Delta\phi_{jj}|$  distribution is split into two bins in  $m_{jj}$ , and an additional cut on the pseudorapidity of the  
 2557 subleading lepton is applied ( $|\eta| < 2.5$ ) to reduce background contributions from fake electrons and  
 2558 charge flip. The  $|\Delta\phi_{jj}|$  distributions used in the fit are shown in Figure 6.10. Due to limited statistics  
 2559 in the LL events, the four lepton flavor channels are not split by charge. The expected significance

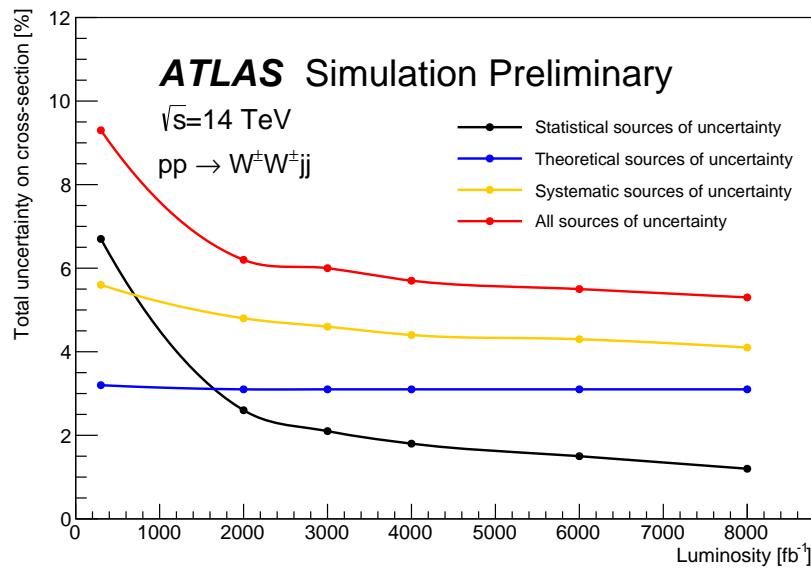


Figure 6.9: Projections of the statistical (black), theoretical (blue), systematic (yellow), and total (red) uncertainties on the measured cross section as a function of integrated luminosity using the optimized event selection.

2560 of the  $W_L^\pm W_L^\pm jj$  process is  $1.8\sigma$  with a precision of 47% on the measurement. Projections of the  
 2561 expected significance as a function of integrated luminosity is shown in Figure 6.11.

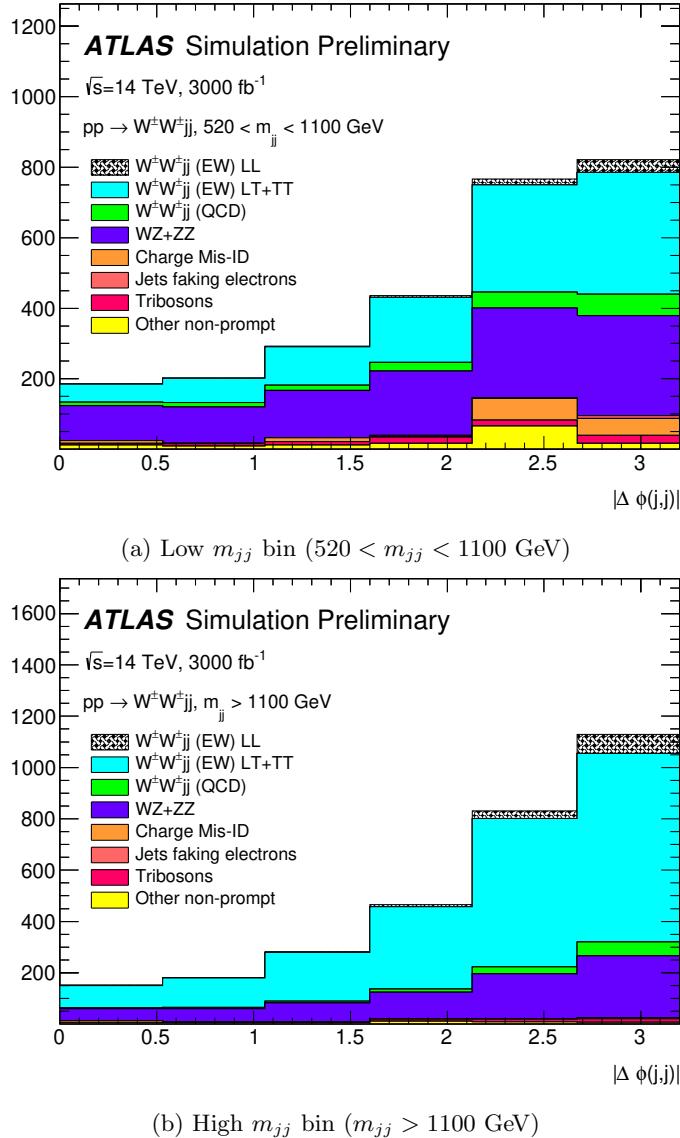


Figure 6.10: Dijet azimuthal separation ( $|\Delta\phi_{jj}|$ ) for the low  $m_{jj}$  region ( $520 < m_{jj} < 1100$  GeV, top) and the high  $m_{jj}$  region ( $m_{jj} > 1100$  GeV, bottom). The purely longitudinal (LL, gray) is plotted separately from the mixed and transverse (LT+TT, cyan) polarizations.

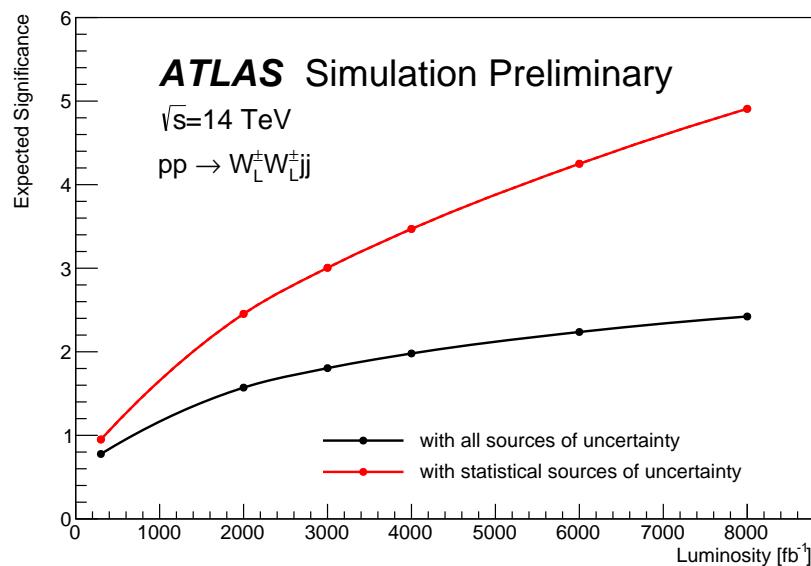


Figure 6.11: Projections of the expected longitudinal scattering significance as a function of integrated luminosity when considering all sources of uncertainties (black) or only statistical uncertainties (red).

