



## ATLAS Note

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

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

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## 62 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.
Heather Russell	EWK group convener. Note editing, developing analysis strategy.
Philip Sommer	EWK group convener. Note editing, developing analysis strategy.

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65 **1 Changes and outstanding items**

66 **1.1 Changelog**

67 This is version 9

68 **1.1.1 Changes relative to v8**

- 69     • Included more references to appendices in the text  
70     • Expanded explanation of fiducial region definition  
71     • Previous draft claimed that both standard and custom PLVs were used. Text is fixed to  
72       state that a custom PLV is used for lepton iso, but standard lepton id is used  
73     • Included plots of PLV output, included WPs used  
74     • specified that non-prompt CR plots are post correction  
75     • changed title of results section

76 **1.1.2 Changes relative to v7**

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

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85 **1.1.3 Changes relative to v5**

- 86     • added list of DSIDs to an appendix  
 87     • included systematics on jet migrations  
 88     • Updated results section to include simultaneous fit over 1-jet and 2-jet bins, describe  
 89        unfolding procedure  
 90     • Updated other sections to account for this change  
 91     • Included info about migrations in Section 5.2

92 **1.1.4 Changes relative to v4**

- 93     • Fixed various typos, clarified wording  
 94     • Expanded info about JER uncertainties, electron systematics, theory uncertainties  
 95     • removed a table on lepton selection, included information in the text instead  
 96     • Plotted lepton Pt Z and W for Zjet CR, rather than lep 1 and 2  
 97     • fixed binning in kinematic plots  
 98     • Included prefit and postfit yield tables  
 99     • added signal modelling systematics  
 100     • included alternate fit studies with tZ included in signal

101 **1.1.5 Changes relative to v3**

- 102     • Merged introduction into executive summary, including unblinding details and list of  
 103        SRs/CRs used  
 104     • listed ptag used (p4133), and release (AB 21.2.127)  
 105     • Included table reftab:xsecUnc listing x-sec uncertainties used  
 106     • Removed selection criteria listed in table ?? (QMisID, AmbiguityType) that were removed  
 107        from the analysis  
 108     • specified variable used to make truth jet flavor determination (HadronConeExclTruthLa-  
 109        belIID)  
 110     • fixed bug in MtLepMet calculation, updated selection/fits to account for this  
 111     • Included plots of MtLepMet and PtZ, swapped lep 1 and 2  $p_T$  plots for lep W and lep Z  
 112        plots

- 113     • updated tZ BDT training to reduce overfitting, updated plots to include error bars, feature  
114       importance
- 115     • updated table 8 to clarify selection, fix the tZ\_BDT cut used
- 116     • replace a few broken ntuples which included large weight events
- 117     • include DL1r distribution for Z+jets and  $t\bar{t}$  VRs
- 118     • Expanded section on fakes, included information on derived scale factors from VRs.
- 119     • Changed the kinematic plots to include  $p_T(Z)$  and  $m_T(W)$ , list lepton  $p_T$  based on W and  
120       Z candidates.

### 121     **1.1.6 Changes relative to v2**

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

### 129     **1.1.7 Changes relative to v1**

- 130     • Added GRL list
- 131     • Fixed latex issue in line 92, typo in line 172
- 132     • Added tables 6 and ??, summarizing the event and object selection
- 133     • Added table 2, which includes the DSID of samples used
- 134     • Included reference to WZ inclusive paper in introduction

## 135     **1.2 Outstanding Items**

- 136     • Unblind, update plots and fits to include data
- 137     • Add cross-section, significance once unblinded

## 138 2 Executive Summary

139 The production of  $WZ$  in association with a heavy flavor jet represents an important background  
 140 for many major analyses. This includes any process with leptons and b-jets in the final state,  
 141 such as  $t\bar{t}H$ ,  $t\bar{t}W$ , and  $t\bar{t}Z$ . While precise measurements have been made of  $WZ$  production  
 142 [1],  $WZ +$  heavy flavor remains poorly understood. This is largely because the QCD processes  
 143 involved in the production of the b-jet make it difficult to simulate accurately. This introduces a  
 144 large uncertainty for analyses that include this process as a background.

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

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

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

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

165 The analysis aims to report a cross-section measurement of  $WZ+b$  and  $WZ+charm$ , along with  
 166 their correlations, for both 1-jet and 2-jet exclusive regions. The proposed fiducial region for  
 167 these measurements includes events with three leptons, where the invariant mass of at least one  
 168 opposite charge, same flavor lepton pair falls within  $10 \text{ GeV}$  of  $91.2 \text{ GeV}$ , with 1 or 2 associated  
 169 jets. An alternate version of the measurement is included in the appendix, which considers  $tZ$  as  
 170 part of the  $WZ+b$  signal.

171 The current state of the analysis shows blinded results for the full Run 2 dataset. Regions  
 172 containing  $>5\%$   $WZ+b$  events are blinded, and results are from Asimov, MC only fits. Expected  
 173 significance and cross-section numbers are reported.

