



## ATLAS Note

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# 2 WZ + Heavy Flavor Production in pp collisions 3 at $\sqrt{s} = 13$ TeV

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A measurement of the cross-section for production of WZ with an associated heavy flavor jet  
7 is performed using  $140 \text{ fb}^{-1}$  of proton-proton collision data at  $\sqrt{s} = 13$  TeV from the ATLAS  
8 experiment at the LHC. A measurement of the fully leptonic decay mode,  $WZ \rightarrow l\nu ll$ , is  
9 performed. The cross-section of  $WZ + b$  and  $WZ + \text{charm}$  in various fiducial regions is  
10 measured.

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## 60 List of contributions

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|              |   |
|--------------|---|
| Aaron Webb   | Main analyser. Responsible for ntuple production, fits, and note writing. |
| Peter Onyisi | Advisor to Aaron Webb. Analysis design and implementation strategy.       |

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63 **1 Changes and outstanding items**

64 **1.1 Changelog**

65 This is version 11

66 **1.1.1 Changes relative to v10**

- 67 • Included Zjets plots with lep Pt, eta split by flavor  
68 • Clarified the text on a few points regarding systematics, results  
69 • Fixed an outdated yield table, combined rare top with ttbar  
70 • resolved a high Vgamma uncertainty caused by a single large weight event  
71 • included correlation plots for the tZ BDT inputs

72 **1.1.2 Changes relative to v9**

- 73 • Reordered note to put fiducial region definition in the intro, tZ BDT before the event  
74 selection  
75 • moved alternative fit strategies from the appendix into the main text of the note  
76 • removed correlation matrix plot from results  
77 • added c/light rejection rates for each DL1r WP  
78 • updated OR procedure - previously had an outdated algorithm  
79 • Updated results section to include latest fits, table summarizing results  
80 • Replaced correlation table with a plot

81 **1.1.3 Changes relative to v8**

- 82 • Included more references to appendices in the text  
83 • Expanded explanation of fiducial region definition  
84 • Previous draft claimed that both standard and custom PLVs were used. Text is fixed to  
85 state that a custom PLV is used for lepton iso, but standard lepton id is used  
86 • Included plots of PLV output, included WPs used  
87 • specified that non-prompt CR plots are post correction

- 88        • changed title of results section

89 **1.1.4 Changes relative to v7**

- 90        • Moved from LO to NLO tZ sample  
91        • Add additional plots of Z+jets and ttbar CRs in Section A.2  
92        • Clarified CDI file used, MC ptag, PFlow jet algorithm  
93        • Included overlap removal procedure  
94        • Included details on PLV  
95        • Added plots of missing tZ BDT input features for each fit region  
96        • Changed reference on PLV to recent ttH/ttW note  
97        • Included alternate fits with WZ+1-2 jet inclusive, tZ floating

98 **1.1.5 Changes relative to v5**

- 99        • added list of DSIDs to an appendix  
100        • included systematics on jet migrations  
101        • Updated results section to include simultaneous fit over 1-jet and 2-jet bins, describe  
102        unfolding procedure  
103        • Updated other sections to account for this change  
104        • Included info about migrations in Section 5.2

105 **1.1.6 Changes relative to v4**

- 106        • Fixed various typos, clarified wording  
107        • Expanded info about JER uncertainties, electron systematics, theory uncertainties  
108        • removed a table on lepton selection, included information in the text instead  
109        • Plotted lepton Pt Z and W for Zjet CR, rather than lep 1 and 2  
110        • fixed binning in kinematic plots  
111        • Included prefit and postfit yield tables  
112        • added signal modelling systematics  
113        • included alternate fit studies with tZ included in signal

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114 **1.1.7 Changes relative to v3**

- 115 • Merged introduction into executive summary, including unblinding details and list of
- 116     SRs/CRs used
- 117 • listed ptag used (p4133), and release (AB 21.2.127)
- 118 • Included table reftab:xsecUnc listing x-sec uncertainties used
- 119 • Removed selection criteria listed in table ?? (QMisID, AmbiguityType) that were removed
- 120     from the analysis
- 121 • specified variable used to make truth jet flavor determination (HadronConeExclTruthLa-
- 122     belID)
- 123 • fixed bug in MtLepMet calculation, updated selection/fits to account for this
- 124 • Included plots of MtLepMet and PtZ, swapped lep 1 and 2  $p_T$  plots for lep W and lep Z
- 125     plots
- 126 • updated tZ BDT training to reduce overfitting, updated plots to include error bars, feature
- 127     importance
- 128 • updated table 8 to clarify selection, fix the tZ\_BDT cut used
- 129 • replace a few broken ntuples which included large weight events
- 130 • include DL1r distribution for Z+jets and tt} VRs
- 131 • Expanded section on fakes, included information on derived scale factors from VRs.
- 132 • Changed the kinematic plots to include  $p_T(Z)$  and  $m_T(W)$ , list lepton  $p_T$  based on W and
- 133     Z candidates.

134 **1.1.8 Changes relative to v2**

- 135 • Added alternate VBS samples to include missing b-jet diagrams
- 136 • Included a section on tZ interference effects, ??.
- 137 • Updated to reflect changes for 2018, including the move to PFlow jets, DL1r, updated
- 138     trigger, and updated AnalysisBase version (now 21.2.127)
- 139 • Revised fit regions, using separate 1-jet and 2-jet fits, with all 2-j regions included
- 140 • updated plots for tZ BDT, added details about the model
- 141 • Included truth jet information

<sup>142</sup> **1.1.9 Changes relative to v1**

- <sup>143</sup>     • Added GRL list
- <sup>144</sup>     • Fixed latex issue in line 92, typo in line 172
- <sup>145</sup>     • Added tables [6](#) and [??](#), summarizing the event and object selection
- <sup>146</sup>     • Added table [2](#), which includes the DSID of samples used
- <sup>147</sup>     • Included reference to WZ inclusive paper in introduction

<sup>148</sup> **1.2 Outstanding Items**

- <sup>149</sup>     • Unblind, update plots and fits to include data
- <sup>150</sup>     • Add cross-section, significance once unblinded

## 151 2 Executive Summary

152 The production of WZ in association with a heavy flavor jet represents an important background  
 153 for many major analyses. This includes any process with multiple leptons and b-jets in the final  
 154 state, such as  $t\bar{t}H$ ,  $t\bar{t}W$ , and  $t\bar{t}Z$ . While precise measurements have been made of inclusive WZ  
 155 production [1], WZ + heavy flavor remains poorly understood. This is largely because the QCD  
 156 processes involved in the production of the b-jet make it difficult to simulate accurately. This  
 157 introduces a large uncertainty for analyses that include this process as a background.

158 We perform a study of the fully leptonic decay mode of this channel; that is, events where both  
 159 the W and Z decay leptonically. Because WZ has no associated jets at leading order, while the  
 160 major backgrounds for this channel tend to have high jet multiplicity, events with more than two  
 161 jets are rejected. This gives a final state signature of three leptons and one or two jets.

162 Events that meet a preselection criteria are sorted into regions based on the b-tagging score of  
 163 their associated jets. This is done to separate WZ + b-jet events from WZ + charm and WZ +  
 164 light jets. These regions are fit to data in order to make a more accurate estimate of the contribution  
 165 of WZ + heavy-flavor, where heavy-flavor jets include b-jets and charm jets. The full Run-2  
 166 dataset collected by the ATLAS detector, representing  $139 \text{ fb}^{-1}$  of data from pp collisions at  
 167  $\sqrt{s} = 13 \text{ TeV}$ , is used for this study.

168 The fiducial volume at particle level is defined based on the number of stable leptons and jets in  
 169 each event. Three light leptons with total charge  $\pm 1$  and one or two associated jets are required.  
 170 Only leptons which do not originate from hadron or  $\tau$  decays are considered. The phase space  
 171 definitions use dressed kinematics of the final state particles. Leptons are dressed by summing  
 172 the momentum of photons within a cone of  $\Delta R < 0.1$  of the lepton to correct the leptons energy.  
 173 Particle level jets are reconstructed using the anti- $k_t$  algorithm with a radius of  $R = 0.4$ . The  
 174 kinematic selection applied to these objects is summarized below:

- 175 • Three light leptons with total charge  $\pm 1$ ,  $|\eta| < 2.5$
- 176 • OS lepton with  $p_T > 10 \text{ GeV}$ , SS leptons with  $p_T > 20 \text{ GeV}$
- 177 • One OSSF lepton pair with  $|M(l\bar{l}) - 91.2 \text{ GeV}| < 10 \text{ GeV}$
- 178 • One or two associated truth jets with  $p_T > 25 \text{ GeV}$ ,  $|\eta| < 2.5$ ,  $R < 0.4$

179 The result of the fit is used to extract the cross-section in this fiducial region for WZ + b and  
 180 WZ + c with one associated jet, and WZ + b and WZ + c with two associated jets, where the  
 181 number and flavor of the jets is determined at particle level. Events with both charm and b-jets  
 182 are counted as WZ + b. The analysis reports a cross-section measurement of WZ + b and WZ +  
 183 c, along with their correlations, for both 1-jet and 2-jet exclusive regions. Normalization factors,  
 184 representing how the MC prediction differs from the observed result, are also reported.

185 Section 3 details the data and Monte Carlo (MC) samples used in the analysis. The reconstruction  
 186 of various physics objects is described in Section 4. Section 6 describes the event selection applied  
 187 to these samples, along the definitions of the various regions used in the fit. The multivariate

188 analysis techniques used to separate the tZ background from WZ + heavy flavor are described in  
 189 Section 5. Section 7 describes the various sources of systematic uncertainties considered in the  
 190 fit. Finally, the results of the analysis are summarized in Section 8, followed by a brief conclusion  
 191 in Section 9.

## 192 3 Data and Monte Carlo Samples

193 Both data and Monte Carlo samples used in this analysis were prepared in the `xAOD` format,  
 194 which was used to produce a `DxAOD` sample in the HIGG8D1 derivation framework. The HIGG8D1  
 195 framework is designed for the  $t\bar{t}H$  multi-lepton analysis, which targets events with multiple  
 196 leptons as well as tau hadrons. This framework reduces the size of the dataset by removing  
 197 events based on event topology and only keeping useful information for each event. Events are  
 198 removed from the derivations that do not meet one of the following selections:

- 199 • at least two light leptons within a range  $|\eta| < 2.6$ , with leading lepton  $p_T > 15$  GeV and  
 200 subleading lepton  $p_T > 5$  GeV
- 201 • OR at least one light lepton with  $p_T > 15$  GeV within a range  $|\eta| < 2.6$ , and at least two  
 202 hadronic taus with  $p_T > 15$  GeV.

203 Samples were then generated from these HIGG8D1 derivations with p-tag of p4134 for data  
 204 and p4133 for Monte Carlo using AnalysisBase version 21.2.127 modified to include custom  
 205 variables.

### 206 3.1 Data Samples

207 The study uses a sample of proton-proton collision data collected by the ATLAS detector from  
 208 2015 through 2018 at an energy of  $\sqrt{s} = 13$  TeV, which represents an integrated luminosity of  
 209  $139 \text{ fb}^{-1}$  [2]. This data set was collected with a bunch-crossing rate of 25 ns. All data used in  
 210 this analysis was verified by data quality checks [3], having been included in the following Good  
 211 Run Lists:

- 212 • data15\_13TeV.periodAllYear\_DetStatus-v79-repro20-02\_DQDefects-00-02-02  
 213 \_PHYS\_StandardGRL\_All\_Good\_25ns.xml
- 214 • data16\_13TeV.periodAllYear\_DetStatus-v88-pro20-21\_DQDefects-00-02-04  
 215 \_PHYS\_StandardGRL\_All\_Good\_25ns.xml
- 216 • data17\_13TeV.periodAllYear\_DetStatus-v97-pro21-13\_Uncknown\_PHYS\_StandardGRL  
 217 \_All\_Good\_25ns\_Triggerno17e33prim.xml
- 218 • data18\_13TeV.periodAllYear\_DetStatus-v102-pro22-04\_Uncknown\_PHYS\_StandardGRL  
 219 \_All\_Good\_25ns\_Triggerno17e33prim.xml

220 Runs included from the AllYear period containers are included.

---

**221 3.2 Monte Carlo Samples**

222 Several different generators were used to produce Monte Carlo simulations of the signal and  
 223 background processes. For all samples, the response of the ATLAS detector is simulated using  
 224 **GEANT4** [4]. The WZ signal samples are simulated using **Sherpa 2.2.2** [5]. Signal events are  
 225 generated using NNPDF30NNLO PDF set with up to one parton at NLO and 2 to 3 partons at  
 226 LO [6].

227 The tZ background is simulated at NLO with **MADGRAPH5\_AMC@NLO**, with **PYTHIA8** used to  
 228 perform parton showering and fragmentation. The NNPDF30NNLO PDF set is used.

229 Specific information about the Monte Carlo samples being used can be found in Table 1. A list  
 230 of the specific samples used by data set ID is shown in Table 2.

Table 1: The configurations used for event generation of signal and background processes, including the event generator, matrix element (ME) order, parton shower algorithm, and parton distribution function (PDF).

| Process                         | Event generator           | ME order             | Parton Shower              | PDF                              |
|---------------------------------|---------------------------|----------------------|----------------------------|----------------------------------|
| WZ, VV                          | SHERPA 2.2.2              | MEPS NLO             | SHERPA                     | CT10 [7]                         |
| tZ                              | MG5_AMC [8]               | NLO                  | PYTHIA 8                   | CTEQ6L1                          |
| t̄tW                            | MG5_AMC<br>(SHERPA 2.1.1) | NLO<br>(LO multileg) | PYTHIA 8<br>(SHERPA)       | NNPDF 3.0 NLO<br>(NNPDF 3.0 NLO) |
| t̄t(Z/γ* → ll)                  | MG5_AMC                   | NLO                  | PYTHIA 8                   | NNPDF 3.0 NLO                    |
| t̄tH                            | MG5_AMC<br>(MG5_AMC)      | NLO<br>(NLO)         | PYTHIA 8<br>(HERWIG++) [9] | NNPDF 3.0 NLO [6]<br>(CT10 [7])  |
| tHqb                            | MG5_AMC                   | LO                   | PYTHIA 8                   | CT10                             |
| tHW                             | MG5_AMC<br>(SHERPA 2.1.1) | NLO<br>(LO multileg) | HERWIG++<br>(SHERPA)       | CT10<br>(NNPDF 3.0 NLO)          |
| tWZ                             | MG5_AMC                   | NLO                  | PYTHIA 8                   | NNPDF 2.3 LO                     |
| t̄t, t̄tt̄t                     | MG5_AMC                   | LO                   | PYTHIA 8                   | NNPDF 2.3 LO [10]                |
| t̄tW+W-                         | MG5_AMC                   | LO                   | PYTHIA 8                   | NNPDF 2.3 LO                     |
| t̄t                             | POWHEG-BOX v2 [11]        | NLO                  | PYTHIA 8                   | NNPDF 3.0 NLO                    |
| t̄tγ                            | MG5_AMC                   | LO                   | PYTHIA 8                   | NNPDF 2.3 LO                     |
| s-, t-channel,<br>Wt single top | POWHEG-BOX v1 [12]        | NLO                  | PYTHIA 6                   | CT10                             |
| qqVV, VVV                       |                           |                      |                            |                                  |
| Z → l+l-                        | SHERPA 2.2.1              | MEPS NLO             | SHERPA                     | NNPDF 3.0 NLO                    |

| Sample            | DSID                                      |
|-------------------|---|
| WZ                | 364253, 364739-42                         |
| VV                | 364250, 364254, 364255, 363355-60, 364890 |
| t̄W               | 410155                                    |
| t̄Z               | 410156, 410157, 410218-20                 |
| low mass t̄Z      | 410276-8                                  |
| Rare Top          | 410397, 410398, 410399                    |
| single Top        | 410658-9, 410644-5                        |
| three Top         | 304014                                    |
| four Top          | 410080                                    |
| t̄WW              | 410081                                    |
| Z + jets          | 364100-41                                 |
| low mass Z + jets | 364198-215                                |
| W + jets          | 364156-97                                 |
| Vγ                | 364500-35                                 |
| tZ                | 412063-5                                  |
| tW                | 410013-4                                  |
| WtZ               | 410408                                    |
| VVV               | 364242-9                                  |
| VH                | 342284-5                                  |
| WtH               | 341998                                    |
| t̄tγ              | 410389                                    |
| t̄t               | 410470                                    |
| t̄tH              | 345873-5, 346343-5                        |

Table 2: List of Monte Carlo samples by data set ID used in the analysis.

## 231 4 Object Reconstruction

232 All regions defined in this analysis share a common lepton, jet, and overall event preselection.  
 233 The selection applied to each physics object is detailed here; the event preselection, and the  
 234 selection used to define the various fit regions, is described in Section 6.

### 235 4.1 Trigger

236 Events are required to be selected by dilepton triggers, as summarized in Table 3.

| Dilepton triggers (2015)      |                            |
|-------------------------------|----------------------------|
| $\mu\mu$ (asymm.)             | HLT_mu18_mu8noL1           |
| $ee$ (symm.)                  | HLT_2e12_lhloose_L12EM10VH |
| $e\mu, \mu e$ ( $\sim$ symm.) | HLT_e17_lhloose_mu14       |
| Dilepton triggers (2016)      |                            |
| $\mu\mu$ (asymm.)             | HLT_mu22_mu8noL1           |
| $ee$ (symm.)                  | HLT_2e17_lhvloose_nod0     |
| $e\mu, \mu e$ ( $\sim$ symm.) | HLT_e17_lhloose_nod0_mu14  |
| Dilepton triggers (2017)      |                            |
| $\mu\mu$ (asymm.)             | HLT_mu22_mu8noL1           |
| $ee$ (symm.)                  | HLT_2e24_lhvloose_nod0     |
| $e\mu, \mu e$ ( $\sim$ symm.) | HLT_e17_lhloose_nod0_mu14  |
| Dilepton triggers (2018)      |                            |
| $\mu\mu$ (asymm.)             | HLT_mu22_mu8noL1           |
| $ee$ (symm.)                  | HLT_2e24_lhvloose_nod0     |
| $e\mu, \mu e$ ( $\sim$ symm.) | HLT_e17_lhloose_nod0_mu14  |

Table 3: List of lowest  $p_T$ -threshold, un-prescaled dilepton triggers used for 2015–2018 data taking.

## 4.2 Light leptons

- 238 Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter  
 239 that are associated with charged particle tracks reconstructed in the inner detector [13]. Electron  
 240 candidates are required to have  $p_T > 10$  GeV and  $|\eta_{\text{cluster}}| < 2.47$ . Muon candidates are  
 241 reconstructed by combining inner detector tracks with track segments or full tracks in the muon  
 242 spectrometer [14]. Muon candidates are required to have  $p_T > 10$  GeV and  $|\eta| < 2.5$ . Candidates  
 243 in the transition region between different electromagnetic calorimeter components,  $1.37 <$   
 244  $|\eta_{\text{cluster}}| < 1.52$ , are rejected. A multivariate likelihood discriminant combining shower shape  
 245 and track information is used to distinguish real electrons from hadronic showers (fake electrons).  
 246 To further reduce the non-prompt electron contribution, the track is required to be consistent  
 247 with originating from the primary vertex; requirements are imposed on the transverse impact  
 248 parameter significance ( $|d_0|/\sigma_{d_0} < 5$ ) and the longitudinal impact parameter ( $|\Delta z_0 \sin \theta_\ell| < 0.5$   
 249 mm). Electron candidates are required to pass TightLH identification.
- 250 Muon candidates are reconstructed by combining inner detector tracks with track segments or  
 251 full tracks in the muon spectrometer [14]. Muon candidates are required to have  $p_T > 10$  GeV  
 252 and  $|\eta| < 2.5$ . The longitudinal impact parameter is the same for both electrons and muons, while  
 253 muons are required to pass a slightly tighter transverse impact parameter,  $|d_0|/\sigma_{d_0} < 3$ . Muons  
 254 are also required to pass Medium ID requirements.

255 Leptons are additionally required to pass a non-prompt BDT selection developed by the  $t\bar{t}H$   
256 multilepton/ $t\bar{t}W$  analysis group. This BDT and the WPs used are summarized in Appendix A.1,  
257 and described in detail in [15]. Optimized working points and scale factors for this BDT are  
258 taken from that analysis.

259 **4.3 Jets**

260 Jets are reconstructed from calibrated topological clusters built from energy deposits in the  
261 calorimeters [16], as well as information from the inner tracking detector, using the anti- $k_t$   
262 algorithm with a radius parameter  $R = 0.4$ . Particle Flow, or PFlow, jets are used in the analysis.  
263 Jets with energy contributions likely arising from noise or detector effects are removed from  
264 consideration [17], and only jets satisfying  $p_T > 25$  GeV and  $|\eta| < 2.5$  are used in this analysis.  
265 For jets with  $p_T < 60$  GeV and  $|\eta| < 2.4$ , a jet-track association algorithm is used to confirm  
266 that the jet originates from the selected primary vertex, in order to reject jets arising from pileup  
267 collisions [18].

268 **4.4 B-tagged Jets**

269 In order to make a measurement of  $WZ +$  heavy flavor it is necessary to distinguish these events  
270 from  $WZ +$  light jets. For this purpose, the DL1r b-tagging algorithm is used to distinguish  
271 heavy flavor jets from lighter ones. The DL1r algorithm [19] uses jet kinematics, particularly  
272 jet vertex information, as input for a neural network which assigns each jet a score designed to  
273 reflect how likely that jet is to have originated from a b-quark.

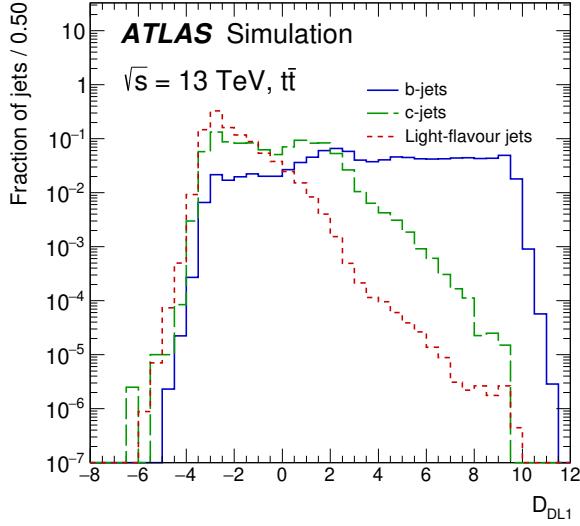


Figure 1: Output distribution of the DL1r algorithm for pure samples of b-jets, charm jets, and light jets, with each normalized to unity [19]

From the output of the BDT, working points (WPs) are developed based on the efficiency of truth b-jets at particular values of the DL1r algorithm. These WPs are taken from the March 2020 CDI file, 2020-21-13TeV-MC16-CDI-2020-03-11\_v2.root. The working points used in this analysis are summarized in Table 4.

| WP  | Rejection  |       |           |
|-----|------------|-------|-----------|
|     | b-jet eff. | c-jet | light jet |
| 85% | 2.6        | 29    |           |
| 77% | 4.9        | 130   |           |
| 70% | 9.4        | 390   |           |
| 60% | 27         | 1300  |           |

Table 4: c-jet and light-flavor jet rejections corresponding to each b-tagging Working Point by b-jet efficiency, evaluated on  $t\bar{t}$  events.

As shown in table 4, a tighter WP will accept fewer b-jets, but reject a higher fraction of charm and light jets. Generally, analyses that include b-jets will use a fixed working point, for example, requiring that a jet pass the 70% threshold. By instead treating these working points as bins, e.g. events with jets that fall between the 85% and 77% WPs fall into one bin, while events with jets passing the 60% WP fall into another, additional information can be gained. This analysis uses each of these working points to form orthogonal regions in order to provide separation between  $WZ + b$ ,  $WZ + c$ , and  $WZ + \text{light}$ .

285 **4.5 Missing transverse energy**

286 Missing transverse momentum ( $E_T^{\text{miss}}$ ) is used as part of the event selection. The missing  
 287 transverse momentum vector is defined as the negative of the vector sum of the transverse  
 288 momenta of all reconstructed physics objects as well as remaining unclustered energy, the latter  
 289 of which is estimated from low- $p_T$  tracks associated with the primary vertex but not assigned  
 290 to a hard object, with object definitions taken from [20]. Light leptons considered in the  $E_T^{\text{miss}}$   
 291 reconstruction are required to have  $p_T > 10 \text{ GeV}$ , while jets are required to have  $p_T > 20 \text{ GeV}$ .

292 **4.6 Overlap removal**

293 To avoid double counting objects and remove leptons originating from decays of hadrons, overlap  
 294 removal is performed in the following order: any electron candidate within  $\Delta R = 0.1$  of another  
 295 electron candidate with higher  $p_T$  is removed; any electron candidate within  $\Delta R = 0.1$  of a muon  
 296 candidate is removed; any jet within  $\Delta R = 0.2$  of an electron candidate is removed; if a muon  
 297 candidate and a jet lie within  $\Delta R = \min(0.4, 0.04 + 10[\text{GeV}]/p_T(\text{muon}))$  of each other, the jet  
 298 is kept and the muon is removed if the jet has at least three associated tracks, otherwise the jet is  
 299 removed and the muon is kept.

300 This algorithm is applied to the preselected objects. The overlap removal procedure is summarized  
 301 in Table 5.

| Keep     | Remove                | Cone size ( $\Delta R$ )   |
|----------|-----------------------|--|
| electron | electron (low $p_T$ ) | 0.1  |
| muon     | electron              | 0.1  |
| electron | jet                   | 0.2  |
| jet      | muon                  | $\min(0.4, 0.04 + 10[\text{GeV}]/p_T(\text{muon}))$ , $n_{\text{track}} > 3$ |
| muon     | jet                   | $\min(0.4, 0.04 + 10[\text{GeV}]/p_T(\text{muon}))$ , $n_{\text{track}} < 3$ |

Table 5: Summary of the overlap removal procedure between electrons, muons, and jets.

302 **5 tZ Separation Multivariate Analysis**

303 Because tZ produces a final state identical to signal, it represents a predominant background in  
 304 the most signal enriched regions. That is, the region with one jet passing the 60% DL1r WP.  
 305 Therefore, a boosted decision tree (BDT) algorithm is trained to separate WZ + heavy flavor  
 306 from tZ.

307 Separation between tZ and WZ + heavy flavor is achieved in part by reconstructing the invariant  
 308 mass of the top candidate, which clusters more closely to the top mass for tZ than WZ + heavy

309 flavor. The result of this BDT is used to create a tZ enriched region in the fit, reducing its impact  
 310 on the measurement of WZ + heavy flavor.

311 **5.1 Top Mass Reconstruction**

312 The reconstruction of the top mass follows the procedure described in detail in section 6.1 of  
 313 [21]. The mass of the top quark candidate is reconstructed from the jet, the lepton not included  
 314 in the Z-candidate, and a reconstructed neutrino. In the case that there is one jet in the event,  
 315 there is only possible b-jet candidate. For events with two jets, the jet with the highest DL1r  
 316 score is used.

317 The neutrino from the W decay is expected to be the only source of  $E_T^{\text{miss}}$ . Therefore, the  $E_T$   
 318 and  $\phi$  of the neutrino are taken from the  $E_T^{\text{miss}}$  measurement. This leaves the z-component of  
 319 the neutrino momentum,  $p_{\nu z}$  as the only unknown.

320 This unknown is solved for by taking the combined invariant mass of the lepton and neutrino to  
 321 give the invariant mass of the W boson:

$$322 \quad (p_l + p_\nu)^2 = m_W^2$$

323 Expanding this out into components, this equation gives:

$$324 \quad \sqrt{p_{T\nu}^2 + p_{z\nu}^2} E_l = \frac{m_W^2 - m_l^2}{2} + p_{T\nu}(p_{lx}\cos\phi_\nu + p_{ly}\sin\phi_\nu) + p_{lz}p_{\nu z}$$

325 This equation gives two solutions for  $p_{\nu z}$ . For cases where only one of these solutions is real,  
 326 that is taken as the value of  $p_{\nu z}$ . For instances with two real solutions, the one which is shown  
 327 to be correct in the largest fraction of simulations is taken. For cases when no real solution is  
 328 found, often because of detector effects, the value of  $E_T^{\text{miss}}$  is varied in decreasing increments of  
 329 100 MeV until a real solution is found.

330 The reconstructed top mass distribution for tZ and WZ + b can be seen in figure 2.

331 **5.2 tZ BDT**

332 A Boosted Decision Tree (BDT), specifically XGBoost [22], is used to provide separation between  
 333 tZ and WZ+b. The following kinematic variables are used as inputs:

- 334 • The invariant mass of the reconstructed top candidate
- 335 •  $p_T$  of each of the leptons, jet
- 336 • The invariant mass of each combination of lepton pairs,  $M(l\bar{l})$

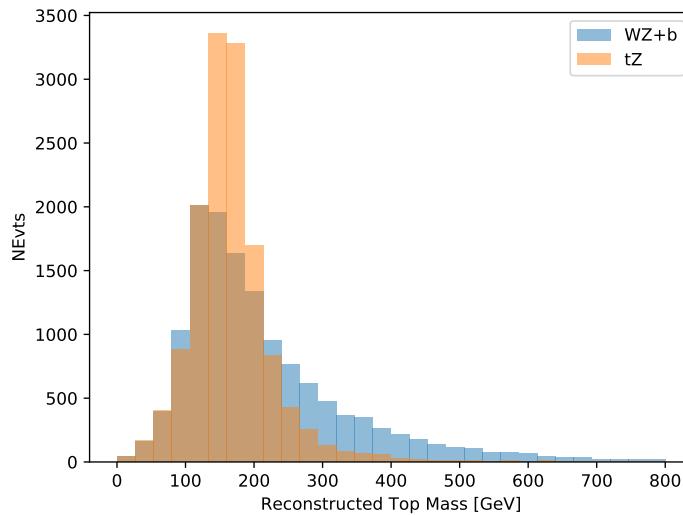


Figure 2: Reconstructed top mass distributions for tZ and WZ + b, measured in MeV.

337 •  $E_T^{\text{miss}}$

338 • Distance between each combination of leptons,  $\Delta R(ll)$

339 • Distance between each lepton and the jet,  $\Delta R(lj)$

340 The training samples included only events meeting the requirements of the 1-jet, 60% b-tag  
 341 region, i.e. passing all the selection described in section 6 and having exactly one jet which  
 342 passes the tightest (60%) DL1r working point.