2562

## CHAPTER 7

---

2563

## Conclusion

---

2564 Here's where you wrap it up.

2565

## APPENDIX A

2566

2567

---

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

---

2568

## A.1 Impact of experimental uncertainty on MC background estimations

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

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

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

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

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

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

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

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

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

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

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

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

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

2574 **A.2 Pre-fit event yields**

2575 Table A.7 contains the event yields for each source and channel before the fit.

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

Table A.7: 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 “ $e/\gamma$  conversions” category. Finally,  $ZZ$ ,  $VVV$ , and  $t\bar{t} + V$  backgrounds are combined in the “Other prompt” category.

## APPENDIX B

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

### B.1 Truth isolation

As mentioned in Section 6.3.1, the size of the background contribution from top processes are much larger than expected when no isolation is applied. The event yields using an earlier version of the event selection with no truth-based isolation requirement are listed in Table B.1. Here, top events make up nearly 90% of the total background, and the contributions from fake and charge-flipped electrons are also large. The event yields using the same event selection with the truth-based isolation 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 | $\mu\mu$ | $ee$    | $\mu e$ | $e\mu$  |
|----------------|--------------|----------|---------|---------|---------|
| signal         | 4011         | 1583.2   | 531.7   | 793.1   | 1103.1  |
| ww qcd         | 252.6        | 105.8    | 30.4    | 48      | 68.4    |
| charge flip    | 2528.4       | 0.0      | 2075.4  | 255.1   | 197.8   |
| fakes          | 7135.4       | 0.0      | 4675.1  | 1904.3  | 555.9   |
| diboson        | 2370.4       | 581.2    | 491.8   | 517.9   | 779.6   |
| triboson       | 125.5        | 49.1     | 17.8    | 24.6    | 34.1    |
| top            | 90150.5      | 26618    | 15301.6 | 25277.9 | 22953.1 |
| z+jets         | 241.2        | 0.0      | 0.0     | 0.0     | 241.2   |
| w+jets         | 31.4         | 3.9      | 7.6     | 13.2    | 6.7     |
| total bkg      | 102803.9     | 27354    | 22592   | 28027.8 | 24830.1 |
| signal         | 4011         | 1583.2   | 531.7   | 793.1   | 1103.1  |

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

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

| yields by type | all channels | $\mu\mu$ | $ee$   | $\mu e$ | $e\mu$ |
|----------------|--------------|----------|--------|---------|--------|
| 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.

### 2588 B.1.1 TRUTH1++ derivations

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

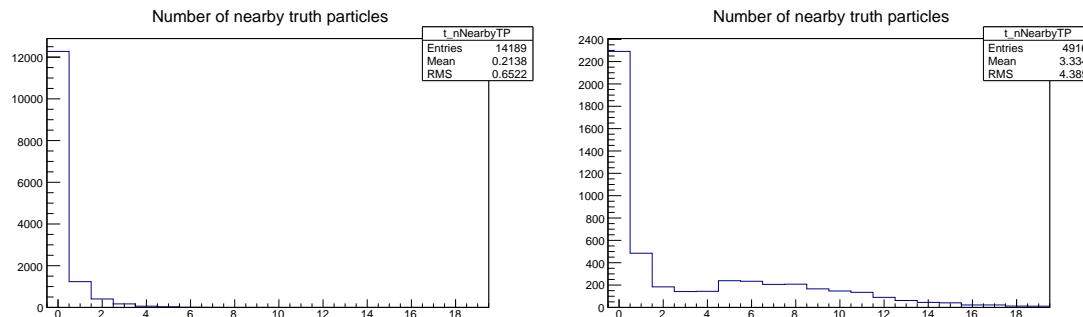


Figure B.1: Number of truth particles within  $\Delta R < 0.4$  of a selected muon or electron using the ATLAS standard `TRUTH1` (left) and the custom `TRUTH1++` (right) derivations in  $t\bar{t}$  simulation. The complete truth record is stored in the `TRUTH1++` derivation, and this is best seen in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

2597 **B.1.2 Check of truth-based isolation**

2598 Since the isolation variables are constructed from truth particles, there is an expectation that the  
 2599 efficiency of the isolation selection will be higher than what would be seen in the full simulation.  
 2600 In order to test this, a truth-level 13 TeV  $t\bar{t}$  MC sample was run through a selection altered to  
 2601 mimic the 13 TeV  $W^\pm W^\pm jj$  measurement as closely as possible. The results were compared to the  
 2602  $t\bar{t}$  background in the 13 TeV analysis extrapolated to 14 TeV and  $3000 \text{ fb}^{-1}$ , and the truth-based  
 2603 isolation reduces the expected events by a factor of approximately 4. However, the statistics in the  
 2604 13 TeV truth-level sample are low, and it is therefore difficult to measure precisely how much the  
 2605 truth-based isolation overperforms.

2606 **B.1.3 Loose isolation working point**

2607 As another check on the truth-based isolation, a second isolation working point was constructed  
 2608 to match the official ATLAS Fixed Cut Loose isolation working point. The definition of this loose  
 2609 isolation are found in Table B.3.

2610 The primary impact of loosening the isolation is a substantial increase in the non-prompt back-  
 2611 round from top processes, and a moderate increase in the charge mis-ID and fake backgrounds.  
 2612 Backgrounds from prompt leptons only did not see major changes. As a result, the tight working  
 2613 point is chosen for the analysis. The event yields by sample and by background type using the  
 2614 loose working point are in Table B.4, and Table B.5 has the numbers using the tight working point  
 2615 (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.

2616 **B.2 Plots of other optimization variables**

2617 Plots of the remaining optimization variables not shown in Section 6.5.3 are presented here for  
 2618 reference. Figures B.2, B.3, and B.4 compare signal and background distributions for the default  
 2619 and optimized cuts. None of these cuts change by much in the optimized selection and their impacts  
 2620 on the overall event selection is minimal.