### 174 **3 Data and Monte Carlo Samples**

175 Both data and Monte Carlo samples used in this analysis were prepared in the `xAOD` format,  
 176 which was used to produce a `DxAOD` sample in the `HIGG8D1` derivation framework. The `HIGG8D1`  
 177 framework is designed for the  $t\bar{t}H$  multi-lepton analysis, which targets events with multiple  
 178 leptons as well as tau hadrons. This framework skims the dataset to remove unneeded variables  
 179 as well as entire events. Events are removed from the derivations that do not meet the following  
 180 selection:

- 181 • at least two light leptons within a range  $|\eta| < 2.6$ , with leading lepton  $p_T > 15$  GeV and  
 182 subleading lepton  $p_T > 5$  GeV
- 183 • at least one light lepton with  $p_T > 15$  GeV within a range  $|\eta| < 2.6$ , and at least two hadronic  
 184 taus with  $p_T > 15$  GeV.

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

#### 188 **3.1 Data Samples**

189 The study uses a sample of proton-proton collision data collected by the ATLAS detector from  
 190 2015 through 2018 at an energy of  $\sqrt{s} = 13$  TeV, which represents an integrated luminosity of  
 191  $139 \text{ fb}^{-1}$ . This data set was collected with a bunch crossing rate of 25 ns. All data used in this  
 192 analysis was verified by data quality checks, having been included in the following Good Run  
 193 Lists:

- 194 • `data15_13TeV.periodAllYear_DetStatus-v79-repro20-02_DQDefects-00-02-02`  
 195   `_PHYS_StandardGRL_All_Good_25ns.xml`
- 196 • `data16_13TeV.periodAllYear_DetStatus-v88-pro20-21_DQDefects-00-02-04`  
 197   `_PHYS_StandardGRL_All_Good_25ns.xml`
- 198 • `data17_13TeV.periodAllYear_DetStatus-v97-pro21-13_Unknown_PHYS_StandardGRL`  
 199   `_All_Good_25ns_Triggerno17e33prim.xml`
- 200 • `data18_13TeV.periodAllYear_DetStatus-v102-pro22-04_Unknown_PHYS_StandardGRL`  
 201   `_All_Good_25ns_Triggerno17e33prim.xml`

202 Runs included from the `AllYear` period containers are included.

203 **3.2 Monte Carlo Samples**

204 Several different generators were used to produce Monte Carlo simulations of the signal and  
 205 background processes. For all samples, the response of the ATLAS detector is simulated using  
 206 Geant4. The WZ signal samples are simulated using Sherpa 2.2.2 [2]. Signal events are generated  
 207 using NNPDF30NNLO PDF set with up to one parton at NLO and 2 to 3 partons at LO.

208 Specific information about the Monte Carlo samples being used can be found in Table 1. A list  
 209 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
tZ	MG5_AMC	NLO	PYTHIA 8	CTEQ6L1
t̄W	MG5_AMC (SHERPA 2.1.1)	NLO (LO multileg)	PYTHIA 8 (SHERPA)	NNPDF 3.0 NLO (NNPDF 3.0 NLO)
t̄t(Z/γ* → ll)	MG5_AMC	NLO	PYTHIA 8	NNPDF 3.0 NLO
t̄H	MG5_AMC (MG5_AMC)	NLO (NLO)	PYTHIA 8 (HERWIG++)	NNPDF 3.0 NLO [3] (CT10 [4])
tHqb	MG5_AMC	LO	PYTHIA 8	CT10
tHW	MG5_AMC (SHERPA 2.1.1)	NLO (LO multileg)	HERWIG++ (SHERPA)	CT10 (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 [5]	NLO	PYTHIA 8	NNPDF 3.0 NLO
t̄t̄γ	MG5_AMC	LO	PYTHIA 8	NNPDF 2.3 LO
s-, t-channel, Wt single top	POWHEG-BOX v1 [6]	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
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.

## 210 4 Object Reconstruction

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

### 214 4.1 Trigger

215 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.

## 216 4.2 Light leptons

217 Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter  
 218 that are associated with charged particle tracks reconstructed in the inner detector [7]. Electron  
 219 candidates are required to have  $p_T > 10$  GeV and  $|\eta_{\text{cluster}}| < 2.47$ . Muon candidates are  
 220 reconstructed by combining inner detector tracks with track segments or full tracks in the muon  
 221 spectrometer [8]. Muon candidates are required to have  $p_T > 10$  GeV and  $|\eta| < 2.5$ . Candidates  
 222 in the transition region between different electromagnetic calorimeter components,  $1.37 <$   
 223  $|\eta_{\text{cluster}}| < 1.52$ , are rejected. A multivariate likelihood discriminant combining shower shape  
 224 and track information is used to distinguish real electrons from hadronic showers (fake electrons).  
 225 To further reduce the non-prompt electron contribution, the track is required to be consistent  
 226 with originating from the primary vertex; requirements are imposed on the transverse impact  
 227 parameter significance ( $|d_0|/\sigma_{d_0} < 5$ ) and the longitudinal impact parameter ( $|\Delta z_0 \sin \theta_\ell| < 0.5$   
 228 mm). Electron candidates are required to pass TightLH identification.