343 The distributions of a few of these features for both signal and background is shown in figure  
 344 3.

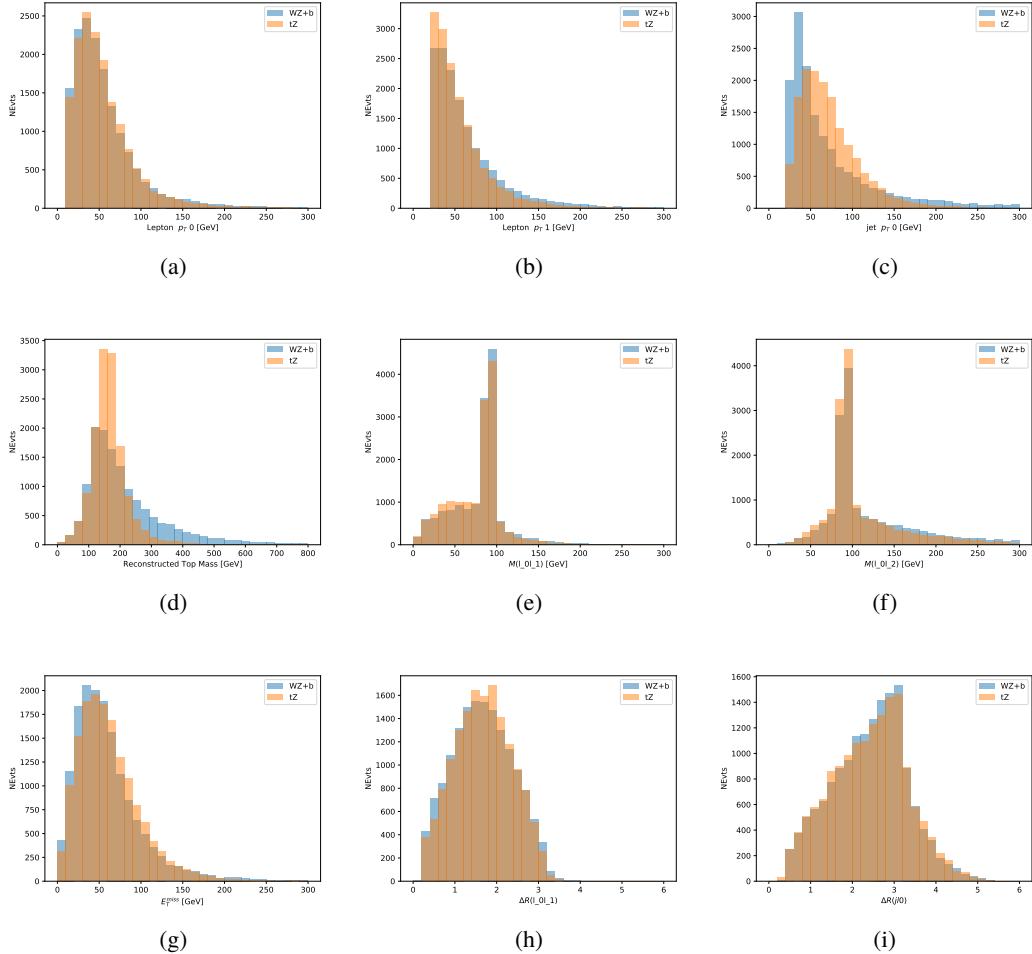


Figure 3: Distribution of input features of the BDT for signal (WZ) and background (tZ). Both are scaled to an equal number of events. (a), (b) and (c) show the  $p_T$  of lepton 0, lepton 1, and the jet, (d) show the reconstructed top mass, (e) and (f) show the invariant mass of leptons 0 and 1, leptons 0 and 2. (g) shows the  $E_T^{\text{miss}}$  of each event. (h) and (i) show the  $\Delta R$  between lepton 0 and lepton 1, and the jet.

345 Correlations between the input features are shown in figure 4.

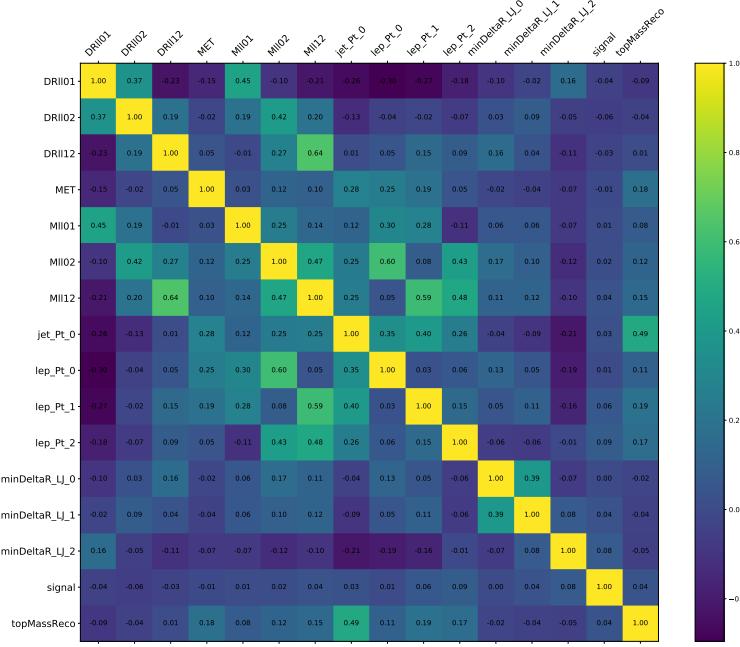


Figure 4: Correlation matrix of the input features of the tZ separation BDT.

346 A sample of 20,000 background (tZ) and signal (WZ+b) Monte Carlo events are used to train  
 347 the BDT. And additional 5,000 events are reserved for testing the model, in order to prevent  
 348 over-fitting. A total of 750 decision trees with a maximum depth of 6 branches are used to build  
 349 the model. These parameters are chosen empirically, by training several models with different  
 350 parameters and selecting the one that gave the best separation for the test sample.

351 The results of the BDT training are shown in figure 5. The output scores for both signal and background events is shown on the left. The right shows the receiving operating characteristic  
 352 (ROC) curve that results from the MVA. The ROC curve represents the background rejection  
 353 as a function of signal efficiency, where each point on the curve represents a different response  
 354 score.  
 355

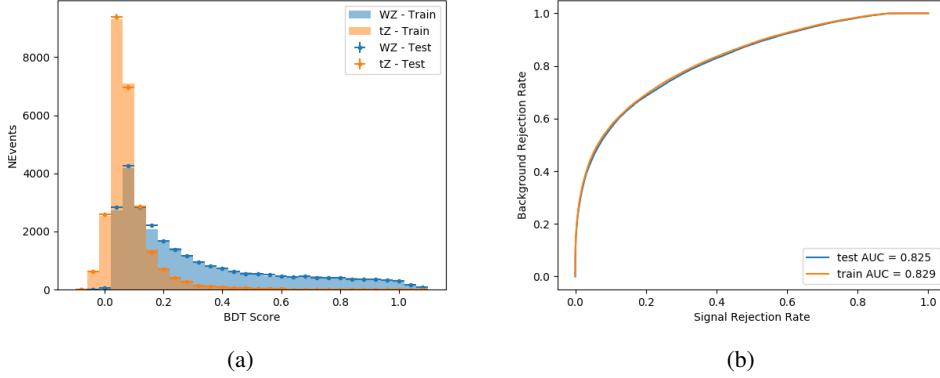


Figure 5: Distribution of the BDT response for signal and background events on the left, the ROC curve for the BDT on the right.

356 The relative important of each input feature in the model, measured by how often they appeared  
 357 in the decision trees, is shown in figure 6.

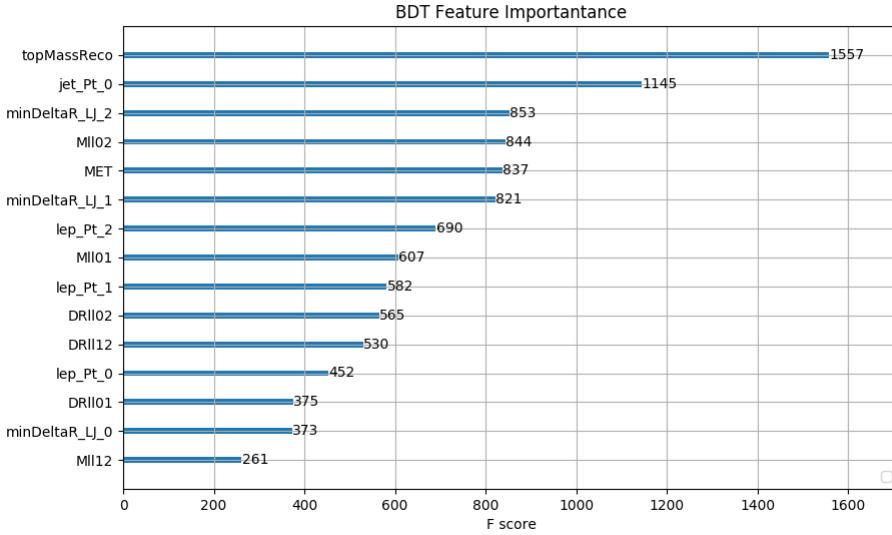


Figure 6: Relative importance of each input feature in the model.

358 These results suggest that some amount of separation can be achieved between these two pro-  
 359 cesses, with a high BDT score selecting a set of events that is pure in WZ + b. A BDT score  
 360 of 0.12 is selected as a cutoff, where events with scores higher than this form a signal enriched  
 361 region, and events with scores lower than this form a tZ control region. This cutoff is selected by

362 varying the value of this cutoff in stat-only Asimov fits, and selecting the value that minimizes  
 363 the statistical uncertainty on WZ + b. A working point of 0.12 produces a background rejection  
 364 rate of 74%, compared to a signal acceptance of 78%.

365 The possibility of using solely the reconstructed top mass shown in Figure 2 to separate tZ  
 366 and WZ + b was considered, and produced the ROC curve shown in Figure 7. This shows  
 367 significantly reduced separation compared to the BDT, justifying the use of the more complex  
 368 BDT in the analysis.

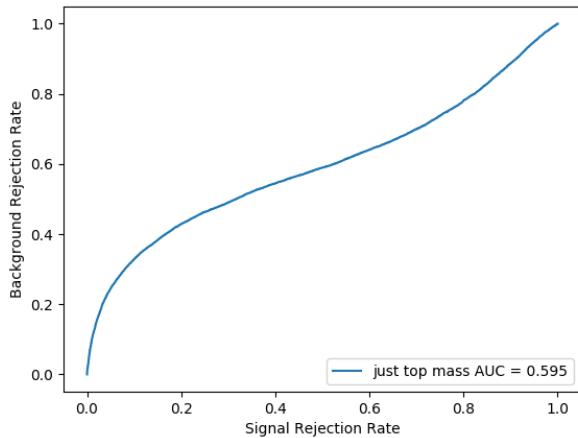


Figure 7: ROC for the separation of tZ and WZ + b produced from the distribution of the reconstructed top mass.

### 369 5.3 tZ Interference Studies

370 Because it includes an on-shell Z boson as well as a b-jet and W from the top decay, tZ  
 371 production represents an identical final state to WZ + b-jet. This implies the possibility of matrix  
 372 level interference between these two processes not accounted for in the Monte Carlo simulations,  
 373 which consider the two processes independently. Truth level studies are performed in order to  
 374 estimate the impact of these interference effects.

375 In order to estimate the matrix level interference effects between tZ and WZ + b-jet, two  
 376 different sets of simulations are produced using MadGraph 5 [23] - one which simulates these  
 377 two processes independently, and another where they are produced simultaneously, such that  
 378 interference effects are present. These two sets of samples are then compared, and the difference  
 379 between them can be taken to represent any interference effects.

380 MadGraph simulations of 10,000 tZ and 10,000 WZ + b-jet events are produced, along with  
 381 20,000 events where both are present, in the fiducial region where three leptons and at least one  
 382 jet are produced.

383 A selection mimicking the preselection used in the main analysis is applied to the samples: The  
384 SS leptons are required to have  $p_T > 20$  GeV, and  $> 10$  GeV is required for the OS lepton. The  
385 associated b-jet is required to have  $p_T > 25$  GeV, and all physics objects are required to fall in a  
386 range of  $|\eta| < 2.5$ .

387 The kinematics of these samples after the selection has been applied are shown below:

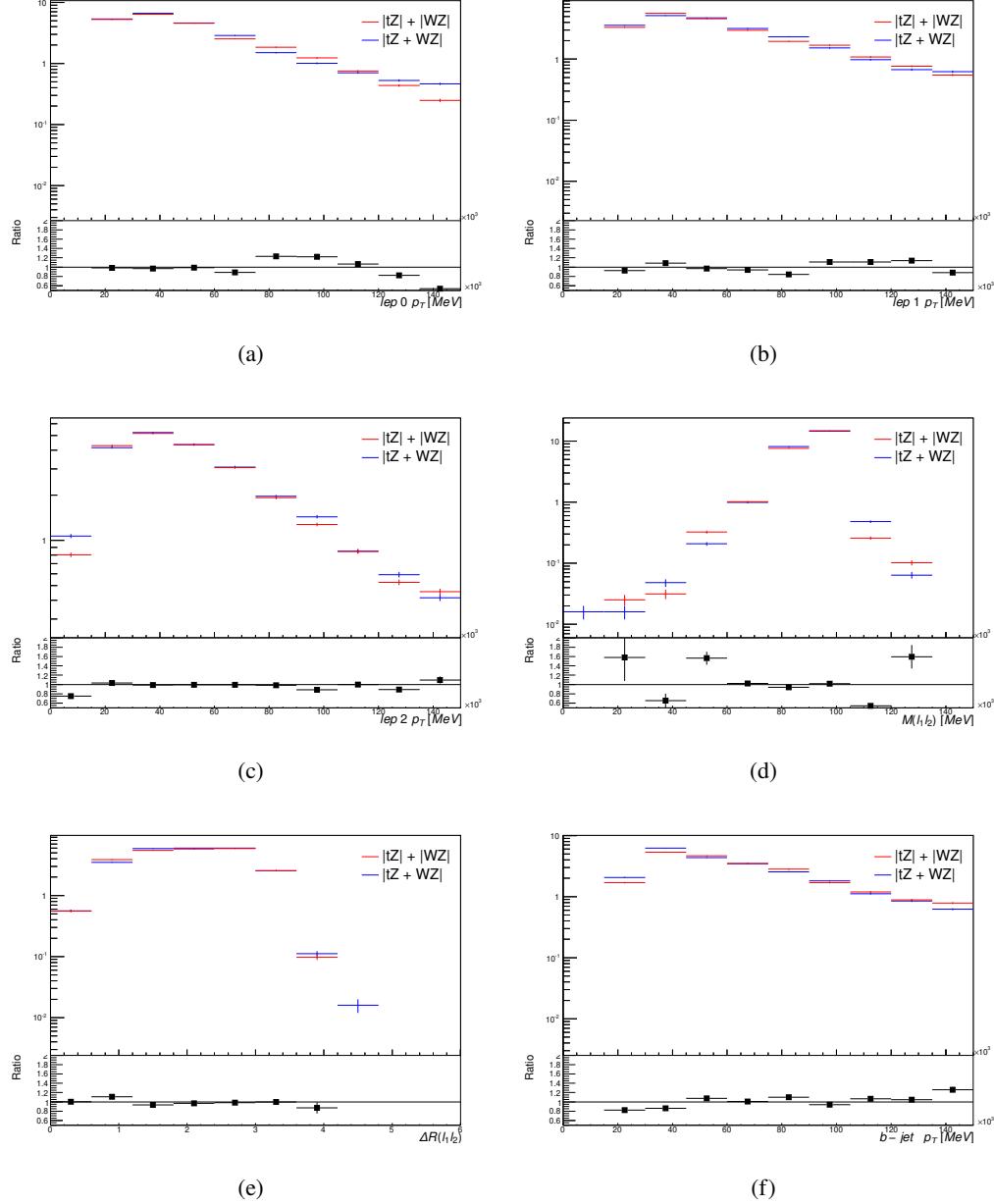


Figure 8: Comparisons between (a) the  $p_T$  of the lepton from the W, (b) and (c) show the  $p_T$  of the lepton from the Z, (d) the invariant mass of the Z-candidate, (e)  $\Delta R$  of the leptons from the Z, and (f) the  $p_T$  of the b-jet, for WZ and tZ events generated with interference effects (blue) and without interference effects (red).

388 The overall cross-section of the two methods agree within error, and no significant differences  
389 in the kinematic distributions are seen. It is therefore concluded that interference effects do not

390 significantly impact the results.

## 391 6 Event Selection and Signal Region Definitions

392 Event are required to pass a preselection described in Section 6.1 and summarized in Table 6.  
 393 Those that pass this preselection are divided into various fit regions described in Section 6.2,  
 394 based on the number of jets in the event, and the b-tag score of those jets.

### 395 6.1 Event Preselection

396 Events are required to include exactly three reconstructed light leptons passing the requirement  
 397 described in 4.2, which have a total charge of  $\pm 1$ .

398 The leptons are ordered in the analysis code as 0, 1, and 2. Lepton 0 is the lepton whose charge  
 399 is opposite the other two. Lepton 1 is the lepton closest to the opposite charge lepton, i.e. the  
 400 smallest  $\Delta R$ , leaving lepton 2 as the lepton further from the opposite charge lepton. Lepton 0 is  
 401 required to have  $p_T > 10$  GeV, as it is found to be prompt the vast majority of the time, while  
 402 the same sign leptons, 1 and 2, are required to have  $p_T > 20$  GeV to reduce the contribution of  
 403 non-prompt leptons, as non-prompt leptons tend to be soft.

404 The invariant mass of at least one pair of opposite sign, same flavor leptons is required to fall  
 405 within 10 GeV of the mass of the Z boson, 91.2 GeV. Events where one of the opposite sign pairs  
 406 has an invariant mass less than 12 GeV are rejected in order to suppress low mass resonances.

407 An additional requirement is placed on the missing transverse energy,  $E_T^{\text{miss}} > 20$  GeV, and the  
 408 transverse mass of the W candidate,  $m(E_T^{\text{miss}} + l_{\text{other}}) > 30$  GeV, defined as

409  $\sqrt{2p_T^{\text{lep}} E_T^{\text{miss}} * (1 - \cos(\phi_{\text{lep}} - \phi_{E_T^{\text{miss}}}))}$ . Here  $E_T^{\text{miss}}$  is the missing transverse energy, and  
 410  $l_{\text{other}}$  is the lepton not included in the Z-candidate.

411 Events are required to have one or two reconstructed jets passing the selection described in  
 412 Section 4.3. Events with more than two jets are rejected in order to reduce the contribution of  
 413 backgrounds such as  $t\bar{t}Z$  and  $t\bar{t}W$ , which tend to have higher jet multiplicity.

| Event Selection   |
|---|
| Exactly three leptons with total charge $\pm 1$   |
| Two same-charge leptons with $p_T > 20$ GeV   |
| One opposite charge lepton with $p_T > 10$ GeV  |
| $m(l^+l^-)$ within 10 GeV of 91.2 GeV   |
| Transverse mass of W-candidate, $\sqrt{2p_T^{lep}E_T^{\text{miss}} * (1 - \cos(\phi_{lep} - \phi_{E_T^{\text{miss}}}))} > 30$ GeV |
| Missing transverse energy, $E_T^{\text{miss}} > 20$ GeV   |
| One or two jets with $p_T > 25$ GeV   |

Table 6: Summary of the selection applied to events for inclusion in the fit

414 The event yields in the preselection region for both data and Monte Carlo are summarized in  
 415 Table 6.1, which shows good agreement between data and Monte Carlo, and demonstrates that  
 416 this region consists primarily of WZ + jets events. The WZ events are split into WZ + b, WZ  
 417 + c, and WZ + l based on the truth flavor of the associated jet in the event. Specifically, this  
 418 determination is made based on the HadronConeExclTruthLabelID of the jet, as recommended  
 419 by the b-tagging working group [24]. In this ordering b-jet supersedes charm, which supersedes  
 420 light. That is, WZ + light events contain no charm and no b jets at truth level, WZ + c contain at  
 421 least one truth charm and no b-jets, and WZ + b contains at least one truth b-jet.

| Process    | Events            |
|------------|-------------------|
| WZ + b     | $143 \pm 43$      |
| WZ + c     | $930 \pm 280$     |
| WZ + l     | $6250 \pm 1900$   |
| Other VV   | $16.6 \pm 4.1$    |
| ZZ         | $460 \pm 55$      |
| t̄W        | $14.8 \pm 2.1$    |
| t̄tZ       | $96 \pm 14$       |
| Single top | $0.1 \pm 0.2$     |
| Three top  | $0.003 \pm 0.002$ |
| Four top   | $0.01 \pm 0.01$   |
| t̄tWW      | $0.20 \pm 0.04$   |
| Z + jets   | $320 \pm 70$      |
| V + γ      | $75 \pm 43$       |
| tZ         | $164 \pm 37$      |
| tW         | $4.9 \pm 1.2$     |
| WtZ        | $21 \pm 11$       |
| VVV        | $23 \pm 11$       |
| VH         | $67 \pm 6$        |
| t̄t        | $84 \pm 9$        |
| t̄tH       | $3.6 \pm 0.4$     |
| Total      | $8700 \pm 2300$   |
| Data       | 8696              |

Table 7: Event yields in the preselection region at  $139.0 \text{ fb}^{-1}$ . Includes the full set of systematic uncertainties

<sup>422</sup> Here Other VV represents diboson processes other than WZ, and consists predominantly of  
<sup>423</sup>  $ZZ \rightarrow ll\bar{l}\bar{l}$  events where one of the leptons is not reconstructed.

<sup>424</sup> Simulations are further validated by comparing the kinematic distributions of the Monte Carlo  
<sup>425</sup> with data, which are shown in Figure 9. Here, bins with 5% or more WZ+b are blinded.

## WZ Fit Region - Inclusive

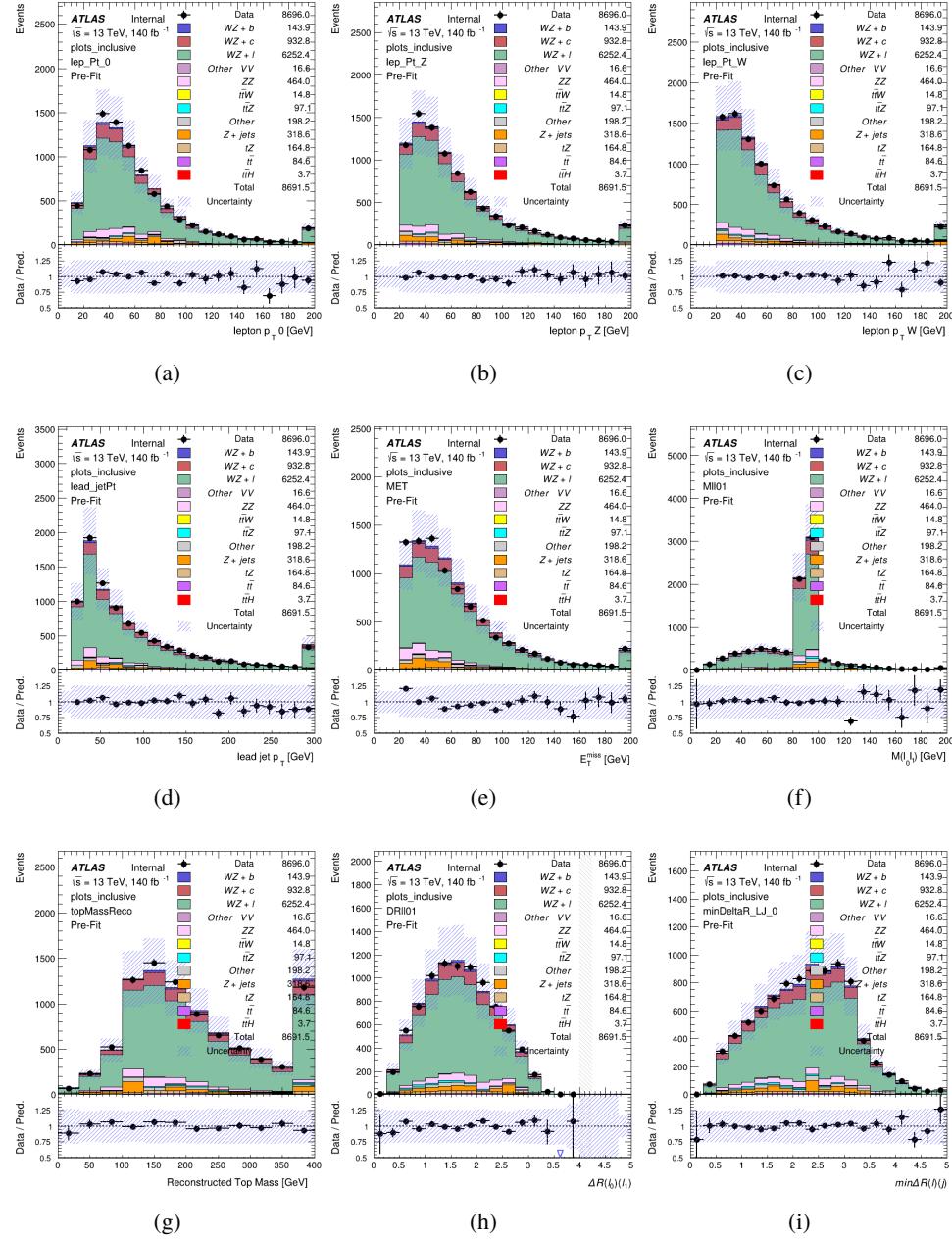


Figure 9: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

426 **6.2 Fit Regions**

427 Once preselection has been applied, the remaining events are categorized into one of twelve  
 428 orthogonal regions. The regions used in the fit are summarized in Table 8.

Table 8: A list of the regions used in the fit and the selection used for each.

| Region      | Selection  |
|-------------|--|
| 1j, <85%    | $N_{\text{jets}} = 1, n_{\text{Jets\_DL1r\_85}} = 0$                                   |
| 1j, 85%-77% | $N_{\text{jets}} = 1, n_{\text{Jets\_DL1r\_85}} = 1, n_{\text{Jets\_DL1r\_77}} = 0$    |
| 1j, 77%-70% | $N_{\text{jets}} = 1, n_{\text{Jets\_DL1r\_77}} = 1, n_{\text{Jets\_DL1r\_70}} = 0$    |
| 1j, 70%-60% | $N_{\text{jets}} = 1, n_{\text{Jets\_DL1r\_70}} = 1, n_{\text{Jets\_DL1r\_60}} = 0$    |
| 1j, 60%     | $N_{\text{jets}} = 1, n_{\text{Jets\_DL1r\_60}} = 1, tZ \text{ BDT} > 0.12$            |
| 1j tZ CR    | $N_{\text{jets}} = 1, n_{\text{Jets\_DL1r\_60}} = 1, tZ \text{ BDT} < 0.12$            |
| 2j, <85%    | $N_{\text{jets}} = 2, n_{\text{Jets\_DL1r\_85}} = 0$                                   |
| 2j, 85%-77% | $N_{\text{jets}} = 2, n_{\text{Jets\_DL1r\_85}} \geq 1, n_{\text{Jets\_DL1r\_77}} = 0$ |
| 2j, 77%-70% | $N_{\text{jets}} = 2, n_{\text{Jets\_DL1r\_77}} \geq 1, n_{\text{Jets\_DL1r\_70}} = 0$ |
| 2j, 70%-60% | $N_{\text{jets}} = 2, n_{\text{Jets\_DL1r\_70}} \geq 1, n_{\text{Jets\_DL1r\_60}} = 0$ |
| 2j, 60%     | $N_{\text{jets}} = 2, n_{\text{Jets\_DL1r\_60}} \geq 1, tZ \text{ BDT} > 0.12$         |
| 2j tZ CR    | $N_{\text{jets}} = 2, n_{\text{Jets\_DL1r\_60}} \geq 1, tZ \text{ BDT} < 0.12$         |

429 The working points discussed in Section 4.4 are used to separate events into fit regions based on  
 430 the highest working point reached by a jet in each event. Because the background composition  
 431 differs significantly based on the number of b-jets, events are further subdivided into 1-jet and  
 432 2-jet regions in order to minimize the impact of background uncertainties.

433 An unfolding procedure is performed to account for differences in the number of reconstructed  
 434 jets compared to the number of truth jets in each event. The `AntiKt4TruthDressedWZJets`  
 435 truth jet collection is used to make this determination. In order to account for migration of  
 436 WZ+1-jet and WZ+2-jet events between the 1-jet and 2-jet bins at reco level, the signal samples  
 437 are separated based on the number of truth jets. Events with 0 jets or more than 3 jets at truth  
 438 level, yet fall within one of the categories listed in Table 8, are categorized as WZ + other, and  
 439 treated as a background. The migration matrix in the number of jets at truth level versus reco  
 440 level is shown in Figure 10. The composition of the number of truth jets in each reco jet bin is  
 441 taken from MC, with uncertainties in these estimates described in detail in Section 7.

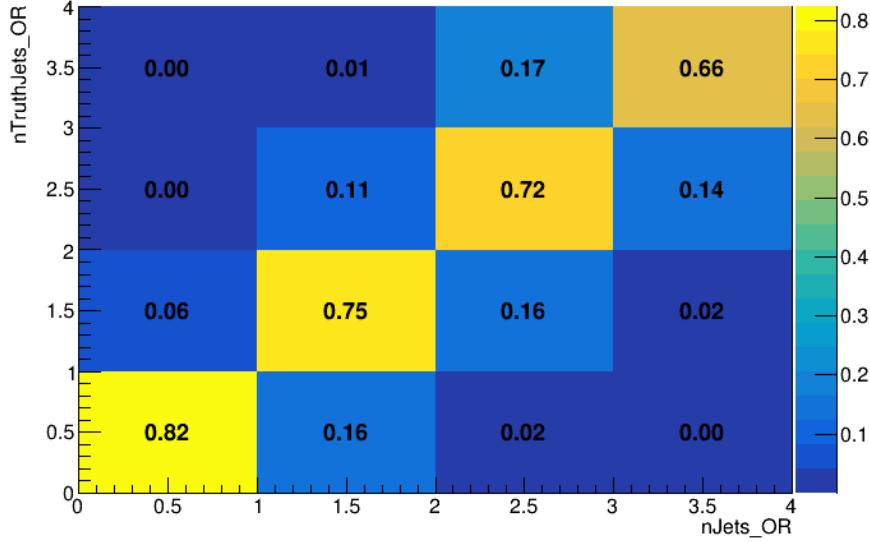


Figure 10: Number of truth jets compared to the number of reconstructed jets in each WZ event falling in the preselection region. Each row is normalized to unity, with overflow bins not shown included in the normalization. That is, each bin represents the absolute fraction of events with a particular truth jet multiplicity that include the corresponding number of reconstructed jets.

An additional tZ control region is created based on the BDT described in Section 5. The region with 1-jet passing the 60% working point is split in two - a signal enriched region of events with a BDT score greater than 0.12, and a tZ control region including events with a score less than 0.12. This cutoff is arrived at by performing a fit an Asimov dataset with a variety of cutoffs, and selecting the value that produces the highest significance for the measurement of WZ + b.