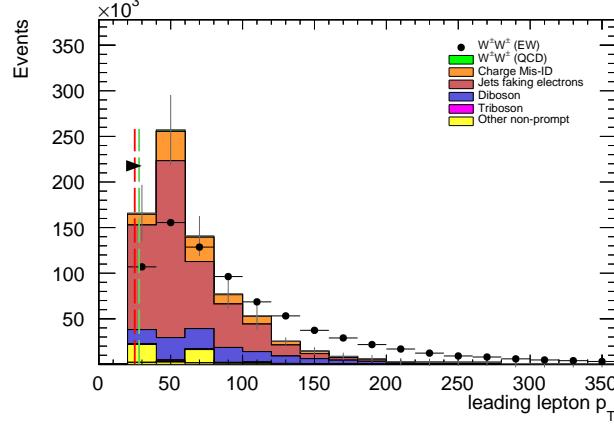


Figure B.2: Leading lepton  $p_T$  distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The  $W^\pm W^\pm jj$  EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

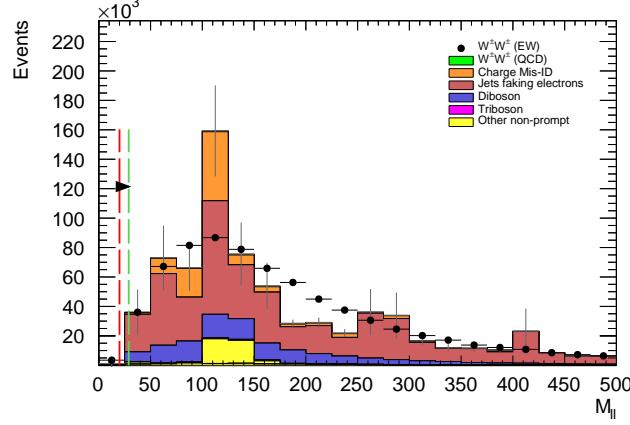


Figure B.3: Dilepton invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The  $W^\pm W^\pm jj$  EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

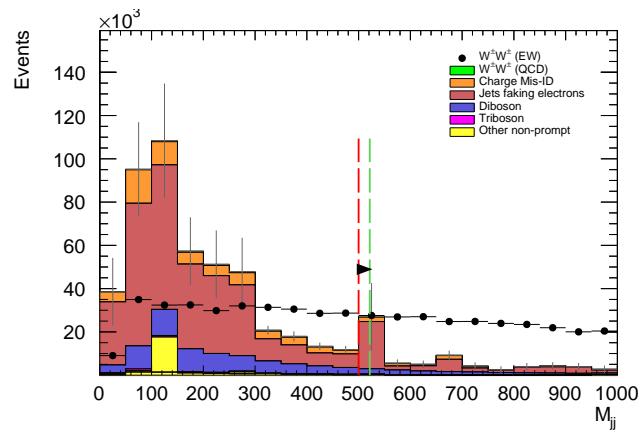


Figure B.4: Dijet invariant mass distribution. The default and optimized cuts are represented by the red and green dashed lines, respectively. The  $W^\pm W^\pm jj$  EWK signal (black points) is normalized to the same area as the sum of the backgrounds (colored histogram).

---

## Bibliography

---

- 2622 [1] ATLAS Collaboration, M. Aaboud et al., *Measurement of the  $W^\pm Z$  boson pair-production*  
 2623 *cross section in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS Detector*, *Phys. Lett.* **B762**  
 2624 (2016) 1–22, arXiv:1606.04017 [hep-ex]. (document)
- 2625 [2] ATLAS Collaboration, *Summary plots from the ATLAS Standard Model physics group*,  
 2626 February, 2019.  
 2627 <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/SM/>. 2.1
- 2628 [3] S. Weinberg, *The Quantum Theory of Fields, Volume 1: Foundations*. Cambridge University  
 2629 Press, 1995. 2.1
- 2630 [4] M. E. Peskin and D. V. Schroeder, *An Introduction to Quantum Field Theory*.  
 2631 Addison-Wesley, 1995. 2.1
- 2632 [5] R. P. Feynman, *Mathematical formulation of the quantum theory of electromagnetic*  
 2633 *interaction*, *Phys. Rev.* **80** (1950) 440–457. 2.1
- 2634 [6] M. Y. Han and Y. Nambu, *Three-triplet model with double SU(3) symmetry*, *Phys. Rev.* **139**  
 2635 (1965) B1006–B1010. 2.1
- 2636 [7] D. J. Gross and F. Wilczek, *Asymptotically Free Gauge Theories - I*, *Phys. Rev.* **D8** (1973)  
 2637 3633–3652. 2.1
- 2638 [8] D. J. Gross and F. Wilczek, *ASYMPTOTICALLY FREE GAUGE THEORIES. 2.*, *Phys.*  
 2639 *Rev.* **D9** (1974) 980–993. 2.1
- 2640 [9] H. D. Politzer, *Reliable Perturbative Results for Strong Interactions?*, *Phys. Rev. Lett.* **30**  
 2641 (1973) 1346–1349. [,274(1973)]. 2.1
- 2642 [10] A. Salam and J. C. Ward, *Weak and Electromagnetic Interactions*, *Nuovo Cimento* **11**  
 2643 (1959) 568–577. 2.1
- 2644 [11] S. L. Glashow, *The Renormalizability of Vector Meson Interactions*, *Nucl. Phys.* **10** (1959)  
 2645 107–117. 2.1
- 2646 [12] ALEPH, DELPHI, L3, OPAL, SLD, LEP Electroweak Working Group, SLD Electroweak  
 2647 Group, SLD Heavy Flavour Group Collaboration, S. Schael et al., *Precision electroweak*