229 Muon candidates are reconstructed by combining inner detector tracks with track segments or  
 230 full tracks in the muon spectrometer [8]. Muon candidates are required to have  $p_T > 10$  GeV  
 231 and  $|\eta| < 2.5$ . The longitudinal impact parameter is the same for both electrons and muons, while  
 232 muons are required to pass a slightly tighter transverse impact parameter,  $|d_0|/\sigma_{d_0} < 3$ . Muons  
 233 are also required to pass Medium ID requirements.

234 Leptons are additionally required to pass a non-prompt BDT selection developed by the  $t\bar{t}H$   
235 multilepton/ $t\bar{t}W$  analysis group. This BDT and the WPs used are summarized in Appendix A.1,  
236 and described in detail in [9]. Optimized working points and scale factors for this BDT are taken  
237 from that analysis.

### 238 4.3 Jets

239 Jets are reconstructed from calibrated topological clusters built from energy deposits in the  
240 calorimeters [10], using the anti- $k_t$  algorithm with a radius parameter  $R = 0.4$ . Particle Flow,  
241 or PFlow, jets are used in the analysis. Jets with energy contributions likely arising from noise  
242 or detector effects are removed from consideration [11], and only jets satisfying  $p_T > 25$  GeV  
243 and  $|\eta| < 2.5$  are used in this analysis. For jets with  $p_T < 60$  GeV and  $|\eta| < 2.4$ , a jet-track  
244 association algorithm is used to confirm that the jet originates from the selected primary vertex,  
245 in order to reject jets arising from pileup collisions [12].

### 246 4.4 B-tagged Jets

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

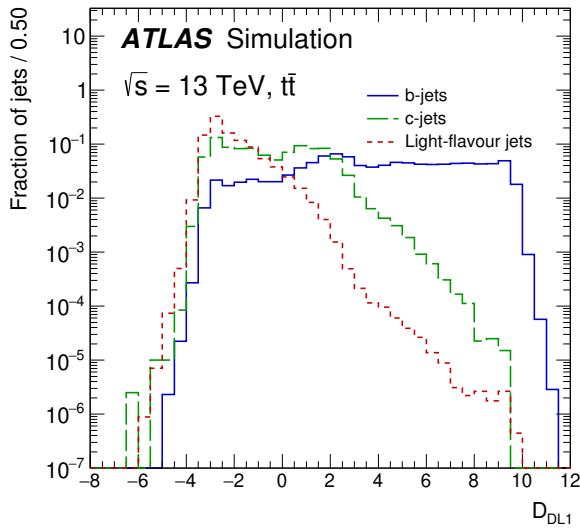


Figure 1: Output distribution of the DL1r algorithm for b-jets, charm jets, and light jets

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

256 A tighter WP will accept fewer b-jets, but reject a higher fraction of charm and light jets.  
 257 Generally, analyses that include b-jets will use a fixed working point, for example, requiring that  
 258 a jet pass the 70% threshold. By instead treating these working point as bins, e.g. events with  
 259 jets that fall between the 85% and 77% WPs fall into one bin, while events with jets passing the  
 260 60% WP fall into another, and looking at the full psuedo-continuous DL1r spectrum of the jets,  
 261 additional information can be gained. The psuedo-continuous b-tag spectrum is used in this case  
 262 to separate out  $WZ + b$ ,  $WZ + \text{charm}$ , and  $WZ + \text{light}$ .

#### 263 4.5 Missing transverse energy

264 Missing transverse momentum ( $E_T^{\text{miss}}$ ) is used as part of the event selection. The missing  
 265 transverse momentum vector is defined as the inverse of the sum of the transverse momenta of  
 266 all reconstructed physics objects as well as remaining unclustered energy, the latter of which is  
 267 estimated from low- $p_T$  tracks associated with the primary vertex but not assigned to a hard object,  
 268 with object definitions taken from [13]. Light leptons considered in the  $E_T^{\text{miss}}$  reconstruction are  
 269 required to have  $p_T > 10$  GeV, while jets are required to have  $p_T > 20$  GeV.

#### 270 4.6 Overlap removal

271 To avoid double counting objects and remove leptons originating from decays of hadrons, overlap  
 272 removal is performed in the following order: any electron candidate within  $\Delta R = 0.1$  of another  
 273 electron candidate with higher  $p_T$  is removed; any electron candidate within  $\Delta R = 0.1$  of a muon  
 274 candidate is removed; any jet within  $\Delta R = 0.3$  of an electron candidate is removed; if a muon  
 275 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  
 276 is kept and the muon is removed.

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

<b>Keep</b>	<b>Remove</b>	<b>Cone size (<math>\Delta R</math>)</b>
electron	electron (low $p_T$ )	0.1
muon	electron	0.1
electron	jet	0.3
jet	muon	$\min(0.4, 0.04 + 10[\text{GeV}]/p_T(\text{muon}))$
electron	tau	0.2

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

## 279 5 Event Selection and Signal Region Definitions

280 Event are required to pass a preselection described in Section 5.1 and summarized in Table 6.  
 281 Those that pass this preselection are divided into various fit regions described in Section 5.2,  
 282 based on the number of jets in the event, and the b-tag score of those jets.