The modeling in each region is validated by comparing data and MC predictions for various kinematic distributions. Events containing 5% or more WZ + b are blinded. These plot are shown in Figures 11-24.

## WZ Fit Region - 1j Inclusive

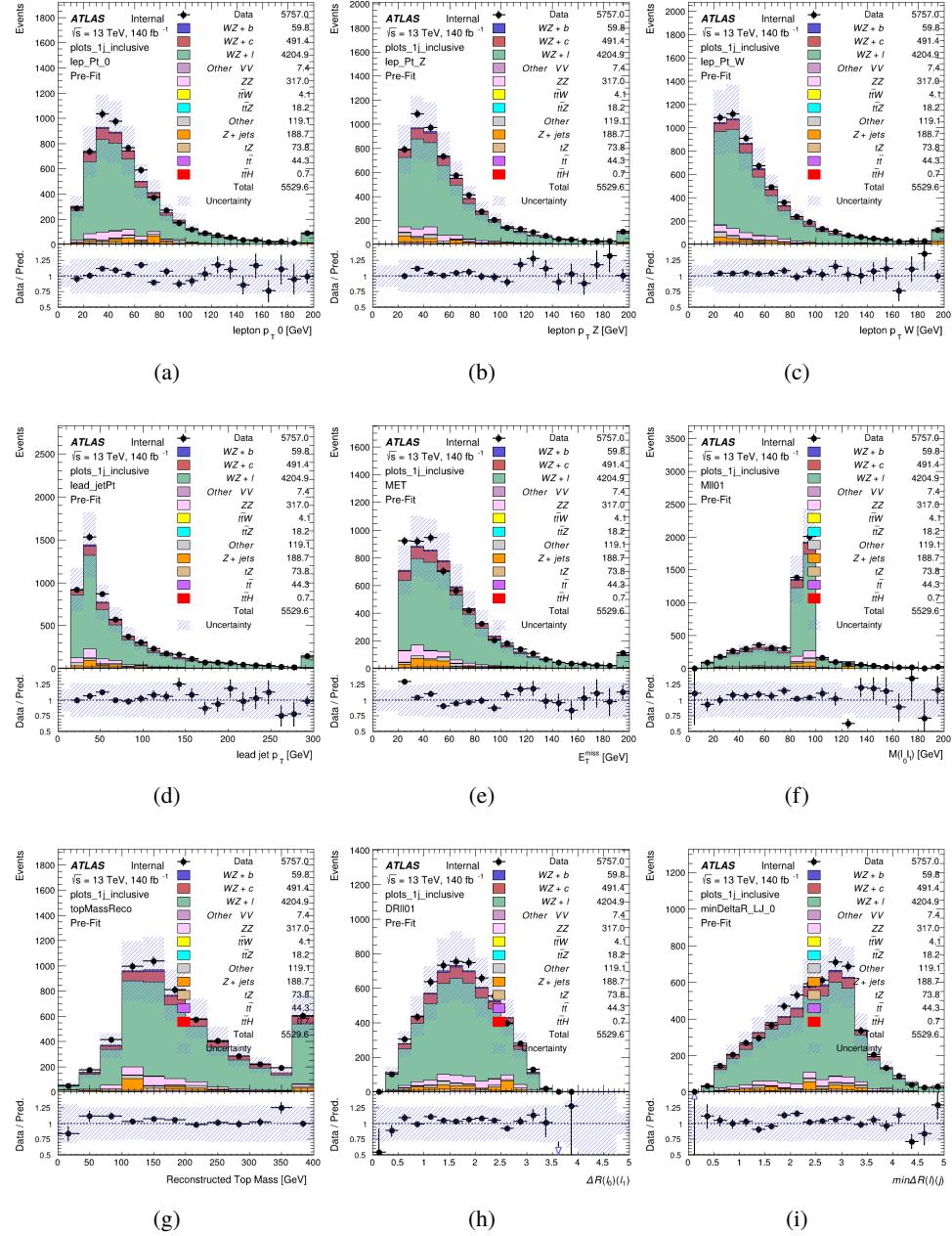


Figure 11: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the  $Z$  candidate, (c) the  $p_T$  of the lepton from the  $W$  candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 1j &lt; 85% WP

