



## ATLAS Note

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

4

The ATLAS Collaboration

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A measurement of WZ produced with an associated heavy flavor jet is performed using 140  
6  $\text{fb}^{-1}$  of proton-proton collision data at  $\sqrt{s} = 13$  TeV from the ATLAS experiment at the  
7 LHC. The measurement is performed in the fully leptonic decay mode,  $\text{WZ} \rightarrow \ell\bar{\nu}\ell\bar{\nu}$ . The  
8 cross-section of  $\text{WZ} + b\text{-jets}$  is measured to be  $X \pm X \pm X$ , while the cross-section of  $\text{WZ} +$   
9 charm is measured as  $X$ , with a correlation of  $X$  between the two processes.

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## 45 1 Changes and outstanding items

### 46 1.1 Changelog

47 This is version 5

#### 48 1.1.1 Changes relative to v4

- 49 • Fixed various typos, clarified wording
- 50 • Expanded info about JER uncertainties, theory uncertainties
- 51 • removed a table on lepton selection, included information in the text instead
- 52 • Plotted lepton Pt Z and W for Zjet CR, rather than lep 1 and 2
- 53 • fixed binning in kinematic plots
- 54 • Included prefit and postfit yield tables
- 55 • added signal modelling systematics

#### 56 1.1.2 Changes relative to v3

- 57 • Merged introduction into executive summary, including unblinding details and list of SRs/CRs used
- 58 • listed ptag used (p4133), and release (AB 21.2.127)
- 59 • Included table reftab:xsecUnc listing x-sec uncertainties used
- 60 • Removed selection criteria listed in table ?? (QMisID, AmbiguityType) that were removed from the analysis
- 61 • specified variable used to make truth jet flavor determination (HadronConeExclTruthLabelID)
- 62 • fixed bug in MtLepMet calculation, updated selection/fits to account for this
- 63 • Included plots of MtLepMet and PtZ, swapped lep 1 and 2  $p_T$  plots for lep W and lep Z plots
- 64 • updated tZ BDT training to reduce overfitting, updated plots to include error bars, feature importance
- 65 • updated table 7 to clarify selection, fix the tZ\_BDT cut used
- 66 • replace a few broken ntuples which included large weight events

- 72     • include DL1r distribution for Z+jets and  $t\bar{t}$  VRs  
 73     • Expanded section on fakes, included information on derived scale factors from VRs.  
 74     • Changed the kinematic plots to include  $p_T(Z)$  and  $m_T(W)$ , list lepton  $p_T$  based on W and  
 75       Z candidates.

76 **1.1.3 Changes relative to v2**

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

84 **1.1.4 Changes relative to v1**

- 85     • Added GRL list  
 86     • Fixed latex issue in line 92, typo in line 172  
 87     • Added tables 5 and ??, summarizing the event and object selection  
 88     • Added table 2, which includes the DSID of samples used  
 89     • Included reference to WZ inclusive paper in introduction

90 **1.2 Outstanding Items**

- 91     • Complete interference studies, apply any interference effects observed as a systematic  
 92     • Update results section with additional studies, possibly including:  
     – Truth jet migration studies  
     – Simultaneous fit over 1j and 2j  
     – Impact of allowing tZ to float  
 93     • Unblind, update plots and fits to include data  
 94     • Add cross-section, significance once unblinded

## 98 2 Executive Summary

99 The production of  $WZ$  in association with a heavy flavor jet represents an important background  
100 for many major analyses. This includes any process with leptons and b-jets in the final state,  
101 such as  $t\bar{t}H$ ,  $t\bar{t}W$ , and  $t\bar{t}Z$ . While precise measurements have been made of  $WZ$  production  
102 [1],  $WZ +$  heavy flavor remains poorly understood. This is largely because the QCD processes  
103 involved in the production of the b-jet make it difficult to simulate accurately. This introduces a  
104 large uncertainty for analyses that include this process as a background.

105 Motivated by its relevance to the  $t\bar{t}H$  multilepton analysis, we perform a study of the fully  
106 leptonic decay mode of this channel; that is, events where both the W and Z decay leptonically.  
107 Because  $WZ$  has no associated jets at leading order, while the major backgrounds for this channel  
108 tend to have high jet multiplicity, events with more than two jets are rejected. This gives a final  
109 state signature of three leptons and one or two jets.

110 Events that meet this selection criteria are sorted into pseudo-continuous b-tagging regions based  
111 on the DL1r b-tag score of their associated jets. This is done to separate  $WZ +$  b-jet events from  
112  $WZ +$  charm and  $WZ +$  light jets. These regions are fit to data in order make a more accurate  
113 estimate of the contribution of  $WZ +$  heavy-flavor, where heavy-flavor jets include b-jets and  
114 charm jets. The full Run-2 dataset collected by the ATLAS detector, representing  $139 \text{ fb}^{-1}$  of  
115 data from pp collisions at  $\sqrt{s} = 13 \text{ TeV}$ , is used for this study.

116 All backgrounds are accounted for using Monte Carlo, with the simulation of non-prompt lepton  
117 backgrounds -  $Z+jets$  and  $t\bar{t}$  - validated using non-prompt Validation Regions.

118 Section 3 details the data and Monte Carlo (MC) samples used in the analysis. The reconstruction  
119 of various physics objects is described in section 4. Section 5 describes the event selection applied  
120 to these samples, along the definitions of the various regions used in the fit. The multivariate  
121 analysis techniques used to separate the  $tZ$  background from  $WZ +$  heavy flavor are described in  
122 section 6. Section 7 describes the various sources of systematic uncertainties considered in the  
123 fit. Finally, the results of the analysis are summarized in section 8, followed by a brief conclusion  
124 in section 9.

125 The current state of thee analysis shows blinded results for thee full Run 2 dataset. Regions  
126 containing  $>5\%$   $WZ+b$  events are blinded, and results are from Asimov, MC only fits. In  
127 addition to adding some additional information to this note, remaining tasks include performing  
128  $WZ/tZ$  interference studies, finalizing the presentation of results, and unblinding.

## 129 3 Data and Monte Carlo Samples

130 Both data and Monte Carlo samples used in this analysis were prepared in the `xAOD` format,  
131 which was used to produce a `DxAOD` sample in the `HIGG8D1` derivation framework. The `HIGG8D1`  
132 framework is designed for the  $t\bar{t}H$  multi-lepton analysis, which targets events with multiple  
133 leptons as well as tau hadrons. This framework skims the dataset to remove unneeded variables

134 as well as entire events. Events are removed from the derivations that do not meet the following  
 135 selection:

- 136 • at least two light leptons within a range  $|\eta| < 2.6$ , with leading lepton  $p_T > 15$  GeV and  
 137 subleading lepton  $p_T > 5$  GeV
- 138 • at least one light lepton with  $p_T > 15$  GeV within a range  $|\eta| < 2.6$ , and at least two hadronic  
 139 taus with  $p_T > 15$  GeV.

140 Samples were then generated from these HIGG8D1 derivations with p-tag of p4134 using Ana-  
 141 lyticBase version 21.2.127 modified to include custom variables..

### 142 **3.1 Data Samples**

143 The study uses a sample of proton-proton collision data collected by the ATLAS detector from  
 144 2015 through 2018 at an energy of  $\sqrt{s} = 13$  TeV, which represents an integrated luminosity of  
 145  $139 \text{ fb}^{-1}$ . This data set was collected with a bunch crossing rate of 25 ns. All data used in this  
 146 analysis was verified by data quality checks, having been included in the following Good Run  
 147 Lists:

- 148 • data15\_13TeV.periodAllYear\_DetStatus-v79-repro20-02\_DQDefects-00-02-02  
 149 \_PHYS\_StandardGRL\_All\_Good\_25ns.xml
- 150 • data16\_13TeV.periodAllYear\_DetStatus-v88-pro20-21\_DQDefects-00-02-04  
 151 \_PHYS\_StandardGRL\_All\_Good\_25ns.xml
- 152 • data17\_13TeV.periodAllYear\_DetStatus-v97-pro21-13\_Unknown\_PHYS\_StandardGRL  
 153 \_All\_Good\_25ns\_Triggerno17e33prim.xml
- 154 • data18\_13TeV.periodAllYear\_DetStatus-v102-pro22-04\_Unknown\_PHYS\_StandardGRL  
 155 \_All\_Good\_25ns\_Triggerno17e33prim.xml

156 Runs included from the AllYear period containers are included.

### 157 **3.2 Monte Carlo Samples**

158 Several different generators were used to produce Monte Carlo simulations of the signal and  
 159 background processes. For all samples, the response of the ATLAS detector is simulated using  
 160 Geant4. The WZ signal samples are simulated using Sherpa 2.2.2 [2]. Specific information  
 161 about the Monte Carlo samples being used can be found in table 1. A list of the specific samples  
 162 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   |
| tZ                              | MG5_AMC                            | LO                   | PYTHIA 6               | CTEQ6L1  |
| t̄W                             | 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++) | NNPDF 3.0 NLO [Ball:2014uwa]<br>(CT10 [ <b>ct10</b> ]) |
| 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, t̄t̄t̄                     | MG5_AMC                            | LO                   | PYTHIA 8               | NNPDF 2.3 LO   |
| t̄tW+W-                         | MG5_AMC                            | LO                   | PYTHIA 8               | NNPDF 2.3 LO   |
| t̄t                             | Powheg-BOX v2 [ <b>powheggtt</b> ] | 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 [ <b>powhegstp</b> ] | NLO                  | PYTHIA 6               | CT10   |
| qqVV, VVV<br>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                | 410560                                    |
| 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.

## 163 4 Object Reconstruction

164 All regions defined in this analysis share a common lepton, jet, and overall event preselection.  
 165 The selection applied to each physics object is detailed here; the event preselection, and the  
 166 selection used to define the various fit regions, is described in section 5.

### 167 4.1 Trigger

168 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

- 169 Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter  
 170 that are associated with charged particle tracks reconstructed in the inner detector [3]. Electron  
 171 candidates are required to have  $p_T > 10$  GeV and  $|\eta_{\text{cluster}}| < 2.47$ . Muon candidates are  
 172 reconstructed by combining inner detector tracks with track segments or full tracks in the muon  
 173 spectrometer [4]. Muon candidates are required to have  $p_T > 10$  GeV and  $|\eta| < 2.5$ . Candidates  
 174 in the transition region between different electromagnetic calorimeter components,  $1.37 <$   
 175  $|\eta_{\text{cluster}}| < 1.52$ , are rejected. A multivariate likelihood discriminant combining shower shape  
 176 and track information is used to distinguish real electrons from hadronic showers (fake electrons).  
 177 To further reduce the non-prompt electron contribution, the track is required to be consistent  
 178 with originating from the primary vertex; requirements are imposed on the transverse impact  
 179 parameter significance ( $|d_0|/\sigma_{d_0} < 5$ ) and the longitudinal impact parameter ( $|\Delta z_0 \sin \theta_\ell| < 0.5$   
 180 mm).  
 181
- 182 Muon candidates are reconstructed by combining inner detector tracks with track segments or  
 183 full tracks in the muon spectrometer [4]. Muon candidates are required to have  $p_T > 10$  GeV  
 184 and  $|\eta| < 2.5$ . The longitudinal impact parameter is the same for both electrons and muons, while  
 185 muons are required to pass a slightly tighter transverse impact parameter,  $|d_0|/\sigma_{d_0} < 3$ .

186 All leptons are required to be isolated, as defined through the standard `isolationFixedCutLoose`  
 187 working point supported by combined performance groups. Leptons are additionally required to  
 188 pass a non-prompt BDT selection described in detail in [5]. Optimized working points and scale  
 189 factors for this BDT are taken from that analysis.

### 190 4.3 Jets

191 Jets are reconstructed from calibrated topological clusters built from energy deposits in the  
 192 calorimeters [6], using the anti- $k_t$  algorithm with a radius parameter  $R = 0.4$ . Jets with energy  
 193 contributions likely arising from noise or detector effects are removed from consideration [7],  
 194 and only jets satisfying  $p_T > 25$  GeV and  $|\eta| < 2.5$  are used in this analysis. For jets with  
 195  $p_T < 60$  GeV and  $|\eta| < 2.4$ , a jet-track association algorithm is used to confirm that the jet  
 196 originates from the selected primary vertex, in order to reject jets arising from pileup collisions  
 197 [8].

### 198 4.4 B-tagged Jets

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

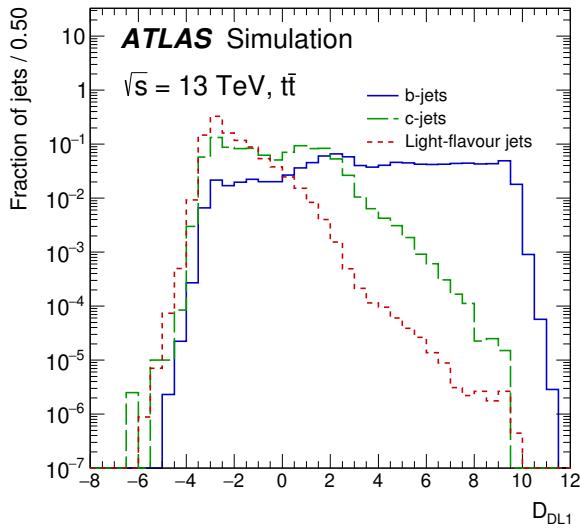


Figure 1: Output distribution of the DL1r algorithm for b-jets, charm jets, and light jets

204 From the output of the BDT, working points (WPs) are developed based on the efficiency of truth  
 205 b-jets at particular values of the DL1r algorithm. The working points used in this analysis are  
 206 summarized in table 4.

| WP     | none | loose | medium | tight | tightest |
|--------|------|-------|--------|-------|----------|
| b eff. | -    | 85%   | 77%    | 70%   | 60%      |

Table 4: B-tagging Working Points by tightness and b-jet efficiency

207 A tighter WP will accept fewer b-jets, but reject a higher fraction of charm and light jets.  
 208 Generally, analyses that include b-jets will use a fixed working point, for example, requiring that  
 209 a jet pass the 70% threshold. By instead treating these working point as bins, e.g. events with  
 210 jets that fall between the 85% and 77% WPs fall into one bin, while events with jets passing the  
 211 60% WP fall into another, and looking at the full psuedo-continuous DL1r spectrum of the jets,  
 212 additional information can be gained. The psuedo-continuous b-tag spectrum is used in this case  
 213 to separate out WZ + b, WZ + charm, and WZ + light.

#### 214 4.5 Missing transverse energy

215 Missing transverse momentum ( $E_T^{\text{miss}}$ ) is used as part of the event selection. The missing  
 216 transverse momentum vector is defined as the inverse of the sum of the transverse momenta of  
 217 all reconstructed physics objects as well as remaining unclustered energy, the latter of which is  
 218 estimated from low- $p_T$  tracks associated with the primary vertex but not assigned to a hard object,  
 219 with object definitions taken from [9]. Light leptons considered in the  $E_T^{\text{miss}}$  reconstruction are  
 220 required to have  $p_T > 10 \text{ GeV}$ , while jets are required to have  $p_T > 20 \text{ GeV}$ .

### 221 5 Event Selection and Signal Region Definitions

222 Event are required to pass a preselection described in section 5.1 and summarized in table 5.  
 223 Those that pass this preselection are divided into various fit regions described in section 5.2,  
 224 based on the number of jets in the event, and the b-tag score of those jets.

#### 225 5.1 Event Preselection

226 Events are required to include exactly three reconstructed light leptons passing the requirement  
 227 described in 4.2, which have a total charge of  $\pm 1$ . As the opposite sign lepton is found to be  
 228 prompt the vast majority of the time [5], it is required to be loose and isolated, as defined though  
 229 the standard `isolationFixedCutLoose` working point supported by combined performance

230 groups. The same sign leptons are required to be very tightly isolated, as per the recommended  
 231 `isolationFixedCutTight`.

232 The leptons are ordered in the analysis code as 0, 1, and 2. Lepton 0 is the lepton whose charge  
 233 is opposite the other two. Lepton 1 is the lepton closest to the opposite charge lepton, i.e. the  
 234 smallest  $\Delta R$ , leaving lepton 2 as the lepton further from the opposite charge lepton. Lepton 0  
 235 is required to have  $p_T > 10$  GeV, while the same sign leptons, 1 and 2, are required to have  
 236  $p_T > 20$  GeV to reduce the contribution of non-prompt leptons.

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

240 An additional requirement is placed on the missing transverse energy,  $E_T^{\text{miss}} > 20$  GeV, and the  
 241 transverse mass of the W candidate,  $m(E_T^{\text{miss}} + l_{\text{other}}) > 30$  GeV, where  $E_T^{\text{miss}}$  is the missing  
 242 transverse energy, and  $l_{\text{other}}$  is the lepton not included in the Z-candidate.

243 Events are required to have one or two reconstructed jets passing the selection described in  
 244 section 4.3. Events with more than two jets are rejected in order to reduce the contribution of  
 245 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 charge  $\pm 1$

Two tight Iso, tight ID same-charge leptons with  $p_T > 20$  GeV

One loose Iso, medium ID opposite charge lepton with  $p_T > 10$  GeV

$m(l^+l^-)$  within 10 GeV of 91.2 GeV

Transverse mass of W-candidate,  $m_T(E_T^{\text{miss}} + \text{lep}_{\text{other}}) > 30$  GeV

Missing transverse energy,  $E_T^{\text{miss}} > 20$  GeV

One or two jets with  $p_T > 25$  GeV

---

Table 5: Summary of the selection applied to events for inclusion in the fit

246 The event yields in the preselection region for both data and Monte Carlo are summarized in  
 247 table 5.1, which shows good agreement between data and Monte Carlo, and demonstrates that  
 248 this region consists primarily of WZ events. The WZ events are split into WZ + b, WZ + c, and  
 249 WZ + l based on the truth flavor of the associated jet in the event. Specifically, this determination  
 250 is made based on the `HadronConeExclTruthLabelID` of the jet, as recommended by the b-  
 251 tagging working group [BtagWG]. In this ordering b-jet supersedes charm, which supersedes  
 252 light. That is, WZ + l events contain no charm and no b jets at truth level, WZ + c contain at  
 253 least one truth charm and no b-jets, and WZ + b contains at least one truth b-jet.

| Process      | Events          |
|--------------|-----------------|
| WZ + b       | $167.6 \pm 6.5$ |
| WZ + c       | $1080 \pm 40$   |
| WZ + l       | $7220 \pm 310$  |
| Other VV     | $850 \pm 140$   |
| t̄tW         | $16.8 \pm 2.3$  |
| t̄tZ         | $115 \pm 17$    |
| rare Top     | $2.2 \pm 0.1$   |
| Single top   | $0.10 \pm 0.45$ |
| Three top    | $0.01 \pm 0.01$ |
| Four top     | $0.02 \pm 0.01$ |
| t̄tWW        | $0.23 \pm 0.05$ |
| Z + jets     | $600 \pm 260$   |
| V + $\gamma$ | $37 \pm 54$     |
| tZ           | $190 \pm 70$    |
| tW           | $5.5 \pm 1.2$   |
| WtZ          | $25.8 \pm 1.1$  |
| VVV          | $26.2 \pm 0.9$  |
| VH           | $94 \pm 7$      |
| t̄t          | $108.68 \pm 8$  |
| t̄tH         | $4.3 \pm 0.5$   |
| Total        | $10600 \pm 530$ |
| Data         | 10574           |

Table 6: Event yields in the preselection region at  $139.0 \text{ fb}^{-1}$ 

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

256 Simulations are further validated by comparing the kinematic distributions of the Monte Carlo  
 257 with data, which are shown in figure 2. Here, bins with 5% or more WZ+b are blinded.