283 **5.1 Event Preselection**

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

286 The leptons are ordered in the analysis code as 0, 1, and 2. Lepton 0 is the lepton whose charge  
 287 is opposite the other two. Lepton 1 is the lepton closest to the opposite charge lepton, i.e. the  
 288 smallest  $\Delta R$ , leaving lepton 2 as the lepton further from the opposite charge lepton. Lepton 0  
 289 is required to have  $p_T > 10 \text{ GeV}$ , while the same sign leptons, 1 and 2, are required to have  
 290  $p_T > 20 \text{ GeV}$  to reduce the contribution of non-prompt leptons.

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

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

297 Events are required to have one or two reconstructed jets passing the selection described in  
 298 Section 4.3. Events with more than two jets are rejected in order to reduce the contribution of  
 299 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 $p_T > 20 \text{ GeV}$
One loose Iso, medium ID opposite charge lepton with $p_T > 10 \text{ GeV}$
$m(l^+l^-)$ within 10 GeV of 91.2 GeV
Transverse mass of W-candidate, $m_T(E_T^{\text{miss}} + \text{lep}_{\text{other}}) > 30 \text{ GeV}$
Missing transverse energy, $E_T^{\text{miss}} > 20 \text{ GeV}$
One or two jets with $p_T > 25 \text{ GeV}$

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

300 The event yields in the preselection region for both data and Monte Carlo are summarized in  
 301 Table 5.1, which shows good agreement between data and Monte Carlo, and demonstrates that  
 302 this region consists primarily of WZ events. The WZ events are split into WZ + b, WZ + c, and  
 303 WZ + l based on the truth flavor of the associated jet in the event. Specifically, this determination  
 304 is made based on the HadronConeExclTruthLabelID of the jet, as recommended by the b-  
 305 tagging working group [15]. In this ordering b-jet supersedes charm, which supersedes light. That  
 306 is, WZ + l events contain no charm and no b jets at truth level, WZ + c contain at least one truth  
 307 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 7: Event yields in the preselection region at  $139.0 \text{ fb}^{-1}$ 