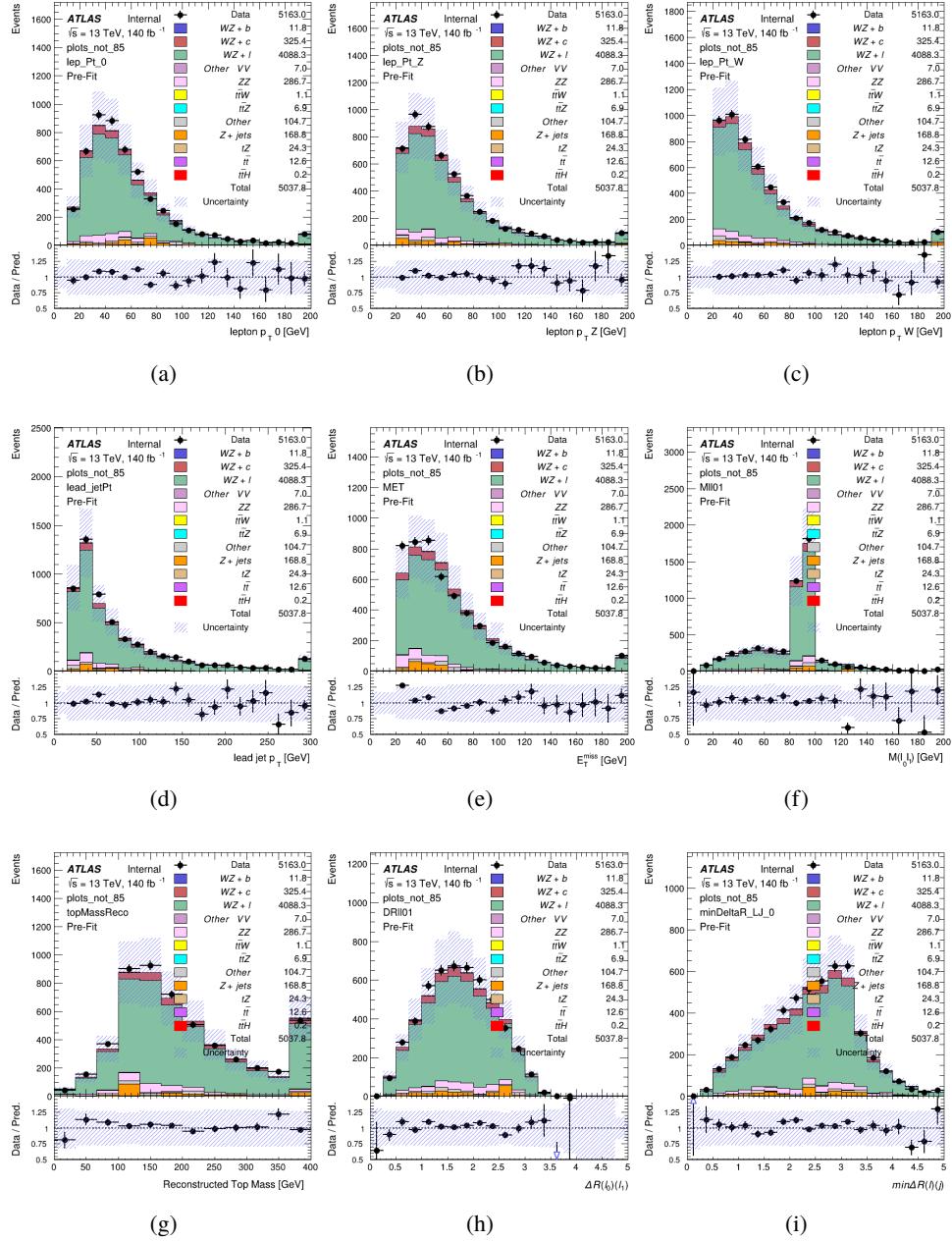


Figure 12: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 1j 77-85% WP

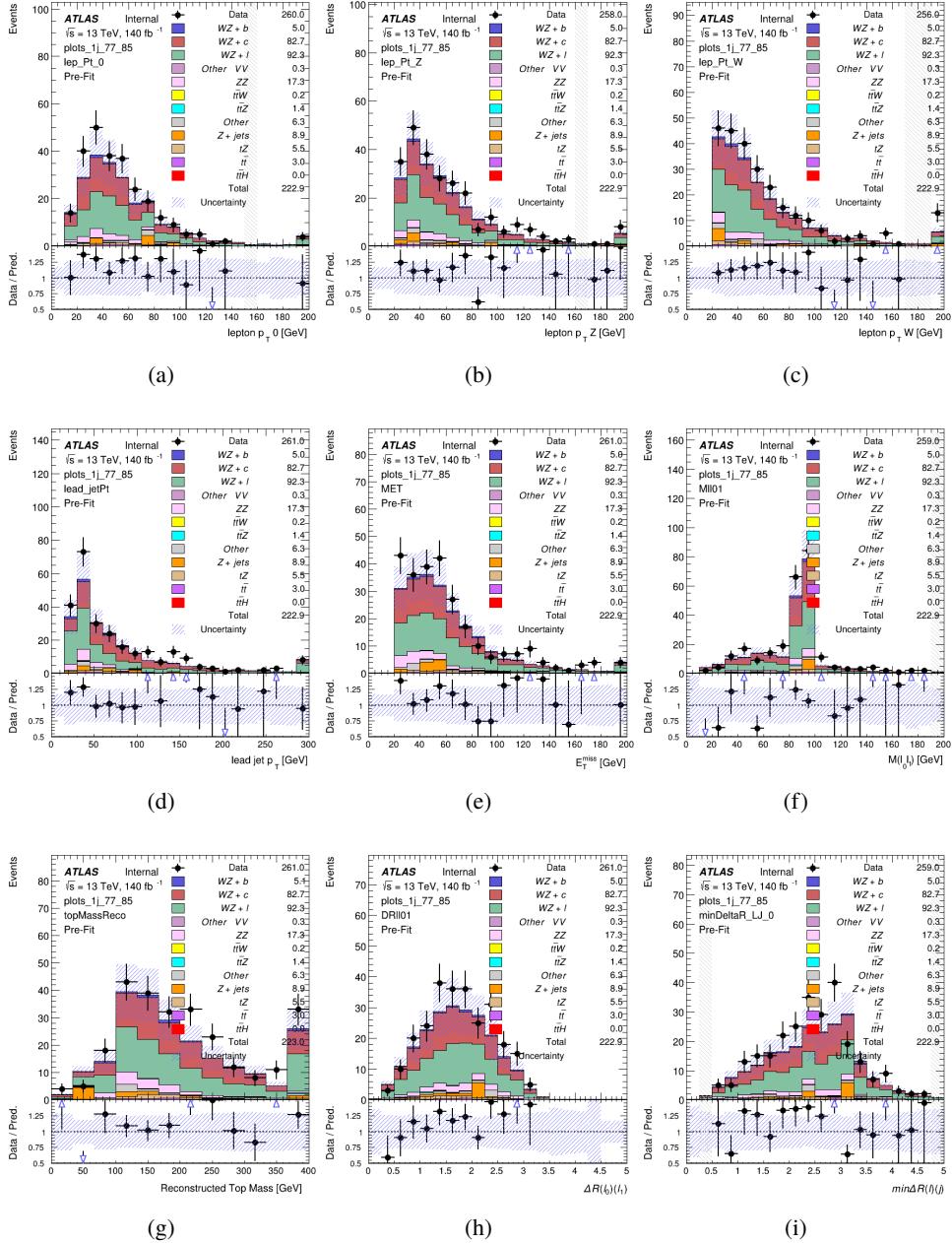


Figure 13: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 1j 70-77% WP

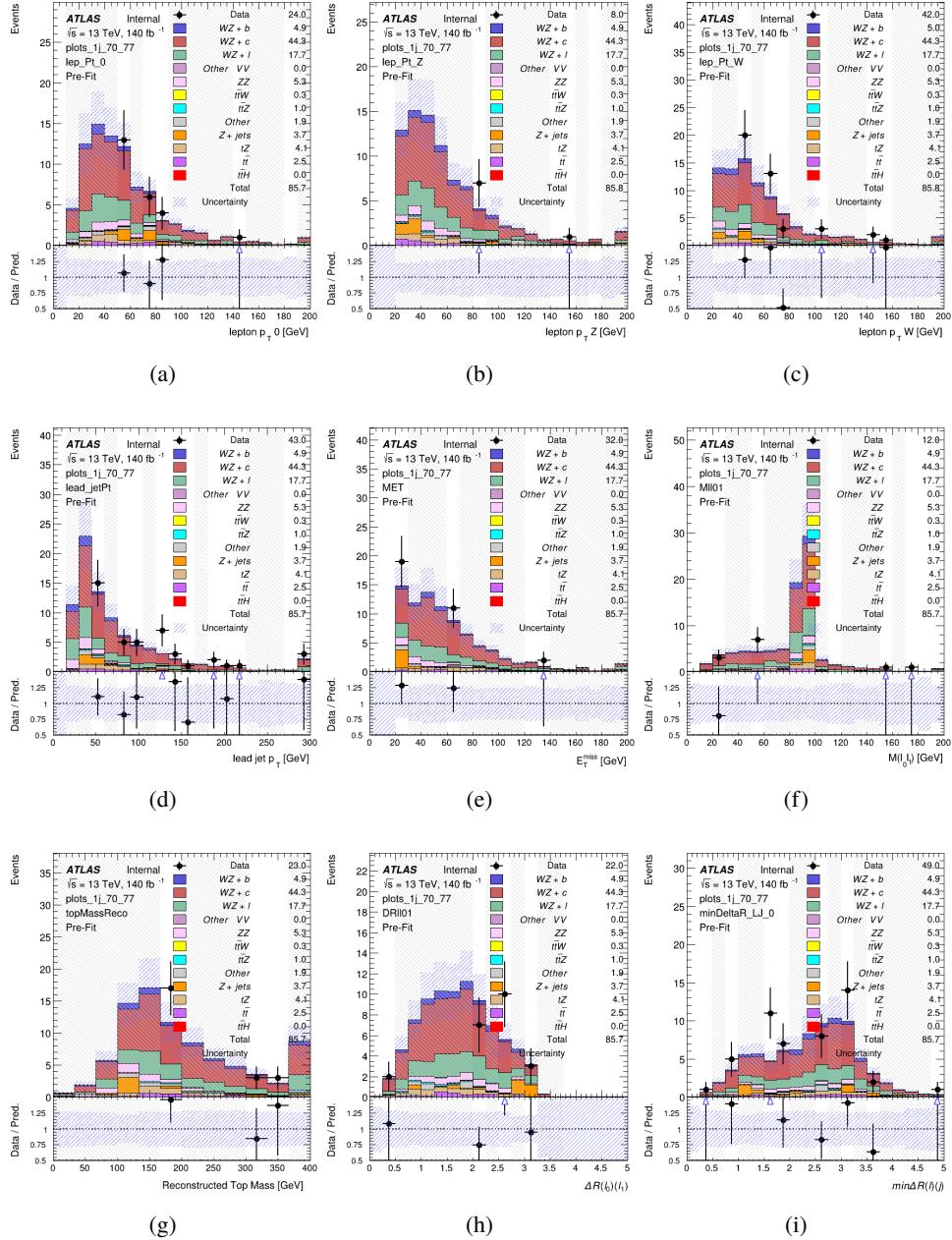


Figure 14: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 1j 60-70% WP

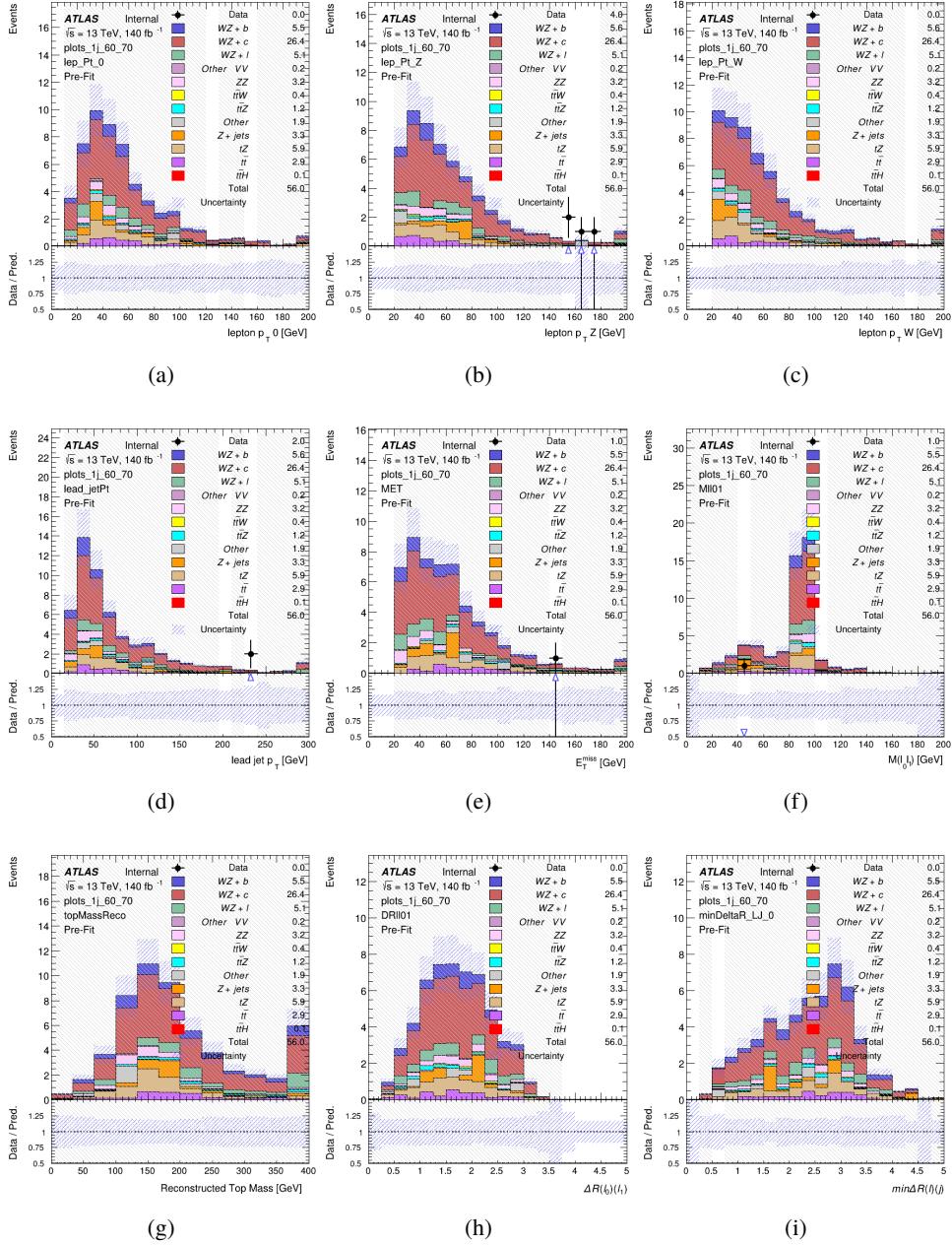


Figure 15: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 1j 60% WP

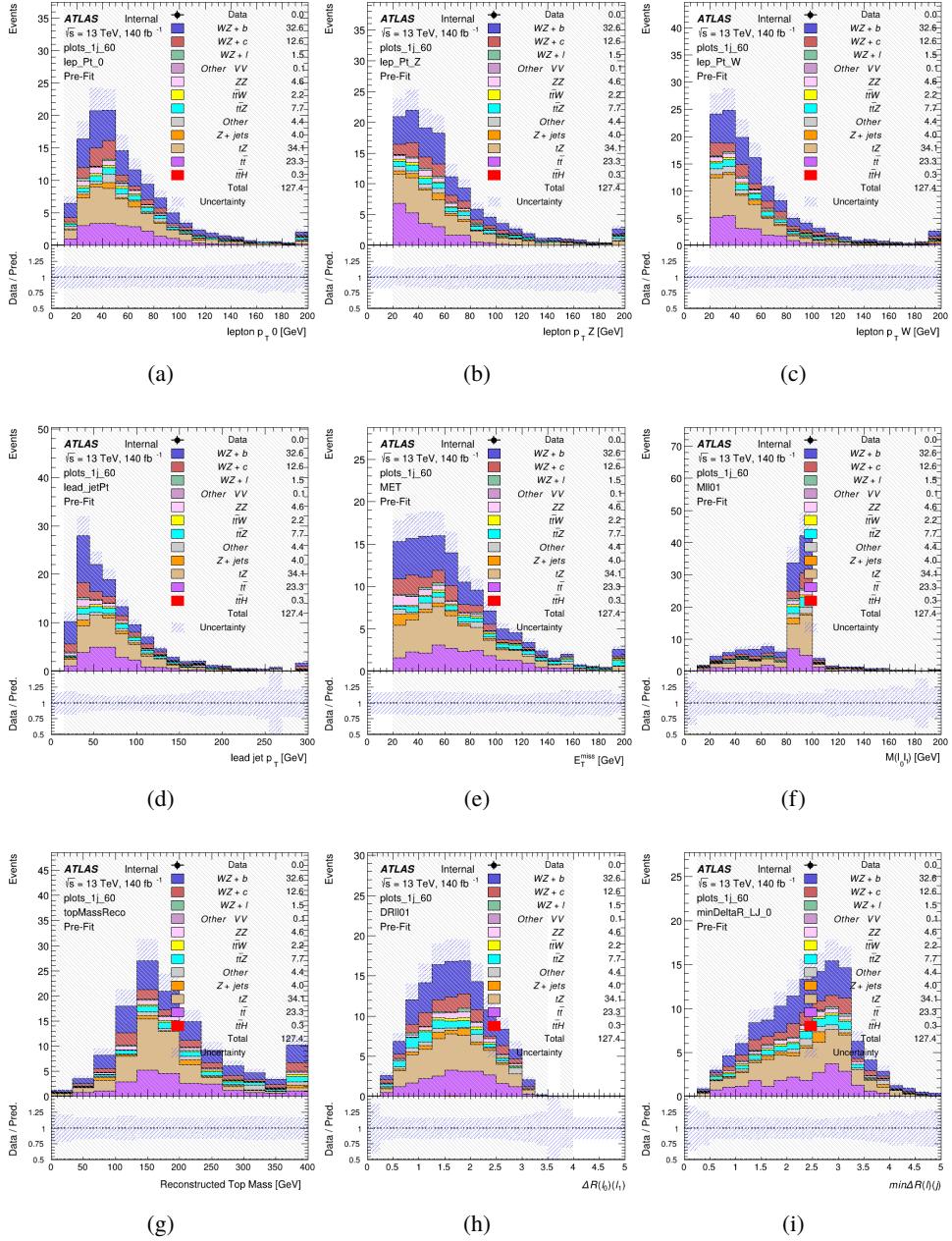


Figure 16: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - tZ-CR

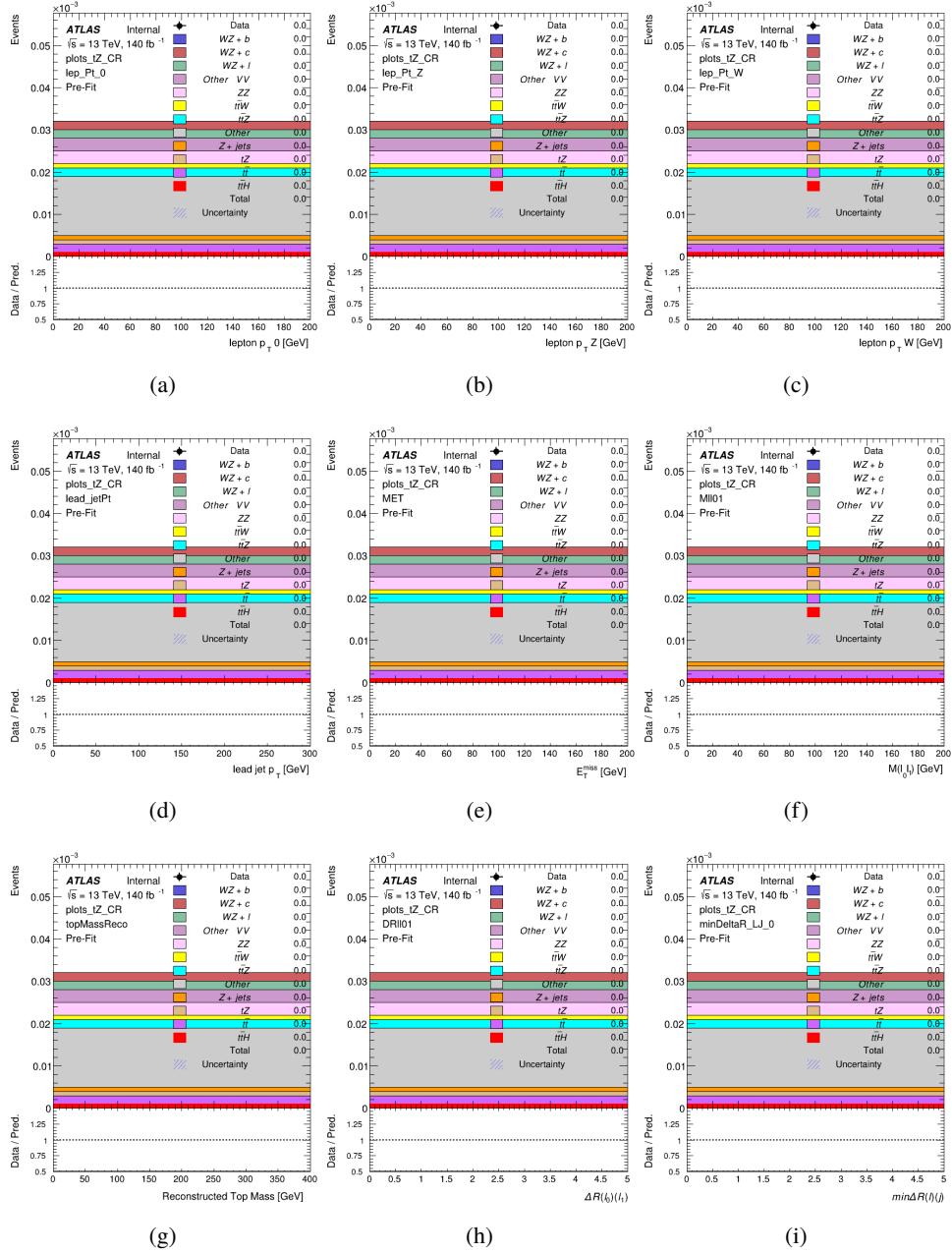


Figure 17: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 2j Inclusive

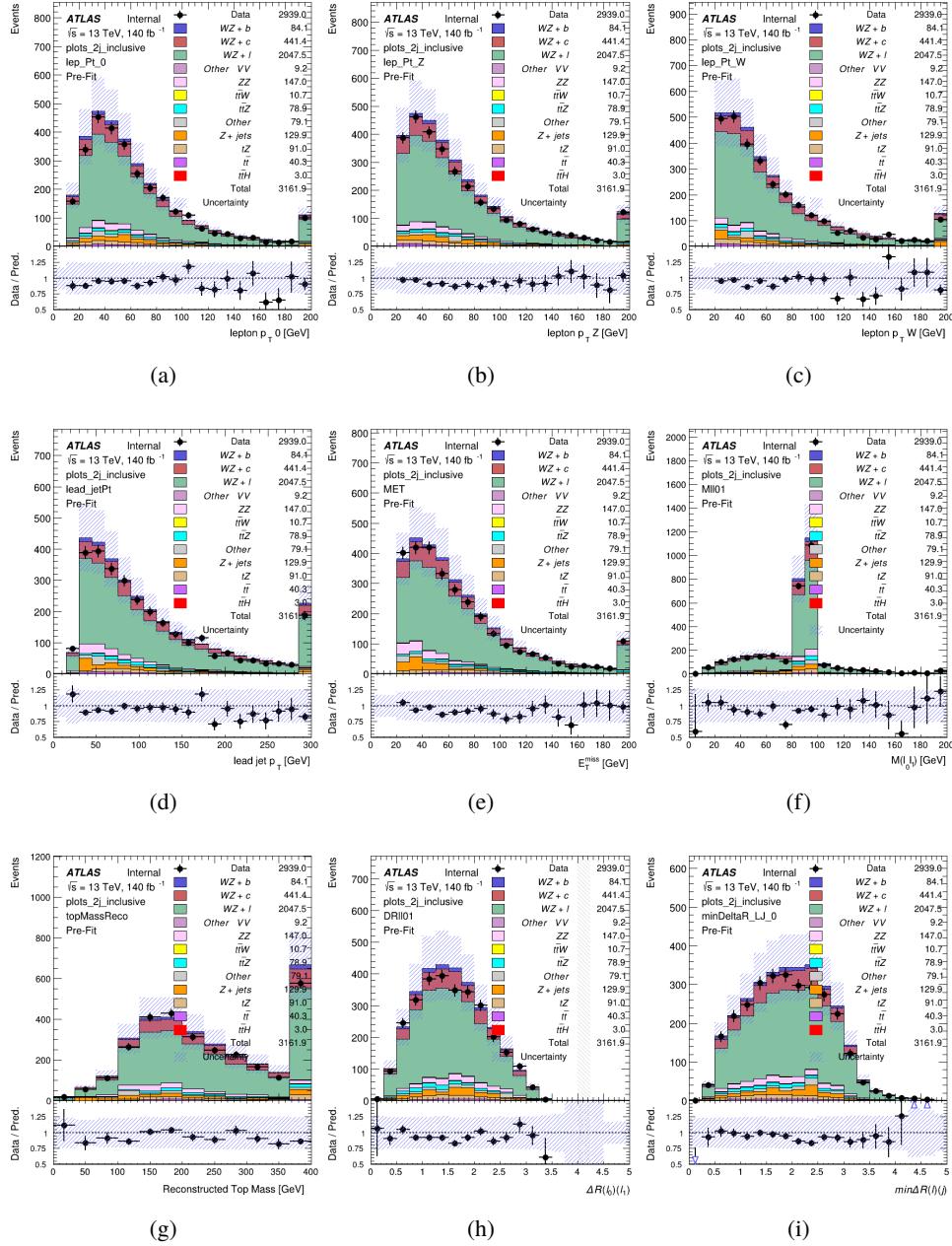


Figure 18: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 2j &lt; 85% WP

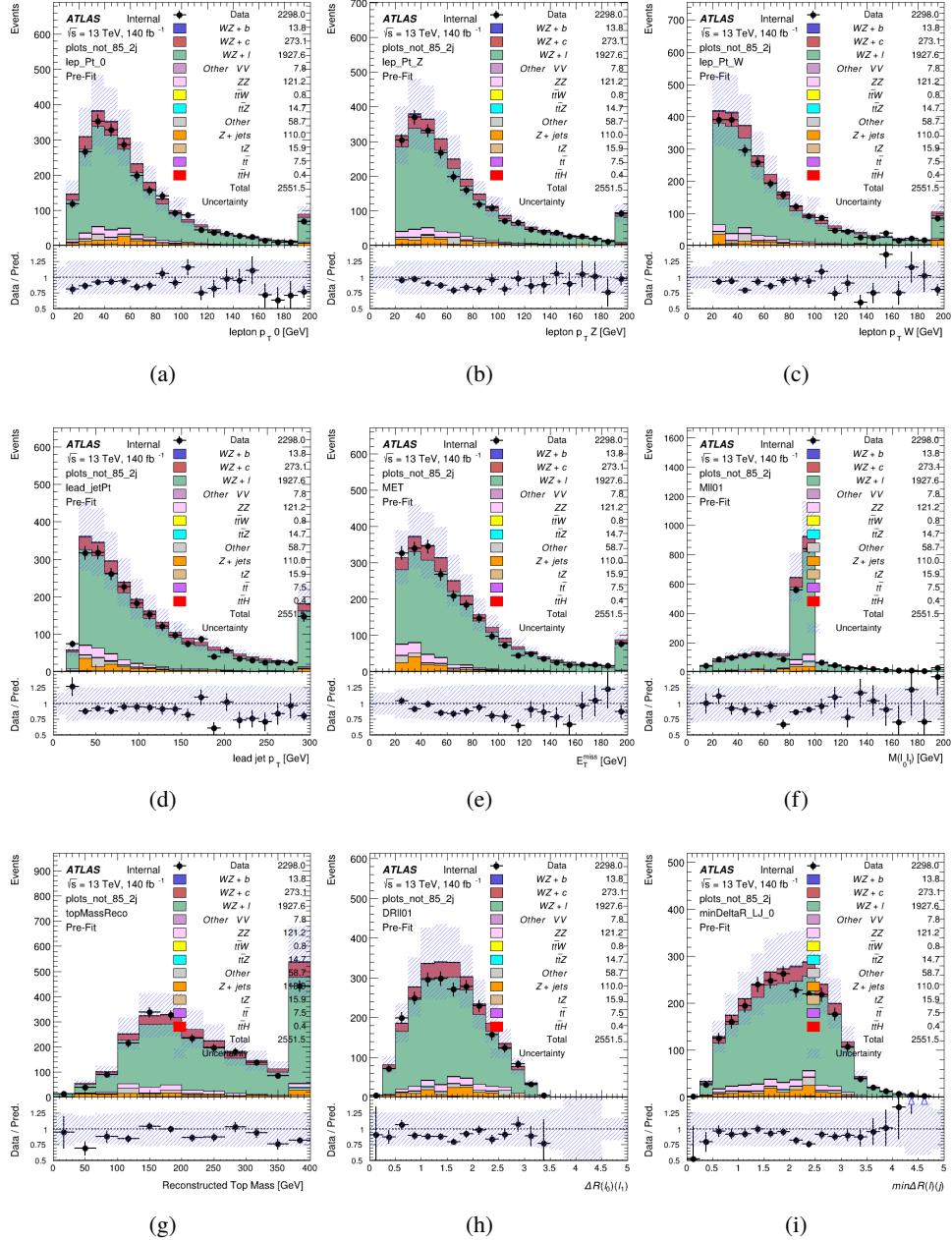


Figure 19: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 2j 77-85% WP

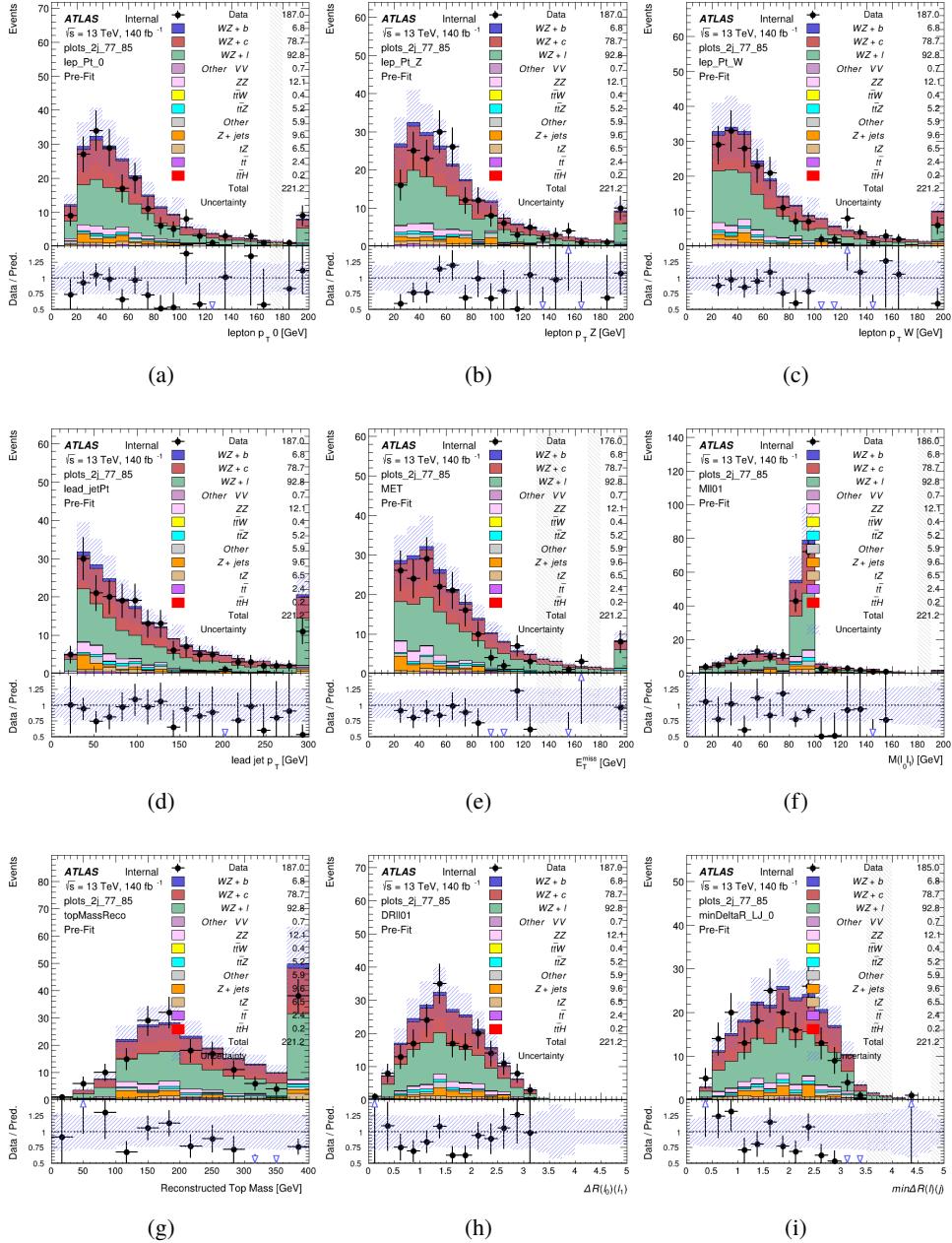


Figure 20: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 2j 70-77% WP

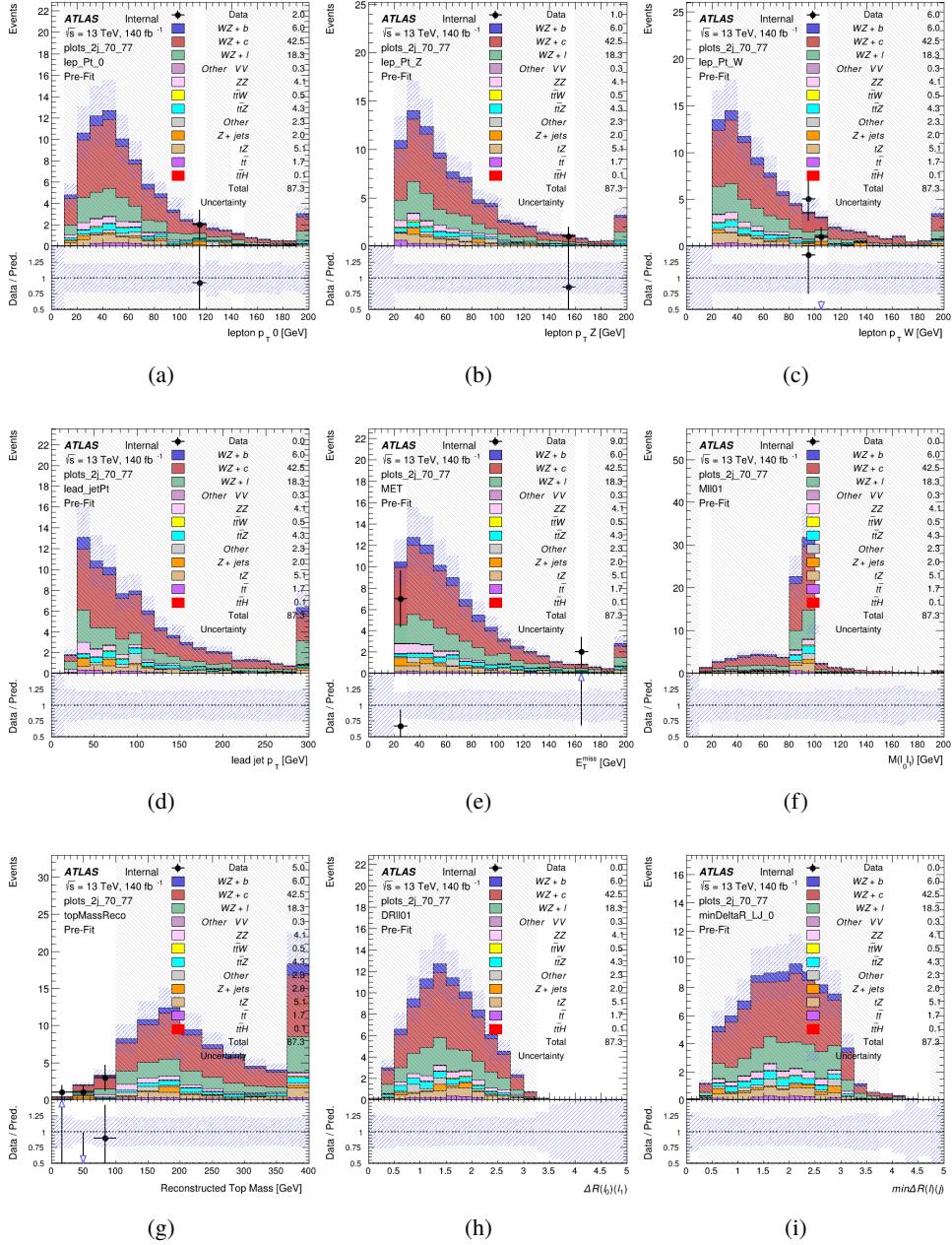


Figure 21: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 2j 60-70% WP

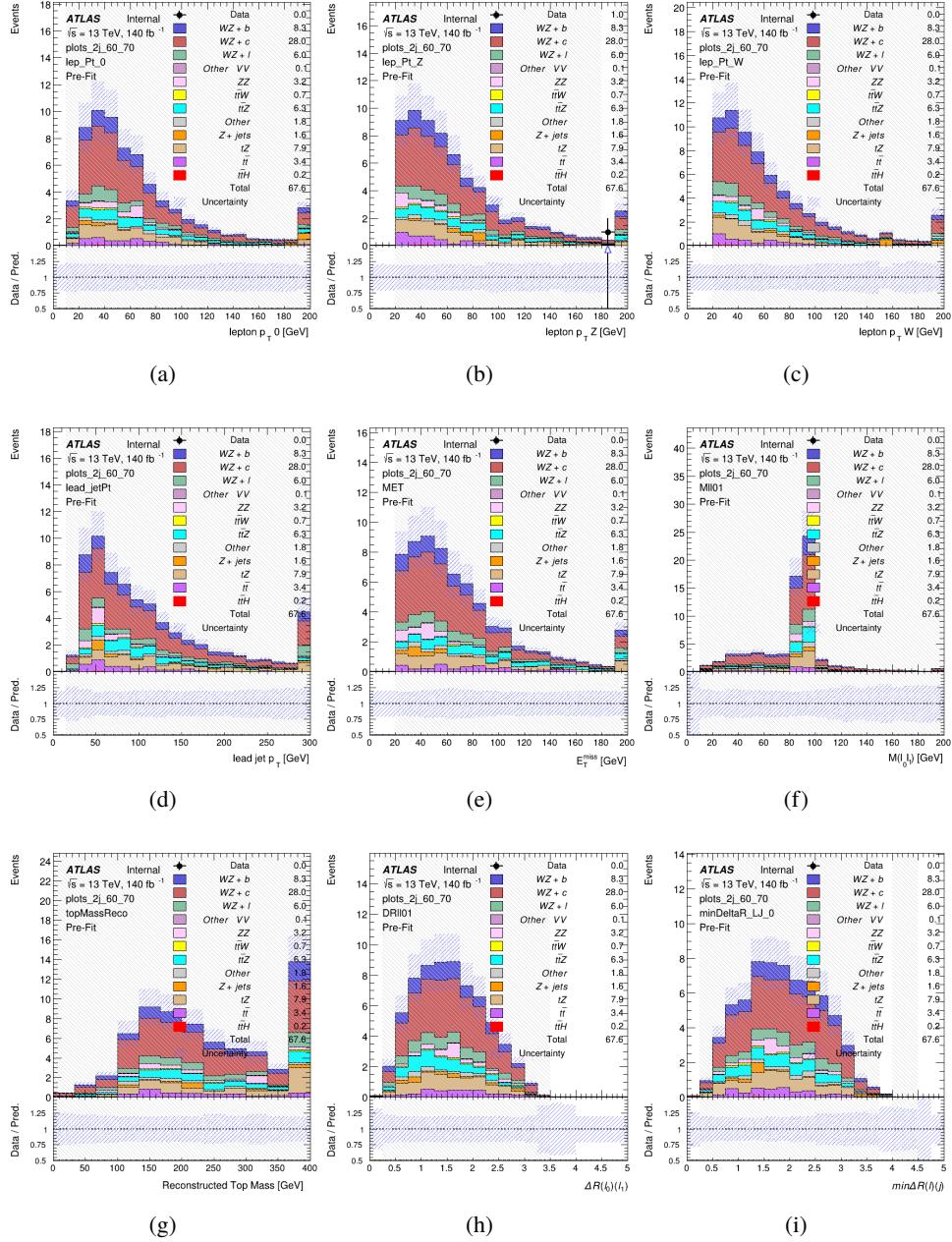


Figure 22: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - 2j 60% WP

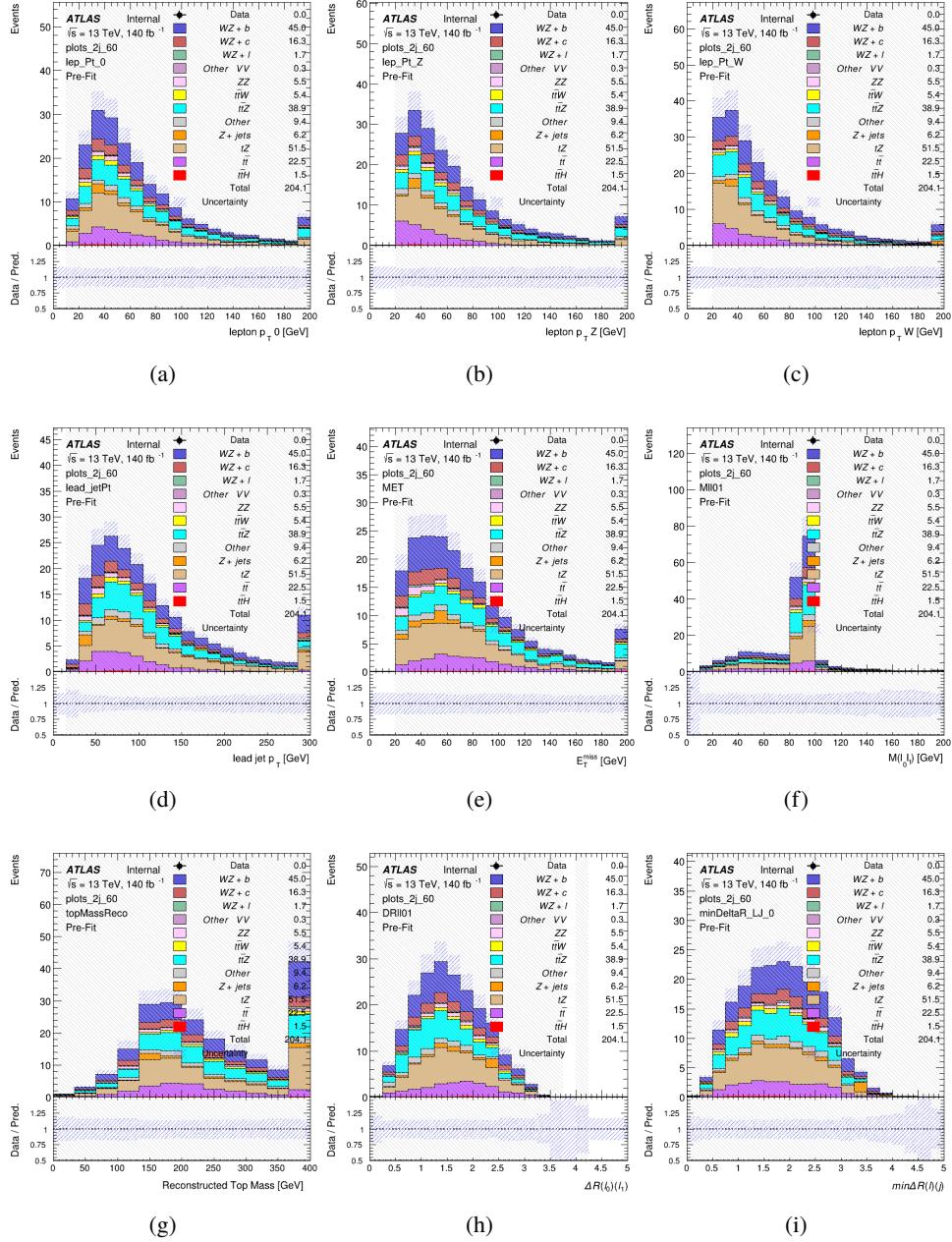


Figure 23: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the  $Z$  candidate, (c) the  $p_T$  of the lepton from the  $W$  candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

## WZ Fit Region - tZ-CR-2j

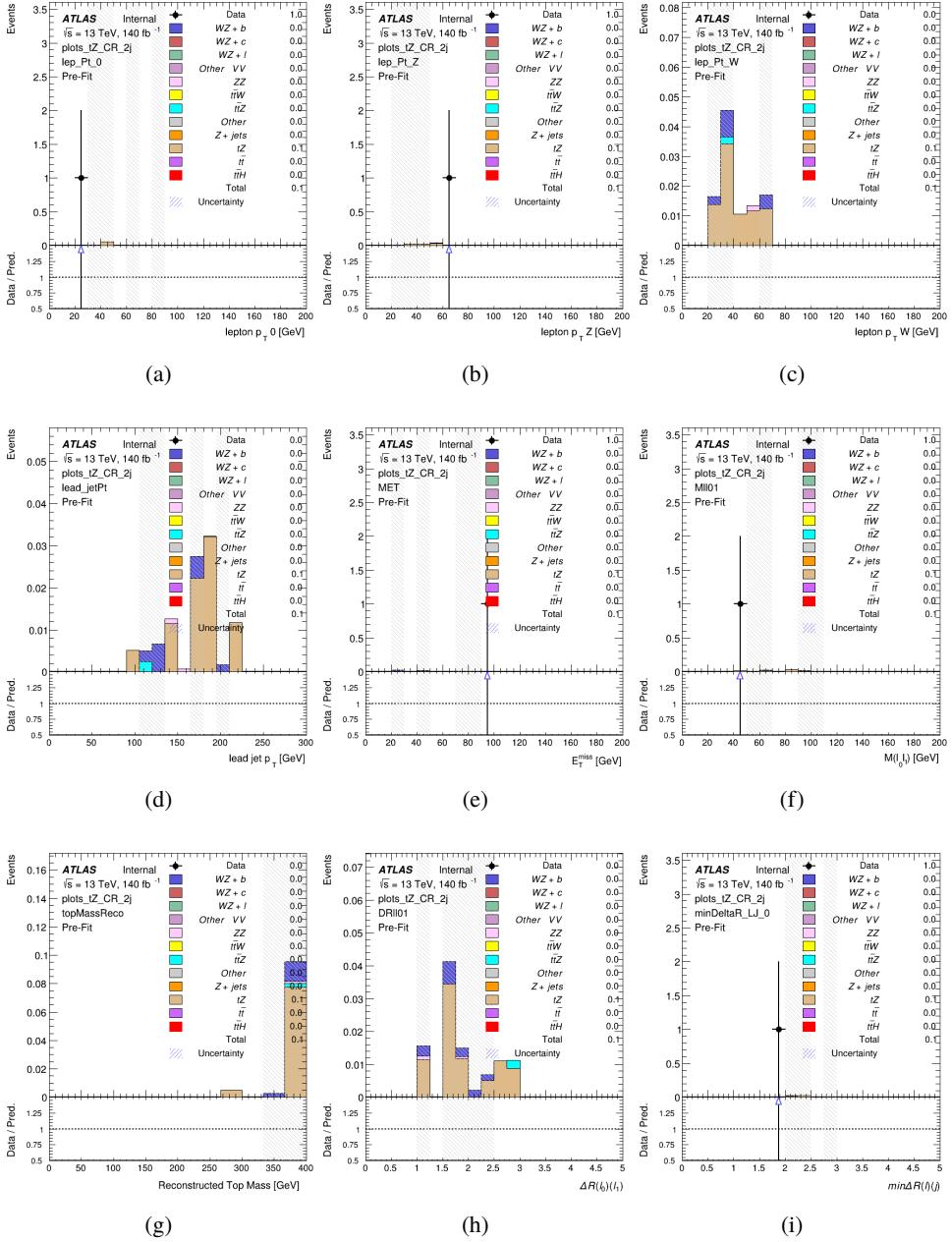


Figure 24: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , and (f) the invariant mass of leptons 0 and 1, (g) the reconstructed top mass, (h)  $\Delta(R)$  between lepton 0 and 1, (i) the  $\Delta(R)$  between the closest lepton and jet.

450 **6.3 Non-Prompt Lepton Estimation**

451 Two processes act as sources of non-prompt leptons appear in the analysis:  $t\bar{t}$  and Z+jet  
 452 production both produce two prompt leptons, and each contribute to the 31 region when an  
 453 additional non-prompt lepton appears in the event. The contribution of these processes is  
 454 estimated with Monte Carlo simulations, which are validated using enriched validation regions.

455 The modelling in the Z+jets and  $t\bar{t}$  CRs is further validated for each of the pseudo-continuous  
 456 b-tag regions used in the analysis. The relevant lepton  $p_T$  spectrum in each b-tag region is shown  
 457 in Appendix A.2 for these CRs after the correction factors derived below have been applied.

458 **6.3.1  $t\bar{t}$  Validation**

459  $t\bar{t}$  events can produce two prompt leptons from the decay of each of the tops. These top decays  
 460 produce two b-quarks, the decay of which can produce additional non-prompt leptons, which  
 461 occasionally pass the event preselection. In order to validate that the Monte Carlo accurately  
 462 simulates this process accurately, the MC prediction in a non-prompt  $t\bar{t}$  enriched validation  
 463 region is compared to data.

464 The  $t\bar{t}$  validation region is similar to the preselection region - three leptons meeting the criteria  
 465 described in Section 6 are required, and the requirements on  $E_T^{\text{miss}}$  remain the same. However,  
 466 the selection requiring that a lepton pair form a Z-candidate are reversed. Events where the  
 467 invariant mass of any two opposite sign, same flavor leptons falls within 10 GeV of 91.2 GeV are  
 468 rejected. This ensures the  $t\bar{t}$  validation region is orthogonal to the preselection region.

469 Further, because the jet multiplicity of  $t\bar{t}$  events tends to be higher than WZ + jets, the number  
 470 of jets in each event is required to be greater than 1. As b-jets are almost invariably produced  
 471 from top decays, at least one b-tagged jet passing the 70% DL1r WP in each event is required.  
 472 Various kinematic plots of this region are shown in Figure 25.

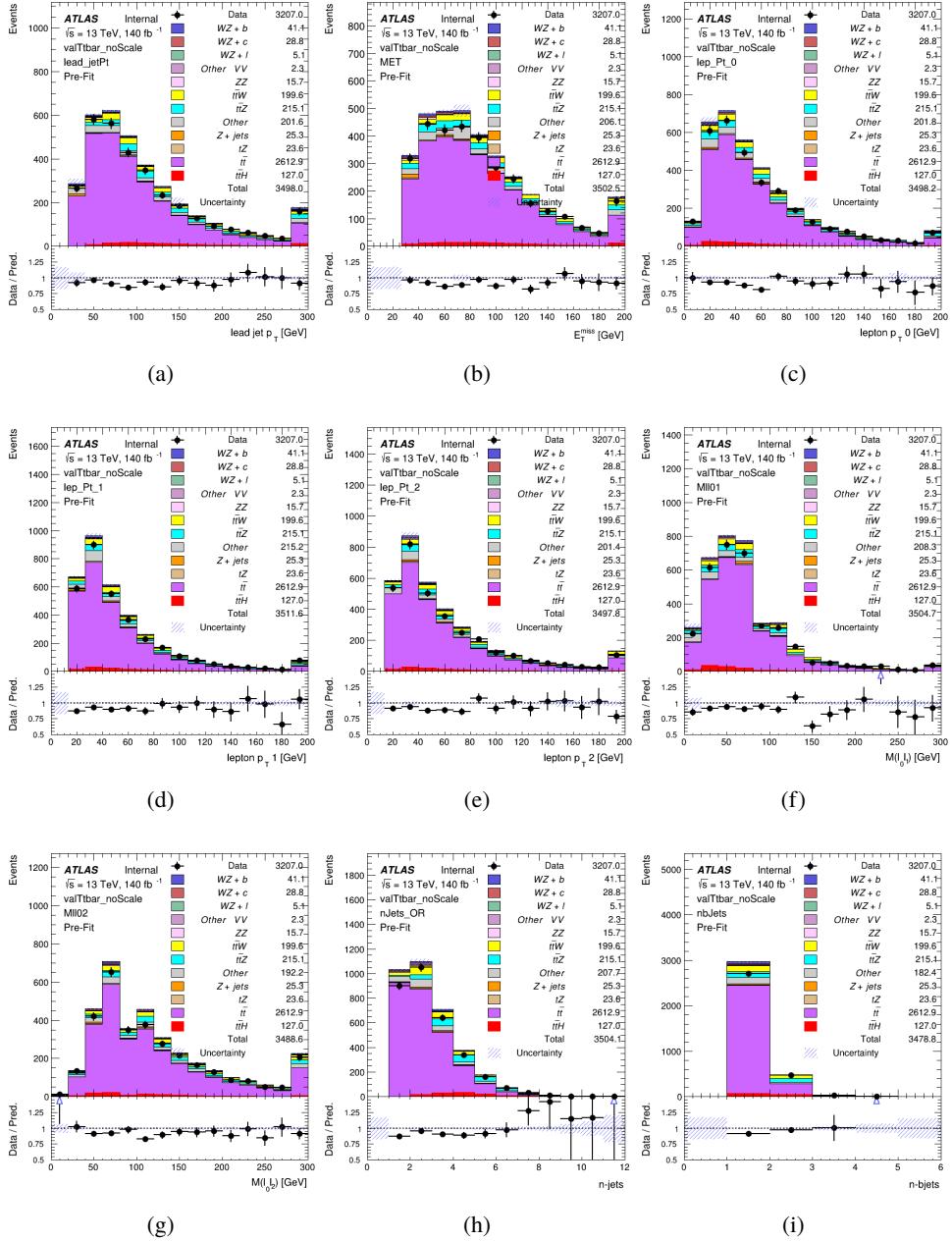


Figure 25: Comparisons between the data and MC distributions in the  $t\bar{t}$  validation region for (a) the  $p_T$  of the leading jet, (b) the missing transverse energy, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of lepton 1, (e)  $p_T$  of lepton 2, (f) the invariant mass of leptons 0 and 1, (g) the invariant mass of leptons 0 and 2, (h) the number of jets, (i) the number of b-tagged jets.

473 The shape of each distribution agrees quite well between data and MC, with a constant offset  
 474 between the two. This is accounted for by applying a constant correction factor of 0.9 to the  $t\bar{t}$

475 MC prediction. Plots showing the kinematics of the  $t\bar{t}$  VR after this correction factor has been  
 476 applied are shown in Figure 26.