- 2648      *measurements on the  $Z$  resonance*, *Phys. Rept.* **427** (2006) 257–454, [arXiv:hep-ex/0509008](https://arxiv.org/abs/hep-ex/0509008)  
 2649 [hep-ex]. 2.1
- 2650 [13] F. Englert and R. Brout, *Broken symmetry and the mass of gauge vector mesons*, *Phys. Rev. Lett.* **13** (1964) 321–323. 2.1
- 2652 [14] P. W. Higgs, *Broken symmetries, massless particles and gauge fields*, *Physics Letters* **12** (1964) 132–133. 2.1
- 2654 [15] P. W. Higgs, *Broken symmetries and the masses of gauge bosons*, *Phys. Rev. Lett.* **13** (1964) 508–509. 2.1
- 2656 [16] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1, [arXiv:1207.7214](https://arxiv.org/abs/1207.7214) [hep-ex]. 2.1, 5.0.1
- 2659 [17] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30, [arXiv:1207.7235](https://arxiv.org/abs/1207.7235) [hep-ex]. 2.1, 5.0.1
- 2661 [18] UA1 Collaboration, G. Arnison et al., *Experimental Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at  $s^{**}(1/2) = 540\text{-GeV}$* , *Phys. Lett. B* **122** (1983) 103–116. [,611(1983)]. 2.2
- 2664 [19] UA1 Collaboration, G. Arnison et al., *Experimental Observation of Lepton Pairs of Invariant Mass Around  $95\text{-GeV}/c^{**2}$  at the CERN SPS Collider*, *Phys. Lett. B* **126** (1983) 398–410. [,7.55(1983)]. 2.2
- 2667 [20] Particle Data Group Collaboration, K. A. Olive et al., *Review of Particle Physics*, *Chin. Phys. C* **38** (2014) 090001. 2.2, 2.2
- 2669 [21] F. Halzen and A. D. Martin, *Quarks and Leptons: An Introductory Course in Modern Particle Physics*. John Wiley & Sons, 1984. 2.2
- 2671 [22] D. R. Green, P. Meade, and M.-A. Pleier, *Multiboson interactions at the LHC*, *Rev. Mod. Phys.* **89** (2017) no. 3, 035008, [arXiv:1610.07572](https://arxiv.org/abs/1610.07572) [hep-ex]. 2.3
- 2673 [23] H.-J. He and W. B. Kilgore, *The Equivalence theorem and its radiative correction - free formulation for all  $R(xi)$  gauges*, *Phys. Rev. D* **55** (1997) 1515–1532, [arXiv:hep-ph/9609326](https://arxiv.org/abs/hep-ph/9609326) [hep-ph]. 2.3
- 2676 [24] B. W. Lee, C. Quigg, and H. B. Thacker, *The Strength of Weak Interactions at Very High-Energies and the Higgs Boson Mass*, *Phys. Rev. Lett.* **38** (1977) 883–885. 2.3
- 2678 [25] S. D. Rindani, *Strong gauge boson scattering at the LHC*, in *Physics at the Large Hadron Collider*, A. Datta, B. Mukhopadhyaya, A. Raychaudhuri, A. K. Gupta, C. L. Khetrapal, T. Padmanabhan, and M. Vijayan, eds., pp. 145–155. 2009. [arXiv:0910.5068](https://arxiv.org/abs/0910.5068) [hep-ph]. 2.3,
- 2682 [26] V. D. Barger, K.-m. Cheung, T. Han, and R. J. N. Phillips, *Strong  $W^+W^+$  scattering signals at pp supercolliders*, *Phys. Rev. D* **42** (1990) 3052–3077. 2.3
- 2684 [27] G. van den Oord, *Recursion, Monte Carlo and Vector Boson Scattering at Hadron Colliders*. PhD thesis, Nijmegen U., 2012.  
[http://www.nikhef.nl/pub/services/biblio/theses\\_pdf/thesis\\_G\\_v\\_d\\_Oord.pdf](http://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_G_v_d_Oord.pdf). 2.3,  
 2.3

- 2688 [28] A. Alboteanu, W. Kilian, and J. Reuter, *Resonances and Unitarity in Weak Boson*  
2689 *Scattering at the LHC*, **JHEP** **11** (2008) 010, arXiv:0806.4145 [hep-ph]. 2.6
- 2690 [29] L. R. Evans and P. Bryant, *LHC Machine*, **JINST** **3** (2008) S08001.  
2691 <https://cds.cern.ch/record/1129806>. This report is an abridged version of the LHC  
2692 Design Report (CERN-2004-003). 3.1
- 2693 [30] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, **JINST**  
2694 **3** (2008) S08003. 3.1, 3.5
- 2695 [31] ALICE Collaboration, K. Aamodt et al., *The ALICE experiment at the CERN LHC*, **JINST**  
2696 **3** (2008) S08002. 3.1
- 2697 [32] CMS Collaboration, S. Chatrchyan et al., *The CMS Experiment at the CERN LHC*, **JINST**  
2698 **3** (2008) S08004. 3.1
- 2699 [33] LHCb Collaboration, A. A. Alves, Jr. et al., *The LHCb Detector at the LHC*, **JINST** **3**  
2700 (2008) S08005. 3.1
- 2701 [34] CERN, *The accelerator complex*, February, 2019.  
2702 <https://home.cern/science/accelerators/accelerator-complex>. 3.1
- 2703 [35] E. Mobs, *The CERN accelerator complex. Complexe des accrateurs du CERN*, .  
2704 <https://cds.cern.ch/record/2197559>. General Photo. 3.1
- 2705 [36] W. Herr and B. Muratori, *Concept of luminosity*, . <https://cds.cern.ch/record/941318>.  
2706 3.1
- 2707 [37] ATLAS Collaboration, *ATLAS Experiment – Public Results: Luminosity Public Results Run*  
2708 *2*, February, 2019.  
2709 <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2>.  
2710 3.1, 3.2, 3.1, 3.3, 3.4
- 2711 [38] ATLAS Collaboration, *ATLAS inner detector: Technical Design Report*, 1. Technical Design  
2712 Report ATLAS. CERN, Geneva, 1997. <https://cds.cern.ch/record/331063>. 3.2.1
- 2713 [39] ATLAS Collaboration, *ATLAS inner detector: Technical Design Report*, 2. Technical Design  
2714 Report ATLAS. CERN, Geneva, 1997. <https://cds.cern.ch/record/331064>. 3.2.1
- 2715 [40] ATLAS Collaboration, *ATLAS Insertable B-Layer Technical Design Report*, Tech. Rep.  
2716 CERN-LHCC-2010-013. ATLAS-TDR-19, Sep, 2010.  
2717 <https://cds.cern.ch/record/1291633>. 3.2.1.1
- 2718 [41] ATLAS Collaboration, G. Darbo, *Experience on 3D Silicon Sensors for ATLAS IBL*, **JINST**  
2719 **10** (2015) no. 05, C05001, arXiv:1411.6937 [physics.ins-det]. 3.2.1.1
- 2720 [42] E. Stanecka, *ATLAS Inner Tracker Performance at the Beginning of the LHC Run 2*, Tech.  
2721 Rep. ATL-INDET-PROC-2016-002, CERN, Geneva, Apr, 2016.  
2722 <https://cds.cern.ch/record/2147407>. 3.2.1.1
- 2723 [43] ATLAS TRT Collaboration, E. Abat et al., *The ATLAS Transition Radiation Tracker*  
2724 (*TRT*) *proportional drift tube: Design and performance*, **JINST** **3** (2008) P02013. 3.2.1.3
- 2725 [44] ATLAS TRT Collaboration, E. Abat et al., *The ATLAS TRT barrel detector*, **JINST** **3**  
2726 (2008) P02014. 3.2.1.3