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

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

## WZ Fit Region - Inclusive

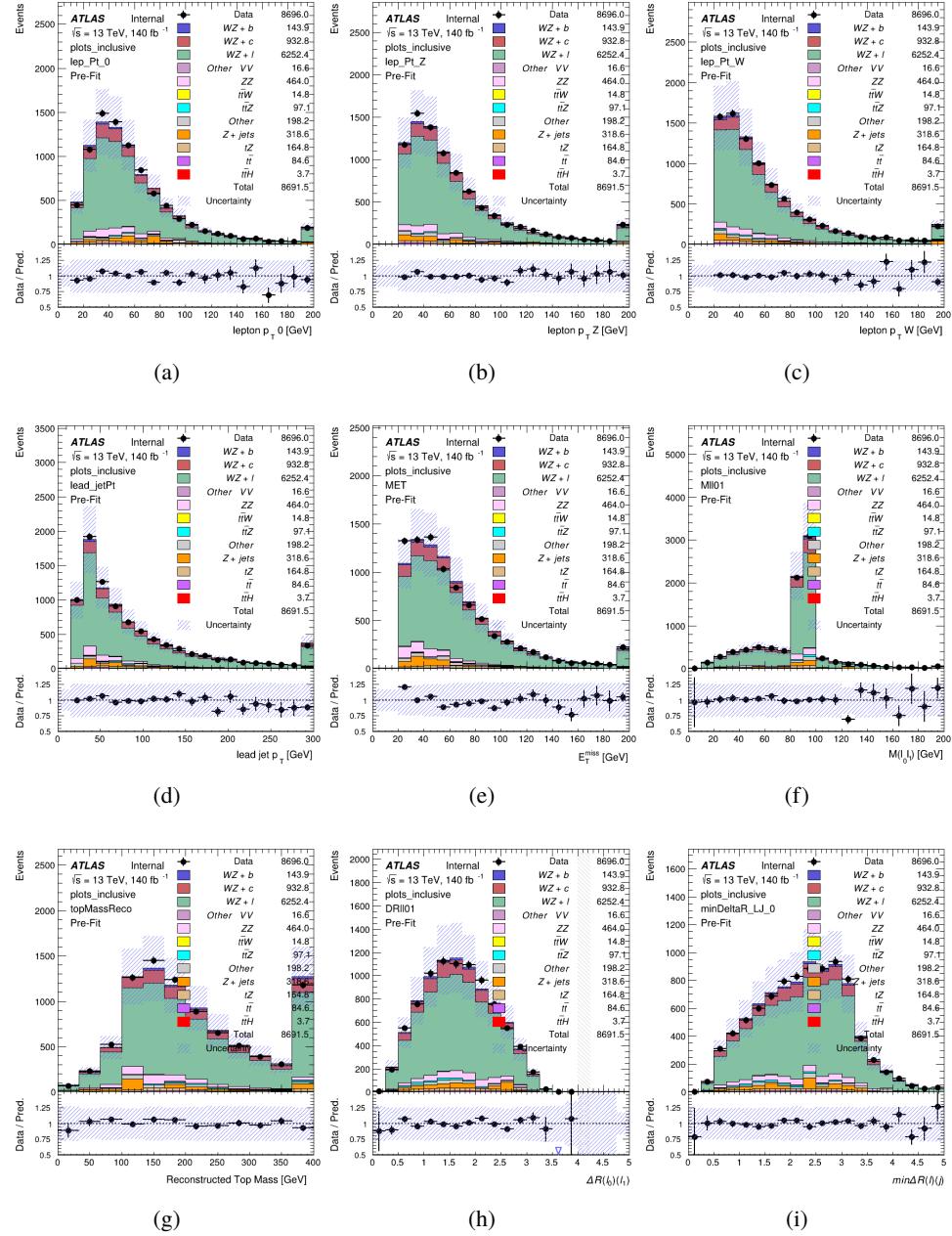


Figure 2: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the  $Z$  candidate, (c) the  $p_T$  of the lepton from the  $W$  candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$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

<sup>312</sup> **5.2 Fit Regions**

<sup>313</sup> Once preselection has been applied, the remaining events are categorized into one of twelve  
<sup>314</sup> 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%	$N_{\text{jets}} = 1, n_{\text{Jets\_DL1r\_60}} = 1, tZ \text{ BDT} > 0.725$
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%	$N_{\text{jets}} = 2, n_{\text{Jets\_DL1r\_85}} \geq 1, n_{\text{Jets\_DL1r\_77}} = 0$
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%	$N_{\text{jets}} = 2, n_{\text{Jets\_DL1r\_60}} \geq 1, tZ \text{ BDT} > 0.725$
2j tZ CR	$N_{\text{jets}} = 2, n_{\text{Jets\_DL1r\_60}} \geq 1, tZ \text{ BDT} < 0.725$

<sup>315</sup> The working points discussed in Section 4.4 are used to separate events into fit regions based on  
<sup>316</sup> the highest working point reached by a jet in each event. Because the background composition  
<sup>317</sup> differs significantly based on the number of b-jets, events are further subdivided into 1-jet and  
<sup>318</sup> 2-jet regions in order to minimize the impact of background uncertainties.

<sup>319</sup> An unfolding procedure is performed to account for differences in the number of reconstructed  
<sup>320</sup> jets compared to the number of truth jets in each event. The `AntiKt4TruthDressedWZJets`  
<sup>321</sup> truth jet collection is used to make this determination. In order to account for migration of  
<sup>322</sup> WZ+1-jet and WZ+2-jet events between the 1-jet and 2-jet bins at reco level, the signal samples  
<sup>323</sup> are separated based on the number of truth jets. Events with 0 jets or more than 3 jets at truth  
<sup>324</sup> level, yet fall within one of the categories listed in Table 8, are categorized as WZ + other, and  
<sup>325</sup> treated as a background. The migration matrix in the number of jets at truth level versus reco  
<sup>326</sup> level is shown in Figure 3. The composition of the number of truth jets in each reco jet bin is  
<sup>327</sup> taken from MC, with uncertainties in these estimates described in detail in Section 7.

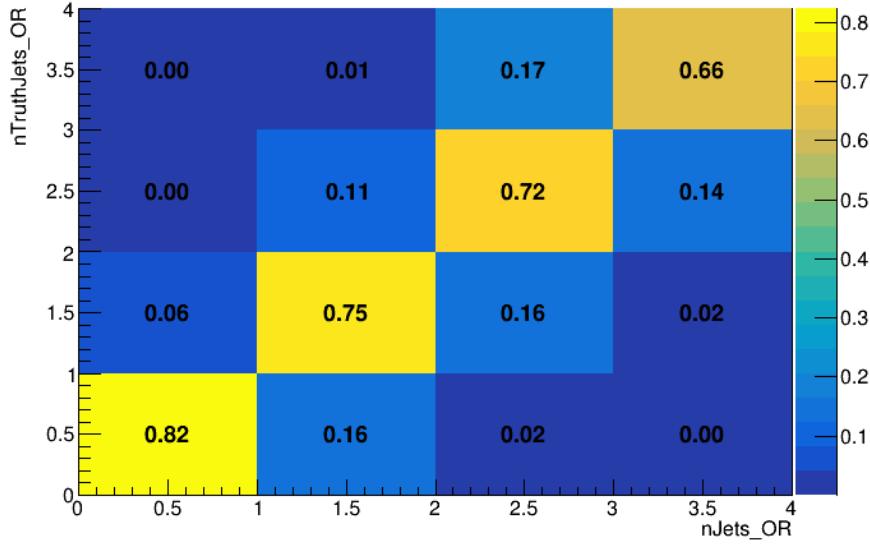


Figure 3: Number of truth jets compared to the number of reconstructed jets in each WZ event falling in the preselection region. Each row is normalized to unity.

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

333 The modeling in each region is validated by comparing data and MC predictions for various  
 334 kinematic distributions. These plot are shown in Figures 4-17.