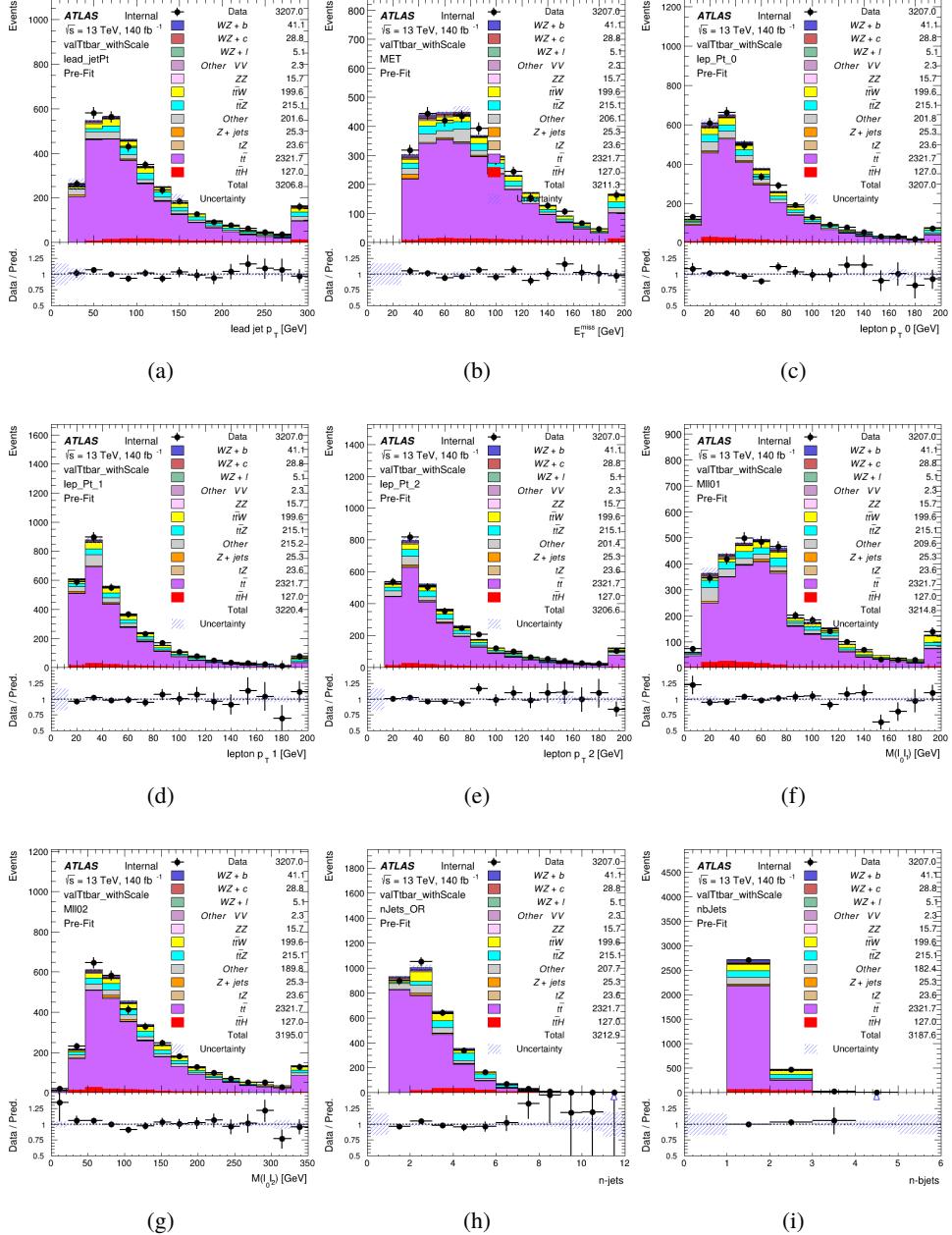


Figure 26: Comparisons between the data and MC distributions in the  $t\bar{t}$  validation region after the correction factor has been applied for (a) the  $p_T$  of the leading jet, (b) the missing transverse energy, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of lepton 1, (e)  $p_T$  of lepton 2, (f) the invariant mass of leptons 0 and 1, (g) the invariant mass of leptons 0 and 2, (h) the number of jets, (i) the number of b-tagged jets.

477 The modeling is further validated by looking at the yield in the  $t\bar{t}$  VR for each DL1r WP, giving  
 478 a clearer correspondence to the signal regions used in the fit. For these plots, the requirement  
 479 that each event contain at least one b-tagged jet is removed. Each region shown in Figure 27  
 480 requires one or more jets pass the listed WP, with no jets passing the next highest WP.

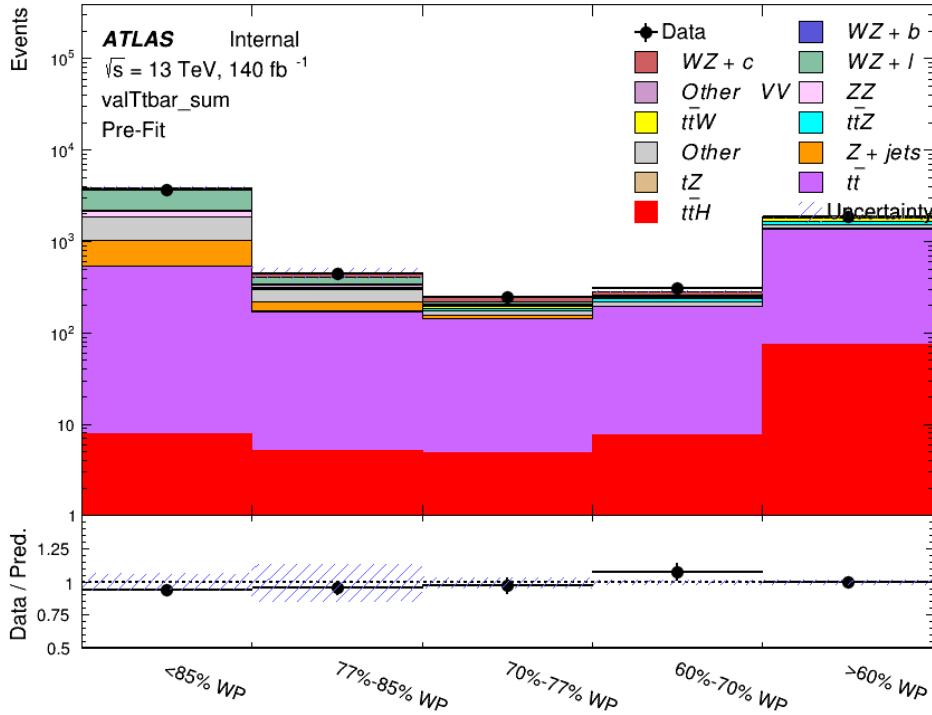


Figure 27: Data and MC comparisons for each DL1r WP for both 1-jet and 2-jet regions, after the  $t\bar{t}$  VR selection and correction factor have been applied

481 As data and MC are found to agree within 20% for each of these working points, a 20% systematic  
 482 uncertainty on the  $t\bar{t}$  prediction is included for the analysis.

### 483 6.3.2 Z+jets Validation

484 Similar to  $t\bar{t}$ , a non-prompt Z+jets validation region is produced in order to validate the MC  
 485 predictions. The lepton requirements remain the same as the preselection region. Because no  
 486 neutrinos are present for this process, the  $E_T^{\text{miss}}$  cut is reversed, requiring  $E_T^{\text{miss}} < 30 \text{ GeV}$ . This  
 487 also ensures this validation region is orthogonal to the preselection region. Further, the number  
 488 of jets in each event is required to be greater than or equal to one. Various kinematic plots of this  
 489 region are shown below. The general agreement between data and MC in each of these suggests  
 490 that the non-prompt contribution of Z+jets is well modeled by Monte Carlo.

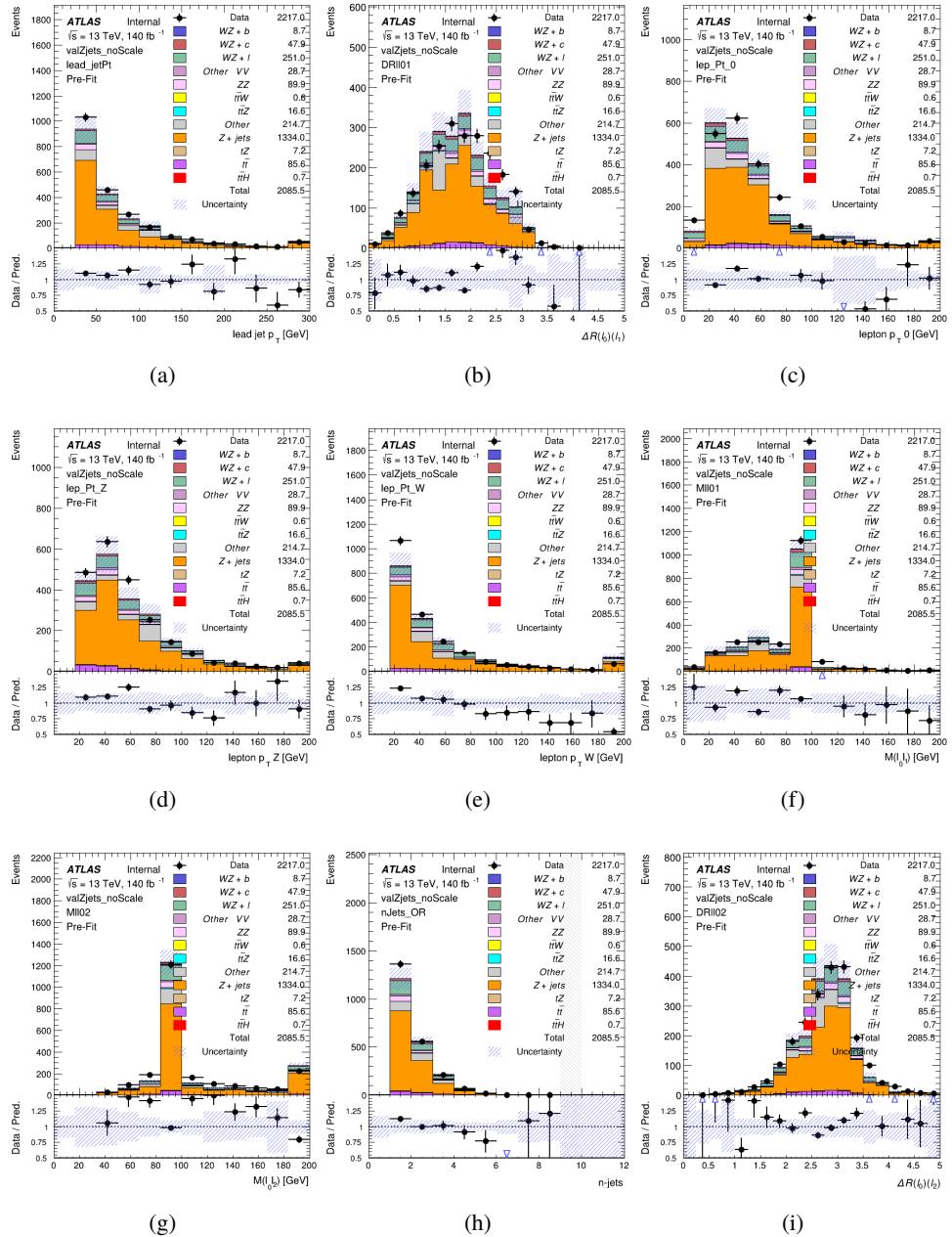


Figure 28: Comparisons between the data and MC distributions in the  $Z+jets$  validation region for (a) the  $p_T$  of the leading jet, (b)  $\Delta R$  between leptons 0 and 1, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of SS lepton from the  $Z$  candidate, (e)  $p_T$  of the SS lepton from the  $W$  candidate, (f) the invariant mass of leptons 0 and 1, (g) the invariant mass of leptons 0 and 2, (h) the number of jets, (i)  $\Delta R$  between leptons 0 and 2. Includes only statistical uncertainties

491 While there is general agreement between data and MC within statistical uncertainty, the shape

of the  $p_T$  spectrum of the lepton from the W candidate is found to differ. As this is the lepton not included in the Z-candidate, in the case of Z+jets, this lepton is most often the non-prompt lepton. A similar effect is seen for both non-prompt muons and electrons in the Z+jets validation region, as shown in Figure 29.

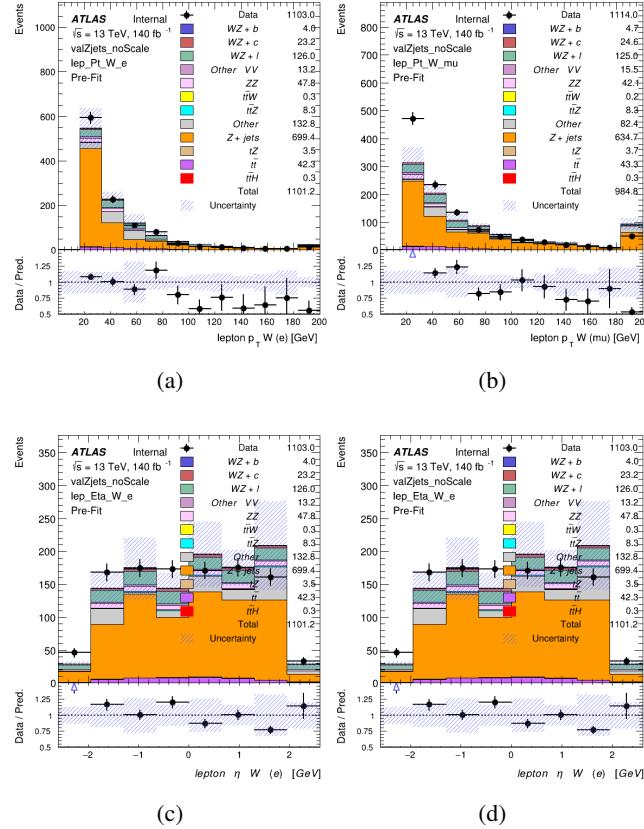


Figure 29:  $p_T$  spectrum of the lepton from the W candidate for (a) electrons and (b) muons, as well as  $\eta$  spectrum for (c) electrons and (d) muons, before the correction has been applied

To account for this discrepancy, a variable correction factor is applied to Z+jets.  $\chi^2$  minimization of the W lepton  $p_T$  spectrum is performed to derive a correction factor as a function of this  $p_T$ . Kinematic plots of the Z + jets validation region after this correction factor has been applied are shown in Figure 30.

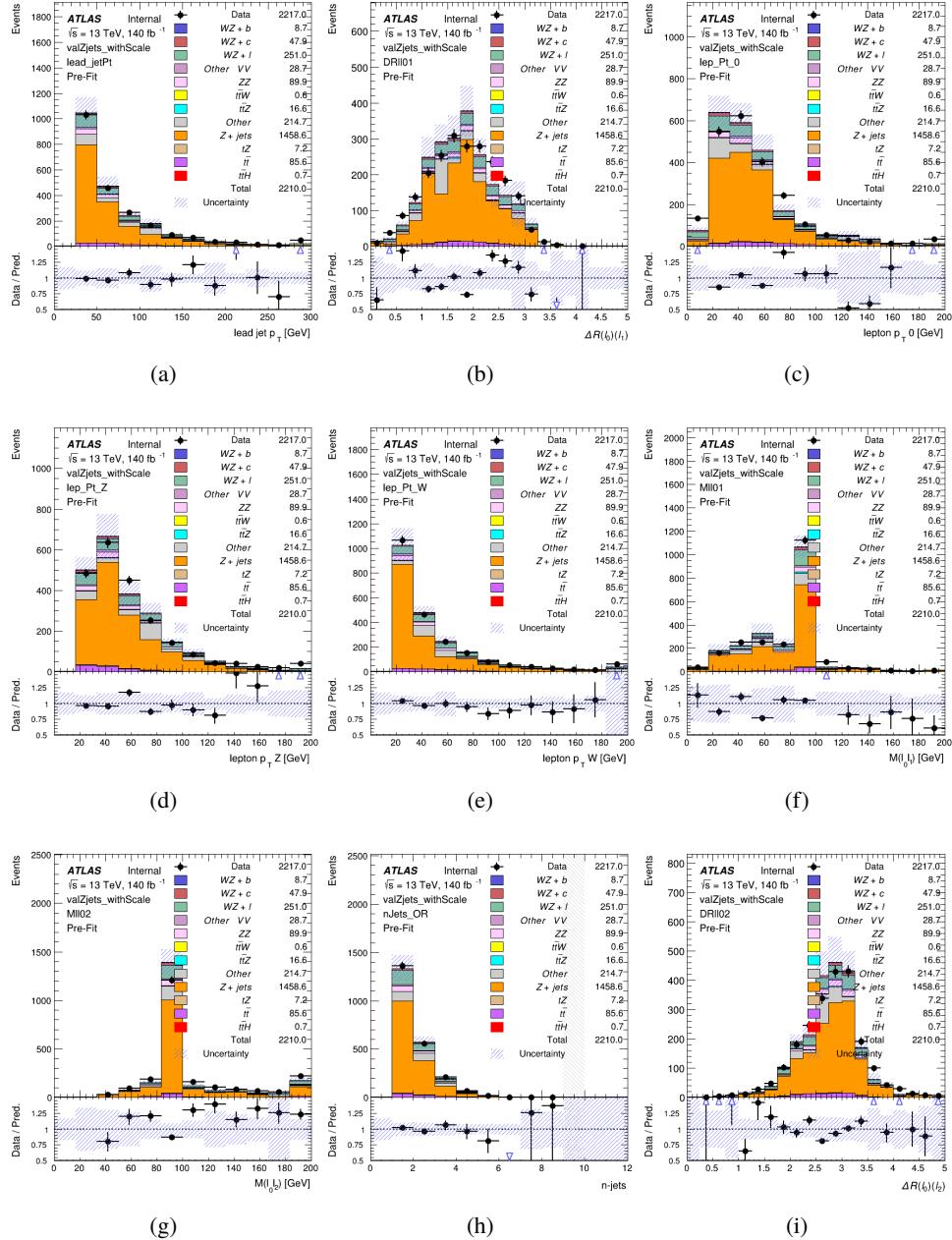


Figure 30: Comparisons between the data and MC distributions in the  $Z$ +jets validation region after the correction factor has been applied for (a) the  $p_T$  of the leading jet, (b)  $\Delta R$  between leptons 0 and 1, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of SS lepton from the  $Z$  candidate, (e)  $p_T$  of the SS lepton from the  $W$  candidate, (f) the invariant mass of leptons 0 and 1, (g) the invariant mass of leptons 0 and 2, (h) the number of jets, (i)  $\Delta R$  between leptons 0 and 2

500 The  $p_T$  and  $\eta$  of the lepton from the  $W$  candidate split by lepton flavor after this correction has

501 been applied is shown in figure 31.

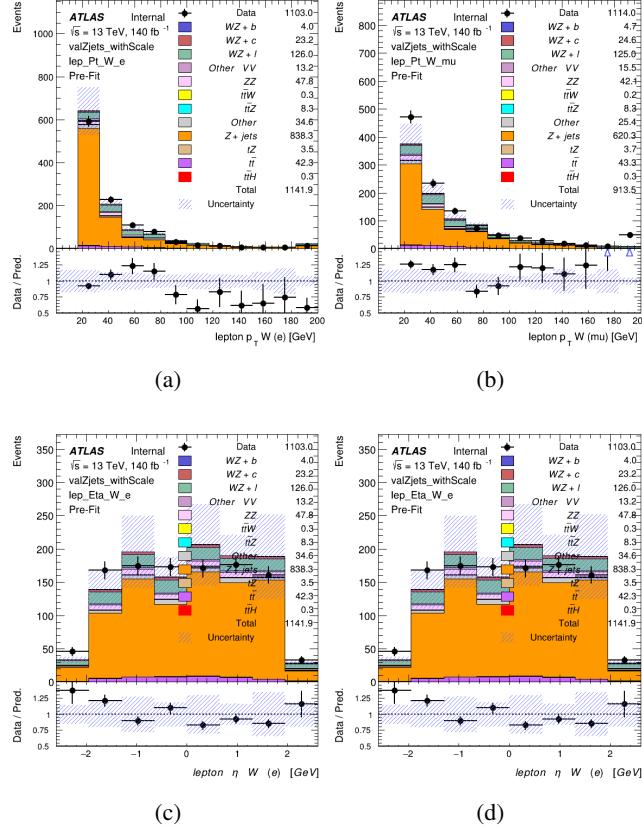


Figure 31:  $p_T$  spectrum of the lepton from the  $W$  candidate for (a) electrons and (b) muons, as well as  $\eta$  spectrum for (c) electrons and (d) muons, after the correction has been applied

502 The modeling is further validated by looking at the yield in the  $Z+\text{jets}$  VR for each DL1r WP,  
 503 giving a clearer correspondence to the signal regions used in the fit. Each region shown in Figure  
 504 32 requires one or more jets pass the listed WP, with no jets passing the next highest WP.

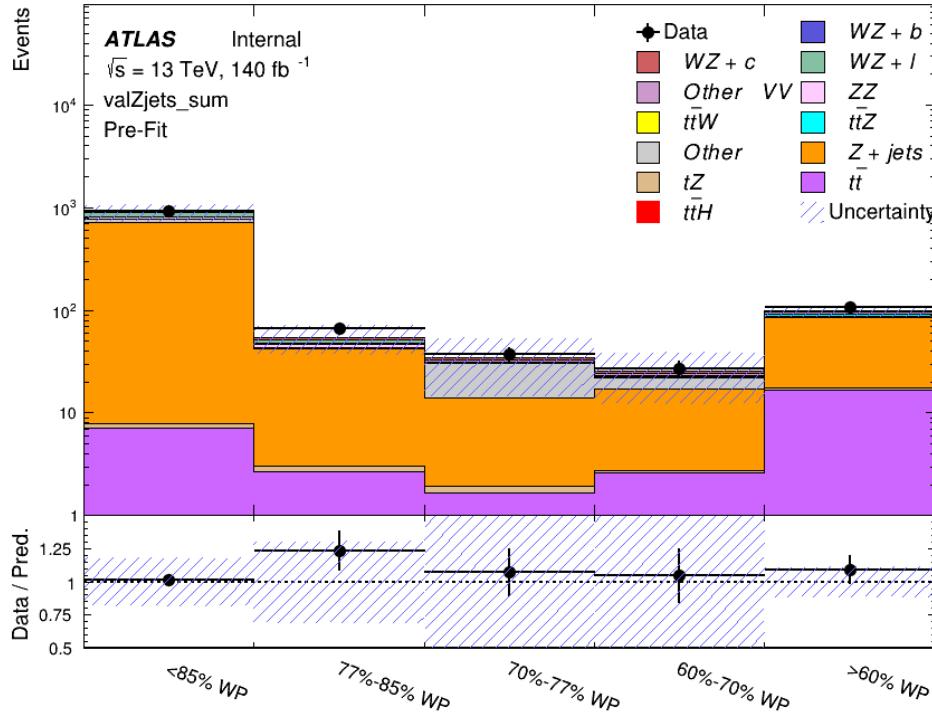


Figure 32: Data and MC comparisons for each DL1r WP for both 1-jet and 2-jet regions, after the Z+jets VR selection and correction factor have been applied

505 For each of the b-tagging working points considered, the data falls within 25% of the MC  
 506 prediction once this correction factor has been applied. Therefore, a 25% systematic uncertainty  
 507 is applied to Z + jets in the analysis.

## 508 7 Systematic Uncertainties

509 The systematic uncertainties that are considered are summarized in Table 9. These are imple-  
 510 mented in the fit either as a normalization factors or as a shape variation or both in the signal and  
 511 background estimations. These systematic uncertainties are treated as independent nuisance  
 512 parameters (NPs) in the fit, and are assumed to be gaussian. Each NP is varied up and down by  
 513 its uncertainty, and the difference in the result of the fit is taken to be the systematic uncertainty  
 514 of that NP. The numerical impact of each of these uncertainties is outlined in Section 8.

Table 9: Sources of systematic uncertainty considered in the analysis.

| Systematic uncertainty                   | Components |
|--|------------|
| Luminosity                               | 1          |
| Pileup reweighting                       | 1          |
| <b>Physics Objects</b>                   |            |
| Electron                                 | 5          |
| Muon                                     | 14         |
| Prompt Lepton Veto                       | 1          |
| Jet energy scale                         | 28         |
| Jet energy resolution                    | 8          |
| Jet vertex fraction                      | 1          |
| Jet flavor tagging                       | 131        |
| $E_T^{\text{miss}}$                      | 3          |
| Total (Experimental)                     | 194        |
| <b>Signal Modeling</b>                   |            |
| Shape modelling                          | 3          |
| Renormalization and factorization scales | 5          |
| nJet Migration                           | 5          |
| <b>Background Modeling</b>               |            |
| Cross section                            | 15         |
| Renormalization and factorization scales | 12         |
| Parton shower and hadronization model    | 2          |
| Shower tune                              | 4          |
| Total (Signal and background modeling)   | 41         |
| Total (Overall)                          | 235        |

515 The uncertainty in the combined 2015–2018 integrated luminosity is 1.7% [25], obtained using  
 516 the LUCID-2 detector [26] for the primary luminosity measurements.

517 The experimental uncertainties are related to the reconstruction and identification of light  
 518 leptons and b-tagging of jets, and to the reconstruction of  $E_T^{\text{miss}}$ . The TOTAL electron ID  
 519 correlation model is used, corresponding to 1 electron ID systematic [27]. Electron ID is found  
 520 to be a subleading systematic that is unconstrained by the fit, making it an appropriate choice for  
 521 this analysis.

522 The sources which contribute to the uncertainty in the jet energy scale (JES) [28] are decom-  
 523 posed into uncorrelated components and treated as independent sources in the analysis. The  
 524 CategoryReduction model is used to account for JES uncertainties, which decomposes the uncer-  
 525 tainties into 30 nuisance parameters included in the fit. The SimpleJER model is used to account

526 for jet energy resolution (JER) uncertainties, and 8 JER uncertainty components included as NPs  
527 in the fit.

528 The uncertainties in the b-tagging efficiencies measured in dedicated calibration analyses  
529 [19] are also decomposed into uncorrelated components. The large number of components for  
530 b-tagging is due to the use of the full continuous b-tagging spectrum: The calibration of the  
531 distribution of the MVA discriminant for each of the individual working points considered for  
532 b— c— and light jets, and the correlations between them, produces a large number of systematic  
533 uncertainties.

534 The full list of systematic uncertainties considered in the analysis is summarized in Tables 10,  
535 11 and 12.

536

| <b>Experimental Systematics on Leptons and <math>E_T^{\text{miss}}</math></b> |                                     |   |                   |
|---|-------------------------------------|---|-------------------|
| Type  | Description                         | Systematics Name                            | Application       |
| <b>Trigger</b>  |                                     |   |                   |
| Scale Factors   | Trigger Efficiency                  | lepSFTrigTight_MU(EL)_SF_Trigger_STAT(SYST) | Event Weight      |
| <b>Muons</b>  |                                     |   |                   |
| Efficiencies  | Reconstruction and Identification   | lepSFObjTight_MU_SF_ID_STAT(SYST)           | Event Weight      |
|   | Isolation                           | lepSFObjTight_MU_SF_Isol_STAT(SYST)         | Event Weight      |
|   | Track To Vertex Association         | lepSFObjTight_MU_SF_TTVA_STAT(SYST )        | Event Weight      |
| $p_T$ Scale   | $p_T$ Scale                         | MUONS_SCALE                                 | $p_T$ Correction  |
| Resolution  | Inner Detector Energy Resolution    | MUONS_ID                                    | $p_T$ Correction  |
|   | Muon Spectrometer Energy Resolution | MUONS_MS                                    | $p_T$ Correction  |
| <b>Electrons</b>  |                                     |   |                   |
| Efficiencies  | Reconstruction                      | lepSFObjTight_EL_SF_ID                      | Event Weight      |
|   | Identification                      | lepSFObjTight_EL_SF_Reco                    | Event Weight      |
|   | Isolation                           | lepSFObjTight_EL_SF_Isol                    | Event Weight      |
| Scale Factor  | Energy Scale                        | EG_SCALE_ALL                                | Energy Correction |
| Resolution  | Energy Resolution                   | EG_RESOLUTION_ALL                           | Energy Correction |
| <b><math>E_T^{\text{miss}}</math></b>   |                                     |   |                   |
| Soft Tracks Terms   | Resolution                          | MET_SoftTrk_ResoPerp                        | $p_T$ Correction  |
|   | Resolution                          | MET_SoftTrk_ResoPara                        | $p_T$ Correction  |
|   | Scale                               | MET_SoftTrk_ScaleUp                         | $p_T$ Correction  |
|   | Scale                               | MET_SoftTrk_ScaleDown                       | $p_T$ Correction  |

Table 10: Summary of experimental systematics considered for leptons and  $E_T^{\text{miss}}$ . Includes type, description, name of systematic as used in the fit, and mode of application. The mode of application indicates the systematic evaluation, e.g. as an overall event re-weighting (Event Weight) or rescaling ( $p_T$  Correction).

| Experimental Systematics on Jets |                          |  |  |
|----------------------------------|--------------------------|--|--|
| Type                             | Origin                   | Systematics Name   | Application  |
| Jet Vertex Tagger                |                          | JVT  | Event Weight   |
| Energy Scale                     | Calibration Method       | JET_21NP_<br>JET_EffectiveNP_1-19  | $p_T$ Correction<br>$p_T$ Correction   |
|                                  | $\eta$ inter-calibration | JET_EtaIntercalibration_Modelling<br>JET_EtaIntercalibration_NonClosure<br>JET_EtaIntercalibration_TotalStat | $p_T$ Correction<br>$p_T$ Correction<br>$p_T$ Correction                     |
|                                  | High $p_T$ jets          | JET_SingleParticle_HighPt  | $p_T$ Correction   |
|                                  | Pile-Up                  | JET_Pileup_OffsetNPV<br>JET_Pileup_OffsetMu<br>JET_Pileup_PtTerm<br>JET_Pileup_RhoTopology                   | $p_T$ Correction<br>$p_T$ Correction<br>$p_T$ Correction<br>$p_T$ Correction |
|                                  | Non Closure              | JET_PunchThrough_MC15  | $p_T$ Correction   |
|                                  | Flavour                  | JET_Flavor_Response<br>JET_BJES_Response<br>JET_Flavor_Composition   | $p_T$ Correction<br>$p_T$ Correction<br>$p_T$ Correction                     |
| Resolution                       |                          | JET_JER_EffectiveNP_NP_1-8   | Event Weight   |

Table 11: Jet systematics take into account effects of jets calibration method,  $\eta$  inter-calibration, high  $p_T$  jets, pile-up, and flavor response. They are all diagonalised into effective parameters.

| Experimental Systematics on b-tagging |   |   |
|---------------------------------------|---|---|
| Type                                  | Origin  | Systematic Name   |
| Scale Factors                         | DL1r b-tagger efficiency<br>on b originated jets in bins of $\eta$                            | DL1r_Continuous_EventWeight_B0-29   |
|                                       | DL1r b-tagger efficiency<br>on c originated jets in bins of $\eta$                            | DL1r_Continuous_EventWeight_C0-19   |
|                                       | DL1r b-tagger efficiency<br>on light flavoured originated jets<br>in bins of $\eta$ and $p_T$ | DL1r_Continuous_EventWeight_Light0-79   |
|                                       | DL1r b-tagger<br>extrapolation efficiency   | DL1r_Continuous_EventWeight_extrapolation<br>DL1r_Continuous_EventWeight_extrapolation_from_charm |

Table 12: Summary of experimental systematics to be included for b-tagging of jets in the analysis, using the continuous DL1r tagging algorithm. All of the b-tagging related systematics are applied as event weights. From left: type, description, and the name of systematic used in the fit.

537     Theoretical uncertainties applied to MC predictions, including cross section, PDF, and scale  
 538     uncertainties are taken from theory calculations, with the exception of non-prompt and diboson  
 539     backgrounds. The cross-section uncertainty on tZ is taken from [29]. Derivation of the non-  
 540     prompt background uncertainties, Z+jets and tt}, are explained in detail in Section 6.3. These  
 541     normalization uncertainties are chosen so as to account for the complete uncertainty in the  
 542     non-prompt contribution, and therefore no additional modelling uncertainties are considered for  
 543     Z+jets and tt}.