WZ Fit Region - Inclusive

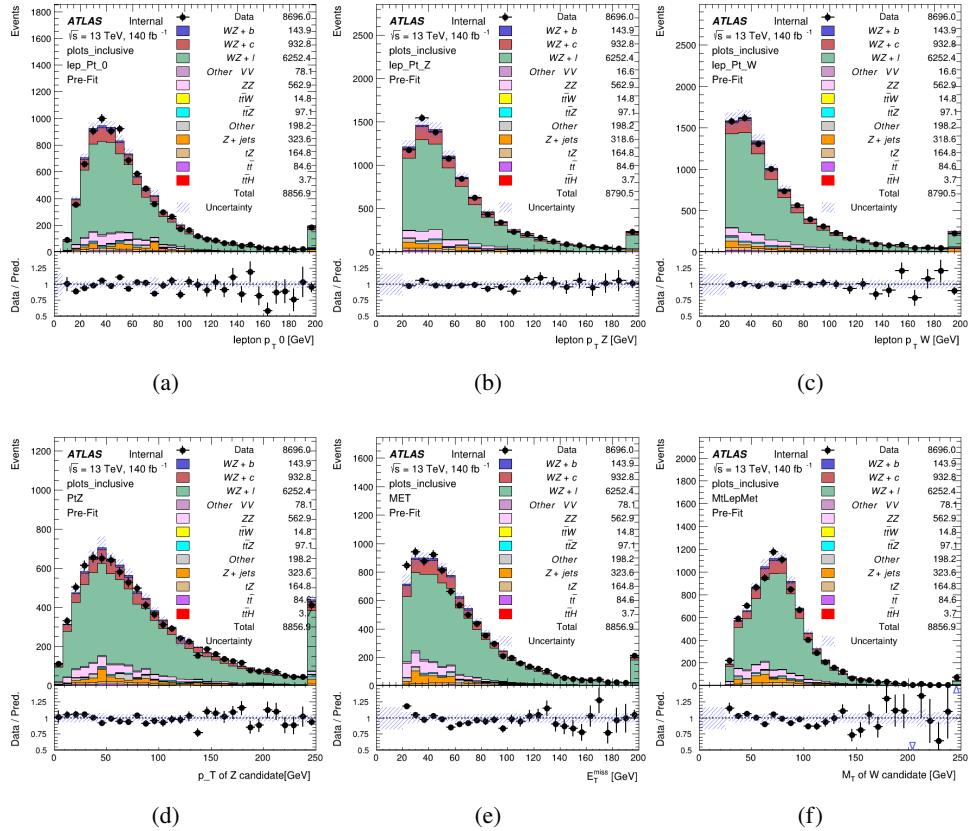


Figure 2: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the  $p_T$  of the Z candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the W candidate.

## 5.2 Fit Regions

Once preselection has been applied, the remaining events are categorized into one of twelve orthogonal regions. The regions used in the fit are summarized in table 7.

Table 7: 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%    | $N_{\text{jets}} = 1, n\text{Jets\_DL1r\_60} = 1, tZ \text{ BDT} > 0.725$    |
| 1j tZ CR    | $N_{\text{jets}} = 1, n\text{Jets\_DL1r\_60} = 1, tZ \text{ BDT} < 0.725$    |
| 2j, <85%    | $N_{\text{jets}} = 2, n\text{Jets\_DL1r\_85} = 0$                            |
| 2j, 85%-77% | $N_{\text{jets}} = 2, n\text{Jets\_DL1r\_85} >= 1, n\text{Jets\_DL1r\_77}=0$ |
| 2j, 77%-70% | $N_{\text{jets}} = 2, n\text{Jets\_DL1r\_77} >= 1, n\text{Jets\_DL1r\_70}=0$ |
| 2j, 70%-60% | $N_{\text{jets}} = 2, n\text{Jets\_DL1r\_70} >= 1, n\text{Jets\_DL1r\_60}=0$ |
| 2j, >60%    | $N_{\text{jets}} = 2, n\text{Jets\_DL1r\_60} >= 1, tZ \text{ BDT} > 0.725$   |
| 2j tZ CR    | $N_{\text{jets}} = 2, n\text{Jets\_DL1r\_60} >= 1, tZ \text{ BDT} < 0.725$   |

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

265 An additional tZ control region is created based on the BDT described in section 6. The region  
 266 with 1-jet passing the 60% working point is split in two - a signal enriched region of events with  
 267 a BDT score greater than 0.03, and a tZ control region including events with less than 0.03. This  
 268 cutoff is arrived at by performing an Asimov fit with a variety of cutoffs, and selecting the value  
 269 that produces the highest significance for the measurement of WZ + b.

270 The modeling in each region is validated by comparing data and MC predictions for various  
 271 kinematic distributions. These plot are shown in figures 3-16.

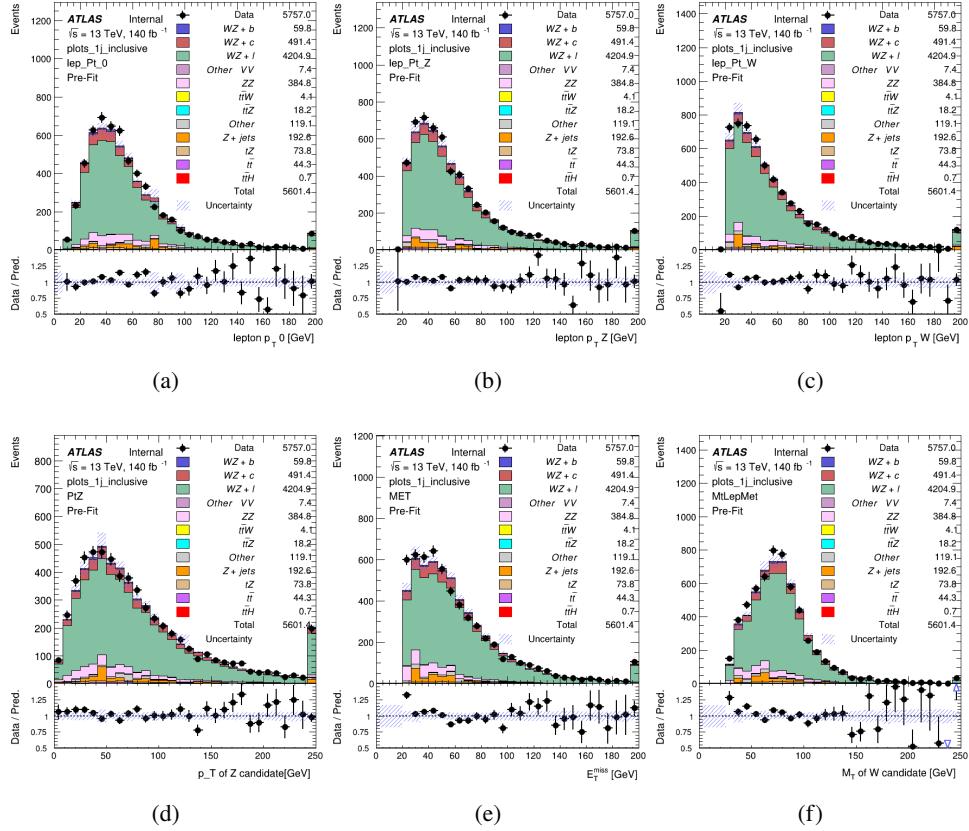
**WZ Fit Region - 1j Inclusive**

Figure 3: 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  $p_T$  of the  $Z$  candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the  $W$  candidate.

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

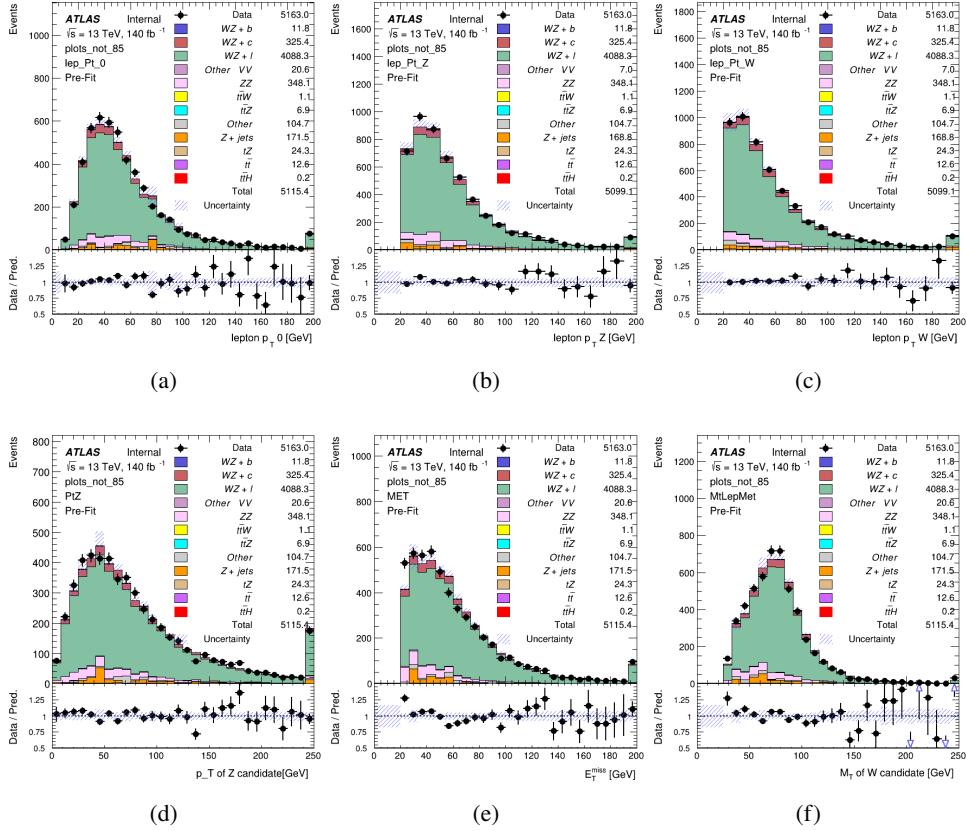


Figure 4: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the  $Z$  candidate, (c) the  $p_T$  of the lepton from the  $W$  candidate, (d) the  $p_T$  of the  $Z$  candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the  $W$  candidate.

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

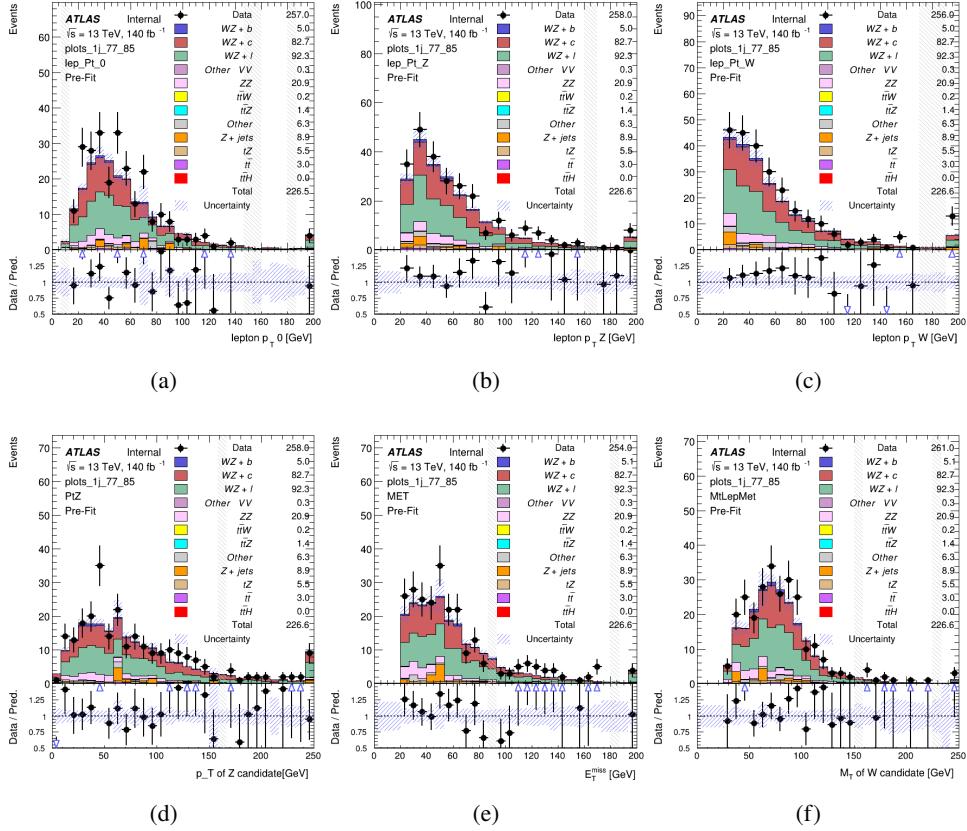


Figure 5: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the  $p_T$  of the Z candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the W candidate.

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

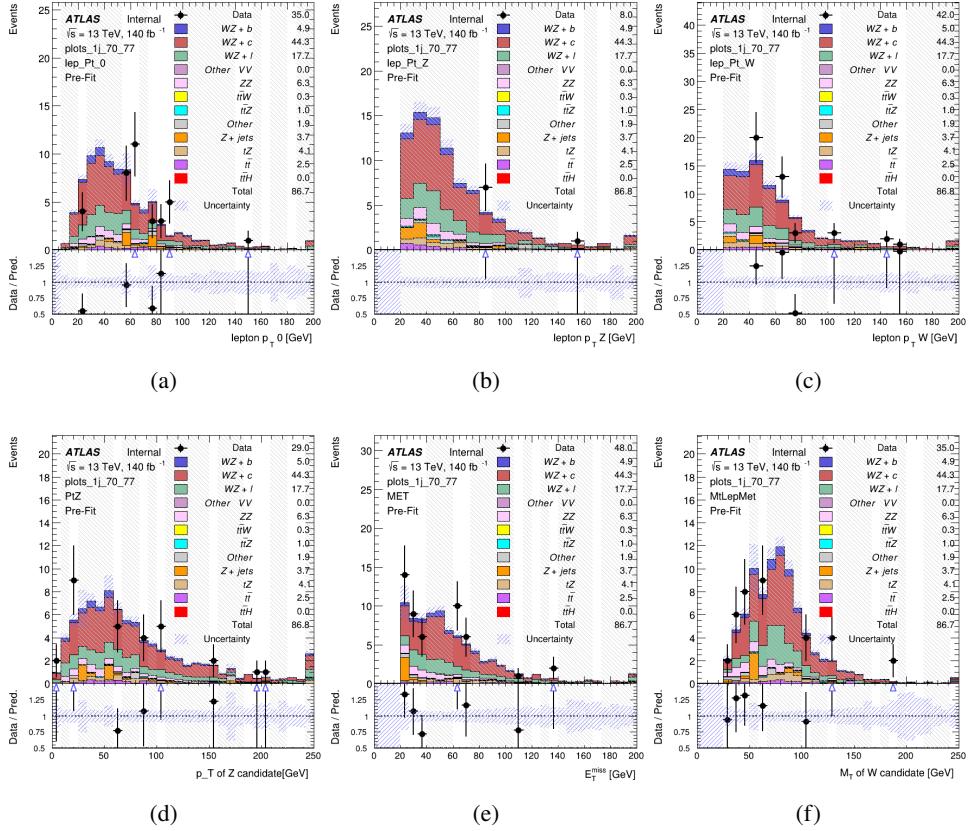


Figure 6: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the  $Z$  candidate, (c) the  $p_T$  of the lepton from the  $W$  candidate, (d) the  $p_T$  of the  $Z$  candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the  $W$  candidate.

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

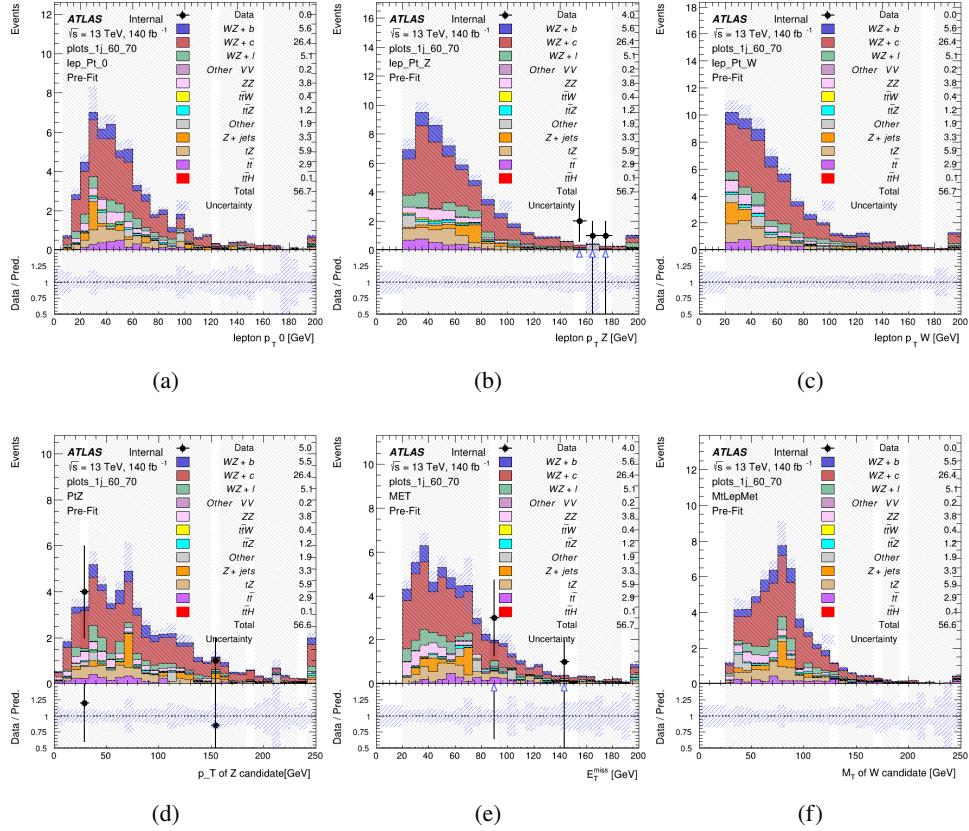


Figure 7: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the  $Z$  candidate, (c) the  $p_T$  of the lepton from the  $W$  candidate, (d) the  $p_T$  of the  $Z$  candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the  $W$  candidate.