- 2727 [45] E. Abat et al., *The ATLAS TRT end-cap detectors*, JINST **3** (2008) P10003. 3.2.1.3
- 2728 [46] ATLAS Collaboration, *ATLAS liquid-argon calorimeter: Technical Design Report*. Technical  
2729 Design Report ATLAS. CERN, Geneva, 1996. <https://cds.cern.ch/record/331061>.  
2730 3.2.2, 3.8
- 2731 [47] ATLAS Collaboration, *ATLAS tile calorimeter: Technical Design Report*. Technical Design  
2732 Report ATLAS. CERN, Geneva, 1996. <https://cds.cern.ch/record/331062>. 3.2.2
- 2733 [48] ATLAS Collaboration, M. Marjanovic, *ATLAS Tile calorimeter calibration and monitoring*  
2734 *systems*, Tech. Rep. arXiv:1806.09156, Jun, 2018. <http://cds.cern.ch/record/2629424>. 8  
2735 pages, 21 figures, IEEE Real Time 2018 proceedings. 3.7
- 2736 [49] ATLAS Collaboration, *ATLAS muon spectrometer: Technical Design Report*. Technical  
2737 Design Report ATLAS. CERN, Geneva, 1997. <https://cds.cern.ch/record/331068>. 3.2.3
- 2738 [50] ATLAS Collaboration, M. Aaboud et al., *Performance of the ATLAS Track Reconstruction*  
2739 *Algorithms in Dense Environments in LHC Run 2*, Eur. Phys. J. **C77** (2017) no. 10, 673,  
2740 arXiv:1704.07983 [hep-ex]. 3.2.4.1
- 2741 [51] R. Fruhwirth, *Application of Kalman filtering to track and vertex fitting*, Nucl. Instrum.  
2742 Meth. **A262** (1987) 444–450. 3.2.4.1
- 2743 [52] T. Cornelissen, M. Elsing, I. Gavrilenco, W. Liebig, E. Moyse, and A. Salzburger, *The new*  
2744 *ATLAS track reconstruction (NEWT)*, J. Phys.: Conf. Ser. **119** (2008) 032014.  
2745 <http://cds.cern.ch/record/1176900>. 3.2.4.1
- 2746 [53] ATLAS Collaboration, *Electron reconstruction and identification in the ATLAS experiment*  
2747 *using the 2015 and 2016 LHC proton-proton collision data at  $\sqrt{s} = 13$  TeV*, Submitted to:  
2748 Eur. Phys. J. (2019) , arXiv:1902.04655 [physics.ins-det]. 3.2.4.2, 3.2.4.2, 3.9, 3.10
- 2749 [54] W. Lampl, S. Laplace, D. Lelas, P. Loch, H. Ma, S. Menke, S. Rajagopalan, D. Rousseau,  
2750 S. Snyder, and G. Unal, *Calorimeter Clustering Algorithms: Description and Performance*,  
2751 Tech. Rep. ATL-LARG-PUB-2008-002. ATL-COM-LARG-2008-003, CERN, Geneva, Apr,  
2752 2008. <https://cds.cern.ch/record/1099735>. 3.2.4.2
- 2753 [55] R. Frhwirth, *A Gaussian-mixture approximation of the BetheHeitler model of electron energy*  
2754 *loss by bremsstrahlung*, Computer Physics Communications **154** (2003) no. 2, 131 – 142.  
2755 <http://www.sciencedirect.com/science/article/pii/S0010465503002923>. 3.2.4.2
- 2756 [56] ATLAS Collaboration, G. Aad et al., *Electron and photon energy calibration with the*  
2757 *ATLAS detector using LHC Run 1 data*, Eur. Phys. J. **C74** (2014) no. 10, 3071,  
2758 arXiv:1407.5063 [hep-ex]. 3.2.4.2
- 2759 [57] ATLAS Collaboration, M. Aaboud et al., *Electron and photon energy calibration with the*  
2760 *ATLAS detector using 2015-2016 LHC proton-proton collision data*, Submitted to: JINST  
2761 (2018) , arXiv:1812.03848 [hep-ex]. 3.2.4.2
- 2762 [58] ATLAS Collaboration, *Electron efficiency measurements with the ATLAS detector using the*  
2763 *2015 LHC proton-proton collision data*, Tech. Rep. ATLAS-CONF-2016-024, CERN,  
2764 Geneva, Jun, 2016. <https://cds.cern.ch/record/2157687>. 3.2.4.2