## WZ Fit Region - 1j Inclusive

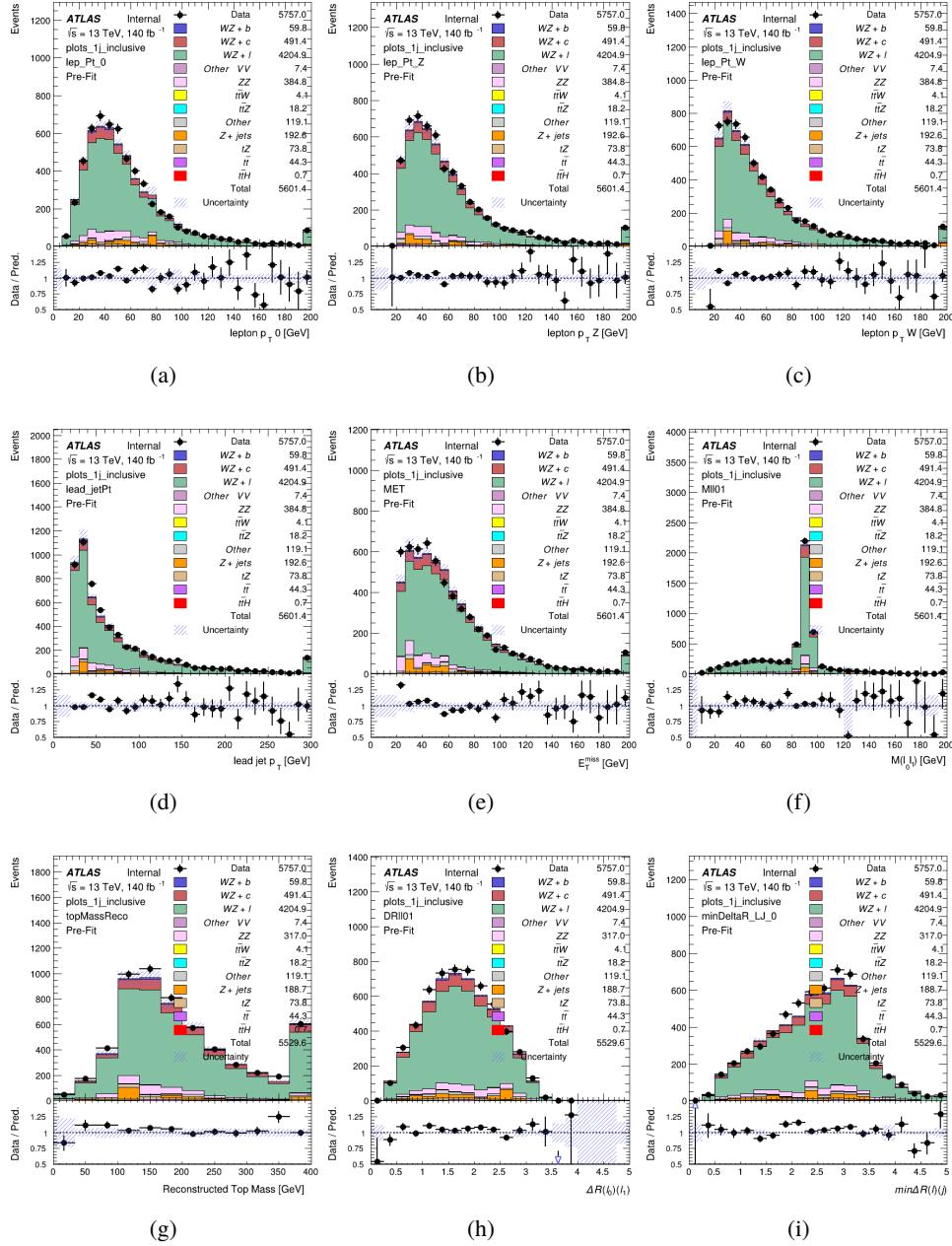


Figure 4: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$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