## WZ Fit Region - 1j 60% WP

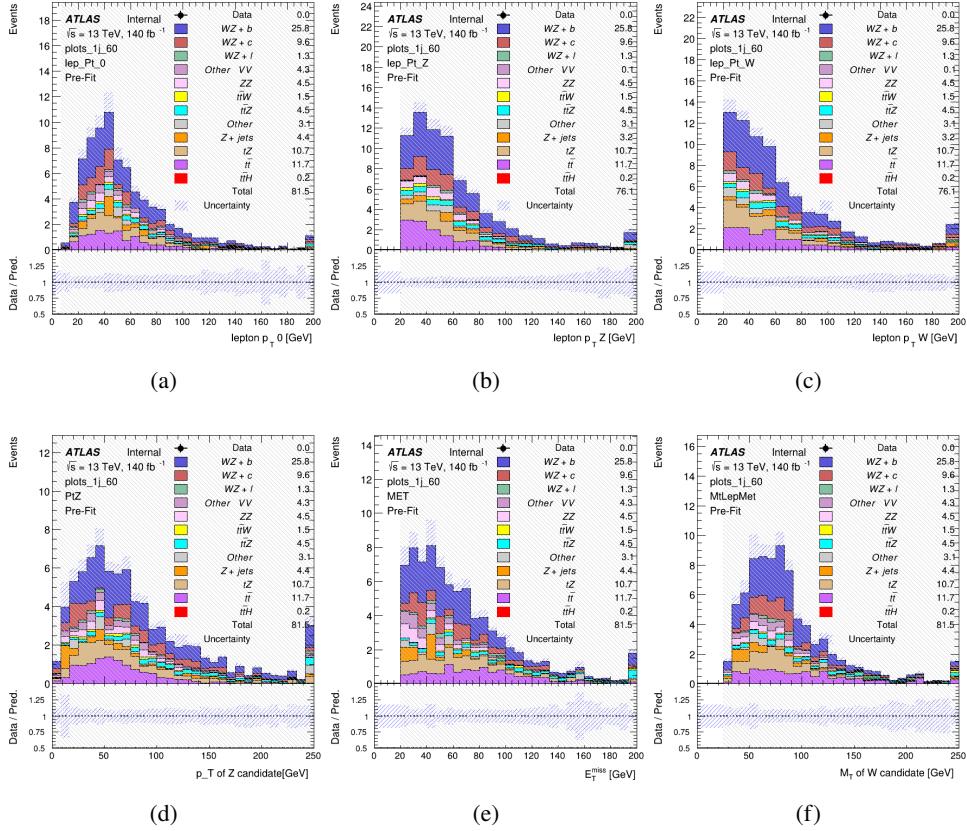


Figure 8: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the  $Z$  candidate, (c) the  $p_T$  of the lepton from the  $W$  candidate, (d) the  $p_T$  of the  $Z$  candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the  $W$  candidate.

## WZ Fit Region - tZ-CR

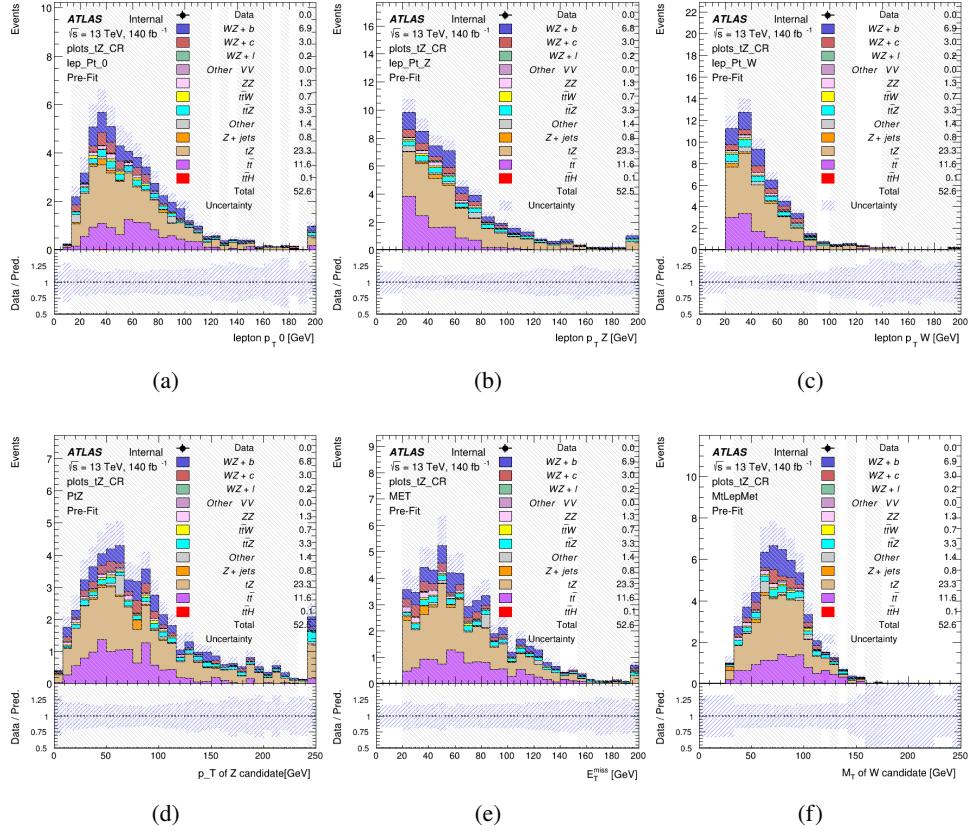


Figure 9: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the  $p_T$  of the Z candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the W candidate.

## WZ Fit Region - 2j Inclusive

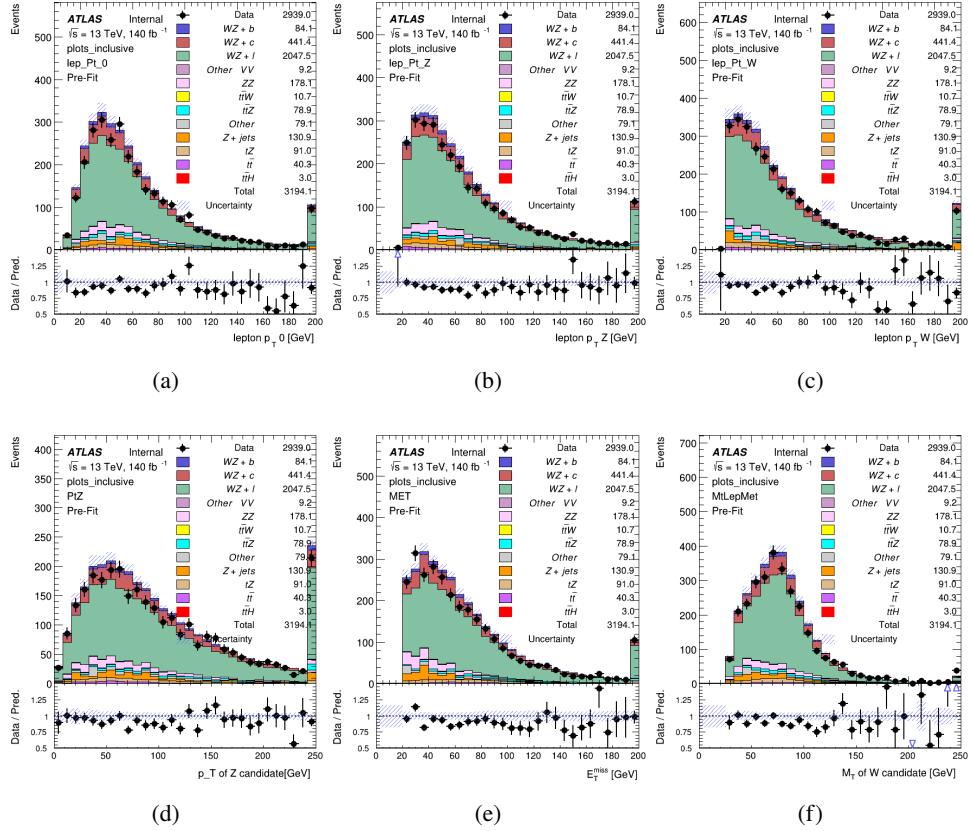


Figure 10: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the  $p_T$  of the Z candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the W candidate.

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

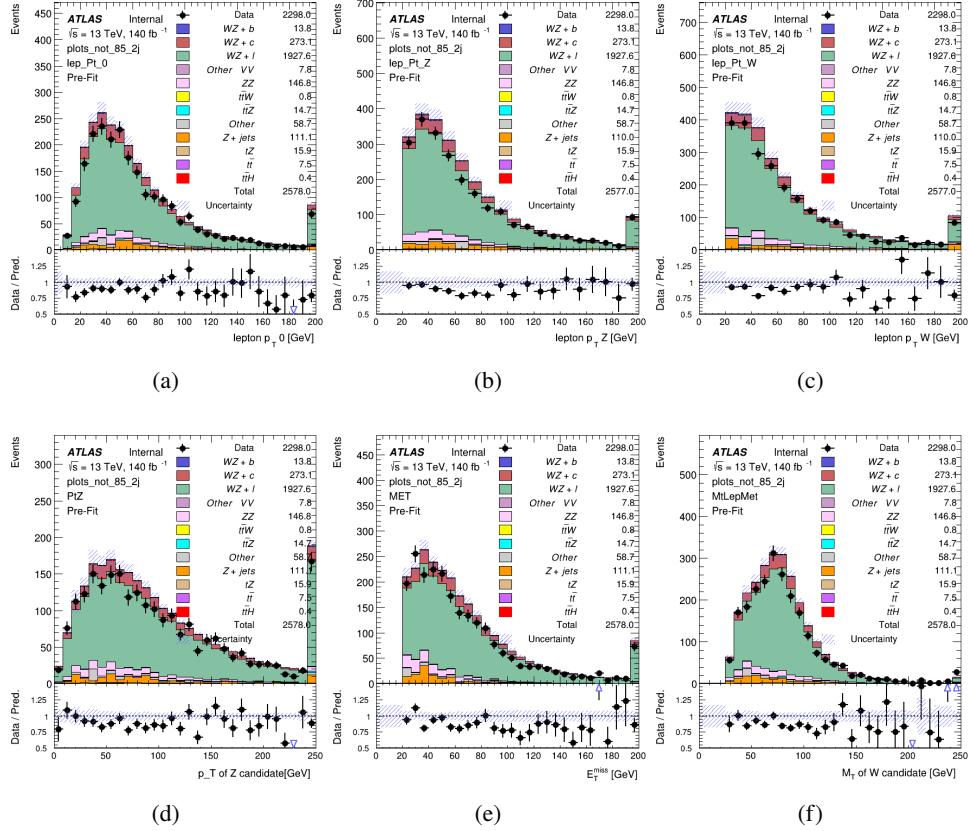


Figure 11: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the  $p_T$  of the Z candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the W candidate.

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

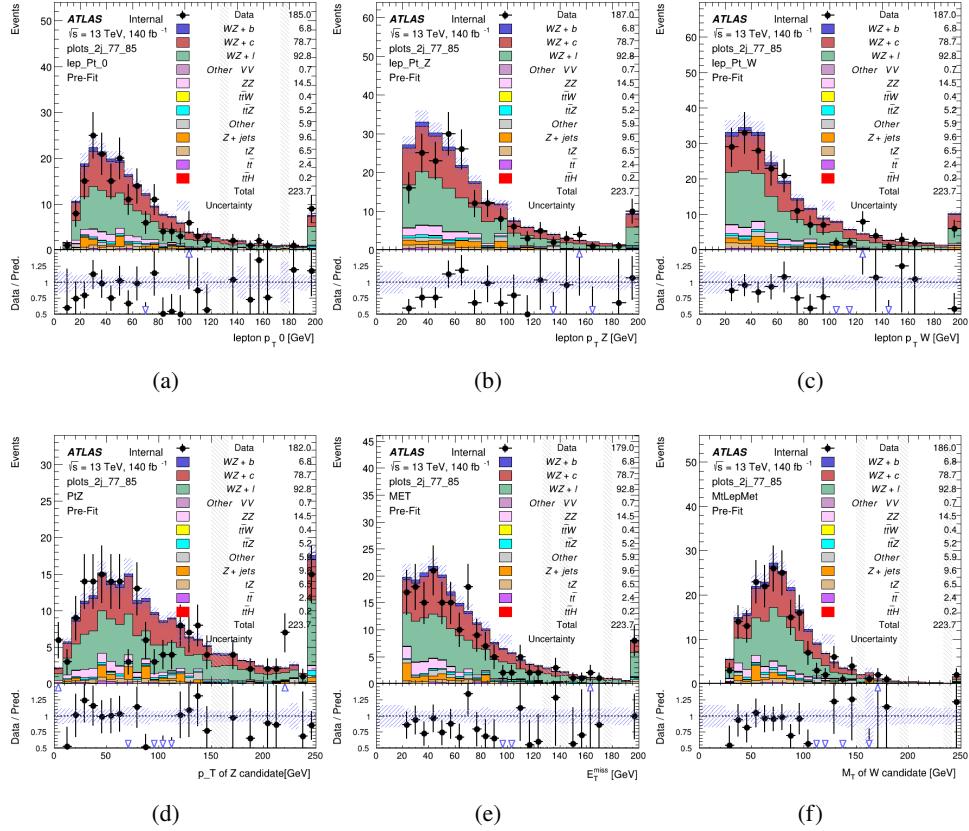


Figure 12: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the  $p_T$  of the Z candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the W candidate.

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

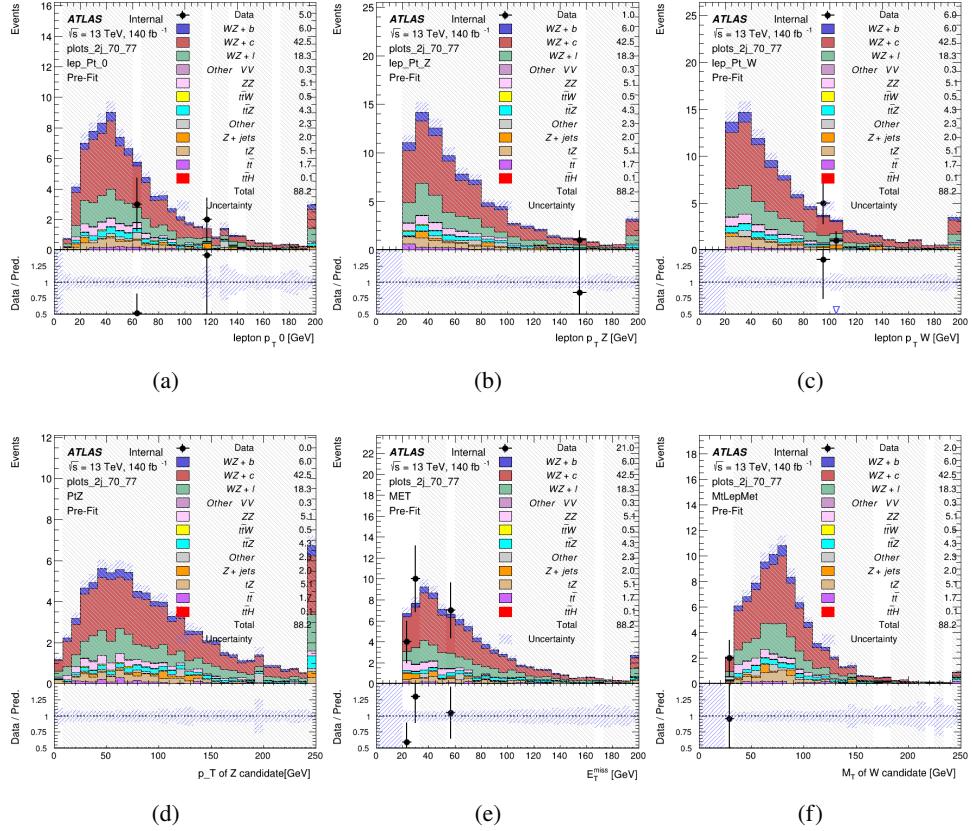


Figure 13: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the  $p_T$  of the Z candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the W candidate.