- 2765 [59] ATLAS Collaboration, G. Aad et al., *Topological cell clustering in the ATLAS calorimeters*  
2766 *and its performance in LHC Run 1*, *Eur. Phys. J.* **C77** (2017) 490, [arXiv:1603.02934](https://arxiv.org/abs/1603.02934)  
2767 [[hep-ex](#)]. 3.2.4.2
- 2768 [60] ATLAS Collaboration, G. Aad et al., *Measurement of the muon reconstruction performance*  
2769 *of the ATLAS detector using 2011 and 2012 LHC protonproton collision data*, *Eur. Phys. J.*  
2770 **C74** (2014) no. 11, 3130, [arXiv:1407.3935](https://arxiv.org/abs/1407.3935) [[hep-ex](#)]. 3.2.4.3
- 2771 [61] ATLAS Collaboration, G. Aad et al., *Muon reconstruction performance of the ATLAS*  
2772 *detector in protonproton collision data at  $\sqrt{s} = 13$  TeV*, *Eur. Phys. J.* **C76** (2016) no. 5, 292,  
2773 [arXiv:1603.05598](https://arxiv.org/abs/1603.05598) [[hep-ex](#)]. 3.2.4.3, 3.12, 5.2.1.1
- 2774 [62] ATLAS Collaboration, *ATLAS Muon Combined Performance with the full 2016 dataset*,  
2775 March, 2017. <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/MUON-2017-001/index.html>. 3.11
- 2777 [63] ATLAS Collaboration, *ATLAS inner detector: Technical Design Report*, Vol. 1. CERN,  
2778 Geneva, 1997. <https://cds.cern.ch/record/331063>. 4
- 2779 [64] P. F. Åkesson, T. Atkinson, M. J. Costa, M. Elsing, S. Fleischmann, A. N. Gaponenko,  
2780 W. Liebig, E. Moyse, A. Salzburger, and M. Siebel, *ATLAS Tracking Event Data Model*,  
2781 Tech. Rep. ATL-SOFT-PUB-2006-004. ATL-COM-SOFT-2006-005.  
2782 CERN-ATL-COM-SOFT-2006-005, CERN, Geneva, Jul, 2006.  
2783 <https://cds.cern.ch/record/973401>. 4.1
- 2784 [65] P. Brückman, A. Hicheur, and S. J. Haywood, *Global chi2 approach to the Alignment of the*  
2785 *ATLAS Silicon Tracking Detectors*, Tech. Rep. ATL-INDET-PUB-2005-002.  
2786 ATL-COM-INDET-2005-004. CERN-ATL-INDET-PUB-2005-002, CERN, Geneva, 2005.  
2787 <https://cds.cern.ch/record/835270>. 4.1, 4.1
- 2788 [66] ATLAS Collaboration, *Alignment of the ATLAS Inner Detector Tracking System with 2010*  
2789 *LHC proton-proton collisions at  $\sqrt{s} = 7$  TeV*, Tech. Rep. ATLAS-CONF-2011-012, CERN,  
2790 Geneva, Mar, 2011. <https://cds.cern.ch/record/1334582>. 4.1, 4.2.3, 4.15
- 2791 [67] R. Härtel and S. Bethke, *Iterative local Chi2 alignment approach for the ATLAS SCT*  
2792 *detector*. PhD thesis, Nov, 2005. <http://cds.cern.ch/record/1511044>. Presented 28 Nov  
2793 2005. 4.1
- 2794 [68] ATLAS Collaboration, P. Brückman de Renstrom, *Alignment strategy for the Inner Detector*  
2795 *of ATLAS*, . <https://cds.cern.ch/record/1047114>. 4.1
- 2796 [69] *Alignment of the ATLAS Inner Detector and its Performance in 2012*, Tech. Rep.  
2797 ATLAS-CONF-2014-047, CERN, Geneva, Jul, 2014.  
2798 <https://cds.cern.ch/record/1741021>. 4.1, 4.2.1, 4.4
- 2799 [70] J. J. Peña, *Alignment of the ATLAS Inner Detector Upgraded for the LHC Run II*, *J. Phys.*  
2800 *Conf. Ser.* **664** (2015) no. 7, 072025. 4.1
- 2801 [71] J. Alison and I. J. Kroll, *The Road to Discovery: Detector Alignment, Electron Identification,*  
2802 *Particle Misidentification, WW Physics, and the Discovery of the Higgs Boson*. PhD thesis,  
2803 Dec, 2015. <https://cds.cern.ch/record/1536507>. Presented 08 Nov 2012. 10

- 2804 [72] *ATLAS Inner Detector Alignment Performance with February 2015 Cosmic Rays Data*,  
 2805 Tech. Rep. ATL-PHYS-PUB-2015-009, CERN, Geneva, Apr, 2015.  
 2806 <https://cds.cern.ch/record/2008724>. 4.3, 4.2
- 2807 [73] *Alignment of the ATLAS Inner Detector with the initial LHC data at  $\sqrt{s} = 13$  TeV*, Tech.  
 2808 Rep. ATL-PHYS-PUB-2015-031, CERN, Geneva, Jul, 2015.  
 2809 <https://cds.cern.ch/record/2038139>. 4.2
- 2810 [74] *Study of the mechanical stability of the ATLAS Insertable B-Layer*, Tech. Rep.  
 2811 ATL-INDET-PUB-2015-001, CERN, Geneva, Jun, 2015.  
 2812 <https://cds.cern.ch/record/2022587>. 4.2.1
- 2813 [75] *Common Framework Implementation for the Track-Based Alignment of the ATLAS  
 2814 Detector*, Tech. Rep. ATL-SOFT-PUB-2014-003, CERN, Geneva, Mar, 2014.  
 2815 <https://cds.cern.ch/record/1670354>. 4.2.1
- 2816 [76] ATLAS Collaboration, *Study of alignment-related systematic effects on the ATLAS Inner  
 2817 Detector track reconstruction*, Tech. Rep. ATLAS-CONF-2012-141, CERN, Geneva, Oct,  
 2818 2012. <https://cds.cern.ch/record/1483518>. 4.4, 4.4, 4.4.1.1, 4.4.1.2
- 2819 [77] S. Marti-Garcia, S. Camarda, T. Golling, M. Danninger, N. A. Styles, J. Wollrath, W. K.  
 2820 Di Clemente, S. Henkelmann, J. Jimenez Peña, O. Estrada Pastor, A. K. Morley, H. Oide,  
 2821 A. T. Vermeulen, P. Butti, E. Ricci, F. M. Follega, and R. Iuppa, *Studies of radial  
 2822 distortions of the ATLAS Inner Detector*, Tech. Rep. ATL-COM-INDET-2018-010, CERN,  
 2823 Geneva, Mar, 2018. <https://cds.cern.ch/record/2306724>. 4.4
- 2824 [78] ATLAS Collaboration, *Electron and photon energy calibration with the ATLAS detector  
 2825 using data collected in 2015 at  $\sqrt{s} = 13$  TeV*, Tech. Rep. ATL-PHYS-PUB-2016-015, CERN,  
 2826 Geneva, Aug, 2016. <https://cds.cern.ch/record/2203514>. 4.4.1
- 2827 [79] ATLAS Collaboration, ATLAS Collaboration, *Evidence for Electroweak Production  
 2828 of  $W^\pm W^\pm jj$  in  $pp$  Collisions at  $\sqrt{s} = 8$  TeV with the ATLAS Detector*, *Phys. Rev. Lett.*  
 2829 **113** (2014) no. 14, 141803, arXiv:1405.6241 [hep-ex]. 5
- 2830 [80] CMS Collaboration, V. Khachatryan et al., *Study of vector boson scattering and search for  
 2831 new physics in events with two same-sign leptons and two jets*, *Phys. Rev. Lett.* **114** (2015)  
 2832 no. 5, 051801, arXiv:1410.6315 [hep-ex]. 5
- 2833 [81] ATLAS Collaboration, *Observation of electroweak production of a same-sign  $W$  boson pair in  
 2834 association with two jets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, Tech.  
 2835 Rep. ATLAS-CONF-2018-030, CERN, Geneva, Jul, 2018.  
 2836 <https://cds.cern.ch/record/2629411>. 5, 5.7, 6.6.2
- 2837 [82] CMS Collaboration, CMS Collaboration, *Observation of electroweak production of same-sign  
 2838  $W$  boson pairs in the two jet and two same-sign lepton final state in proton-proton collisions  
 2839 at  $\sqrt{s} = 13$  TeV*, arXiv:1709.05822 [hep-ex]. 5
- 2840 [83] C. Bittrich, W. K. Di Clemente, et al., *Support note for measurement of electroweak  
 2841  $W^\pm W^\pm jj$  production at  $\sqrt{s} = 13$  TeV*, Tech. Rep. ATL-COM-PHYS-2018-252, CERN,  
 2842 Geneva, Mar, 2018. <https://cds.cern.ch/record/2309552>. 5, 5.3.3, 2, 4, 5.4.3
- 2843 [84] J. M. Campbell and R. K. Ellis, *Higgs Constraints from Vector Boson Fusion and  
 2844 Scattering*, *JHEP* **04** (2015) 030, arXiv:1502.02990 [hep-ph]. 5.0.1, 5.0.2