544     The other VV + heavy flavor processes (namely VV+b and VV+charm, which primarily consist  
 545     of ZZ events) are also poorly understood, because these processes involve the same physics as  
 546     WZ + heavy flavor, and have also not been measured. Therefore, an arbitrary 50% uncertainty is  
 547     applied to those samples, as it is found to have little impact on the significance of the final result:  
 548     Fits are performed with this uncertainty decreased to 25% and increased to 75% and no change  
 549     in the final result was observed.

550     The theory uncertainties applied to the predominate background estimates are summarized in  
 551     Table 13.

| Process                                 | X-section [%]  |
|---|--|
| WZ                                      | QCD Scale: $^{+3.7}_{-3.4}$<br>PDF( $+\alpha_S$ ): $\pm 3.1$   |
| tZ                                      | X-sec: $\pm 15.2$  |
| t <bar>t} H<br/>(aMC@NLO+Pythia8)</bar> | QCD Scale: $^{+5.8}_{-9.2}$<br>PDF( $+\alpha_S$ ): $\pm 3.6$   |
| t <bar>t} Z<br/>(aMC@NLO+Pythia8)</bar> | QCD Scale: $^{+9.6}_{-11.3}$<br>PDF( $+\alpha_S$ ): $\pm 4$    |
| t <bar>t} W<br/>(aMC@NLO+Pythia8)</bar> | QCD Scale: $^{+12.9}_{-11.5}$<br>PDF( $+\alpha_S$ ): $\pm 3.4$ |
| VV + b/charm<br>(Sherpa 2.2.1)          | $\pm 50$   |
| VV + light<br>(Sherpa 2.2.1)            | $\pm 6$  |
| t <bar>t}</bar>                         | $\pm 20$   |
| Z + jets                                | $\pm 25$   |
| Others                                  | $\pm 50$   |

Table 13: Summary of theoretical uncertainties for MC predictions in the analysis.

552 Due to its importance as a background, additional modelling uncertainties are considered for tZ.  
 553 Alternative tZ samples with variations in scale (DSID 412064-5) and shower modelling (DSID  
 554 501046) are included as systematics..

555 The fit involves varying the overall normalization of signal templates over the regions de-  
 556 scribed in Section 6.2, which are defined by the flavor and number of associated jets at truth-  
 557 level. The modelling of these template shapes therefore significantly impacts the final result.  
 558 Additional signal uncertainties, probing the shape of the signal templates as well as the rate of  
 559 migrations between the number of truth-jets and reconstructed jets, are estimated by comparing  
 560 estimates from the nominal Sherpa WZ samples with alternative WZ samples generated with  
 561 Powheg+Pythia8 (DSID 361601). Separate systematics are included in the fit for WZ + b, WZ  
 562 + c and WZ + light, where the distribution among each of the fit regions is varied based on the  
 563 prediction of the Powheg sample.

564 The variations in the signal templates are shown in Figures 33 and 34. Each of these plots are  
 565 normalized to unity in order to capture the relevant differences in shape.

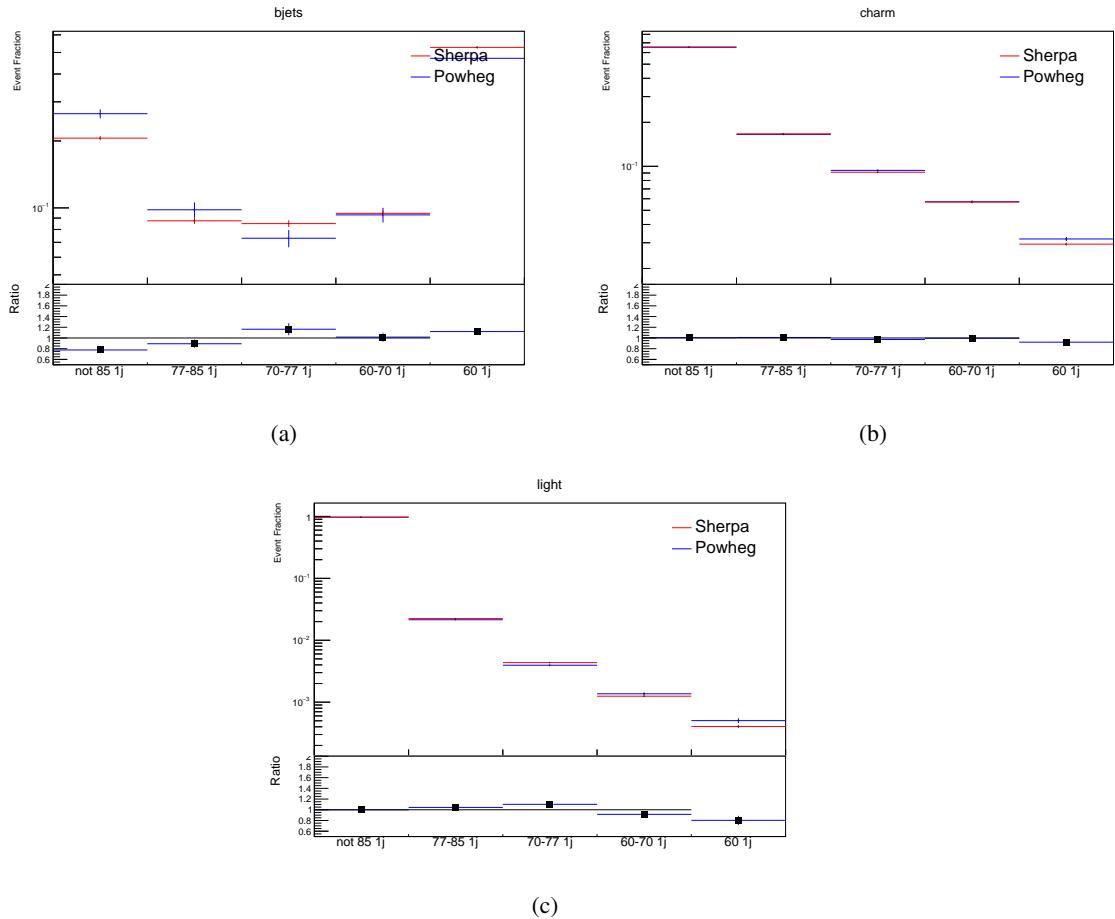


Figure 33: Comparison between Sherpa and Powheg predictions of the distribution of (a) WZ + b, (b) WZ + charm, and (c) WZ + light among the various b-tag WPs used in the 1-jet fit.

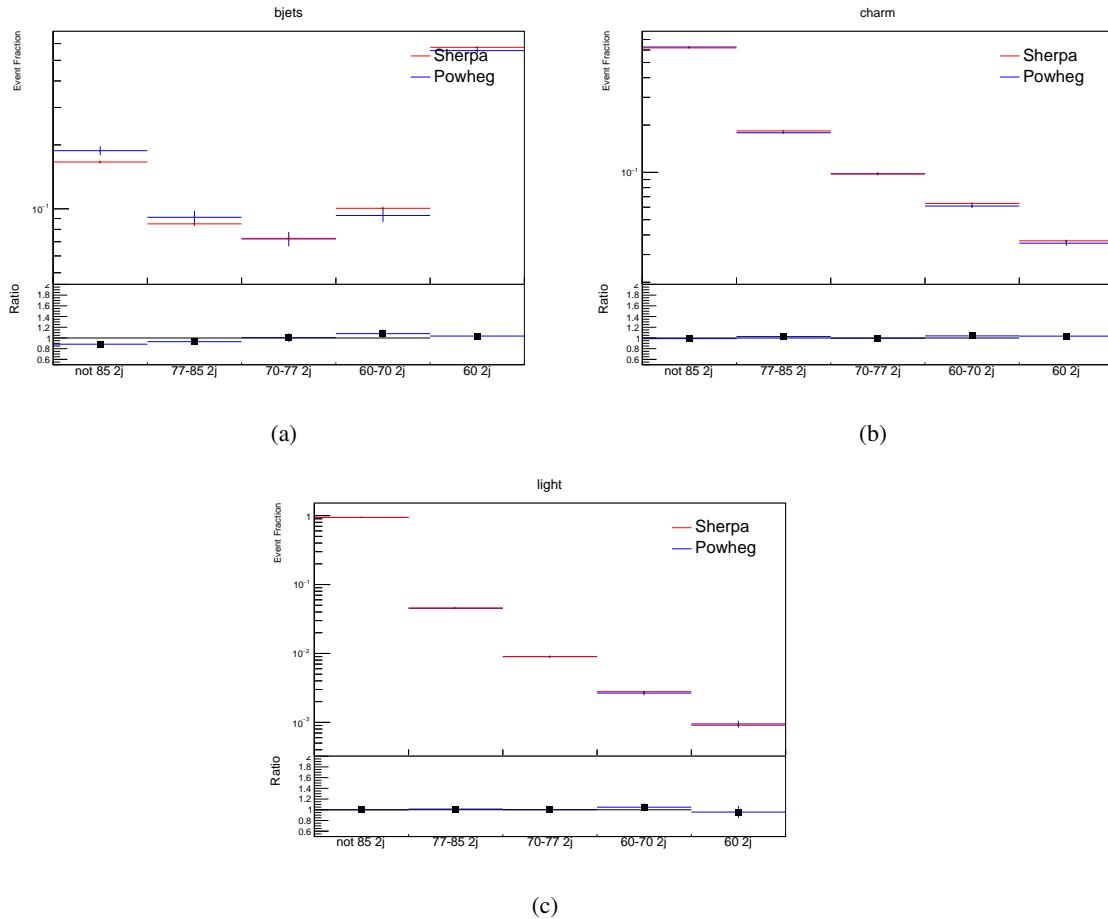


Figure 34: Comparison between Sherpa and Powheg predictions of the distribution of (a) WZ + b, (b) WZ + charm, and (c) WZ + light among the various b-tag WPs used in the 2-jet fit.

566 Separate systematics are included in the fit for WZ + b, WZ + charm and WZ + light, where  
 567 the distribution among each of the fit regions is varied based on the prediction of the Powheg  
 568 sample.

569 A similar approach is taken to account for uncertainties in migrations between the number of  
 570 reco and truth jets. The fraction of events with 1 truth jet which fall into the 1 jet bin versus the  
 571 2 jet bin at reco level is compared for Sherpa and Powheg. The same is done for events with 2  
 572 truth jets. This comparison is shown in figure 35.

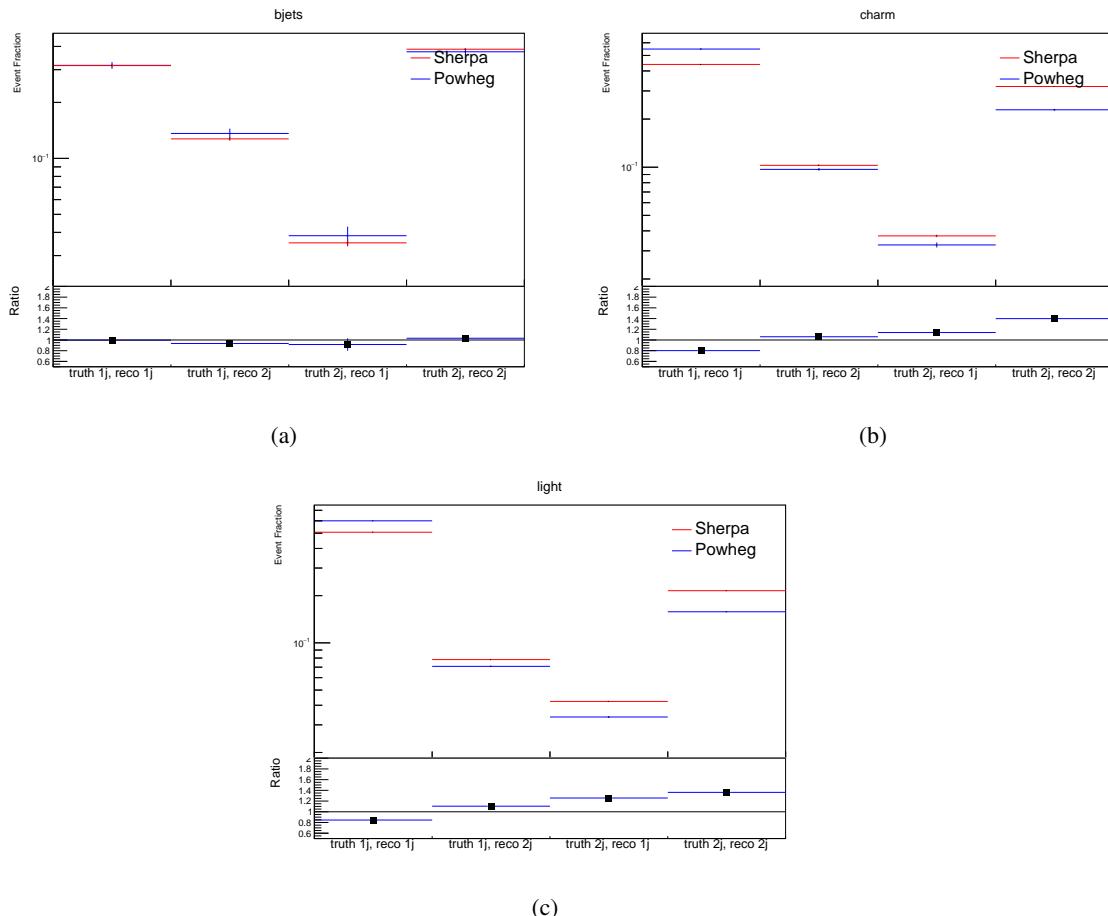


Figure 35: Comparison between Sherpa and Powheg predictions for truth jet migrations between the 1 and 2 jet reco bins for (a) WZ + b, (b) WZ + charm, and (c) WZ + light

573 A systematic is included where events are shifted between the 1-jet and 2-jet regions based on  
574 the differences between these two shapes. This is done independently for each of the WZ + b,  
575 WZ + charm, and WZ + light templates.

Additional systematics are included to account for the uncertainty in the contamination of 0 jet and 3 or more jet events (at truth level) in the 1 and 2 reco jet bins. Because these events fall outside the scope of this measurement, these events are included as a background. As such, a normalization, rather than a shape, uncertainty is applied for this background.

580 The number of WZ events with 0-jets and  $\geq 3$ -jets in the reconstructed 1-jet and 2-jet regions  
 581 are compared for Sherpa and Powheg, as seen in figure 36. These differences are taken as separate  
 582 normalization systematics on the yield of WZ+0-jet and WZ+ $\geq 3$ -jet events.

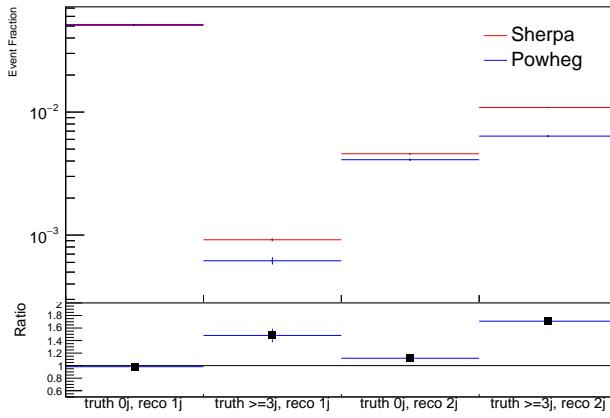


Figure 36: Comparison between Sherpa and Powheg predictions for 0 and  $\geq 3$  truth jet contributions in the 1 and 2 jet reco bins

## 8 Results

### 8.1 Fit Procedure

A maximum-likelihood fit is performed over the unfolded signal templates in the various fit regions described in Section 6 in order to extract the best-fit value of the WZ + b-jet and WZ + charm jet contributions for events with both 1 and 2 associated jets.

Because the fit regions are defined by the number of associated jets at reco-level, an unfolding procedure is applied to the signal in order to account for differences in the number of truth jets compared to the number of reco-jets. The WZ + b, WZ + charm and WZ + light contributions are separated into independent samples based on the number of truth jets in each event. WZ + 1 truth-jet and WZ + 2 truth-jets are treated as signal samples, while WZ + 0 truth-jets and WZ +  $\geq 3$  truth-jets are treated as an additional background.

A maximum likelihood fit to data is performed simultaneously in the regions described in Section 6, summarized in figure 37. The six signal templates, which include WZ+b 1-jet, WZ+c 1-jet, WZ+l 1-jet, WZ+b 2-jets, WZ+c 2-jets, WZ+l 2-jets, are allowed to float, while the remaining background contributions are held fixed. The parameters  $\mu_{WZ+b-1-jet}$ ,  $\mu_{WZ+charm1-jet}$ ,  $\mu_{WZ+light-1-jet}$ ,  $\mu_{WZ+b-2-jet}$ ,  $\mu_{WZ+charm2-jet}$ ,  $\mu_{WZ+light-2-jet}$ , where  $\mu = \sigma_{\text{observed}}/\sigma_{\text{SM}}$ , are extracted from the fit. A simultaneous fit is performed over all 1-jet and 2-jet regions.

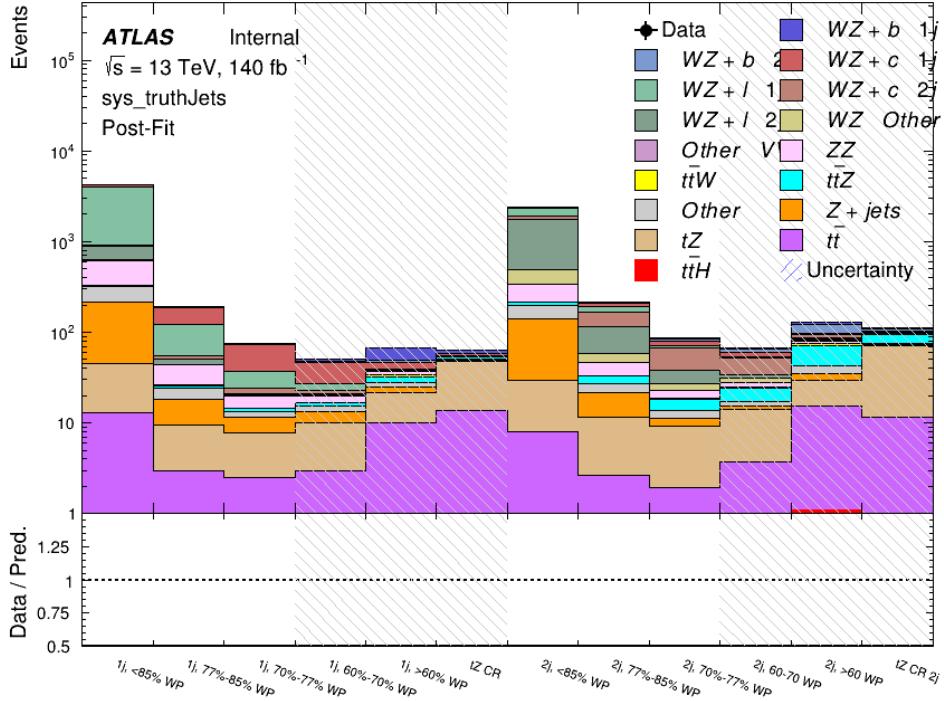


Figure 37: Post-fit summary of the fit regions.

As described in Section 7, there are 235 systematic uncertainties that are considered as NPs in the fit. These NPs are constrained by Gaussian or log-normal probability density functions. The latter are used for normalisation factors to ensure that they are always positive. The expected number of signal and background events are functions of the likelihood. The prior for each NP is added as a penalty term, decreasing the likelihood as it is shifted away from its nominal value.

Several alternative fit strategies are documented in Sections 8.3–8.4.1. These include a measurement of  $WZ + 1$  or  $2$  jets inclusively, a fit where  $tZ$  is allowed to float, and a case where  $tZ$  is included as part of the signal.

## 8.2 Results of the Simultaneous Fit

The Asimov fit for 1-jet events gives an expected  $\mu$  value of  $1.00^{+0.47}_{-0.43}(\text{stat})^{+0.30}_{-0.27}(\text{sys})$  for  $WZ + b$ . The normalization factors extracted from the fit for  $WZ + \text{charm}$  and  $WZ + \text{light}$  are  $1.00^{+0.18}_{-0.17}(\text{stat})^{+0.19}_{-0.17}(\text{sys})$  and  $1.00 \pm 0.06 \pm 0.14$ , respectively.

The expected cross-section of  $WZ+b$  with 1-jet in the fiducial region outlined in Section 2 is  $1.74^{+0.82}_{-0.75}(\text{stat})^{+0.53}_{-0.48}(\text{sys}) \text{ fb}$ , and  $14.6 \pm 2.5(\text{stat}) \pm 2.3(\text{sys}) \text{ fb}$  for  $WZ + \text{charm}$ , with a

614 correlation of -0.15 between them. An expected significance of 2.0 is observed for WZ + b in  
 615 this region.

616 For 2-jet events, the fit gives an expected  $\mu$  value of  $1.00^{+0.53}_{-0.51}(\text{stat})^{+0.39}_{-0.34}(\text{sys})$  for WZ + b. The  
 617 fitted cross-section modifiers for WZ + charm and WZ + light are  $1.00^{+0.25}_{-0.24}(\text{stat})^{+0.32}_{-0.27}(\text{sys})$   
 618 and  $1.00 \pm 0.06 \pm 0.16$ , respectively.

619 The expected WZ + b cross-section in the fiducial region with 2 associated jets is  $2.5^{+1.3}_{-1.3}(\text{stat})^{+0.95}_{-0.83}(\text{sys})$   
 620 fb with an expected significance of  $1.7\sigma$ . The 2-jet expected cross-section of WZ + charm is  
 621  $12.7^{+3.3}_{-3.2}(\text{stat})^{+3.9}_{-3.4}(\text{sys}) \pm 3.2(\text{stat}) \pm 2.7(\text{sys})$  fb, and the correlation between WZ + charm  
 622 and WZ + b is -0.22.

623 The results of the fit to an Asimov dataset for the fiducial regions considered, including both the  
 624 normalization factors as well as the expected cross-sections, along with their uncertainties, are  
 625 summarized in Table 14.

626

| Process        | $\mu$   | $\sigma$   |
|----------------|---|--|
| WZ + b - 1-jet | $1.00^{+0.47}_{-0.43}(\text{stat})^{+0.30}_{-0.27}(\text{sys})$ | $1.74^{+0.82}_{-0.75}(\text{stat})^{+0.53}_{-0.48}(\text{sys})$ fb |
| WZ + c - 1-jet | $1.00^{+0.18}_{-0.17}(\text{stat})^{+0.19}_{-0.17}(\text{sys})$ | $14.6^{+2.5}_{-2.3}(\text{stat})^{+2.6}_{-2.3}(\text{sys})$ fb     |
| WZ + b - 2-jet | $1.00^{+0.53}_{-0.51}(\text{stat})^{+0.39}_{-0.34}(\text{sys})$ | $2.5^{+1.3}_{-1.3}(\text{stat})^{+0.95}_{-0.83}(\text{sys})$ fb    |
| WZ + c - 2-jet | $1.00^{+0.25}_{-0.24}(\text{stat})^{+0.32}_{-0.27}(\text{sys})$ | $12.7^{+3.3}_{-3.2}(\text{stat})^{+3.9}_{-3.4}(\text{sys})$ fb     |

Table 14: Normalization factors and cross-sections extracted from the fit for each of the fiducial regions considered

627 An expected significance of  $2.0\sigma$  is observed for WZ + b with 1-jet, and  $1.7\sigma$  for WZ + b with  
 628 two jets. A summary of the correlations between these various measurements is shown in Figure  
 629 38.

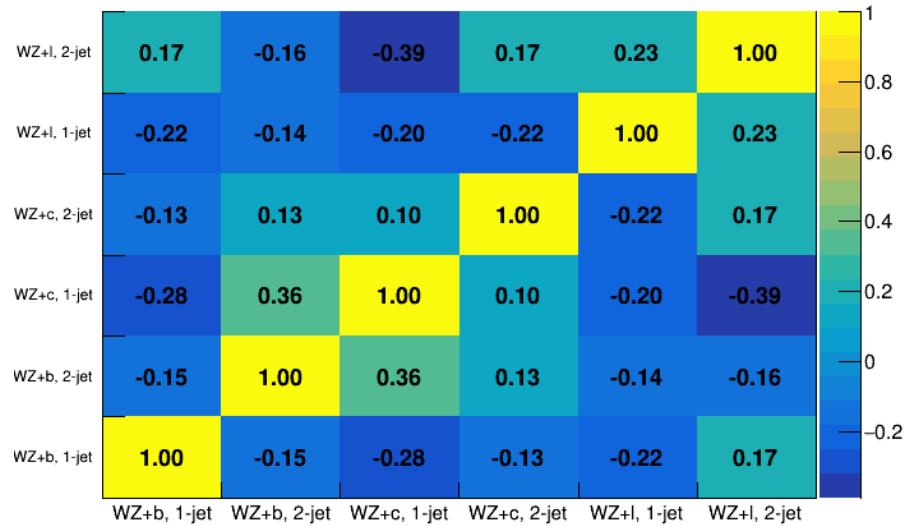


Figure 38: Correlations between the various measured components of WZ.

630 The pre-fit yields in each of the 1-jet regions used in the fit are shown in Table 15.

631

| Sample              | 1j, <85% WP     | 1j, 77%-85% WP  | 1j, 70%-77% WP  | 1j, 60%-70% WP  | 1j, 60% WP      | tZ CR           |
|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| WZ + b – 1j         | $8.1 \pm 1.6$   | $4.7 \pm 0.5$   | $4.6 \pm 0.4$   | $5.1 \pm 0.4$   | $18.1 \pm 2.4$  | $5.0 \pm 0.6$   |
| WZ + c – 1j         | $260 \pm 22$    | $81 \pm 6$      | $43.1 \pm 3.6$  | $25.8 \pm 2.6$  | $9.4 \pm 1.8$   | $2.9 \pm 0.6$   |
| WZ + l – 1j         | $3090 \pm 250$  | $91 \pm 13$     | $17 \pm 3$      | $4.9 \pm 1.6$   | $1.3 \pm 0.4$   | $0.2 \pm 0.1$   |
| WZ + b – 2j         | $1.10 \pm 0.37$ | $0.44 \pm 0.11$ | $0.39 \pm 0.06$ | $0.62 \pm 0.14$ | $2.1 \pm 0.5$   | $0.59 \pm 0.14$ |
| WZ + c – 2j         | $21 \pm 5$      | $5.6 \pm 1.2$   | $3.0 \pm 0.7$   | $2.0 \pm 0.5$   | $0.70 \pm 0.20$ | $0.30 \pm 0.08$ |
| WZ + l – 2j         | $250 \pm 60$    | $5.7 \pm 1.6$   | $0.73 \pm 0.53$ | $0.31 \pm 0.15$ | $0.07 \pm 0.06$ | $0.01 \pm 0.01$ |
| WZ – Other          | $13 \pm 5$      | $1.4 \pm 0.4$   | $0.42 \pm 0.08$ | $0.2 \pm 0.01$  | $0.30 \pm 0.05$ | $0.67 \pm 0.15$ |
| Other VV            | $6.2 \pm 0.6$   | $0.2 \pm 0.4$   | $0.2 \pm 0.04$  | $0.07 \pm 0.1$  | $0.1 \pm 0.1$   | $0.1 \pm 0.2$   |
| ZZ                  | $336 \pm 26$    | $17.8 \pm 2.1$  | $4.3 \pm 0.6$   | $1.7 \pm 0.5$   | $0.36 \pm 0.08$ | $0.10 \pm 0.03$ |
| t <bar>t&gt;W</bar> | $1.1 \pm 0.2$   | $0.2 \pm 0.1$   | $0.3 \pm 0.1$   | $0.4 \pm 0.1$   | $1.5 \pm 0.3$   | $0.7 \pm 0.2$   |
| t <bar>t&gt;Z</bar> | $6.8 \pm 1.2$   | $1.4 \pm 0.3$   | $1.0 \pm 0.2$   | $1.2 \pm 0.2$   | $4.4 \pm 0.8$   | $3.2 \pm 0.6$   |
| Z + jets            | $169 \pm 38$    | $8.9 \pm 1.9$   | $3.7 \pm 0.8$   | $3.3 \pm 0.7$   | $3.2 \pm 0.7$   | $0.8 \pm 0.17$  |
| V + $\gamma$        | $45 \pm 28$     | $1.9 \pm 2.4$   | $0.1 \pm 0.1$   | $0.02 \pm 0.01$ | $1.0 \pm 0.9$   | $0.02 \pm 0.03$ |
| tZ                  | $31.8 \pm 4.3$  | $6.4 \pm 1.1$   | $5.3 \pm 0.8$   | $7.2 \pm 1.1$   | $11.8 \pm 2.0$  | $33.9 \pm 4.5$  |
| tW                  | $1.4 \pm 0.8$   | $0.2 \pm 0.5$   | $0.0 \pm 0.2$   | $0.7 \pm 0.6$   | $0.26 \pm 0.42$ | $0.39 \pm 0.41$ |
| WtZ                 | $2.3 \pm 1.2$   | $0.6 \pm 0.3$   | $0.3 \pm 0.21$  | $0.27 \pm 0.2$  | $1.1 \pm 0.7$   | $0.6 \pm 0.5$   |
| VVV                 | $12.4 \pm 0.5$  | $0.93 \pm 0.06$ | $0.35 \pm 0.03$ | $0.13 \pm 0.02$ | $0.14 \pm 0.03$ | $0.02 \pm 0.01$ |
| VH                  | $40 \pm 6$      | $2.6 \pm 1.4$   | $0.9 \pm 0.8$   | $0.7 \pm 0.8$   | $0.5 \pm 0.6$   | $0.0 \pm 0.0$   |
| t <bar>t&gt;</bar>  | $12.1 \pm 1.6$  | $2.9 \pm 0.6$   | $2.5 \pm 0.5$   | $2.8 \pm 0.5$   | $11.2 \pm 1.4$  | $10.9 \pm 1.5$  |
| t <bar>t&gt;H</bar> | $0.24 \pm 0.03$ | $0.05 \pm 0.01$ | $0.04 \pm 0.01$ | $0.06 \pm 0.01$ | $0.20 \pm 0.03$ | $0.13 \pm 0.02$ |
| Total               | $5010 \pm 260$  | $227 \pm 24$    | $88 \pm 12$     | $57 \pm 8$      | $76 \pm 16$     | $53 \pm 8$      |

Table 15: Pre-fit yields in each of the 1-jet regions.

<sup>632</sup> Here <85% includes jets that fail to pass the 85% WP, and 60% includes jets that pass the highest WP. The post-fit yields in each region are summarized in Table 16.