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

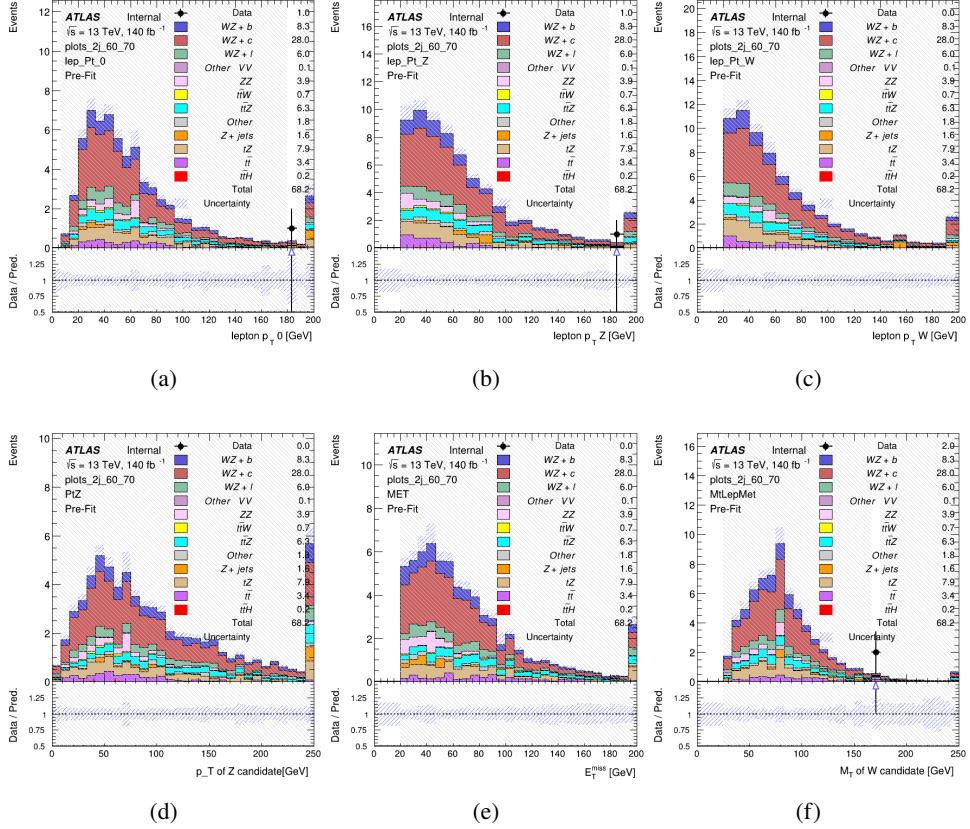


Figure 14: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the  $p_T$  of the Z candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the W candidate.

## WZ Fit Region - 2j 60% WP

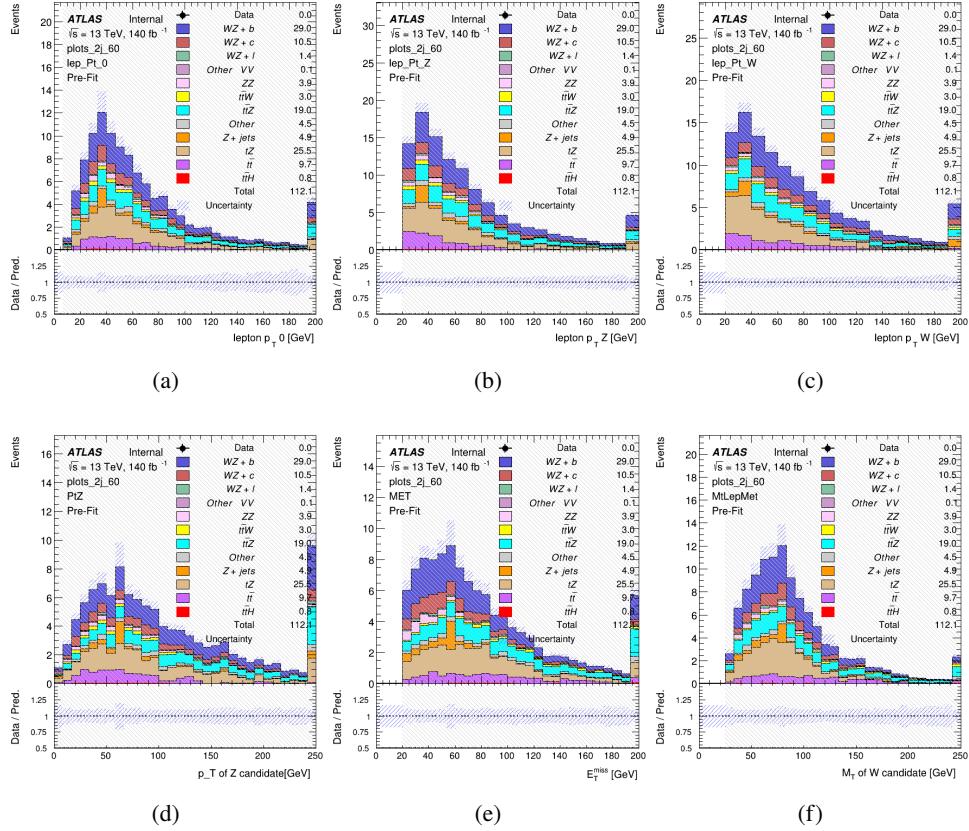


Figure 15: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the  $p_T$  of the Z candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $M_T$  of the W candidate.

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

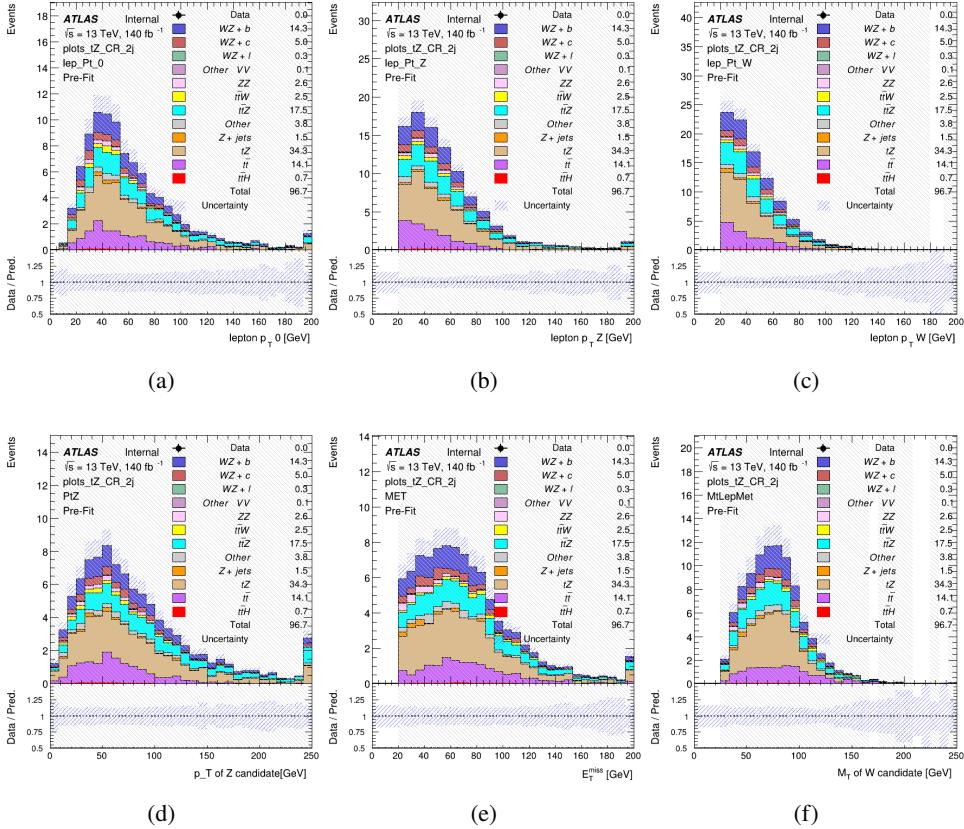


Figure 16: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the  $Z$  candidate, (c) the  $p_T$  of the lepton from the  $W$  candidate, (d) the  $p_T$  of the  $Z$  candidate, (e) the  $E_T^{\text{miss}}$ , and (f) the  $m_T$  of the  $W$  candidate.

### 5.3 Non-Prompt Lepton Estimation

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

#### 5.3.1 $t\bar{t}$ Validation

$t\bar{t}$  events can produce two prompt leptons from the decay of each of the tops. These top decays produce two b-quarks, the decay of which can produce additional non-prompt leptons, which occasionally pass the event preselection. In order to validate that the Monte Carlo accurately

281 simulates this process accurately, the MC prediction in a non-prompt  $t\bar{t}$  enriched validation  
282 region is compared to data.

283 The  $t\bar{t}$  validation region is similar to the preselection region - three leptons meeting the criteria  
284 described in section 5 are required, and the requirements on  $E_T^{\text{miss}}$  remain the same. However,  
285 the selection requiring a lepton pair form a Z-candidate are reversed. Events where the invariant  
286 mass of any two opposite sign, same flavor leptons falls within 10 GeV of 91.2 GeV are rejected.  
287 This ensures the  $t\bar{t}$  validation region is orthogonal to the preselection region.

288 Further, because the jet multiplicity of  $t\bar{t}$  events tends to be higher than WZ, the number of jets  
289 in each event is required to be greater than 1. As b-jets are almost invariably produced from top  
290 decays, at least one b-tagged jet passing the 70% DL1r WP in each event is required. Various  
291 kinematic plots of this region are shown in figure 17.

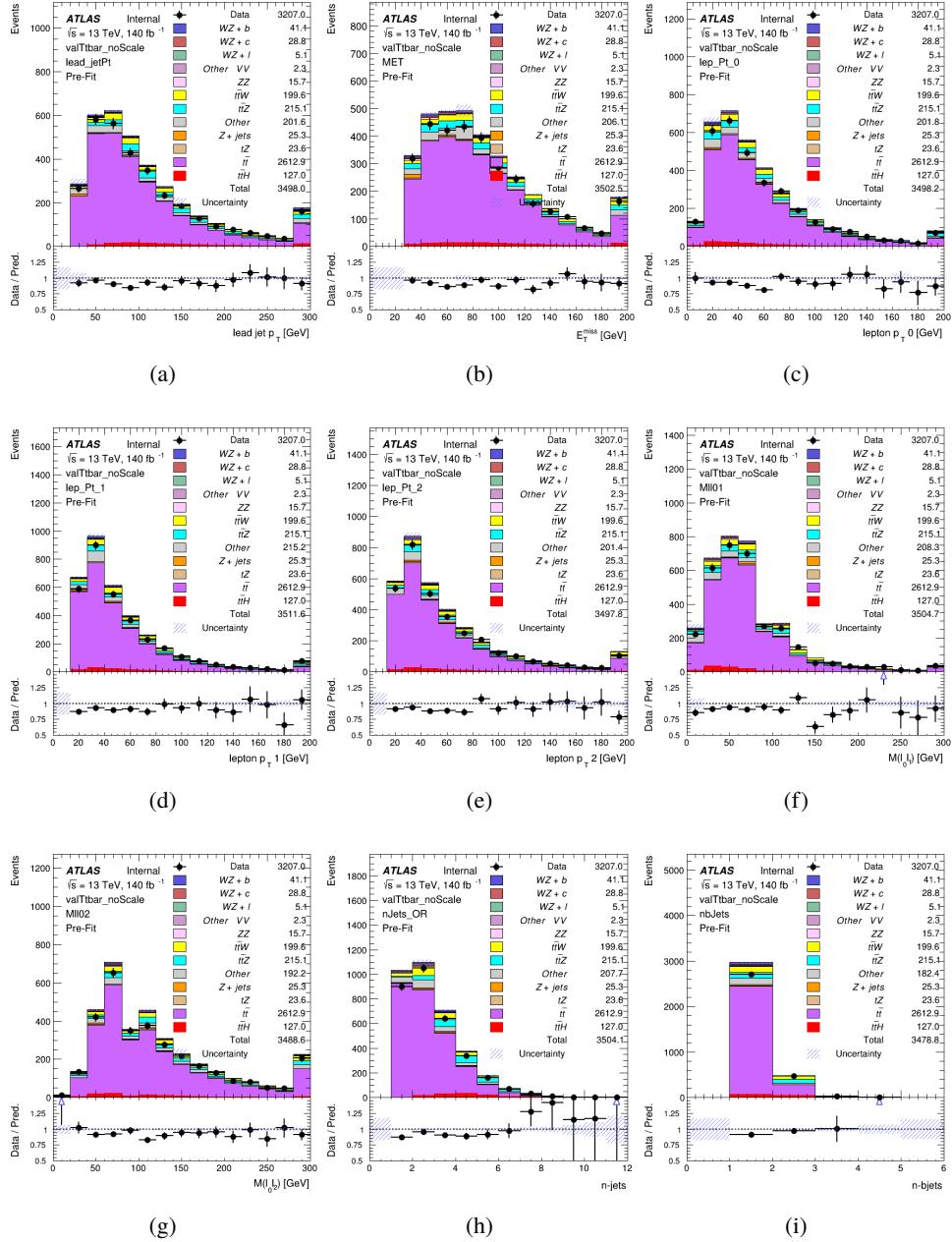


Figure 17: Comparisons between the data and MC distributions in the  $t\bar{t}$  validation region for (a) the  $p_T$  of the leading jet, (b) the missing transverse energy, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of lepton 1, (e)  $p_T$  of lepton 2, (f) the invariant mass of leptons 0 and 1, (g) the invariant mass of leptons 0 and 2, (h) the number of jets, (i) the number of b-tagged jets.

292 The shape of each distribution agrees quite well between data and MC, with a constant offset  
293 between the two. This is accounted for by applying a constant correction factor of 0.883 to the  $t\bar{t}$

294 MC prediction. Plots showing the kinematics of the  $t\bar{t}$  VR after this correction factor has been  
 295 applied are shown in figure 18.

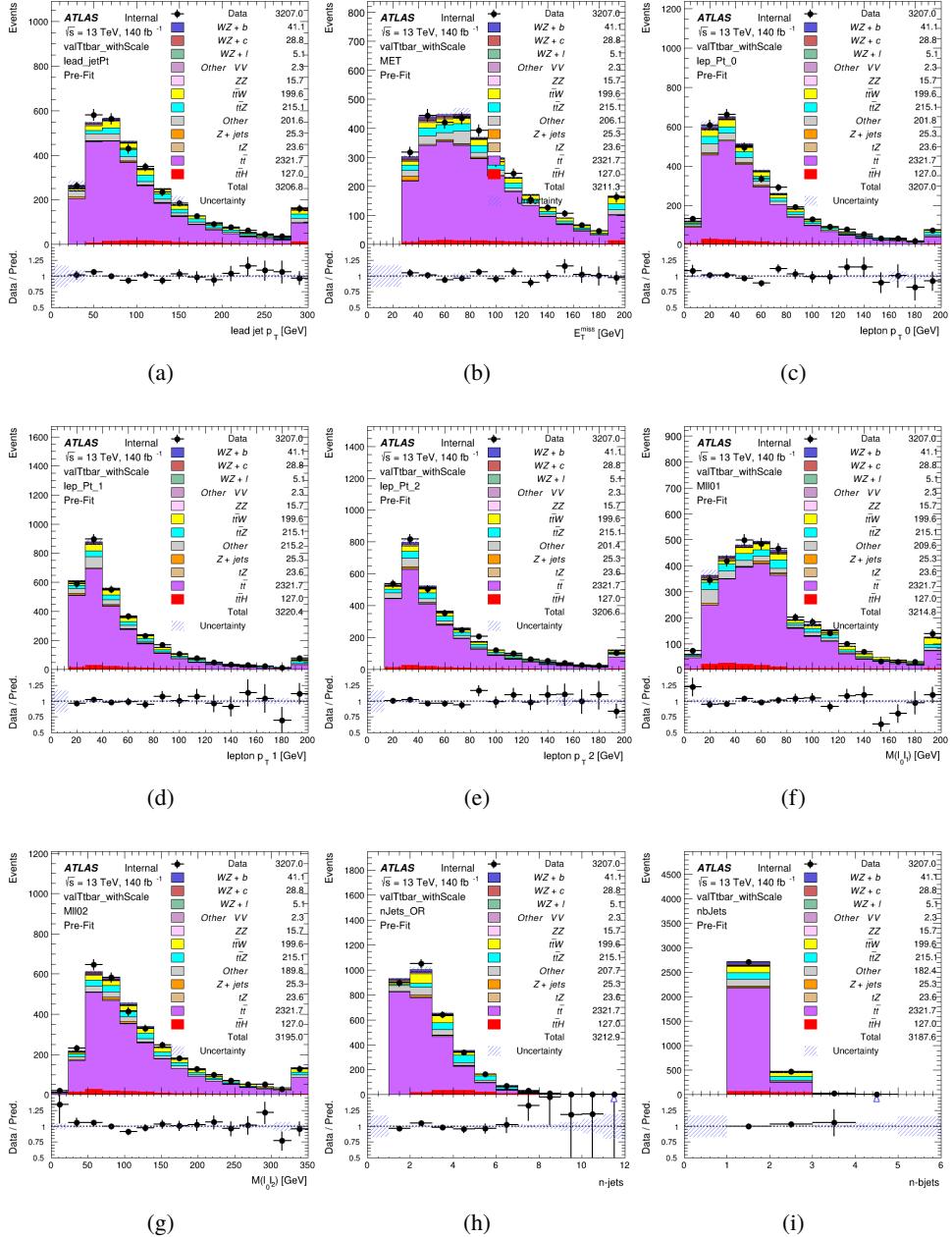


Figure 18: Comparisons between the data and MC distributions in the  $t\bar{t}$  validation region after the correction factor has been applied for (a) the  $p_T$  of the leading jet, (b) the missing transverse energy, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of lepton 1, (e)  $p_T$  of lepton 2, (f) 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.

296 The modeling is further validated by looking at the yield in the  $t\bar{t}$  VR for each DL1r WP, giving  
 297 a clearer correspondence to the signal regions used in the fit. Each region shown in figure 22  
 298 requires one or more jets pass the listed WP, with no jets passing the next highest WP.

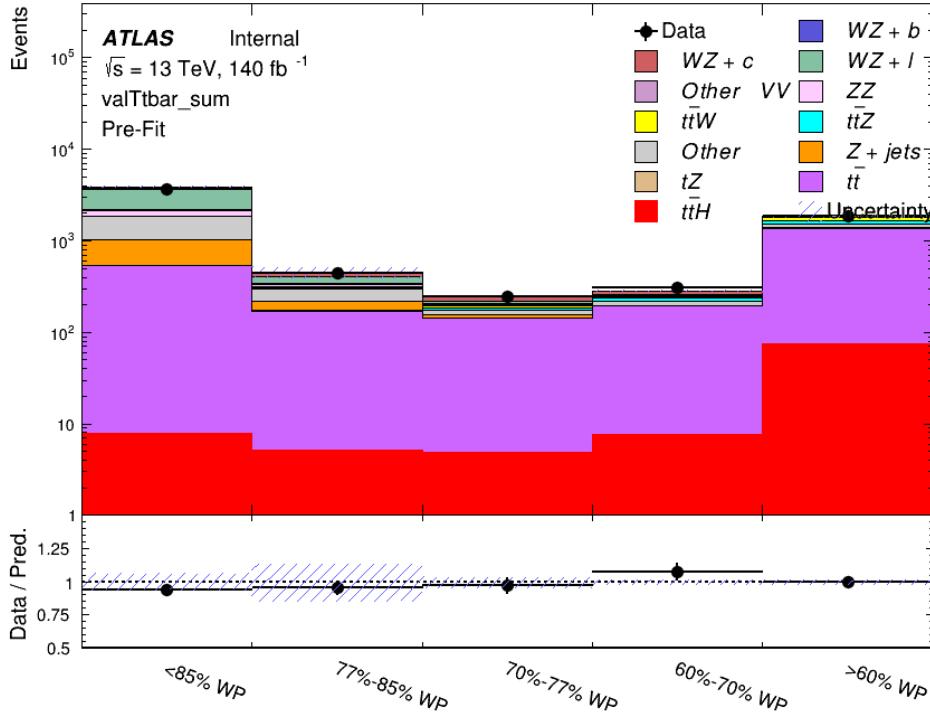


Figure 19: Data and MC comparisons for each DL1r WP for both 1-jet and 2-jet regions, after the  $t\bar{t}$  VR selection and correction factor have been applied

299 As data and MC are found to agree within 10% for each of these working points, a 10% systematic  
 300 uncertainty on the  $t\bar{t}$  prediction is included for the analysis.