- 2845 [85] M. Szleper, *The Higgs boson and the physics of WW scattering before and after Higgs*  
 2846 *discovery*, arXiv:1412.8367 [hep-ph]. 5.0.1
- 2847 [86] E. Accomando, A. Ballestrero, A. Belhouari, and E. Maina, *Isolating Vector Boson Scattering*  
 2848 *at the LHC: Gauge cancellations and the Equivalent Vector Boson Approximation vs*  
 2849 *complete calculations*, Phys. Rev. **D74** (2006) 073010, arXiv:hep-ph/0608019 [hep-ph]. 5.0.1
- 2850 [87] C. Gumpert, M. Kobel, B. Heinemann, and U. Klein, *Measurement of Electroweak Gauge*  
 2851 *Boson Scattering in the Channel  $pp \rightarrow W^\pm W^\pm jj$  with the ATLAS Detector at the Large*  
 2852 *Hadron Collider*. PhD thesis, Dec, 2014. <https://cds.cern.ch/record/2003240>.  
 2853 Presented 27 Feb 2015. 5.0.2, 5.1
- 2854 [88] B. Jager, L. Salfelder, M. Worek, and D. Zeppenfeld, *Physics opportunities for vector-boson*  
 2855 *scattering at a future 100 TeV hadron collider*, Phys. Rev. **D96** (2017) no. 7, 073008,  
 2856 arXiv:1704.04911 [hep-ph]. 5.6
- 2857 [89] J. Almond, L. Bianchini, et al., *Search for heavy neutrino,  $W_R$  and  $Z_R$  gauge bosons in*  
 2858 *events with two high- $P_T$  leptons and jets with the ATLAS detector in pp collisions at  $\sqrt{s} = 8$*   
 2859 *TeV*, Tech. Rep. ATL-COM-PHYS-2013-810, CERN, Geneva, Jun, 2013.  
 2860 <https://cds.cern.ch/record/1555805>. Supporting note for EXOT-2012-24, published as  
 2861 JHEP07 (2015) 162. 5.0.3
- 2862 [90] 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,  
 2863 arXiv:1608.03953 [hep-ex]. 5.1
- 2864 [91] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in*  
 2865 *ATLAS*, JINST **13** (2018) no. 07, P07017. 5.1
- 2866 [92] ATLAS Collaboration, G. Aad et al., *The ATLAS Simulation Infrastructure*, Eur. Phys. J. **C70** (2010) 823–874, arXiv:1005.4568 [physics.ins-det]. 5.1.1
- 2867 [93] S. Agostinelli et al., *GEANT4 - a simulation toolkit*, Nucl. Instrum. Meth. **A506** (2003)  
 2868 250–303. 5.1.1
- 2869 [94] T. Sjostrand, S. Mrenna, and P. Skands, *A Brief Introduction to PYTHIA 8.1*, Comput.  
 2870 Phys. Commun. **178** (2008) 852–867, arXiv:0710.3820 [hep-ph]. 5.1.1
- 2871 [95] T. Gleisberg et al., *Event generation with SHERPA 1.1*, JHEP **02** (2009) 007,  
 2872 arXiv:0811.4622 [hep-ph]. 5.1.1
- 2873 [96] S. Schumann and F. Krauss, *A parton shower algorithm based on Catani-Seymour dipole*  
 2874 *factorization*, JHEP **03** (2008) 038, arXiv:0709.1027 [hep-ph]. 5.1.1
- 2875 [97] S. Höche, F. Krauss, S. Schumann, and F. Siegert, *QCD matrix elements and truncated*  
 2876 *showers*, JHEP **05** (2009) 053, arXiv:0903.1219 [hep-ph]. 5.1.1
- 2877 [98] R. D. Ball et al., *Parton distributions for the LHC Run II*, JHEP **04** (2015) 040,  
 2878 arXiv:1410.8849 [hep-ph]. 5.1.1
- 2879 [99] S. Alioli, P. Nason, C. Oleari, and E. Re, *A general framework for implementing NLO*  
 2880 *calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **06** (2010) 043,  
 2881 arXiv:1002.2581 [hep-ph]. 5.1.1