<sup>634</sup>

|              | 1j, <85% WP     | 1j, 77%-85% WP  | 1j, 70%-77% WP  | 1j, 60%-70% WP  | 1j, 60% WP      | tZ CR           |
|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| WZ + b – 1j  | $8.1 \pm 4.9$   | $4.7 \pm 2.0$   | $4.6 \pm 2.0$   | $5.1 \pm 2.1$   | $18 \pm 10$     | $5.0 \pm 2.5$   |
| WZ + c – 1j  | $260 \pm 60$    | $80 \pm 14$     | $43 \pm 7$      | $26 \pm 5$      | $7.4 \pm 2.3$   | $2.1 \pm 0.7$   |
| WZ + l – 1j  | $3090 \pm 130$  | $90 \pm 11$     | $17.3 \pm 2.8$  | $4.9 \pm 1.6$   | $1.3 \pm 0.4$   | $0.23 \pm 0.13$ |
| WZ + b – 2j  | $1.10 \pm 0.37$ | $0.44 \pm 0.11$ | $0.39 \pm 0.06$ | $0.62 \pm 0.14$ | $2.1 \pm 0.5$   | $0.59 \pm 0.14$ |
| WZ + c – 2j  | $21 \pm 5$      | $5.6 \pm 1.2$   | $3.0 \pm 0.7$   | $2.0 \pm 0.5$   | $0.70 \pm 0.20$ | $0.30 \pm 0.08$ |
| WZ + l – 2j  | $250 \pm 60$    | $5.7 \pm 1.6$   | $0.73 \pm 0.53$ | $0.31 \pm 0.15$ | $0.07 \pm 0.06$ | $0.01 \pm 0.01$ |
| WZ – Other   | $13 \pm 5$      | $1.4 \pm 0.4$   | $0.42 \pm 0.08$ | $0.2 \pm 0.01$  | $0.30 \pm 0.05$ | $0.67 \pm 0.15$ |
| Other VV     | $6.2 \pm 0.6$   | $0.92 \pm 0.07$ | $0.02 \pm 0.01$ | $0.01 \pm 0.01$ | $0.01 \pm 0.01$ | $0.01 \pm 0.01$ |
| ZZ           | $346 \pm 57$    | $19 \pm 5$      | $4.3 \pm 0.8$   | $2.7 \pm 0.5$   | $2.4 \pm 0.1$   | $2.1 \pm 0.6$   |
| t̄tW         | $1.09 \pm 0.21$ | $0.2 \pm 0.1$   | $0.1 \pm 0.1$   | $0.4 \pm 0.1$   | $1.5 \pm 0.3$   | $0.1 \pm 0.2$   |
| t̄tZ         | $6.8 \pm 1.2$   | $1.4 \pm 0.3$   | $1.0 \pm 0.2$   | $1.2 \pm 0.2$   | $4.4 \pm 0.7$   | $3.2 \pm 0.5$   |
| rare Top     | $0.14 \pm 0.04$ | $0.04 \pm 0.02$ | $0.04 \pm 0.0$  | $0.1 \pm 0.03$  | $0.14 \pm 0.04$ | $0.15 \pm 0.05$ |
| t̄tWW        | $0.04 \pm 0.03$ | $0.01 \pm 0.02$ | $0.01 \pm 0.01$ | $0.01 \pm 0.01$ | $0.01 \pm 0.02$ | $0.01 \pm 0.01$ |
| Z + jets     | $169 \pm 37$    | $8.9 \pm 1.9$   | $3.7 \pm 0.8$   | $3.3 \pm 0.7$   | $3.2 \pm 0.7$   | $0.8 \pm 0.2$   |
| W + jets     | $0.01 \pm 0.01$ |
| V + $\gamma$ | $46 \pm 28$     | $1.9 \pm 2.4$   | $0.1 \pm 0.1$   | $0.0 \pm 0.2$   | $1.0 \pm 0.9$   | $0.0 \pm 0.0$   |
| tZ           | $31 \pm 4$      | $6.0 \pm 1.0$   | $5.3 \pm 0.8$   | $7.2 \pm 1.0$   | $11.8 \pm 1.8$  | $33.9 \pm 4.5$  |
| tW           | $1.37 \pm 0.82$ | $0.18 \pm 0.26$ | $0.01 \pm 0.12$ | $0.67 \pm 0.64$ | $0.26 \pm 0.42$ | $0.39 \pm 0.41$ |
| WtZ          | $2.3 \pm 1.2$   | $0.6 \pm 0.3$   | $0.3 \pm 0.2$   | $0.3 \pm 0.2$   | $1.1 \pm 0.6$   | $0.6 \pm 0.3$   |
| VVV          | $12.4 \pm 0.4$  | $0.9 \pm 0.1$   | $0.4 \pm 0.1$   | $0.13 \pm 0.02$ | $0.14 \pm 0.03$ | $0.02 \pm 0.01$ |
| VH           | $40 \pm 6$      | $2.6 \pm 1.4$   | $0.9 \pm 0.8$   | $0.7 \pm 0.8$   | $0.4 \pm 0.6$   | $0.01 \pm 0.01$ |
| t̄t          | $12.1 \pm 1.6$  | $2.9 \pm 0.6$   | $2.5 \pm 0.5$   | $2.8 \pm 0.5$   | $11.2 \pm 1.5$  | $10.9 \pm 1.4$  |
| t̄tH         | $0.24 \pm 0.03$ | $0.05 \pm 0.01$ | $0.04 \pm 0.01$ | $0.06 \pm 0.01$ | $0.20 \pm 0.03$ | $0.13 \pm 0.02$ |
| Total        | $5100 \pm 110$  | $227 \pm 12$    | $87 \pm 6$      | $56.7 \pm 4.4$  | $76 \pm 9$      | $52.5 \pm 4.2$  |

Table 16: Post-fit yields in each of the 1-jet regions.

635 The impact of each NP is calculated by performing the fit with the parameter of interest held  
 636 fixed, varied from its fitted value by its uncertainty, and calculating  $\Delta\mu$  relative to the baseline  
 637 fit. The impact of the most significant sources of systematic uncertainties on WZ + b with one  
 638 associated jet is summarized in Table 17.

| Uncertainty Source              | $\Delta\mu$ |       |
|---------------------------------|-------------|-------|
| WZ + 1-jet light cross-section  | 0.13        | -0.15 |
| WZ + 1-jet charm cross-section  | -0.10       | 0.12  |
| Jet Energy Scale                | 0.1         | -0.13 |
| Other Diboson + b cross-section | -0.09       | 0.09  |
| tZ cross-section                | -0.08       | 0.08  |
| WZ 1-jet/2-jet Migration        | 0.08        | -0.07 |
| Jet Energy Resolution           | -0.07       | 0.08  |
| Luminosity                      | -0.06       | 0.07  |
| Flavor tagging                  | 0.05        | 0.05  |
| t <bar>t} cross-section</bar>   | -0.05       | 0.05  |
| Total Systematic Uncertainty    | 0.28        | 0.33  |

Table 17: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + b with exactly one associated jet.

| Uncertainty Source              | $\Delta\sigma/\sigma_{\text{nominal}}$ |        |
|---------------------------------|--|--------|
| WZ + c 1j/2j migration          | 0.12                                   | -0.09  |
| Flavor Tagging                  | 0.09                                   | 0.08   |
| WZ + b, 1-jet cross-section     | -0.04                                  | 0.05   |
| Luminosity                      | -0.04                                  | 0.04   |
| Jet Energy Resolution           | 0.04                                   | 0.04   |
| WZ + b, 2-jet cross-section     | 0.04                                   | -0.03  |
| WZ cross-section - QCD scale    | -0.04                                  | 0.04   |
| Jet Energy Scaling              | 0.04                                   | 0.02   |
| WZ cross-section - PDF          | -0.03                                  | 0.03   |
| WZ + light, 1-jet cross-section | 0.03                                   | -0.03  |
| total                           | 0.1879                                 | 0.1753 |

Table 18: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + c with exactly one associated jet.

<sup>639</sup> The ranking and impact of those nuisance parameters with the largest contribution to the overall  
<sup>640</sup> uncertainty is shown in Figure 39.

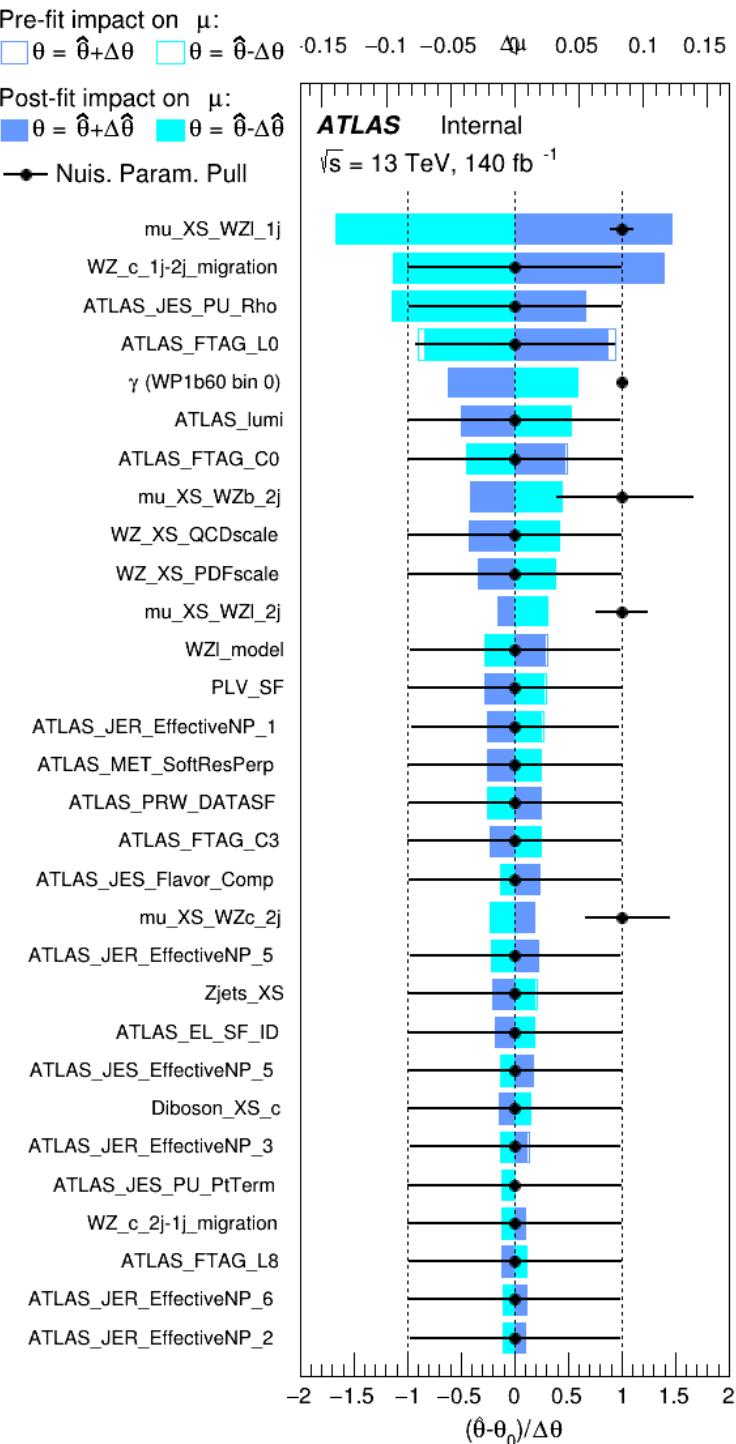


Figure 39: Impact of systematic uncertainties on the signal-strength of  $WZ + b$  for events with exactly one jet

<sup>641</sup> Here  $\gamma$  represents the impact of the statistical uncertainty of the MC prediction in that particular  
<sup>642</sup> bin. The large impact of the Jet Energy Scale and Jet Flavor Tagging is unsurprising, as the  
<sup>643</sup> definition of the fit regions depends heavily on the modeling of the jets. The other major sources  
<sup>644</sup> of uncertainty come from background modelling and cross-section uncertainty.

<sup>645</sup> Pre-fit yields in each of the 2-jet fit are shown in Table 19.

|                | 2j, <85% WP      | 2j, 77%-85% WP  | 2j, 70%-77% WP  | 2j, 60%-70% WP  | 2j, 60% WP      | tZ CR 2j        |
|----------------|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| WZ + b - 2j    | $3.1 \pm 1.6$    | $6.7 \pm 0.5$   | $5.6 \pm 0.4$   | $8.0 \pm 0.6$   | $24 \pm 2$      | $5 \pm 1$       |
| WZ + c - 2j    | $180 \pm 20$     | $54 \pm 6$      | $41 \pm 3$      | $24 \pm 3$      | $17 \pm 2$      | $7.0 \pm 0.6$   |
| WZ + l - 2j    | $1250 \pm 150$   | $90 \pm 14$     | $18 \pm 3$      | $5.8 \pm 1.4$   | $1.4 \pm 0.4$   | $0.25 \pm 0.15$ |
| WZ + b - 1j    | $3.4 \pm 0.6$    | $1.52 \pm 0.35$ | $1.58 \pm 0.23$ | $1.95 \pm 0.39$ | $7.8 \pm 1.1$   | $0.8 \pm 0.6$   |
| WZ + c - 1j    | $56 \pm 14$      | $17.6 \pm 4.0$  | $8.6 \pm 2.2$   | $6.3 \pm 1.8$   | $3.0 \pm 0.9$   | $0.7 \pm 0.2$   |
| WZ + l - 1j    | $427 \pm 120$    | $24 \pm 7$      | $4.7 \pm 2.3$   | $1.6 \pm 0.7$   | $0.3 \pm 0.2$   | $0.01 \pm 0.01$ |
| WZ - Other     | $129 \pm 29$     | $6.1 \pm 4.6$   | $1.2 \pm 0.3$   | $0.3 \pm 0.2$   | $2.9 \pm 0.5$   | $3.6 \pm 0.6$   |
| Other VV       | $7.63 \pm 0.63$  | $0.6 \pm 0.5$   | $0.16 \pm 0.03$ | $0.01 \pm 0.01$ | $0.1 \pm 0.1$   | $0.1 \pm 0.1$   |
| ZZ             | $135 \pm 20$     | $14.1 \pm 3.2$  | $4.7 \pm 0.8$   | $4.0 \pm 0.6$   | $4.1 \pm 0.7$   | $3.1 \pm 0.5$   |
| t $\bar{t}$ W  | $0.8 \pm 0.2$    | $0.4 \pm 0.1$   | $0.5 \pm 0.1$   | $0.7 \pm 0.2$   | $4.3 \pm 0.6$   | $3.9 \pm 0.6$   |
| t $\bar{t}$ Z  | $14.7 \pm 2.2$   | $5.6 \pm 0.8$   | $4.5 \pm 0.7$   | $6.5 \pm 1.1$   | $25.4 \pm 4.0$  | $21.9 \pm 3.4$  |
| rare Top       | $0.14 \pm 0.04$  | $0.07 \pm 0.03$ | $0.03 \pm 0.02$ | $0.09 \pm 0.03$ | $0.37 \pm 0.07$ | $0.6 \pm 0.1$   |
| t $\bar{t}$ WW | $0.04 \pm 0.03$  | $0.02 \pm 0.02$ | $0.01 \pm 0.01$ | $0.01 \pm 0.00$ | $0.03 \pm 0.03$ | $0.01 \pm 0.01$ |
| Z + jets       | $110.0 \pm 22.9$ | $9.6 \pm 2.0$   | $2.1 \pm 0.50$  | $1.6 \pm 0.4$   | $5.1 \pm 1.1$   | $1.5 \pm 0.3$   |
| W + jets       | $0.0 \pm 0.0$    | $0.0 \pm 0.0$   | $0.0 \pm 0.0$   | $0.0 \pm 0.0$   | $0.0 \pm 0.0$   | $0.0 \pm 0.0$   |
| V + $\gamma$   | $25 \pm 18$      | $0.5 \pm 0.2$   | $0.1 \pm 0.1$   | $0.1 \pm 0.1$   | $0.0 \pm 0.02$  | $0.05 \pm 0.07$ |
| tZ             | $21.9 \pm 2.9$   | $9.6 \pm 1.3$   | $9.1 \pm 1.0$   | $10.0 \pm 1.5$  | $14.7 \pm 3.2$  | $60 \pm 6$      |
| tW             | $0.9 \pm 0.7$    | $0.2 \pm 0.3$   | $0.0 \pm 0.1$   | $0.0 \pm 0.0$   | $0.8 \pm 0.6$   | $0.2 \pm 0.2$   |
| WtZ            | $4.9 \pm 2.5$    | $1.5 \pm 0.8$   | $1.1 \pm 0.6$   | $1.3 \pm 0.7$   | $4.6 \pm 2.4$   | $3.3 \pm 1.7$   |
| VVV            | $7.4 \pm 0.3$    | $1.0 \pm 0.1$   | $0.4 \pm 0.1$   | $0.2 \pm 0.1$   | $0.13 \pm 0.03$ | $0.04 \pm 0.01$ |
| VH             | $19.5 \pm 4.2$   | $2.8 \pm 1.6$   | $0.7 \pm 0.7$   | $0.1 \pm 0.2$   | $0.0 \pm 0.0$   | $0.0 \pm 0.0$   |
| t $\bar{t}$    | $0.7 \pm 0.4$    | $0.1 \pm 0.1$   | $0.05 \pm 0.06$ | $0.15 \pm 0.13$ | $0.8 \pm 0.5$   | $2.3 \pm 1.2$   |
| t $\bar{t}$    | $6.8 \pm 1.0$    | $2.4 \pm 0.5$   | $1.8 \pm 0.4$   | $3.3 \pm 0.6$   | $8.4 \pm 1.2$   | $13.6 \pm 1.7$  |
| t $\bar{t}$ H  | $0.4 \pm 0.1$    | $0.2 \pm 0.1$   | $0.16 \pm 0.02$ | $0.23 \pm 0.03$ | $0.94 \pm 0.11$ | $1.03 \pm 0.12$ |
| Total          | $2580 \pm 160$   | $229 \pm 24$    | $89 \pm 13$     | $69 \pm 11$     | $120 \pm 15$    | $108 \pm 11$    |

Table 19: Pre-fit yields in each of the 2-jet regions.

<sup>646</sup> The post-fit yields in each region are summarized in Table 20.

|             | 2j, <85% WP     | 2j, 77%-85% WP  | 2j, 70%-77% WP  | 2j, 60%-70% WP  | 2j, 60% WP      | tZ CR 2j        |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| WZ + b      | $13 \pm 6$      | $6.7 \pm 2.9$   | $5.8 \pm 2.5$   | $8.0 \pm 3.5$   | $31 \pm 13$     | $14 \pm 5$      |
| WZ + c      | $260 \pm 60$    | $77 \pm 15$     | $41 \pm 8$      | $26 \pm 5$      | $10.9 \pm 2.4$  | $4.8 \pm 1.1$   |
| WZ + l      | $1860 \pm 90$   | $90 \pm 12$     | $17.6 \pm 2.8$  | $5.8 \pm 1.3$   | $1.4 \pm 0.4$   | $0.3 \pm 0.2$   |
| WZ + b - 1j | $3.4 \pm 0.6$   | $1.52 \pm 0.35$ | $1.58 \pm 0.23$ | $1.95 \pm 0.39$ | $6.7 \pm 1.1$   | $1.9 \pm 0.6$   |
| WZ + c - 1j | $56 \pm 14$     | $17.6 \pm 4.0$  | $8.6 \pm 2.2$   | $6.3 \pm 1.8$   | $3.0 \pm 0.9$   | $0.7 \pm 0.2$   |
| WZ + l - 1j | $427 \pm 120$   | $24 \pm 7$      | $4.7 \pm 2.3$   | $1.6 \pm 0.7$   | $0.3 \pm 0.2$   | $0.01 \pm 0.01$ |
| WZ - Other  | $129 \pm 29$    | $6.1 \pm 4.6$   | $1.2 \pm 0.3$   | $0.3 \pm 0.2$   | $2.9 \pm 0.5$   | $3.6 \pm 0.6$   |
| Other VV    | $7.6 \pm 0.6$   | $0.3 \pm 0.3$   | $0.3 \pm 0.1$   | $0.1 \pm 0.06$  | $0.03 \pm 0.02$ | $0.1 \pm 0.1$   |
| ZZ          | $145 \pm 30$    | $11.3 \pm 4.4$  | $2.7 \pm 1.6$   | $1.0 \pm 0.3$   | $4.0 \pm 0.1$   | $2.4 \pm 0.1$   |
| t̄W         | $0.8 \pm 0.2$   | $0.4 \pm 0.1$   | $0.54 \pm 0.12$ | $0.74 \pm 0.15$ | $4.3 \pm 0.6$   | $3.9 \pm 0.6$   |
| t̄Z         | $14.7 \pm 2.2$  | $5.6 \pm 0.8$   | $4.5 \pm 0.7$   | $6.5 \pm 1.0$   | $25.4 \pm 3.9$  | $21.9 \pm 3.3$  |
| rare Top    | $0.14 \pm 0.04$ | $0.07 \pm 0.03$ | $0.03 \pm 0.02$ | $0.09 \pm 0.03$ | $0.4 \pm 0.1$   | $0.6 \pm 0.1$   |
| t̄WW        | $0.04 \pm 0.03$ | $0.02 \pm 0.02$ | $0.01 \pm 0.01$ | $0.01 \pm 0.01$ | $0.03 \pm 0.03$ | $0.01 \pm 0.01$ |
| Z + jets    | $110 \pm 23$    | $9.6 \pm 2.0$   | $2.1 \pm 0.5$   | $1.6 \pm 0.4$   | $5.1 \pm 1.1$   | $1.5 \pm 0.3$   |
| W + jets    | $0.0 \pm 0.0$   |
| V + γ       | $25 \pm 19$     | $0.5 \pm 0.2$   | $0.1 \pm 0.1$   | $0.13 \pm 0.14$ | $0.0 \pm 0.02$  | $0.05 \pm 0.07$ |
| tZ          | $21.9 \pm 2.7$  | $9.6 \pm 1.2$   | $7.1 \pm 0.9$   | $10.0 \pm 1.4$  | $14.7 \pm 3.0$  | $60 \pm 6$      |
| tW          | $0.1 \pm 0.7$   | $0.2 \pm 0.3$   | $0.0 \pm 0.1$   | $0.0 \pm 0.0$   | $0.8 \pm 0.6$   | $0.2 \pm 0.2$   |
| WtZ         | $4.9 \pm 2.5$   | $1.5 \pm 0.8$   | $1.1 \pm 0.6$   | $1.3 \pm 0.7$   | $4.6 \pm 2.3$   | $3.3 \pm 1.7$   |
| VVV         | $7.4 \pm 0.3$   | $1.0 \pm 0.1$   | $0.36 \pm 0.03$ | $0.19 \pm 0.03$ | $0.13 \pm 0.03$ | $0.04 \pm 0.01$ |
| VH          | $19 \pm 4$      | $2.8 \pm 1.6$   | $0.7 \pm 0.7$   | $0.1 \pm 0.2$   | $0.0 \pm 0.0$   | $0.0 \pm 0.0$   |
| t̄t         | $6.8 \pm 1.0$   | $2.4 \pm 0.5$   | $1.8 \pm 0.4$   | $3.3 \pm 0.6$   | $8.4 \pm 1.2$   | $13.6 \pm 1.7$  |
| t̄tH        | $0.40 \pm 0.05$ | $0.19 \pm 0.03$ | $0.16 \pm 0.02$ | $0.23 \pm 0.03$ | $0.94 \pm 0.11$ | $1.03 \pm 0.11$ |
| Total       | $2580 \pm 60$   | $229 \pm 11$    | $89 \pm 6$      | $69.1 \pm 4.1$  | $120 \pm 10$    | $108 \pm 6$     |

Table 20: Post-fit yields in each of the 2-jet regions.

<sup>647</sup> The same set of systematic uncertainties consider for the 1-jet fit are included in the 2-jet fit as  
<sup>648</sup> well. The impact of the most significant systematic uncertainties is summarized in Table 21.

| Uncertainty Source            | $\Delta\mu$ |       |
|-------------------------------|-------------|-------|
| WZ + c 2-jet cross-section    | -0.13       | 0.16  |
| WZ + l 2-jet cross-section    | 0.12        | -0.09 |
| ttZ cross-section - QCD scale | -0.10       | 0.13  |
| WZ + b 1-jet cross-section    | -0.11       | 0.10  |
| Jet Energy Scale              | -0.11       | 0.11  |
| Luminosity                    | -0.11       | 0.12  |
| tZ cross-section              | -0.11       | 0.11  |
| WtZ cross-section             | -0.07       | 0.07  |
| Flavor tagging                | 0.05        | 0.05  |
| Other VV + b cross-section    | -0.05       | 0.05  |
| Total                         | 0.35        | 0.37  |

Table 21: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + b 2-jet events.

| Uncertainty Source           | $\Delta\sigma/\sigma_{\text{nominal}}$ |        |
|------------------------------|--|--------|
| WZ + c 1j/2j migration       | -0.17                                  | 0.25   |
| Flavor Tagging               | 0.14                                   | 0.13   |
| WZ + b, 1-jet cross-section  | -0.09                                  | 0.09   |
| Jet Energy Scale             | 0.06                                   | 0.08   |
| Jet Energy Resolution        | 0.05                                   | 0.05   |
| WZ $\geq 3j/2j$ migration    | -0.04                                  | 0.04   |
| WZ + c 2j/1j migration       | -0.04                                  | 0.04   |
| WZ cross-section - QCD scale | -0.04                                  | 0.04   |
| WZ + light modelling         | 0.04                                   | -0.03  |
| Luminosity                   | -0.03                                  | 0.03   |
| total                        | 0.2694                                 | 0.3274 |

Table 22: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + c with 2 associated jets.

649 The ranking and impact of those nuisance parameters with the largest contribution to the overall  
 650 uncertainty is shown in Figure 40.

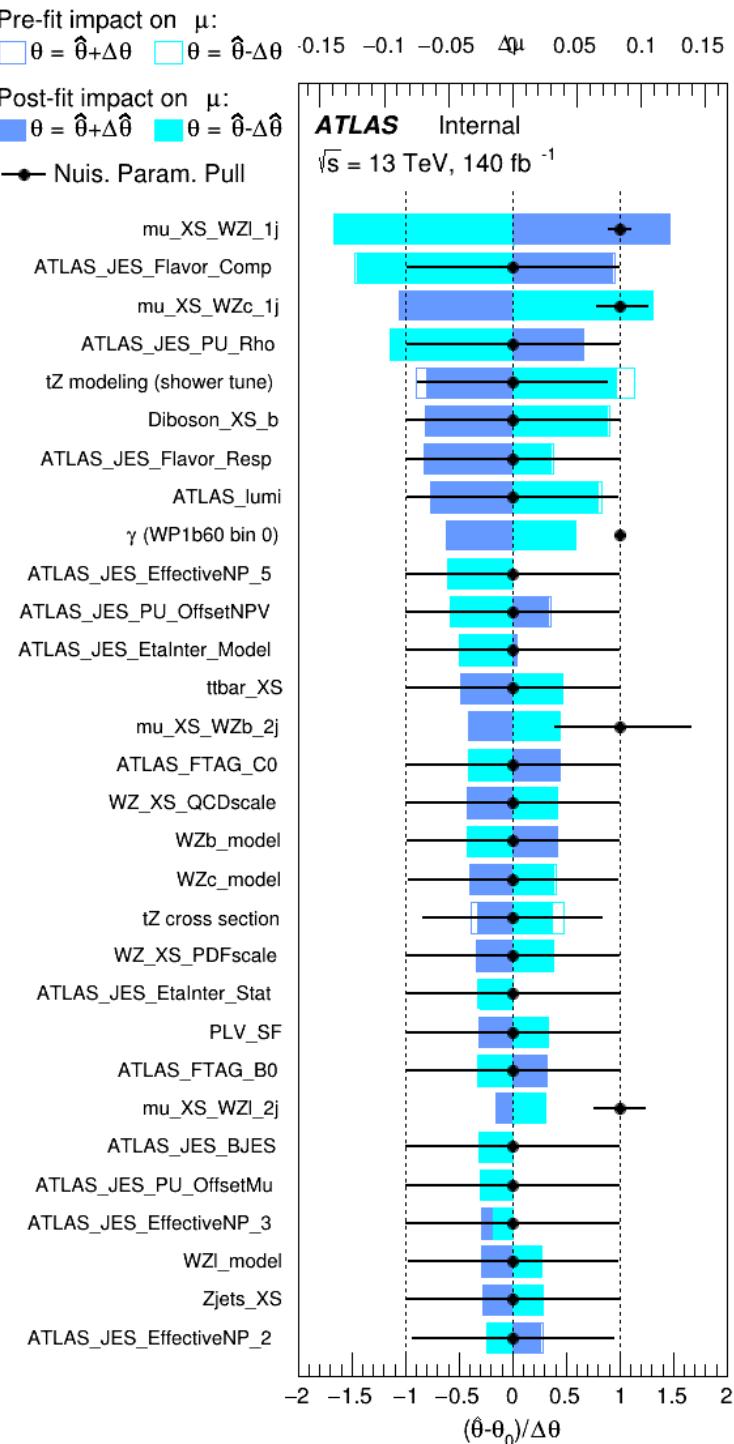


Figure 40: Impact of systematic uncertainties on the signal-strength of  $WZ + b$  in 2-jet events.

651 The large impact of the Jet Energy Scale and Jet Flavor Tagging is unsurprising, as the shape of  
652 the fit regions depends heavily on the modeling of the jets. The other major sources of uncertainty  
653 come from background modelling and cross-section uncertainty.

654 **8.3 Inclusive 1+2 Jet Fit**

655 An alternative fit is performed which combines the WZ + 1-jet and WZ + 2-jet samples rather than  
656 fitting them independently. This is done primarily as a cross-check of the nominal analysis, to  
657 see if measuring 1-jet and 2-jet events separately and combining them gives drastically different  
658 results than measuring them together.

659 For this study, three signal templates, WZ + b, WZ + charm and WZ + light, are fit to data, and  
660 the systematics accounting for migrations between 1-jet and 2-jet bins are removed. All other  
661 background and nuisance parameters remain the same as the nominal fit.

662 The measured  $\mu$  value for WZ + b is  $\mu = 1.00^{+0.30}_{-0.29}(\text{stat})^{+0.25}_{-23}(\text{sys})$ , with a significance of  $2.8\sigma$ ,  
663 and the uncertainty on WZ + charm is  $\mu = 1.00 \pm 0.12(\text{stat}) \pm 0.13(\text{sys})$ . This is compared to  
664 combined uncertainty of  $\mu = 1.00^{+0.32}_{-0.30}(\text{stat})^{+0.24}_{-23}(\text{sys})$  for WZ + b when 1-jet and 2-jet events  
665 are measured separately and then combined.