### 301 5.3.2 Z+jets Validation

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

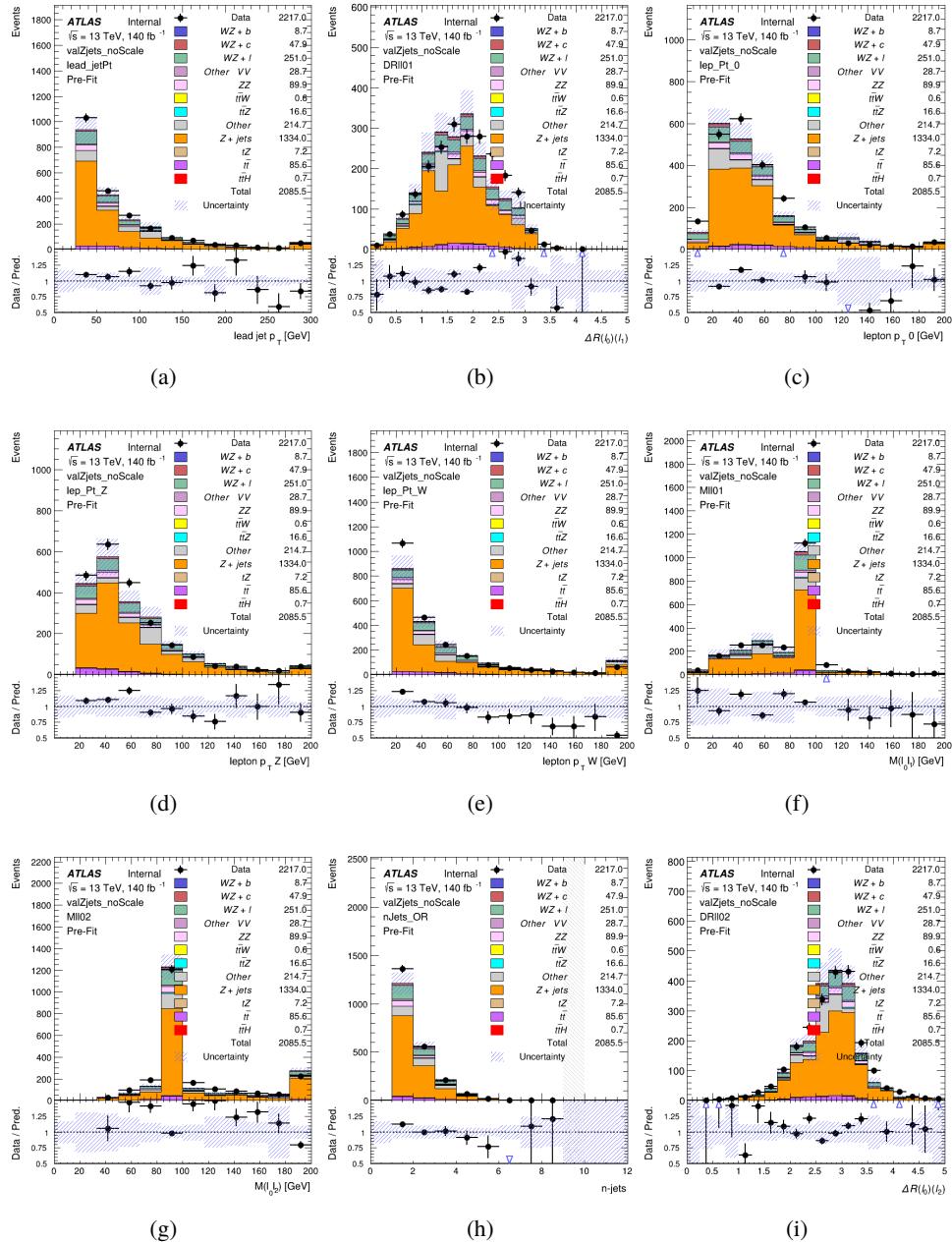


Figure 20: Comparisons between the data and MC distributions in the Z+jets validation region for (a) the  $p_T$  of the leading jet, (b)  $\Delta R$  between leptons 0 and 1, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of SS lepton from the Z candidate, (e)  $p_T$  of the SS lepton from the W candidate, (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

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

<sup>310</sup> of the  $p_T$  spectrum of the lepton from the  $W$  is found to differ. To account for this discrepancy,  
<sup>311</sup> a variable correction factor is applied to  $Z+jets$ .  $\chi^2$  minimization of the lepton 2  $p_T$  spectrum is  
<sup>312</sup> performed to derive a correction factor of  $1.53 - 6.6 \cdot 10^{-6}(lep\_Pt\_W)$ . Kinematic plots of the  
<sup>313</sup>  $Z + jets$  validation region after this correction factor has been applied are shown in figure 21.

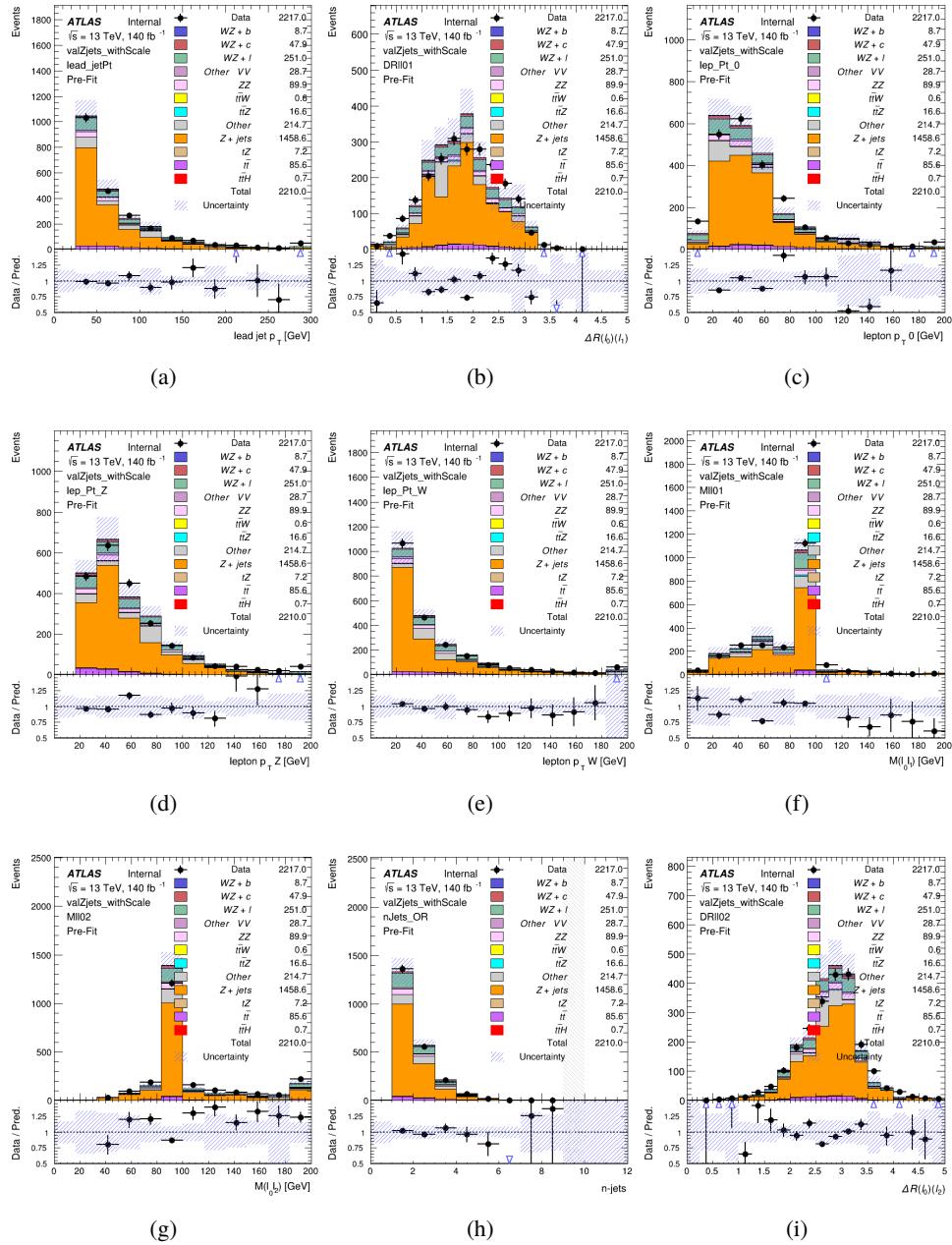


Figure 21: Comparisons between the data and MC distributions in the Z+jets validation region after the correction factor has been applied for (a) the  $p_T$  of the leading jet, (b)  $\Delta R$  between leptons 0 and 1, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of SS lepton from the Z candidate, (e)  $p_T$  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

314 The modeling is further validated by looking at the yield in the Z+jets VR for each DL1r WP,

315 giving a clearer correspondence to the signal regions used in the fit. Each region shown in figure  
 316 22 requires one or more jets pass the listed WP, with no jets passing the next highest WP.

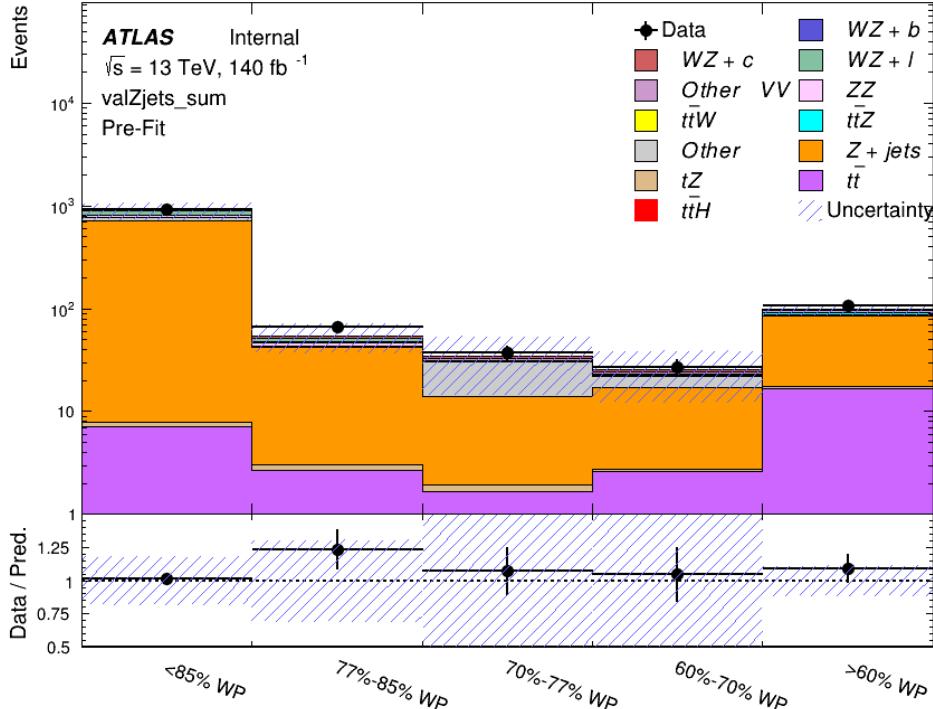


Figure 22: Data and MC comparisons for each DL1r WP for both 1-jet and 2-jet regions, after the Z+jets VR selection and correction factor have been applied

317 For each of the b-tagging working points considered, the data falls within 20% of the MC  
 318 prediction once this correction factor has been applied. Therefore, a 20% systematic uncertainty  
 319 is applied to Z + jets in the analysis.

## 320 6 tZ Interference Studies and Separation Multivariate Analysis

321 Because tZ produces a final state identical to signal, it represents a predominant background in  
 322 the most signal enriched regions. That is, the region with one jet passing the 60% DL1r WP.  
 323 Therefore, a boosted decision tree (BDT) algorithm is trained using TMVA [10] to separate WZ  
 324 + heavy flavor from tZ.

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

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

330 **6.1 Top Mass Reconstruction**

331 The reconstruction of the top mass follows the procedure described in detail in section 6.1 of  
 332 [11]. The mass of the top quark candidate is reconstructed from the jet, the lepton not included  
 333 in the Z-candidate, and a reconstructed neutrino. In the case that there is one jet in the event,  
 334 there is only possible b-jet candidate. For events with two jets, the jet with the highest DL1r  
 335 score is used.

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

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

$$341 \quad (p_l + p_\nu)^2 = m_W^2$$

342 Expanding this out into components, this equation gives:

$$343 \quad \sqrt{p_{T\nu}^2 + p_{z\nu}^2} E_l = \frac{m_w^2 - m_l^2}{2} + p_{T\nu}(p_{lx}\cos\phi_\nu + p_{ly}\sin\phi_\nu) + p_{lz}p_{\nu z}$$

344 This equation gives two solutions for  $p_{\nu z}$ . For cases where only one of these solutions is real,  
 345 that is taken as the value of  $p_{\nu z}$ . For instances with two real solutions, the one which is shown  
 346 to be correct in the largest fraction of simulations is taken. For cases when no real solution is  
 347 found, often because of detector effects, the value of  $E_T^{\text{miss}}$  is varied in decreasing increments of  
 348 100 MeV until a real solution is found.

349 The reconstructed top mass distribution for tZ and WZ + b can be seen in figure 23.

350 **6.2 tZ BDT**

351 A Boosted Decision Tree (BDT), specifically XGBoost [xgboost\_cite], is used to provide separa-  
 352 tion between tZ and WZ+b. The following kinematic variables are used as inputs:

- 353     • The invariant mass of the reconstructed top candidate
- 354     •  $p_T$  of each of the leptons, jet
- 355     • The invariant mass of each combination of lepton pairs,  $M(l\bar{l})$
- 356     •  $E_T^{\text{miss}}$

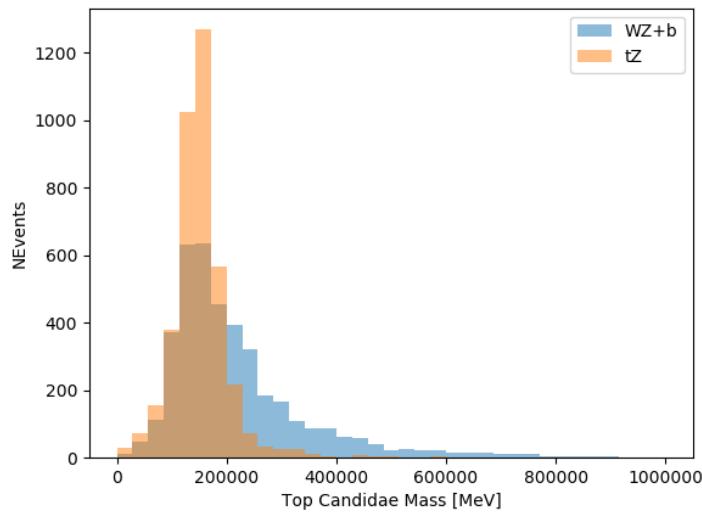


Figure 23: Reconstructed top mass distributions for tZ and WZ + b, measured in MeV.

- 357     • Distance between each combination of leptons,  $\Delta R(ll)$
- 358     • Distance between each lepton and the jet,  $\Delta R(lj)$

359     The training samples included only events meeting the requirements of the 1-jet, >60% region,  
 360     i.e. passing all the selection described in section 5 and having exactly one jet which passes the  
 361     tightest (60%) DL1r working point.

362     The distributions of a few of these features for both signal and background is shown in figure  
 363     24.

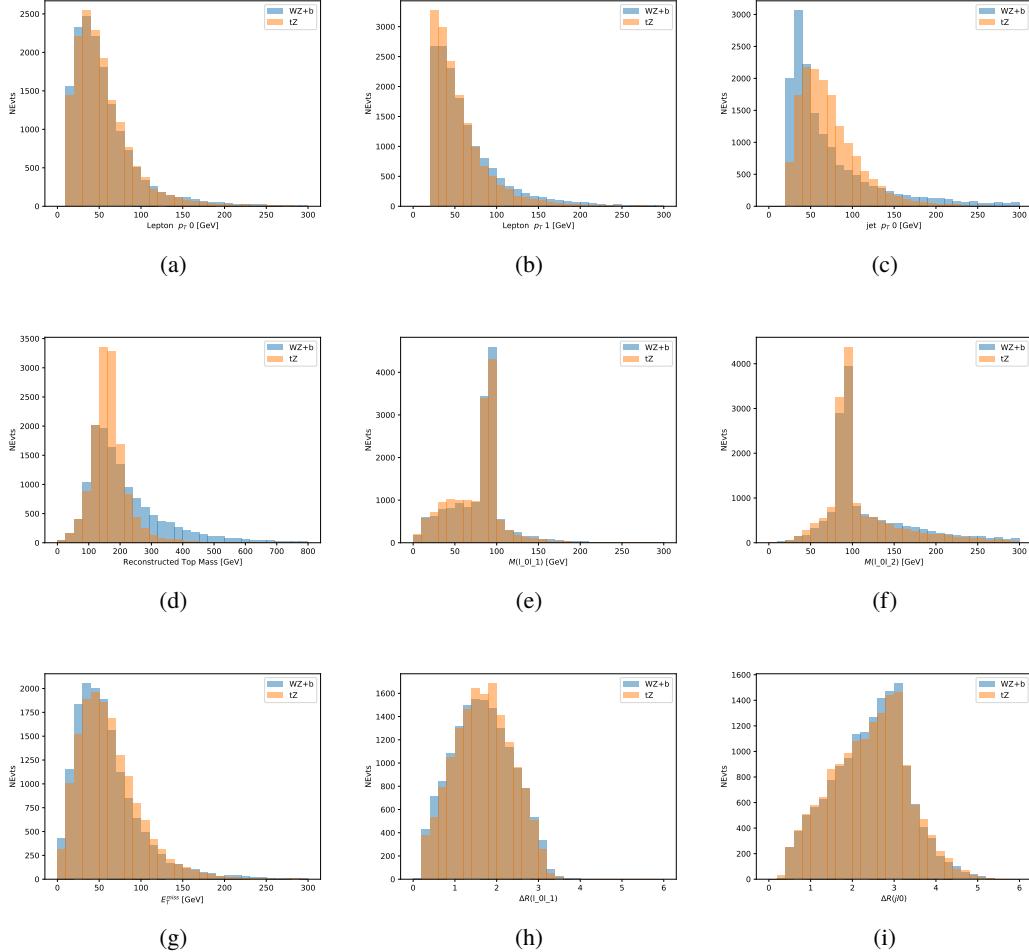


Figure 24: Distribution of input features of the BDT for signal (WZ) and background (tZ). Both are scaled to an equal number of events. (a), (b) and (c) show the  $p_T$  of lepton 0, lepton 1, and the jet, (d) show the reconstructed top mass, (e) and (f) show the invariant mass of leptons 0 and 1, leptons 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.