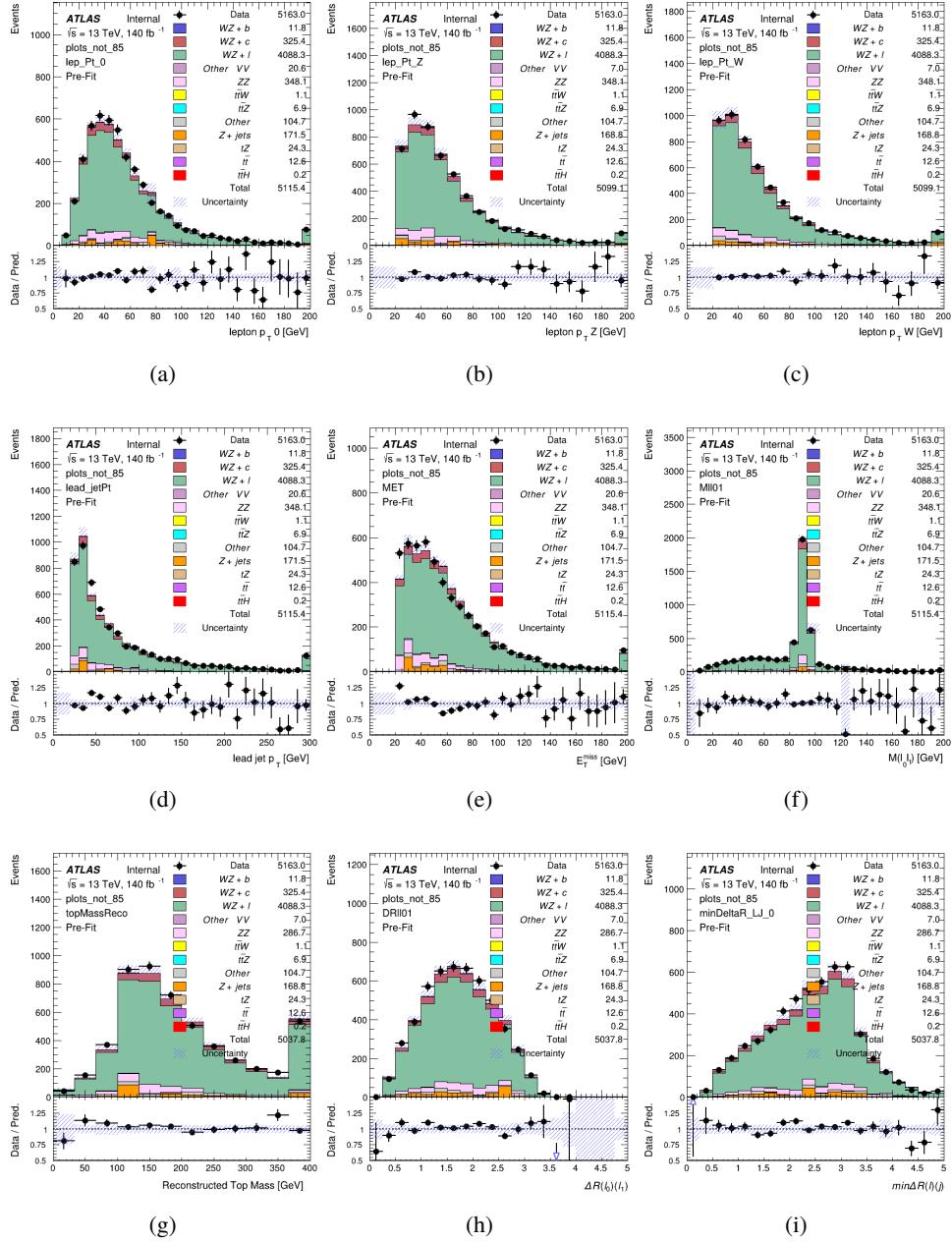


Figure 5: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$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