- 2884 [100] A. Ballestrero et al., *Precise predictions for same-sign W-boson scattering at the LHC*, *Eur.*  
 2885 *Phys. J.* **C78** (2018) no. 8, 671, arXiv:1803.07943 [hep-ph]. 5.1.1
- 2886 [101] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao,  
 2887 T. Stelzer, P. Torrielli, and M. Zaro, *The automated computation of tree-level and*  
 2888 *next-to-leading order differential cross sections, and their matching to parton shower*  
 2889 *simulations*, *JHEP* **07** (2014) 079, arXiv:1405.0301 [hep-ph]. 5.1.1
- 2890 [102] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin, and C. P. Yuan, *New*  
 2891 *parton distributions for collider physics*, *Phys. Rev. D* **82** (2010) 074024, arXiv:1007.2241  
 2892 [hep-ph]. 5.1.1
- 2893 [103] T. Sjostrand, S. Mrenna, and P. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006)  
 2894 026, arXiv:0603175 [hep-ph]. 5.1.1
- 2895 [104] M. Cacciari, G. P. Salam, G. Soyez, *The anti- $k_t$  jet clustering algorithm*, *JHEP* **04** (2008)  
 2896 063, arXiv:0802.1189 [hep-ph]. 5.2.1.3
- 2897 [105] ATLAS Collaboration, M. Aaboud et al., *Jet energy scale measurements and their systematic*  
 2898 *uncertainties in proton-proton collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector*, *Phys.*  
 2899 *Rev. D* **96** (2017) no. 7, 072002, arXiv:1703.09665 [hep-ex]. 5.2.1.3
- 2900 [106] *Tagging and suppression of pileup jets with the ATLAS detector*, Tech. Rep.  
 2901 ATLAS-CONF-2014-018, CERN, Geneva, May, 2014.  
 2902 <http://cds.cern.ch/record/1700870>. 5.2.1.3
- 2903 [107] D. Adams, C. Anastopoulos, et al., *Recommendations of the Physics Objects and Analysis*  
 2904 *Harmonisation Study Groups 2014*, Tech. Rep. ATL-PHYS-INT-2014-018, CERN, Geneva,  
 2905 Jul, 2014. <https://cds.cern.ch/record/1743654>. 5.2.1.4
- 2906 [108] ATLAS Collaboration, M. Aaboud et al., *Measurement of the cross-section for producing a*  
 2907 *W boson in association with a single top quark in pp collisions at  $\sqrt{s} = 13$  TeV with ATLAS*,  
 2908 *JHEP* **01** (2018) 063, arXiv:1612.07231 [hep-ex]. 5.2.1.4
- 2909 [109] ATLAS Collaboration, M. Aaboud et al., *Performance of missing transverse momentum*  
 2910 *reconstruction with the ATLAS detector using proton-proton collisions at  $\sqrt{s} = 13$  TeV*,  
 2911 *Eur. Phys. J.* **C78** (2018) no. 11, 903, arXiv:1802.08168 [hep-ex]. 5.2.2
- 2912 [110] ATLAS Collaboration, M. Aaboud et al., *Measurements of b-jet tagging efficiency with the*  
 2913 *ATLAS detector using  $t\bar{t}$  events at  $\sqrt{s} = 13$  TeV*, *JHEP* **08** (2018) 089, arXiv:1805.01845  
 2914 [hep-ex]. 5.2.2
- 2915 [111] J.-F. Arguin, J. Claude, G. Gonella, B. P. Kersevan, K. Koneke, K. Lohwasser,  
 2916 K. Mochizuki, M. Muskinja, C. Piaulet, and P. Sommer, *Support Note for Electron ID:*  
 2917 *charge mis-identification*, Tech. Rep. ATL-COM-PHYS-2017-1014, CERN, Geneva, Jul,  
 2918 2017. <https://cds.cern.ch/record/2273365>. 5.3.3
- 2919 [112] C.-H. Kom and W. J. Stirling, *Charge asymmetry in  $W + \text{jets}$  production at the LHC*, *Eur.*  
 2920 *Phys. J.* **C69** (2010) 67–73, arXiv:1004.3404 [hep-ph]. 5.4
- 2921 [113] R. Steerenberg, *LHC Report: Another run is over and LS2 has just begun...*,  
 2922 [https://home.cern/news/news/accelerators/](https://home.cern/news/news/accelerators/lhc-report-another-run-over-and-ls2-has-just-begun)  
 2923 [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

- 2924 [114] *Letter of Intent for the Phase-I Upgrade of the ATLAS Experiment*, Tech. Rep.  
2925 CERN-LHCC-2011-012. LHCC-I-020, CERN, Geneva, Nov, 2011.  
2926 <http://cds.cern.ch/record/1402470>. 6
- 2927 [115] G. Apollinari, I. Bjar Alonso, O. Brning, M. Lamont, and L. Rossi, *High-Luminosity Large*  
2928 *Hadron Collider (HL-LHC): Preliminary Design Report*. CERN Yellow Reports:  
2929 Monographs. CERN, Geneva, 2015. <https://cds.cern.ch/record/2116337>. 6
- 2930 [116] ATLAS Collaboration, ATLAS Collaboration, *ATLAS Phase-II Upgrade Scoping Document*,  
2931 Cern-lhcc-2015-020, Geneva, Sep, 2015. <http://cds.cern.ch/record/2055248>. 6
- 2932 [117] D. Espriu and B. Yencho, *Longitudinal WW scattering in light of the “Higgs boson”*  
2933 *discovery*, *Phys. Rev. D* **87** (2013) 055017, arXiv:1212.4158 [hep-ph]. 6, 6.1
- 2934 [118] ATLAS Collaboration, *Prospects for the measurement of the  $W^\pm W^\pm$  scattering cross section*  
2935 *and extraction of the longitudinal scattering component in pp collisions at the*  
2936 *High-Luminosity LHC with the ATLAS experiment*, Tech. Rep. ATL-PHYS-PUB-2018-052,  
2937 CERN, Geneva, Dec, 2018. <http://cds.cern.ch/record/2652447>. 6
- 2938 [119] ATLAS Collaboration, *Studies on the impact of an extended Inner Detector tracker and a*  
2939 *forward muon tagger on  $W^\pm W^\pm$  scattering in pp collisions at the High-Luminosity LHC*  
2940 *with the ATLAS experiment*, Tech. Rep. ATL-PHYS-PUB-2017-023, CERN, Geneva, Dec,  
2941 2017. <https://cds.cern.ch/record/2298958>. 6, 6.4
- 2942 [120] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel,  
2943 C. O. Rasmussen, and P. Z. Skands, *An Introduction to PYTHIA 8.2*, *Comput. Phys.*  
2944 *Commun.* **191** (2015) 159–177, arXiv:1410.3012 [hep-ph]. 6.2
- 2945 [121] ATLAS Collaboration, *Expected performance for an upgraded ATLAS detector at*  
2946 *High-Luminosity LHC*, Tech. Rep. ATL-PHYS-PUB-2016-026, CERN, Geneva, Oct, 2016.  
2947 <http://cds.cern.ch/record/2223839>. 6.3
- 2948 [122] P. C. Bhat, H. B. Prosper, S. Sekmen, and C. Stewart, *Optimizing Event Selection with the*  
2949 *Random Grid Search*, *Comput. Phys. Commun.* **228** (2018) 245–257, arXiv:1706.09907  
2950 [hep-ph]. 6.5.1
- 2951 [123] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Asymptotic formulae for likelihood-based*  
2952 *tests of new physics*, *Eur. Phys. J.* **C71** (2011) 1554, arXiv:1007.1727 [physics.data-an].  
2953 [Erratum: Eur. Phys. J.C73,2501(2013)]. 6.5.1