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

369 The results of the BDT training are shown in figure 25. The output scores for both signal and  
 370 background events is shown on the left. The right shows the receiving operating characteristic  
 371 (ROC) curve that results from the MVA. The ROC curve represents the background rejection  
 372 as a function of signal efficiency, where each point on the curve represents a different response

373 score. The ROC curve of the BDT is compared to the performance of using an optimal set of flat  
 374 selections on the same set of input variables.

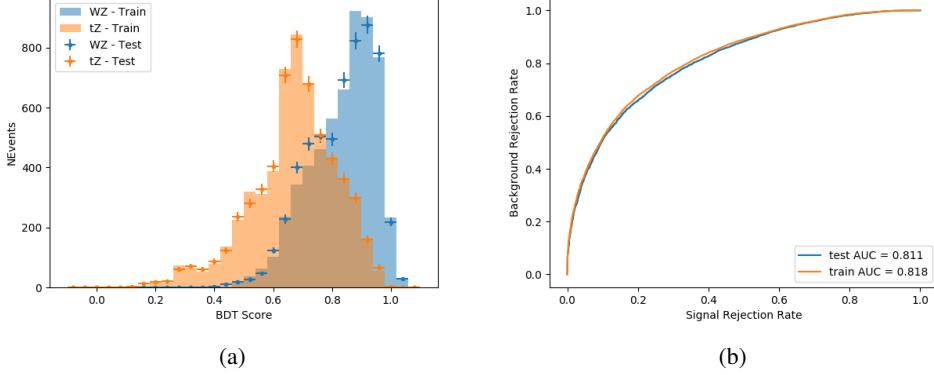


Figure 25: Distribution of the BDT response for signal and background events on the left, the ROC curve for the BDT on the right.

375 The relative important of each input feature in the model, measured by how often they appeared  
 376 in the decision trees, is shown in figure 26.

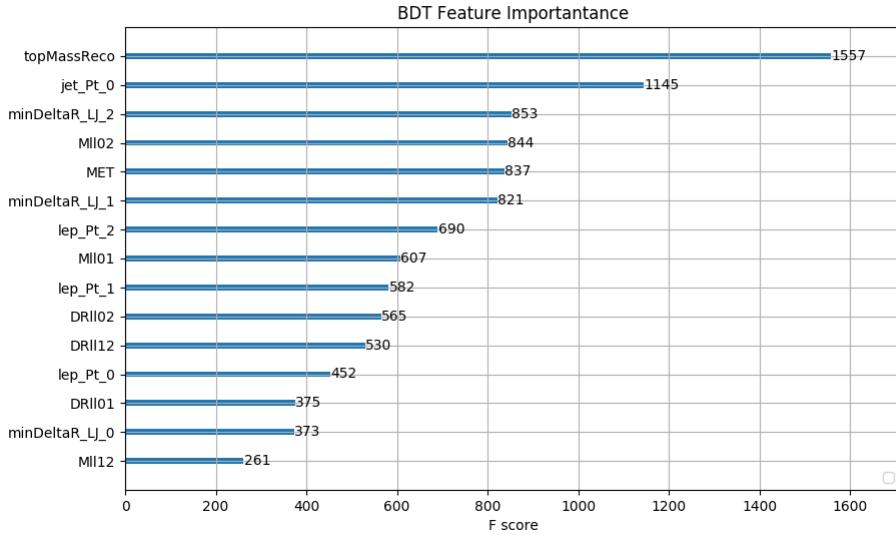


Figure 26: Relative importance of each input feature in the model.

377 These results suggest that some amount of separation can be achieved between these two pro-  
 378 cesses, with a high BDT score selecting a set of events that is pure in  $WZ + b$ . A BDT score

379 of 0.725 is selected as a cutoff, where events with scores higher than this form a signal enriched  
 380 region, and events with scores lower than this form a tZ control region. This cutoff is selected by  
 381 varying the value of this cutoff in stat-only Asimov fits, and selecting the value that minimizes  
 382 the statistical uncertainty on WZ + b.

## 383 7 Systematic Uncertainties

384 The systematic uncertainties that are considered are summarized in table 8. These are imple-  
 385 mented in the fit either as a normalization factors or as a shape variation or both in the signal  
 386 and background estimations. The numerical impact of each of these uncertainties is outlined in  
 387 section 8.

Table 8: Sources of systematic uncertainty considered in the analysis.

| Systematic uncertainty                   | Components |
|--|------------|
| Luminosity                               | 1          |
| Pileup reweighting                       | 1          |
| <b>Physics Objects</b>                   |            |
| Electron                                 | 6          |
| Muon                                     | 15         |
| Jet energy scale and resolution          | 28         |
| Jet vertex fraction                      | 1          |
| Jet flavor tagging                       | 131        |
| $E_T^{\text{miss}}$                      | 3          |
| Total (Experimental)                     | 186        |
| <b>Background Modeling</b>               |            |
| Cross section                            | 24         |
| Renormalization and factorization scales | 10         |
| Parton shower and hadronization model    | 2          |
| Shower tune                              | 4          |
| Total (Signal and background modeling)   | 40         |
| Total (Overall)                          | 226        |

388 The uncertainty in the combined integrated luminosity is derived from a calibration of the  
 389 luminosity scale performed for 13 TeV proton-proton collisions [12], [**LUCID2**].

390 The experimental uncertainties are related to the reconstruction and identification of light leptons  
 391 and b-tagging of jets, and to the reconstruction of  $E_T^{\text{miss}}$ . The sources which contribute to the  
 392 uncertainty in the jet energy scale (JES) [13] are decomposed into uncorrelated components and  
 393 treated as independent sources in the analysis. The CategoryReduction model is used to account  
 394 for JES uncertainties, which decomposes the uncertainties into 30 nuisance parameters included

395 in the fit. The SimpleJER model is used to account for jet energy resolution (JER) uncertainties,  
396 and 8 JER uncertainty components unclded as NPs in the fit.

397 The uncertainties in the b-tagging efficiencies measured in dedicated calibration analyses [14] are  
398 also decomposed into uncorrelated components. The large number of components for b-tagging  
399 is due to the calibration of the distribution of the MVA discriminant.

400 The systematic uncertainties associated with the signal and background processes are accounted  
401 for by varying the cross-section of each process within its uncertainty.

402 The full list of systematic uncertainties considered in the analysis is summarized in tables 9, 10  
403 and 11.

404

| Experimental Systematics on Leptons and $E_T^{\text{miss}}$ |                                     |   |                   |
|---|-------------------------------------|---|-------------------|
| 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 9: 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_SINGLE_NP  | Event Weight   |

Table 10: 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 11: 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.

- 405 Theoretical uncertainties applied to MC predictions, including cross section, PDF, and scale  
 406 uncertainties are taken from theory calculations, with the exception of non-prompt and diboson  
 407 backgrounds. The cross-section uncertainty on tZ is taken from [tZ\_paper]. Derivation of the  
 408 non-prompt background uncertainties, Z+jets and tt>, are explained in detail in section 5.3.  
 409 The other VV + heavy flavor processes (namely VV+b and VV+charm, which primarily comprise  
 410 of ZZ events) are also poorly understood, because these processes involve much of the same  
 411 physics as WZ + heavy flavor, and have also not been measured. Therefore, a conservative 50%  
 412 uncertainty is applied to those samples.  
 413 The theory uncertainties applied to the predominate background estimates are summarized in  
 414 table 12.

| Process                        | X-section [%]   |
|--------------------------------|---|
| WZ                             | QCD Scale: $^{+3.7}_{-3.4}$<br>PDF( $+\alpha_S$ ): $\pm 3.1$                      |
| tZ                             | X-sec: $\pm 15.2$<br>QCD Scale: $^{+5.2}_{-1.3}$<br>PDF( $+\alpha_S$ ): $\pm 1.2$ |
| t̄H<br>(aMC@NLO+Pythia8)       | QCD Scale: $^{+5.8}_{-9.2}$<br>PDF( $+\alpha_S$ ): $\pm 3.6$                      |
| t̄Z<br>(aMC@NLO+Pythia8)       | QCD Scale: $^{+9.6}_{-11.3}$<br>PDF( $+\alpha_S$ ): $\pm 4$                       |
| t̄W<br>(aMC@NLO+Pythia8)       | 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)   | $\pm 6$   |
| t̄t                            | $\pm 10$  |
| Z + jets                       | $\pm 20$  |

Table 12: Summary of theoretical uncertainties for MC predictions in the analysis.

415 Additional signal uncertainties are estimated by comparing estimates from the nominal Sherpa  
 416 WZ samples with alternate WZ samples generated with Powheg+PYTHIA8 (DSID 361601).  
 417 The shape of the templates used in the fit are compared between these two samples for WZ + b,  
 418 WZ + charm and WZ + light, as shown in figures 27 and 28. Each of these plots are normalized  
 419 to unity in order to capture differences in shape.

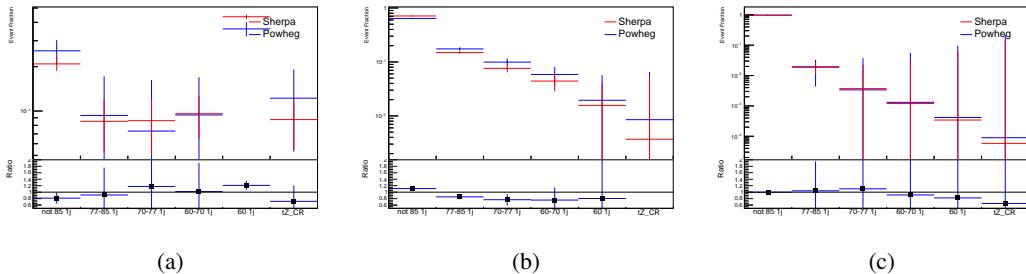


Figure 27: Comparison between Sherpa and Powheg predictions of the distribution of (a) WZ + b, (b) WZ + charm, and (c) WZ + light among the various b-tag WPs used in the 1-jet fit.

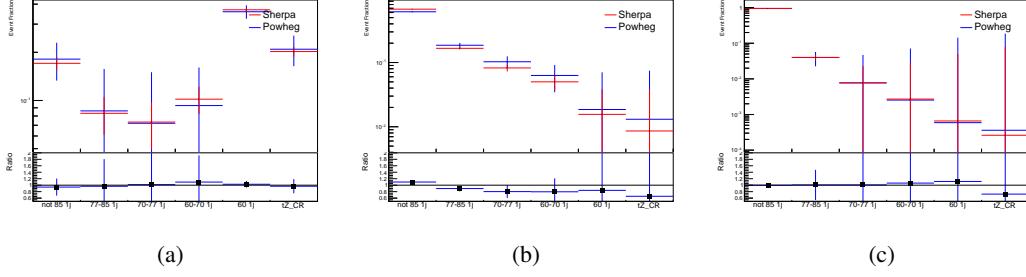


Figure 28: Comparison between Sherpa and Powheg predictions of the distribution of (a) WZ + b, (b) WZ + charm, and (c) WZ + light among the various b-tag WPs used in the 2-jet fit.

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

## 8 Results

424 A separate maximum-likelihood fit is performed over the 1-jet and 2-jet fit regions in order to  
 425 extract the best-fit value of the WZ + b-jet and WZ + charm jet contributions. The WZ + b,  
 426 WZ + charm and WZ + light contributions are allowed to float, with the remaining background  
 427 contributions are held fixed. **The current fit strategy treats the WZ + b-jet contribution as**  
 428 **the parameter of interest, with the normalization of the WZ + charm and the WZ + light**  
 429 **contributions taken as systematic uncertainties. This could however be adjusted, depending**  
 430 **on whether it is decided the goal of the analysis should be to measure WZ+b specifically or**  
 431 **WZ + heavy flavor overall.** The result of the fit is used to extract the cross-section of WZ +  
 432 heavy-flavor production.

433 A maximum likelihood fit to data is performed simultaneously in the regions described in section  
 434 5. The parameters  $\mu_{WZ+b}$ ,  $\mu_{WZ+charm}$ ,  $\mu_{WZ+light}$ , where  $\mu = \sigma_{\text{observed}}/\sigma_{\text{SM}}$ , are extracted  
 435 from the fit.

436 While in the nominal fit events with an intermediate top quark are treated as a separate process, an  
 437 alternative version of the measurement is performed which considers tZ as part of the signal.

### 8.1 1-jet Fit Results

439 **The results of the fit are currently blinded.**

440 The pre-fit yields in each of the regions used in the fit are shown in table 8.1.

441

| Sample   | 1j, <85% WP | 1j, 77%-85% WP | 1j, 70%-77% WP | 1j, 60%-70% WP | 1j, >60% WP | tZ CR       |
|----------|-------------|----------------|----------------|----------------|-------------|-------------|
| WZ + b   | 11 ± 2      | 4.7 ± 0.5      | 4.6 ± 0.4      | 5.1 ± 0.4      | 24 ± 2      | 6.0 ± 0.5   |
| WZ + c   | 318 ± 22    | 81 ± 6         | 43.1 ± 3.6     | 25.8 ± 2.6     | 9.4 ± 1.8   | 2.9 ± 0.6   |
| WZ + l   | 4020 ± 250  | 91 ± 13        | 17 ± 3         | 4.9 ± 1.6      | 1.3 ± 0.4   | 0.2 ± 0.1   |
| Other VV | 6.2 ± 0.6   | 0.2 ± 0.4      | 0.2 ± 0.04     | 0.07 ± 0.1     | 0.1 ± 0.1   | 0.1 ± 0.2   |
| ZZ       | 336 ± nan   | 17.81 ± nan    | 4.33 ± nan     | 1.66 ± nan     | 0.36 ± nan  | 0.10 ± nan  |
| t̄W      | 1.1 ± 0.2   | 0.2 ± 0.1      | 0.3 ± 0.1      | 0.4 ± 0.1      | 1.5 ± 0.3   | 0.7 ± 0.2   |
| t̄tZ     | 6.8 ± 1.2   | 1.4 ± 0.3      | 1.0 ± 0.2      | 1.2 ± 0.2      | 4.4 ± 0.8   | 3.2 ± 0.6   |
| Z + jets | 169 ± 38    | 8.9 ± 1.9      | 3.7 ± 0.8      | 3.3 ± 0.7      | 3.2 ± 0.7   | 0.8 ± 0.17  |
| V + γ    | 45 ± 28     | 1.9 ± 2.4      | 0.1 ± 0.1      | 0.02 ± 0.01    | 1.0 ± 0.9   | 0.02 ± 0.03 |
| tZ       | 24.3 ± 4.3  | 5.5 ± 1.1      | 4.1 ± 0.8      | 5.9 ± 1.1      | 10.7 ± 2.0  | 23 ± 4      |
| tW       | 1.4 ± 0.8   | 0.2 ± 0.5      | 0.0 ± 0.2      | 0.7 ± 0.6      | 0.26 ± 0.42 | 0.39 ± 0.41 |
| WtZ      | 2.3 ± 1.2   | 0.6 ± 0.3      | 0.3 ± 0.21     | 0.27 ± 0.2     | 1.1 ± 0.7   | 0.6 ± 0.5   |
| VVV      | 12.4 ± 0.5  | 0.93 ± 0.06    | 0.35 ± 0.03    | 0.13 ± 0.02    | 0.14 ± 0.03 | 0.02 ± 0.01 |
| VH       | 40 ± 6      | 2.6 ± 1.4      | 0.9 ± 0.8      | 0.7 ± 0.8      | 0.5 ± 0.6   | 0.0 ± 0.0   |
| t̄t      | 12.1 ± 1.6  | 2.9 ± 0.6      | 2.5 ± 0.5      | 2.8 ± 0.5      | 11.2 ± 1.4  | 10.9 ± 1.5  |
| t̄tH     | 0.24 ± 0.03 | 0.05 ± 0.01    | 0.04 ± 0.01    | 0.06 ± 0.01    | 0.20 ± 0.03 | 0.13 ± 0.02 |
| Total    | 5010 ± nan  | 227 ± nan      | 87.7 ± nan     | 56.7 ± nan     | 76.1 ± nan  | 52.5 ± nan  |

Table 13: Pre-fit yields in each of the 1-jet fit regions.

<sup>442</sup> The post-fit yields in each region are summarized in figure 8.1.

<sup>443</sup>

|              | 1j, <85% WP     | 1j, 77%-85% WP  | 1j, 70%-77% WP  | 1j, 60%-70% WP  | 1j, >60% WP     | tZ CR           |
|--------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| WZ + b       | $11 \pm 5$      | $4.7 \pm 2.0$   | $4.6 \pm 2.0$   | $5.1 \pm 2.1$   | $24 \pm 10$     | $6.0 \pm 2.50$  |
| WZ + c       | $320 \pm 60$    | $80 \pm 14$     | $43 \pm 7$      | $26 \pm 5$      | $9.4 \pm 2.3$   | $2.9 \pm 0.7$   |
| WZ + l       | $4020 \pm 130$  | $90 \pm 11$     | $17.3 \pm 2.8$  | $4.9 \pm 1.6$   | $1.3 \pm 0.4$   | $0.23 \pm 0.13$ |
| 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           | $24 \pm 4$      | $5.5 \pm 1.0$   | $4.1 \pm 0.8$   | $5.9 \pm 1.1$   | $10.7 \pm 1.8$  | $23.3 \pm 3.7$  |
| 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 14: Post-fit yields in each of the 1-jet fit regions.