666 A post-fit summary plot of the fit regions is shown in Figure 41:

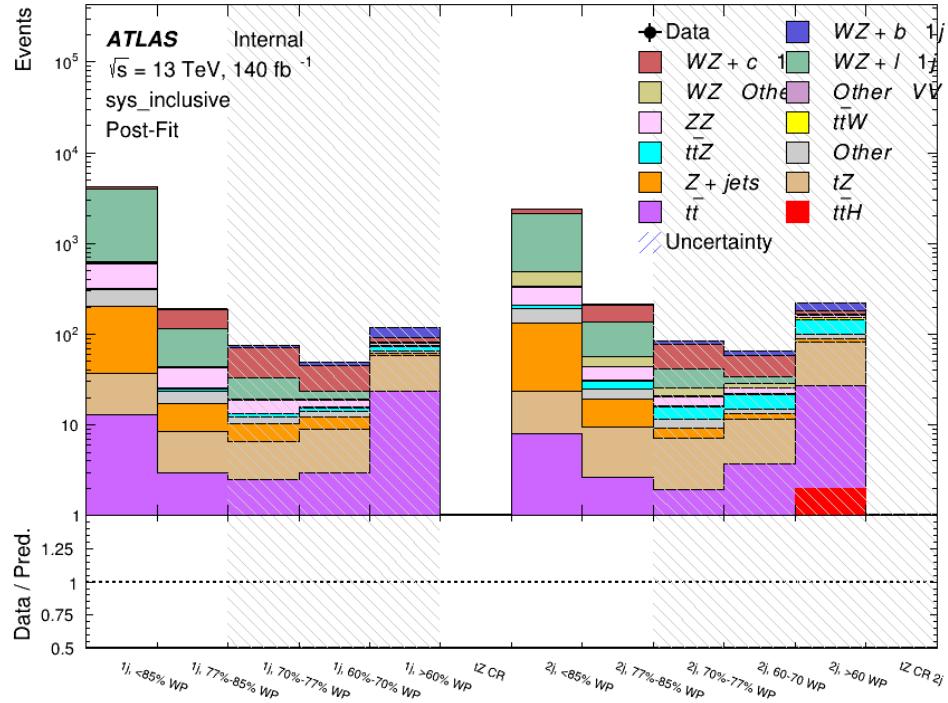


Figure 41: Post-fit summary of the 1-jet fit regions.

667 The impact of the most significant sources of systematic uncertainties on the measurement of  
 668 WZ+b is summarized in Table 23.

| Uncertainty Source              | $\Delta\mu$ |       |
|---------------------------------|-------------|-------|
| WZ + light cross-section        | 0.13        | -0.12 |
| WZ + charm cross-section        | -0.10       | 0.12  |
| Jet Energy Scale                | 0.08        | 0.13  |
| tZ cross-section                | -0.10       | 0.10  |
| Jet Energy Resolution           | -0.10       | 0.10  |
| Luminosity                      | -0.08       | 0.09  |
| Other Diboson + b cross-section | -0.07       | 0.07  |
| Flavor tagging                  | 0.05        | 0.05  |
| t̄t cross-section               | -0.05       | 0.05  |
| WZ cross-section - QCD scale    | -0.04       | 0.03  |
| Total Systematic Uncertainty    | 0.28        | 0.32  |

Table 23: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + b with one or two associated jets.

669 The ranking and impact of those nuisance parameters with the largest contribution to the overall  
670 uncertainty is shown in Figure 42.

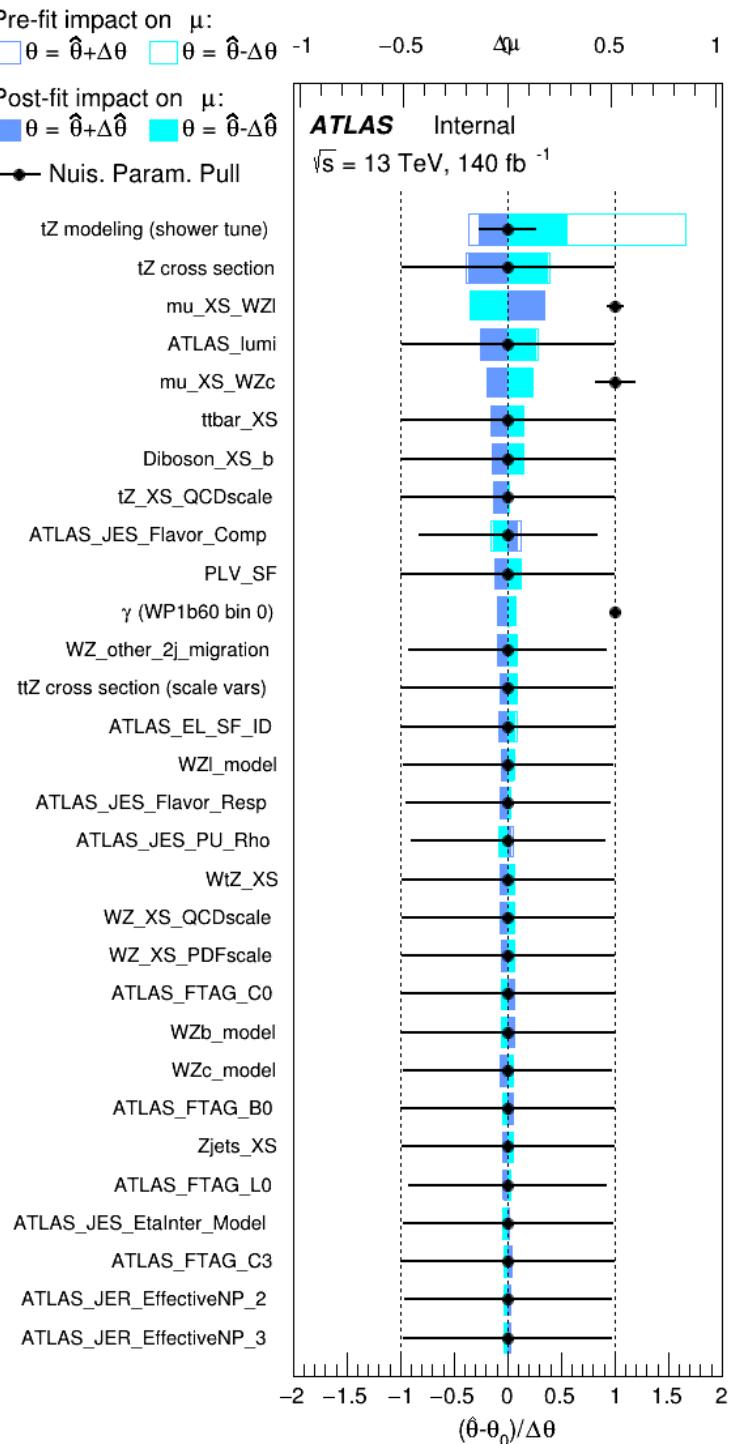


Figure 42: Impact of systematic uncertainties on the signal-strength of  $WZ + b$  for events with one or two jets

671 **8.4 Alternate tZ Inclusive Fit**

672 **8.4.1 tZ Inclusive Fit**

673 While tZ is often considered as a distinct process from WZ + b, this could also be considered part  
 674 of the signal. Alternate studies are performed where, using the same framework as the nominal  
 675 analysis, a measurement of WZ + b is performed that includes tZ as part of WZ+b.

676 Because of this change, the tZ CR is no longer necessary, and only the five pseudo-continuous  
 677 b-tag regions are used in the fit. Further, systematics related to the tZ cross-section are removed  
 678 from the fit, as they are now encompassed by the normalization measurement of WZ + b. All  
 679 other systematic uncertainties are carried over from the nominal analysis.

680 An expected WZ + b cross-section of  $4.1^{+0.78}_{-0.74}(\text{stat})^{+0.53}_{-0.52}(\text{sys}) \text{ fb}$  is extracted from the fit, with  
 681 an expected significance of  $4.0\sigma$ .

682 The impact of the predominate systematics are summarized in Table 24.

| Uncertainty Source              | $\Delta\mu$ |       |
|---------------------------------|-------------|-------|
| WZ + light cross-section        | 0.08        | -0.08 |
| Jet Energy Scale                | -0.06       | 0.08  |
| Luminosity                      | -0.05       | 0.06  |
| WZ + charm cross-section        | -0.04       | 0.05  |
| Other Diboson + b cross-section | -0.04       | 0.04  |
| WZ cross-section - QCD scale    | -0.04       | 0.03  |
| t̄t cross-section               | -0.03       | 0.03  |
| Jet Energy Resolution           | -0.03       | 0.03  |
| Flavor tagging                  | -0.03       | 0.03  |
| Z+jets cross section            | -0.02       | 0.02  |
| Total Systematic Uncertainty    | -0.15       | 0.16  |

Table 24: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + b with exactly one associated jet.

683 **8.4.2 Floating tZ**

684 In order to quantify the impact of the tZ uncertainty on the fit, an alternative fit strategy is  
 685 used where the tZ normalization is allowed to float. This normalization factor replaces the  
 686 cross-section uncertainty on tZ, and all other parameters of the fit remain the same.

687 An uncertainty of 17% on the normalization of tZ is extracted from the fit, compared to a theory  
 688 uncertainty of 15% applied to the tZ cross-section. The measured uncertainties on WZ remain  
 689 the same.

## 690 9 Conclusion

691 A measurement of WZ + heavy flavor is performed using 140  $\text{fb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$  proton-  
 692 proton collision data collected by the ATLAS detector at the LHC. The expected cross-section  
 693 of WZ+b with 1-jet is  $1.74^{+0.82}_{-0.75}(\text{stat})^{+0.53}_{-0.48}(\text{sys}) \text{ fb}$ , and  $14.6 \pm 2.5(\text{stat}) \pm 2.3(\text{sys}) \text{ fb}$  for WZ  
 694 + charm, with a correlation of -0.22 between them. An expected significance of 2.0 is observed  
 695 for WZ + b in this region.

696 For the 2-jet regions, an expected significance of 1.7 is observed for WZ + b, with an ex-  
 697 pected cross-section of  $2.5^{+1.3}_{-1.3}(\text{stat})^{+0.95}_{-0.83}(\text{sys}) \text{ fb}$ . For WZ + charm, a cross-section of  
 698  $12.7 \pm 3.2(\text{stat}) \pm 2.7(\text{sys}) \text{ fb}$  is expected for 2-jet events. A correlation of -0.26 is observed  
 699 for WZ+b and WZ + charm.

700 **This section will be include final results once unblinded.**

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794 **A Appendices**

795 **A.1 Non-prompt lepton MVA**

796 A lepton MVA has been developed to better reject non-prompt leptons than standard cut  
 797 based selections based upon impact parameter, isolation and PID. The name of this MVA is  
 798 **PromptLeptonVeto**. The full set of studies and detailed explanation can be found in [15].

799 The decays of W and Z bosons are commonly selected by the identification of one or two electrons  
 800 or muons. The negligible lifetimes of these bosons mean that the leptons produced in the decay  
 801 originate from the interaction vertex and are thus labelled “prompt”. Analyses using these  
 802 light leptons impose strict reconstruction quality, isolation and impact parameter requirements  
 803 to remove “fake” leptons. A significant source of the fake light leptons are non-prompt leptons  
 804 produced in decays of hadrons that contain bottom (b) or charm (c) quarks. Such hadrons  
 805 typically have microscopically significant lifetimes that can be detected experimentally.

806 These non-prompt leptons can also pass the tight selection criteria. In analyses that involve top (t)  
 807 quarks, which decay almost exclusively into a W boson and a b quark, non-prompt leptons from  
 808 the semileptonic decay of bottom and charm hadrons can be a significant source of background  
 809 events. This is particularly the case in the selection of same-sign dilepton and multilepton final  
 810 states.

811 The main idea is to identify non-prompt light leptons using lifetime information associated with a  
 812 track jet that matches the selected light lepton. This lifetime information is computed using tracks  
 813 contained within the jet. Typically, lepton lifetime is determined using the impact parameter of the  
 814 track reconstructed by the inner tracking detector which is matched to the reconstructed lepton.  
 815 Using additional reconstructed charged particle tracks increases the precision of identifying the  
 816 displaced decay vertex of bottom or charm hadrons that produced a non-prompt light lepton.  
 817 The MVA also includes information related to the isolation of the lepton to reject non-prompt  
 818 leptons.

819 **PromptLeptonVeto** is a gradient boosted BDT. The training of the BDT is performed on leptons  
 820 selected from the POWHEG+PYTHIA6 non-allhad  $t\bar{t}$  MC sample. Eight variables are used to train  
 821 the BDT in order to discriminate between prompt and non-prompt leptons. The track jets that  
 822 are matched to the non-prompt leptons correspond to jets initiated by b or c quarks, and may  
 823 contain a displaced vertex. Consequently, three of the selected variables are used to identify  
 824 b-tag jets by standard ATLAS flavour tagging algorithms. Two variables use the relationship  
 825 between the track jet and lepton: the ratio of the lepton  $p_T$  with respect to the track jet  $p_T$  and  
 826  $\Delta R$  between the lepton and the track jet axis. Finally three additional variables test whether the  
 827 reconstructed lepton is isolated: the number of tracks collected by the track jet and the lepton  
 828 track and calorimeter isolation variables. Table 25 describes the variables used to train the BDT  
 829 algorithm. The choice of input variables has been extensively discussed with Egamma, Muon,  
 830 Tracking, and Flavour Tagging CP groups.

831 The output distribution of the BDT is shown in Figure A.1.

| Variable                                     | Description   |
|--|---|
| $N_{\text{track}}$ in track jet              | Number of tracks collected by the track jet   |
| $\text{IP2 log}(P_b/P_{\text{light}})$       | Log-likelihood ratio between the b and light jet hypotheses with the IP2D algorithm   |
| $\text{IP3 log}(P_b/P_{\text{light}})$       | Log-likelihood ratio between the b and light jet hypotheses with the IP3D algorithm   |
| $N_{\text{TrkAtVtx}}$ SV + JF                | Number of tracks used in the secondary vertex found by the SV1 algorithm<br>in addition to the number of tracks from secondary vertices found by the JetFitter algorithm with at least two tracks |
| $p_T^{\text{lepton}}/p_T^{\text{track jet}}$ | The ratio of the lepton $p_T$ and the track jet $p_T$   |
| $\Delta R(\text{lepton}, \text{track jet})$  | $\Delta R$ between the lepton and the track jet axis  |
| $p_T^{\text{VarCone30}}/p_T$                 | Lepton track isolation, with track collecting radius of $\Delta R < 0.3$  |
| $E_T^{\text{TopoCone30}}/p_T$                | Lepton calorimeter isolation, with topological cluster collecting radius of $\Delta R < 0.3$  |

Table 25: A table of the variables used in the training of `PromptLeptonVeto`.

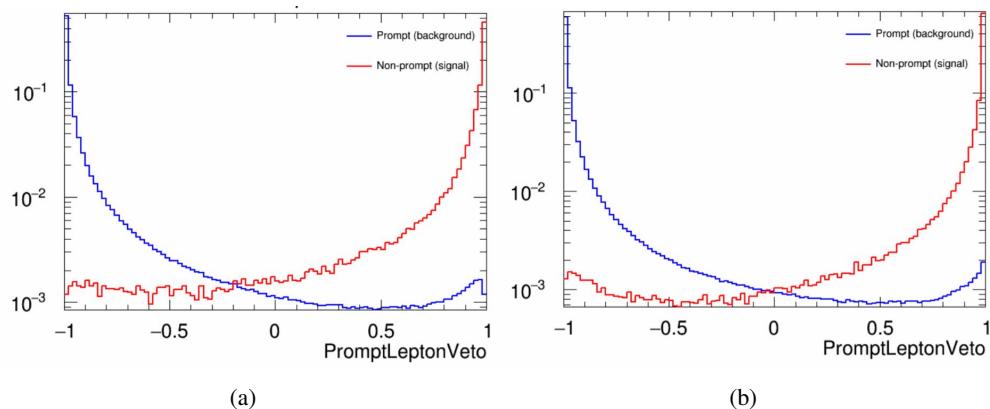


Figure 43: Distribution of the PLV BDT discriminant for (a) electrons and (b) muons.

832 The ROC curve for the BDT response, compared to the standard `FixedCutTight` WP, is shown  
833 in figure A.1, which shows a clear improvement when using this alternative training.

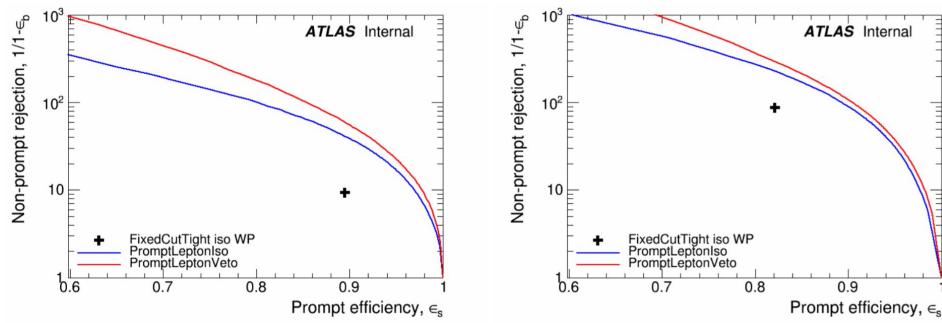


Figure 44: ROC curves for the PLV as well as the performance of the standard FixedCutTight WP for (left) electrons and (right) muons. Plot also includes curves for PROMPTLEPTONIso, which is not considered in this analysis.

834 A cutoff value of -0.7 for electrons and -0.5 for muons are chosen as the WPs for this MVA, based  
 835 on an optimisation of  $S/\sqrt{B}$  performed in the preselection regions of the  $t\bar{t}H$  – ML analysis,  
 836 which have a signature similar to that of this analysis.

837 The efficiency of the tight `PromptLeptonVeto` working point is measured using the tag and  
 838 probe method with  $Z \rightarrow \ell^+\ell^-$  events. Such calibration are performed by analysers from this  
 839 analysis in communication with the Egamma and Muon combined performance groups. The  
 840 scale factor are approximately 0.92 for  $10 < p_T < 15$  GeV, and averaging at 0.98 to 0.99 for  
 841 higher  $p_T$  leptons. An extra systematic is applied to muons within  $\Delta R < 0.6$  of a calorimeter  
 842 jet, since there is a strong dependence on the scale factor due to the presence of these jets. For  
 843 electrons, the dominant systematics is coming from pile-up dependence. Overall the systematics  
 844 are a maximum of 3% at low  $p_T$  and decreasing at a function of  $p_T$ .

## 845 **A.2 Non-prompt CR Modelling**

846 In order to further validate the modeling in each of the non-prompt CRs, additional kinematic  
 847 plots are made in the Z+jets CR and  $t\bar{t}$  CR in each of the continuous b-tag regions, after the  
 848 correction factors detailed in Section 6.3 have been applied.

849 In the case of the Z+jets CR, the  $p_T$  spectrum of the lepton originating from the W candidate is  
 850 shown, as this is the distribution used to extract the scale factor applied to Z+jets. These plots  
 851 are shown in Figures 45 and 46.

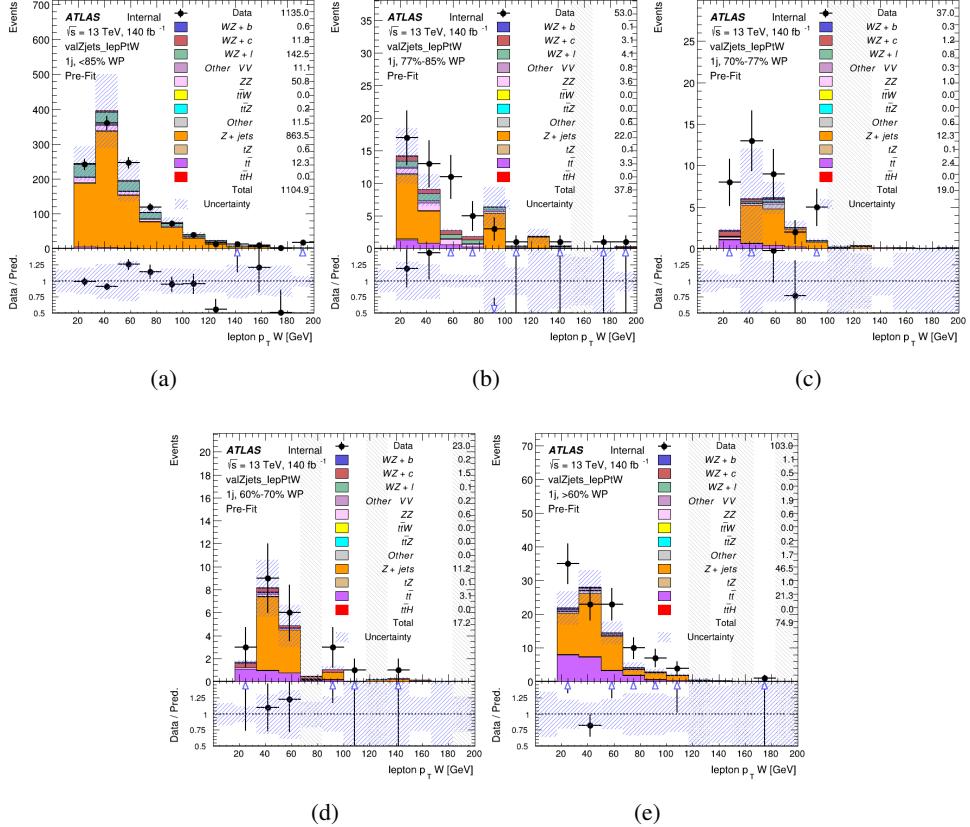


Figure 45: Comparisons between the data and MC distributions of the  $p_T$  of the lepton originating from the W-candidate in the Z+jets CR for each of the 1-jet b-tag working point regions

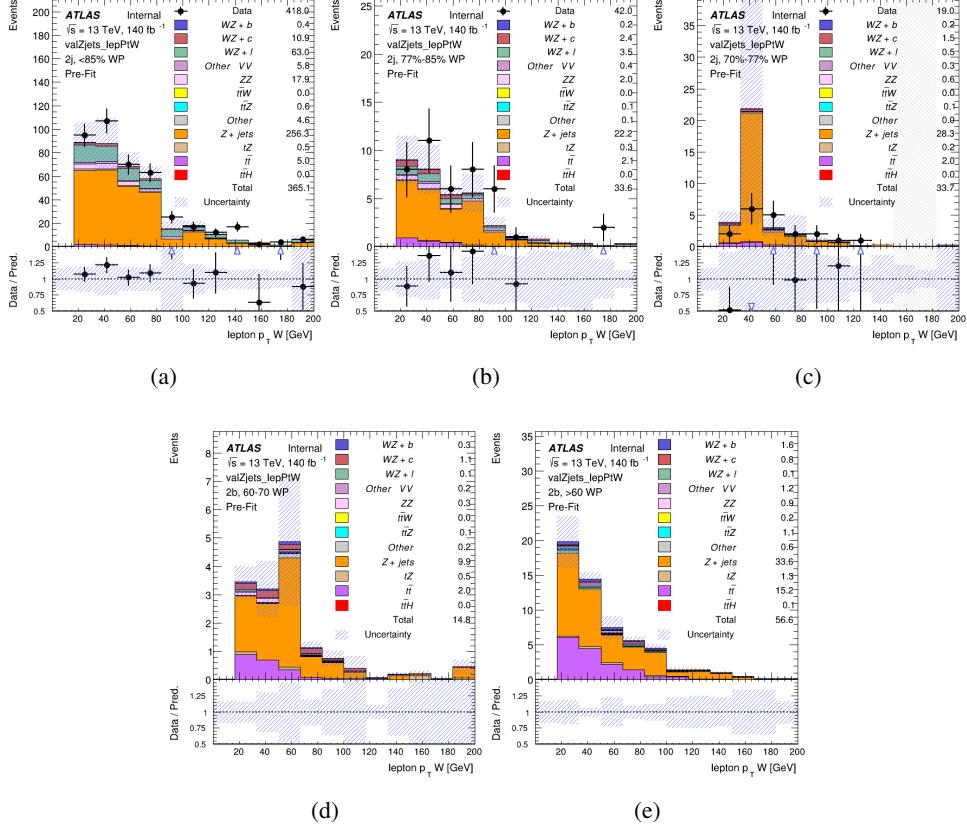


Figure 46: Comparisons between the data and MC distributions of the  $p_T$  of the lepton originating from the W-candidate in the Z+jets CR for each of the 2-jet b-tag working point regions

852 The same is shown for the  $t\bar{t}$  CR, but the  $p_T$  of the OS lepton is used instead as a representation  
 853 of the modeling, as the lepton from the W is not well defined for  $t\bar{t}$  events. These plots are shown  
 854 in Figures 47 and 48.

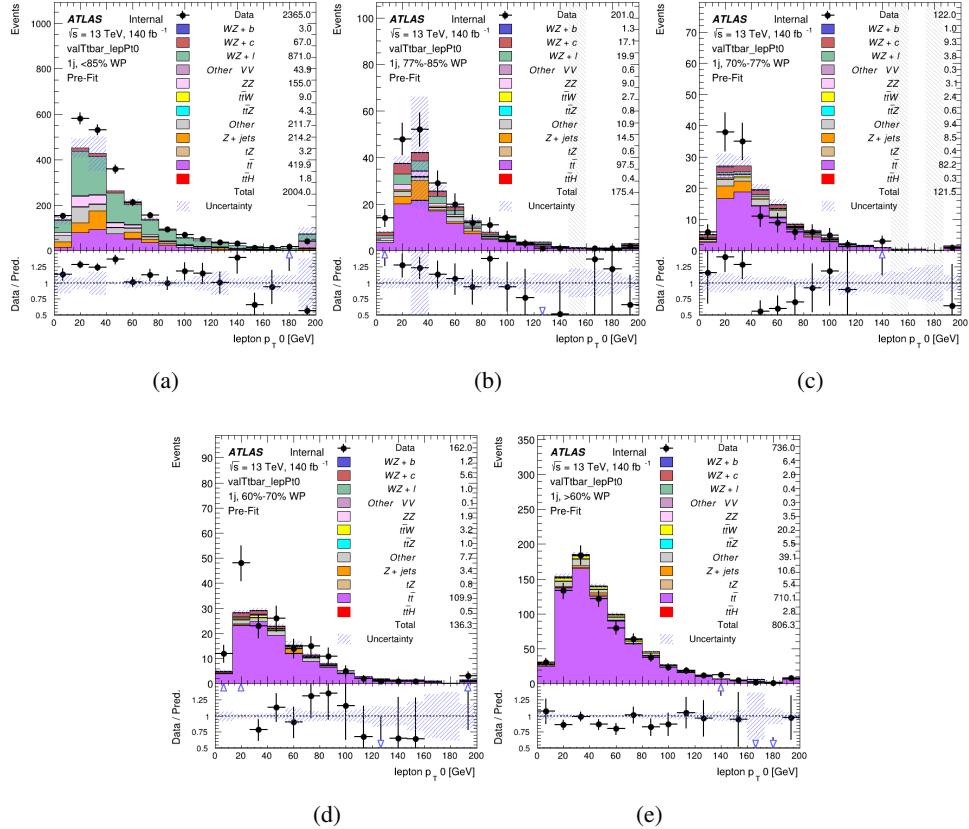


Figure 47: Comparisons between the data and MC distributions of the  $p_T$  of the OS lepton in the  $t\bar{t}$  CR for each of the 1-jet b-tag working point regions

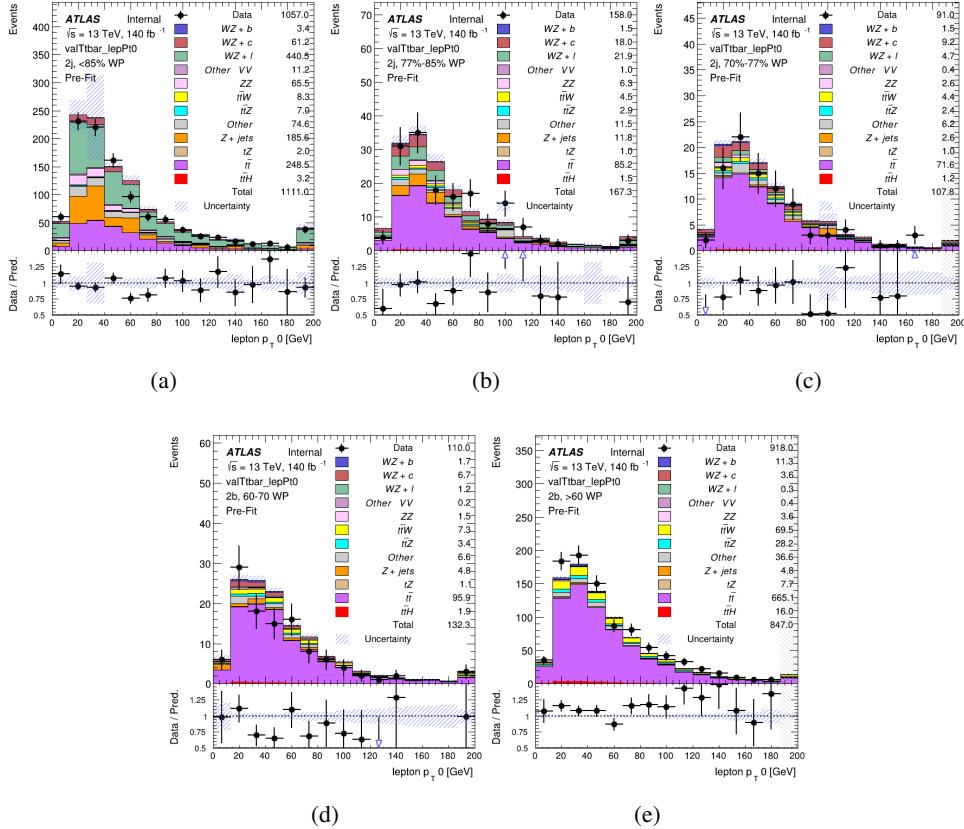


Figure 48: Comparisons between the data and MC distributions of the  $p_T$  of the OS lepton in the  $t\bar{t}$  CR for each of the 2-jet b-tag working point regions

### 855 A.3 DSID list

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 mc16\_13TeV.410644.PowhegPythia8EvtGen\_A14\_singleton\_schan\_lept\_top.deriv.DAOD\_HIGG8D1.e6527\_e5984\_s3126\_r10201\_r10210\_p4133  
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mc16\_13TeV.364506.Sherpa\_222\_NNPDF30NNLO\_mumugamma\_pty\_15\_35.deriv.DAOD\_HIGG8D1.e5928\_e5984\_s3126\_r10201\_r10210\_p4133  
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mc16e:

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 mc16\_13TeV.364255.Sherpa\_222\_NNPDF30NNLO\_lvvv.deriv.DAOD\_HIGG8D1.e5916\_e5984\_s3126\_r10724\_r10726\_p4133  
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