<sup>444</sup> A post-fit summary plot of the 1-jet fitted regions is shown in figure 29:

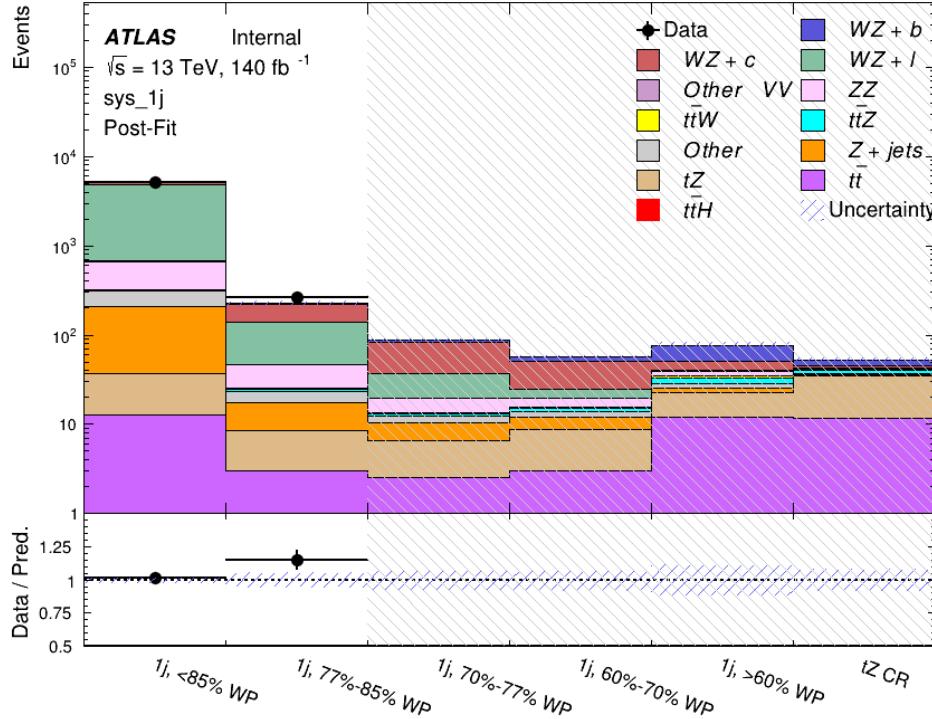


Figure 29: Post-fit summary of the 1-jet fit regions.

445 As described in section 7, there are 226 systematic uncertainties that are considered as NPs in  
 446 the fit. These NPs are constrained by Gaussian or log-normal probability density functions. The  
 447 latter are used for normalisation factors to ensure that they are always positive. The expected  
 448 numbers of signal and background events are functions of the likelihood. The prior for each  
 449 NP is added as a penalty term, decreasing the likelihood as it is shifted away from its nominal  
 450 value.

451 The impact of each NP is calculated by performing the fit with the parameter of interest held  
 452 fixed, varied from its fitted value by its uncertainty, and calculating  $\Delta\mu$  relative to the baseline  
 453 fit. The impact of the most significant sources of systematic uncertainties is summarized in table  
 454 15.

| Uncertainty Source             | $\Delta\mu$ |         |
|--------------------------------|-------------|---------|
| WZ + charm cross-section       | -0.1966     | 0.2171  |
| tZ cross-section               | -0.1521     | 0.1518  |
| WZ + light cross-section       | 0.1485      | -0.1411 |
| Other VV + b cross-section     | -0.1115     | 0.1163  |
| Flavor Tagging                 | 0.0955      | 0.0957  |
| Jet Energy Scale               | 0.0613      | 0.081   |
| t <bar>t</bar>                 | -0.0662     | 0.0654  |
| Luminosity                     | -0.0609     | 0.0655  |
| Z + jets cross-section         | -0.0284     | 0.0284  |
| Other VV + charm cross-section | 0.0207      | -0.0202 |
| Muon Trigger Scale Factor      | 0.019       | 0.0209  |
| Total Systematic Uncertainty   | 0.3511      | 0.3679  |

Table 15: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + b with exactly one associated jet.

<sup>455</sup> The ranking and impact of those nuisance parameters with the largest contribution to the overall  
<sup>456</sup> uncertainty is shown in figure 30.

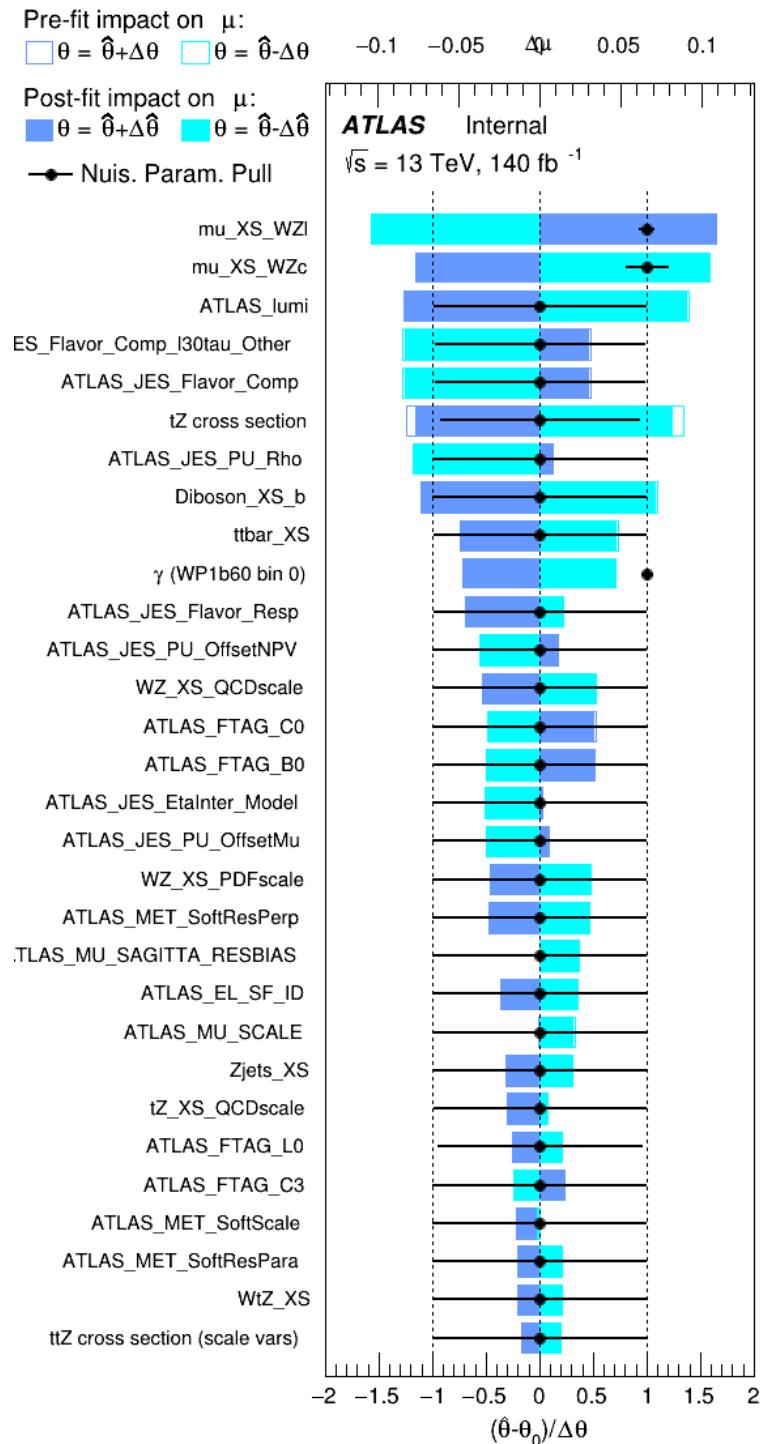


Figure 30: Impact of systematic uncertainties on the signal-strength of  $WZ + b$  for events with exactly one jet

457 The large impact of the Jet Energy Scale and Jet Flavor Tagging is unsurprising, as the shape  
 458 of the fit regions depends heavily on the modeling of the jets. The other major sources of  
 459 uncertainty come from background modelling and cross-section uncertainty. The pie charts in  
 460 figure 31 show that for the modelling uncertainties that contribute most correspond to the most  
 461 significant backgrounds.

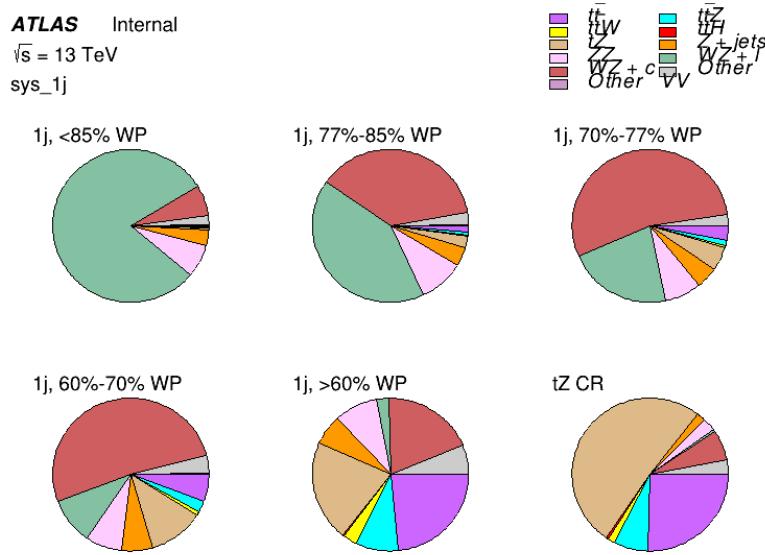


Figure 31: Post-fit background composition of the fit regions.

462 The correlations between these nuisance parameters are summarized in figure 32.

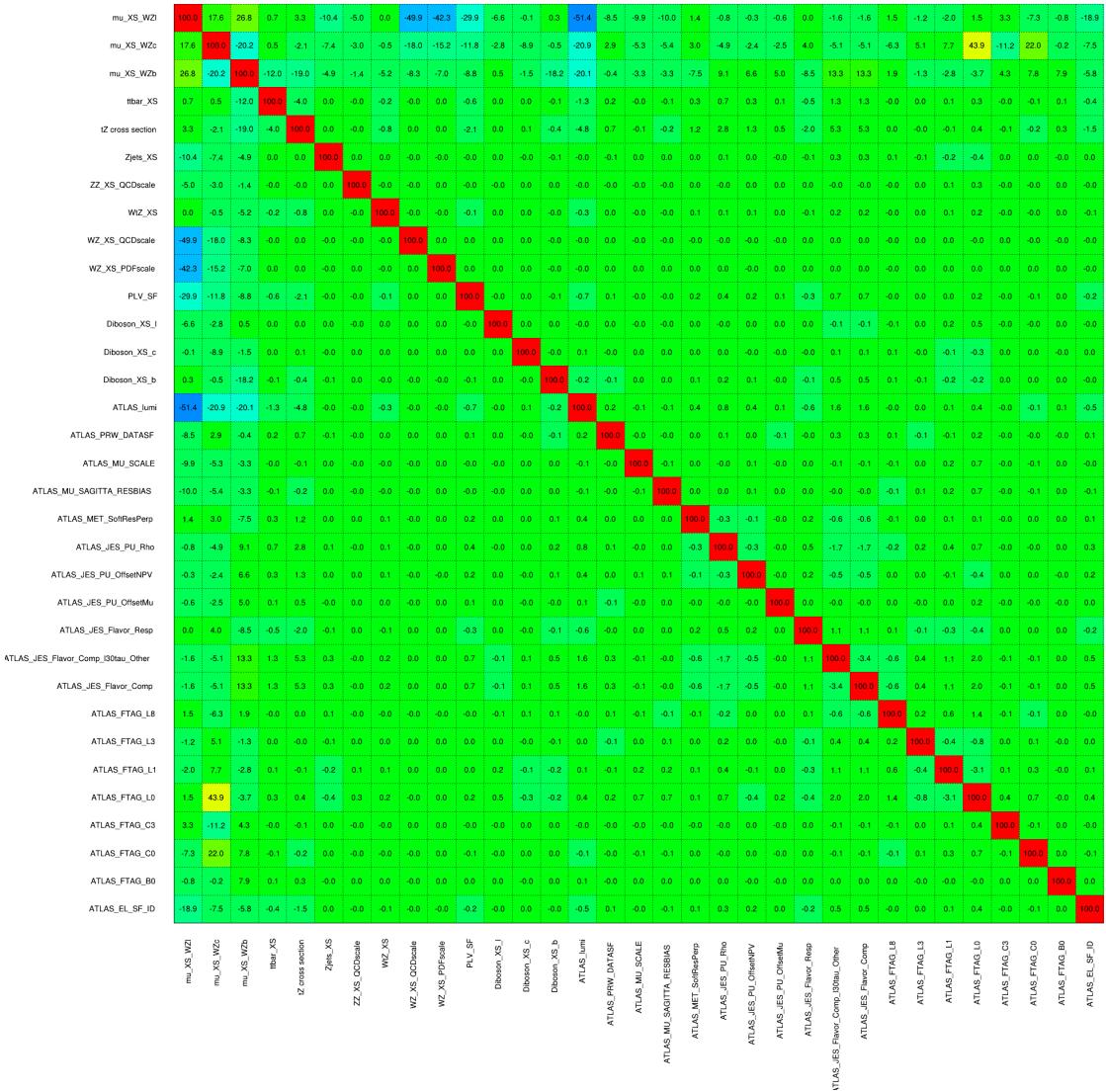


Figure 32: Correlations between nuisance parameters

The negative correlations between  $\mu_{WZ+\text{charm}}$  and  $\mu_{WZ+b}$  and  $\mu_{WZ+\text{light}}$  are expected: WZ + charm is present in both the WZ + b and WZ + light enriched regions, therefore increasing the fraction of charm requires increasing the fraction of WZ + b and WZ + light. This reasoning also explains the positive correlation between  $\mu_{WZ+b}$  and  $\mu_{WZ+\text{light}}$ .

Two of the major backgrounds in the region with the highest purity of WZ + b are tZ and Other VV + b, explaining the negative correlations between  $\mu_{WZ+b}$  and the tZ cross section, and the VV + b cross section.

<sup>470</sup> The high correlation between the luminosity and  $\mu_{WZ+light}$  arises from the fact that the uncer-  
<sup>471</sup> tainty on  $\mu_{WZ+light}$  is very low (around 4%). Small changes in luminosity cause a change in  
<sup>472</sup> the yield of  $WZ + light$  that is large compared to its uncertainty, producing a large correlation  
<sup>473</sup> between these two parameters.

## <sup>474</sup> 8.2 2-jet Fit Results

<sup>475</sup> The results of the fit are currently blinded.

<sup>476</sup> Pre-fit yields in each of the 2-jet fit regions are shown in figure 8.2.

|               | 2j, <85% WP             | 2j, 77%-85% WP         | 2j, 70%-77% WP         | 2j, 60%-70% WP         | 2j, >60% WP             | tZ CR 2j                |
|---------------|-------------------------|------------------------|------------------------|------------------------|-------------------------|-------------------------|
| WZ + b        | $13 \pm 2$              | $6.7 \pm 0.5$          | $5.6 \pm 0.4$          | $8.0 \pm 0.6$          | $31 \pm 2$              | $14 \pm 1$              |
| WZ + c        | $260 \pm 20$            | $77 \pm 6$             | $41 \pm 3$             | $27 \pm 3$             | $11 \pm 2$              | $4.8 \pm 0.6$           |
| WZ + l        | $1860 \pm 150$          | $90 \pm 14$            | $18 \pm 3$             | $5.8 \pm 1.4$          | $1.4 \pm 0.4$           | $0.25 \pm 0.15$         |
| 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            | $135.41 \pm \text{nan}$ | $14.33 \pm \text{nan}$ | $4.71 \pm \text{nan}$  | $4.04 \pm \text{nan}$  | $4.13 \pm \text{nan}$   | $3.09 \pm \text{nan}$   |
| 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            | $15.9 \pm 2.9$          | $6.9 \pm 1.3$          | $5.1 \pm 1.0$          | $8.0 \pm 1.5$          | $18.7 \pm 3.2$          | $36.4 \pm 6.1$          |
| 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         | $2580 \pm \text{nan}$   | $229 \pm \text{nan}$   | $89.30 \pm \text{nan}$ | $69.12 \pm \text{nan}$ | $120.37 \pm \text{nan}$ | $108.41 \pm \text{nan}$ |

Table 16: Pre-fit yields in each of the 2-jet fit regions.

<sup>477</sup> The post-fit yields in each region are summarized in figure 8.2.

|          | 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   | $1860 \pm 90$   | $90 \pm 12$     | $17.6 \pm 2.8$  | $5.8 \pm 1.3$   | $1.4 \pm 0.4$   | $0.3 \pm 0.2$   |
| 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       | $145 \pm 30$    | $11.3 \pm 4.4$  | $2.7 \pm 1.6$   | $1.0 \pm 0.3$   | $4.0 \pm 0.1$   | $2.4 \pm 0.1$   |
| t̄tW     | $0.8 \pm 0.2$   | $0.4 \pm 0.1$   | $0.54 \pm 0.12$ | $0.74 \pm 0.15$ | $4.3 \pm 0.6$   | $3.9 \pm 0.6$   |
| t̄tZ     | $14.7 \pm 2.2$  | $5.6 \pm 0.8$   | $4.5 \pm 0.7$   | $6.5 \pm 1.0$   | $25.4 \pm 3.9$  | $21.9 \pm 3.3$  |
| rare Top | $0.14 \pm 0.04$ | $0.07 \pm 0.03$ | $0.03 \pm 0.02$ | $0.09 \pm 0.03$ | $0.4 \pm 0.1$   | $0.6 \pm 0.1$   |
| t̄tWW    | $0.04 \pm 0.03$ | $0.02 \pm 0.02$ | $0.01 \pm 0.01$ | $0.01 \pm 0.01$ | $0.03 \pm 0.03$ | $0.01 \pm 0.01$ |
| 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       | $15.9 \pm 2.7$  | $6.9 \pm 1.2$   | $5.1 \pm 0.9$   | $8.0 \pm 1.4$   | $18.7 \pm 3.0$  | $36 \pm 6$      |
| 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 17: Post-fit yields in each of the 2-jet fit regions.

<sup>478</sup> A post-fit summary plot of the fitted regions is shown in figure 33:

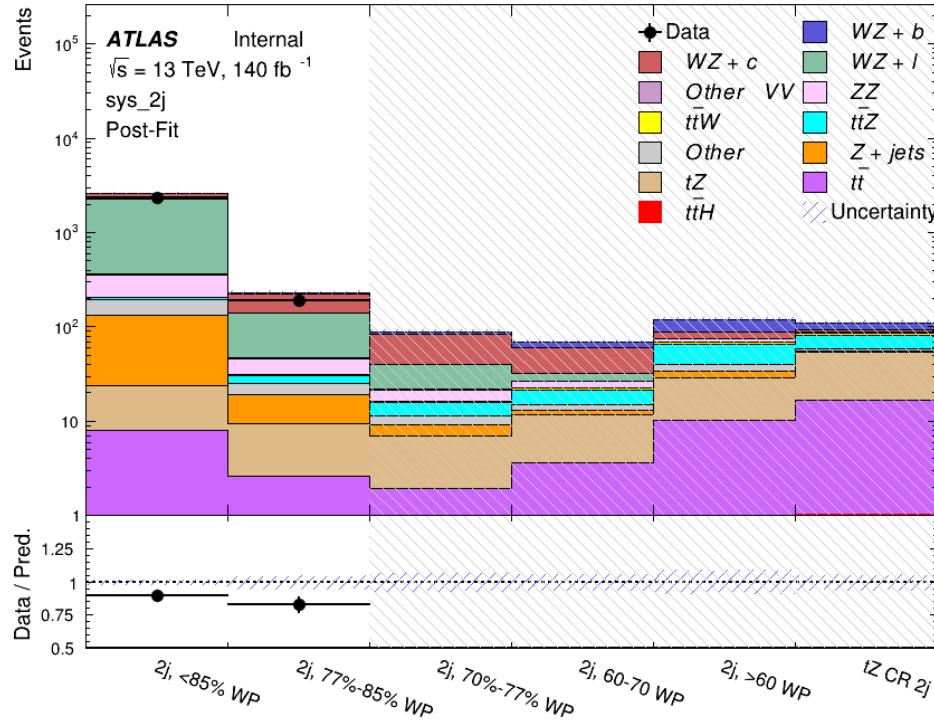


Figure 33: Post-fit summary of the fit over 2-jet regions.

479 The same set of systematic uncertainties consider for the 1-jet fit are included in the 2-jet fit as  
 480 well. The impact of the most significant systematic uncertainties is summarized in table 18.

| Uncertainty Source             | $\Delta\mu$ |         |
|--------------------------------|-------------|---------|
| WZ + charm cross-section       | -0.1966     | 0.2171  |
| tZ cross-section               | -0.1521     | 0.1518  |
| WZ + light cross-section       | 0.1485      | -0.1411 |
| Other VV + b cross-section     | -0.1115     | 0.1163  |
| Flavor Tagging                 | 0.0955      | 0.0957  |
| Jet Energy Scale               | 0.0613      | 0.081   |
| t <bar>t</bar>                 | -0.0662     | 0.0654  |
| Luminosity                     | -0.0609     | 0.0655  |
| Z + jets cross-section         | -0.0284     | 0.0284  |
| Other VV + charm cross-section | 0.0207      | -0.0202 |
| Muon Trigger Scale Factor      | 0.019       | 0.0209  |
| Total Systematic Uncertainty   | 0.3511      | 0.3679  |

Table 18: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + b 2-jet events.

<sup>481</sup> The ranking and impact of those nuisance parameters with the largest contribution to the overall  
<sup>482</sup> uncertainty is shown in figure 34.

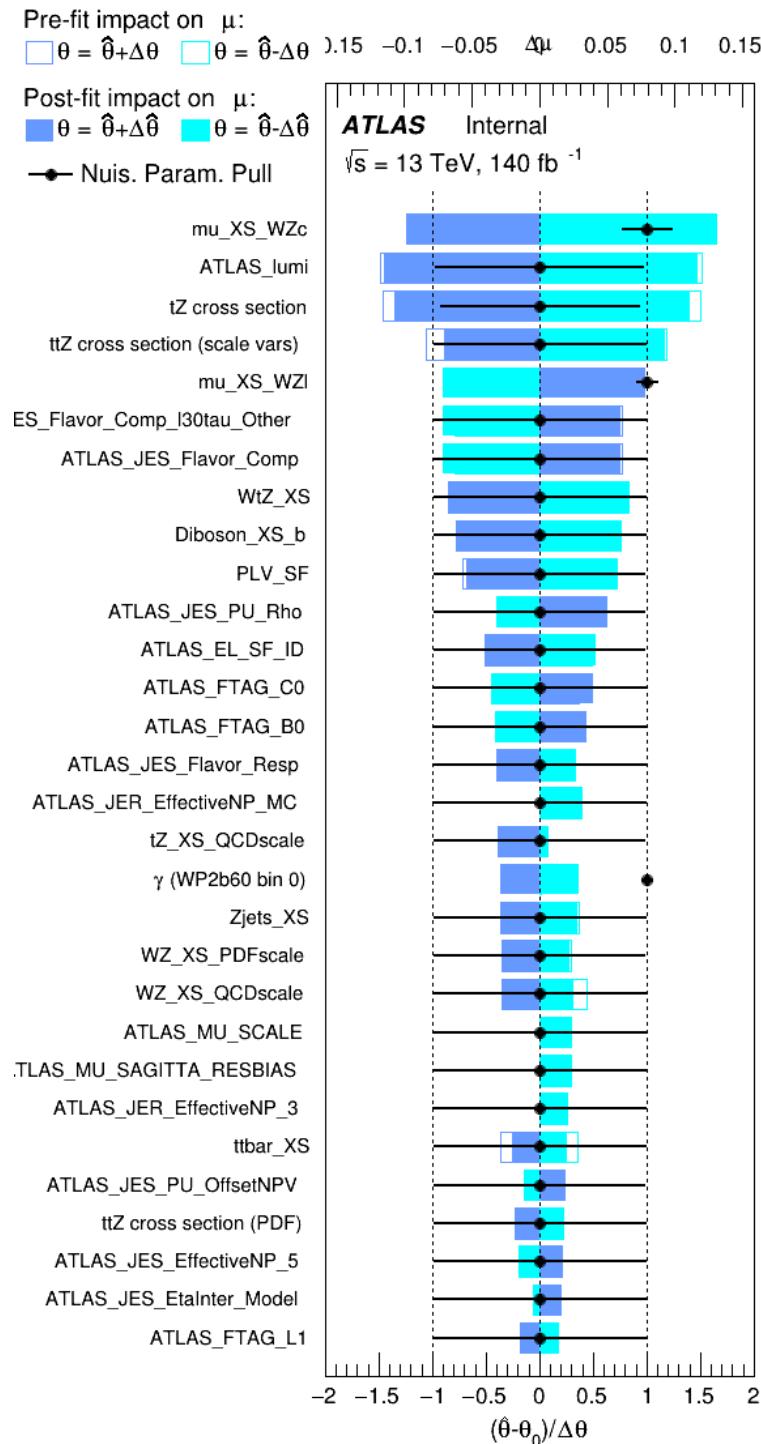


Figure 34: Impact of systematic uncertainties on the signal-strength of  $WZ + b$  in 2-jet events.

483 The large impact of the Jet Energy Scale and Jet Flavor Tagging is unsurprising, as the shape  
 484 of the fit regions depends heavily on the modeling of the jets. The other major sources of  
 485 uncertainty come from background modelling and cross-section uncertainty. The pie charts in  
 486 figure 35 show that for the modelling uncertainties that contribute most correspond to the most  
 487 significant backgrounds.

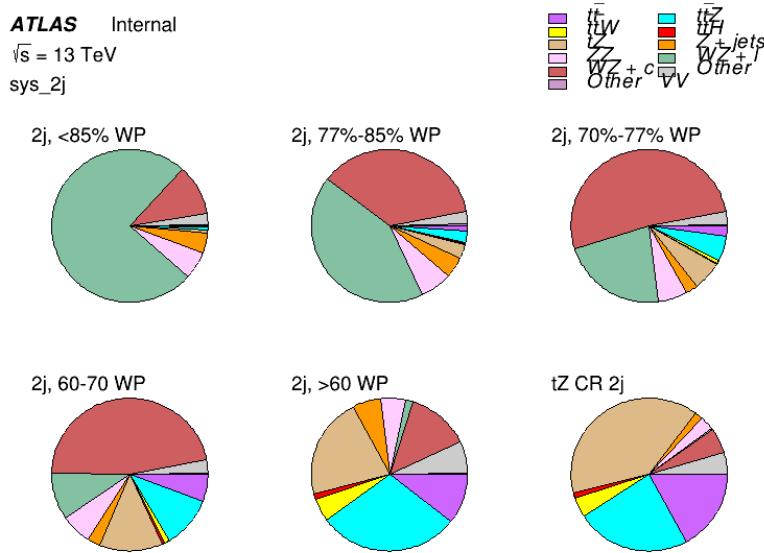


Figure 35: Post-fit background composition of the 2-jet fit regions.

<sup>488</sup> The correlations between these nuisance parameters are summarized in figure 36.

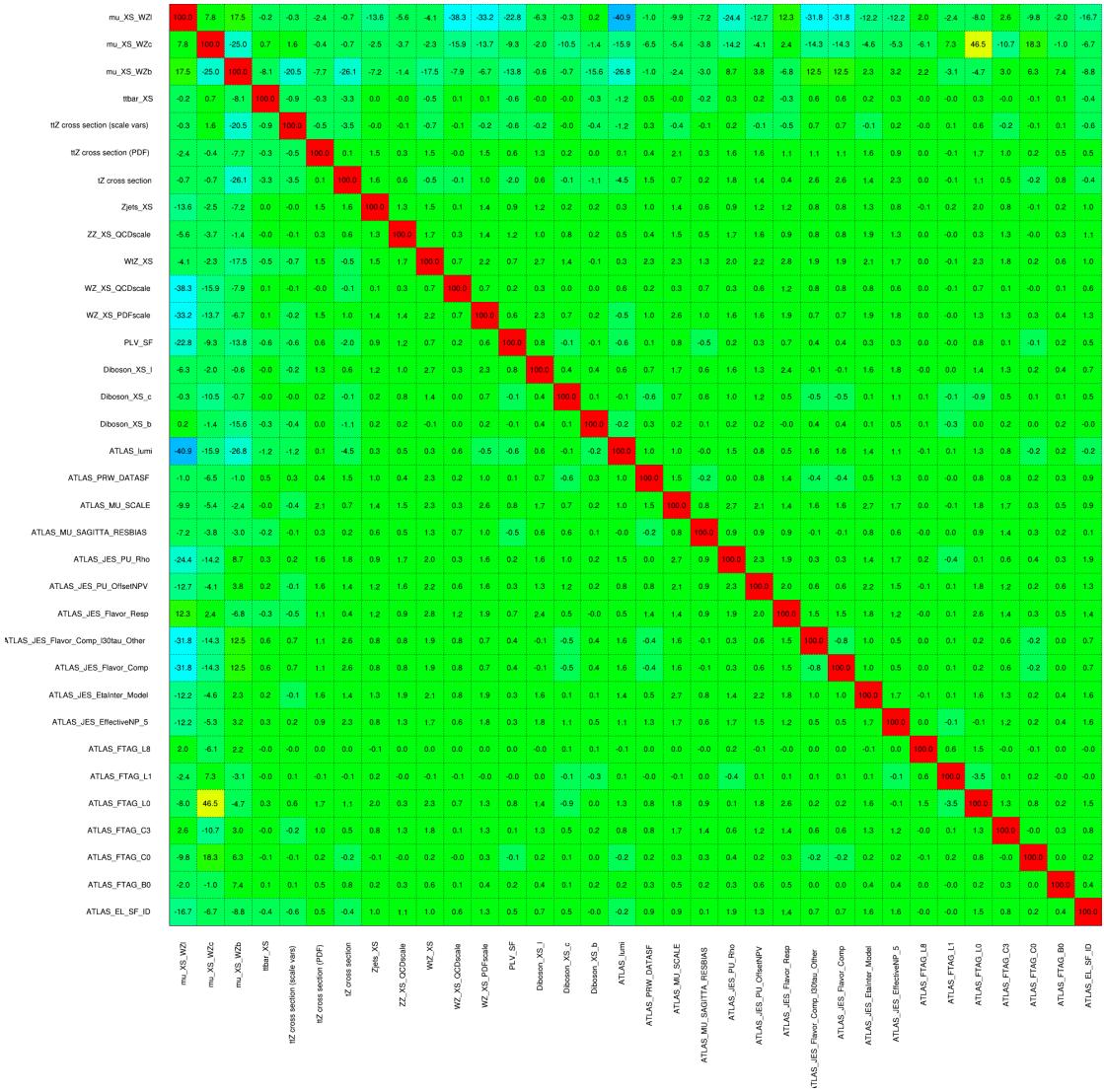


Figure 36: Correlations between nuisance parameters in the 2-jet fit

489 As in the 1-jet case, no significant, unexpected correlations are found between nuisance para-  
490 meters.

### 8.3 tZ Inclusive Results

492 While tZ is often considered as a distinct process form WZ + b,

## 493 9 Conclusion

494 A measurement of  $WZ + \text{heavy flavor}$  is performed using  $140 \text{ fb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$  proton-  
495 proton collision data collected by the ATLAS detector at the LHC. **This section will be include**  
496 **final results once unblinded.**

497 **Appendices**

498 **tZ Interference Studies**

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

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

509 MadGraph simulations of 10,000 tZ and 10,000 WZ + b-jet events are produced, along with  
510 20,000 events where both are present, in the fiducial region where three leptons and at least one  
511 jet are produced.

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

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

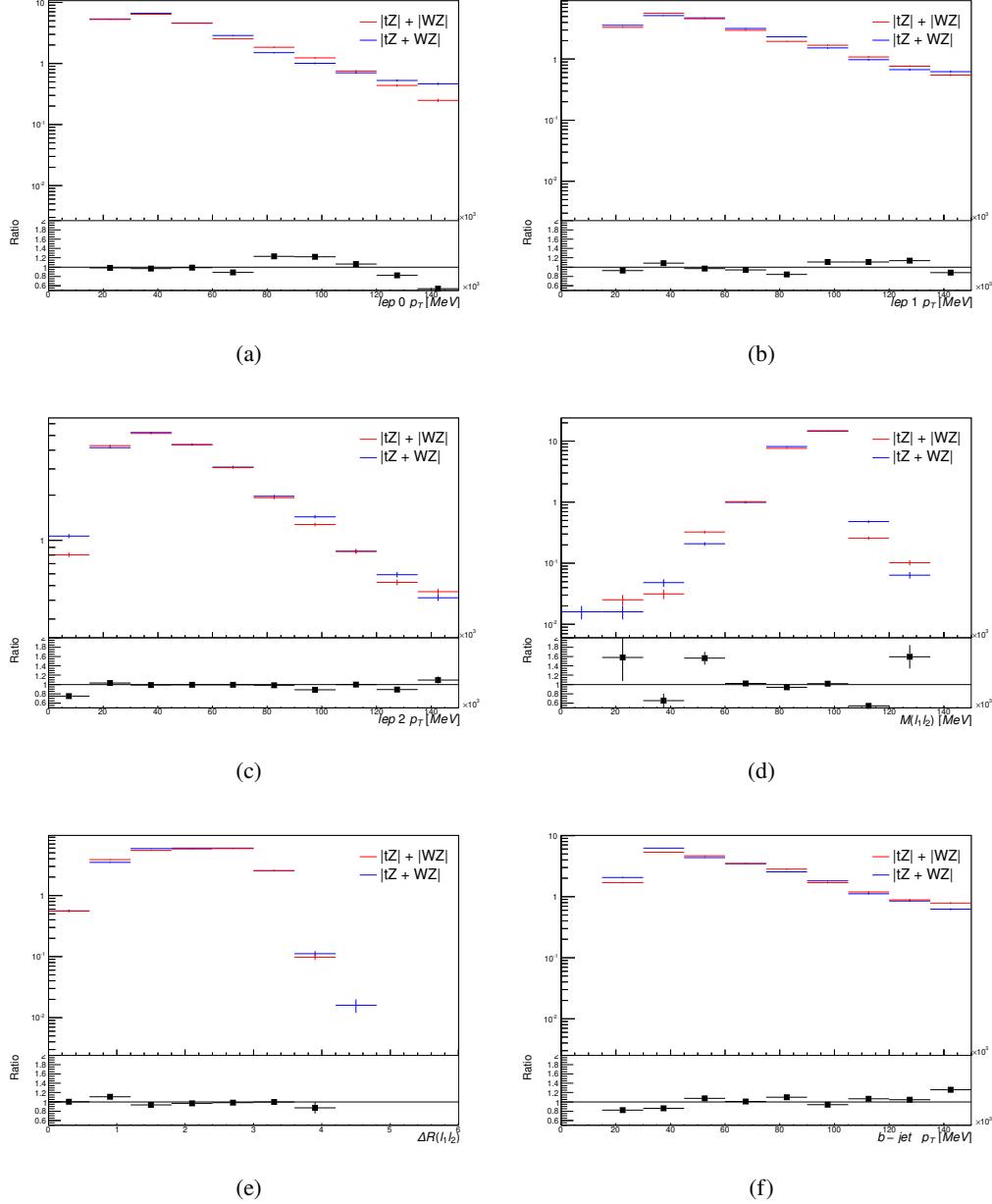


Figure 37: Comparisons between (a) the  $p_T$  of the lepton from the W, (b) and (c) show the  $p_T$  of the lepton from the Z, (d) the invariant mass of the Z-candidate, (e)  $\Delta R$  of the leptons from the Z, and (f) the  $p_T$  of the b-jet, for WZ and tZ events generated with interference effects (blue) and without interference effects (red).

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

519 significantly impact the results.

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