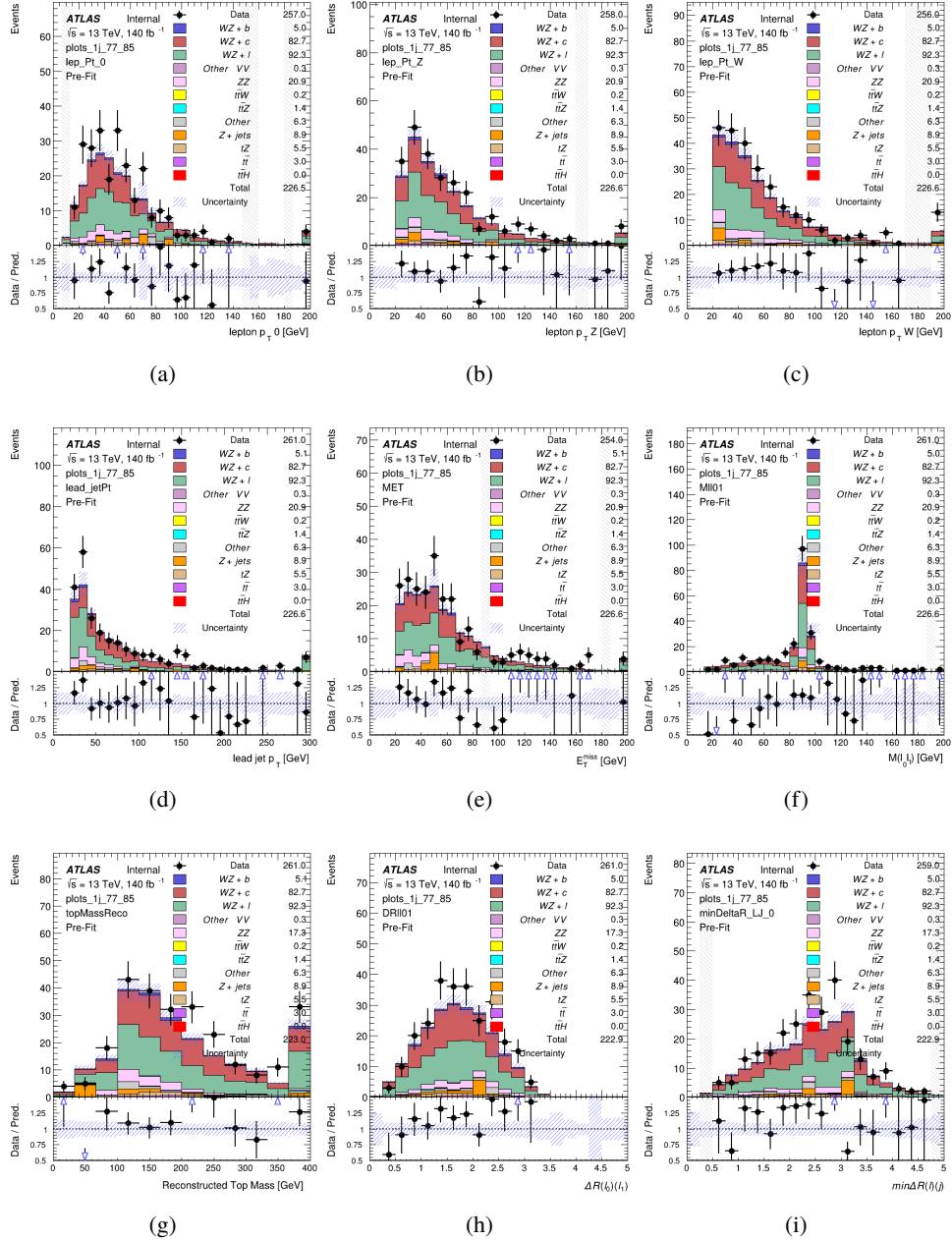


Figure 6: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$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

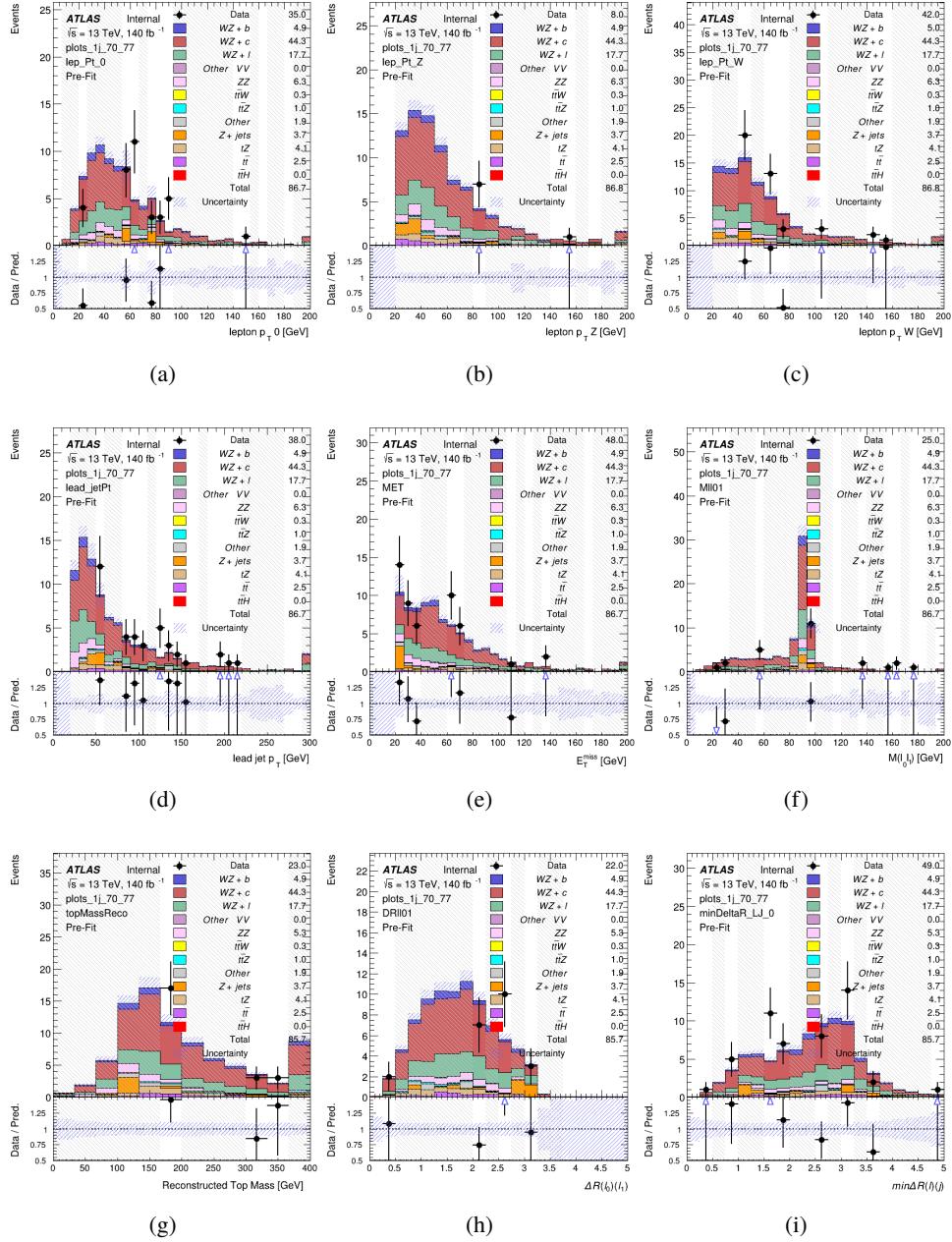


Figure 7: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$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

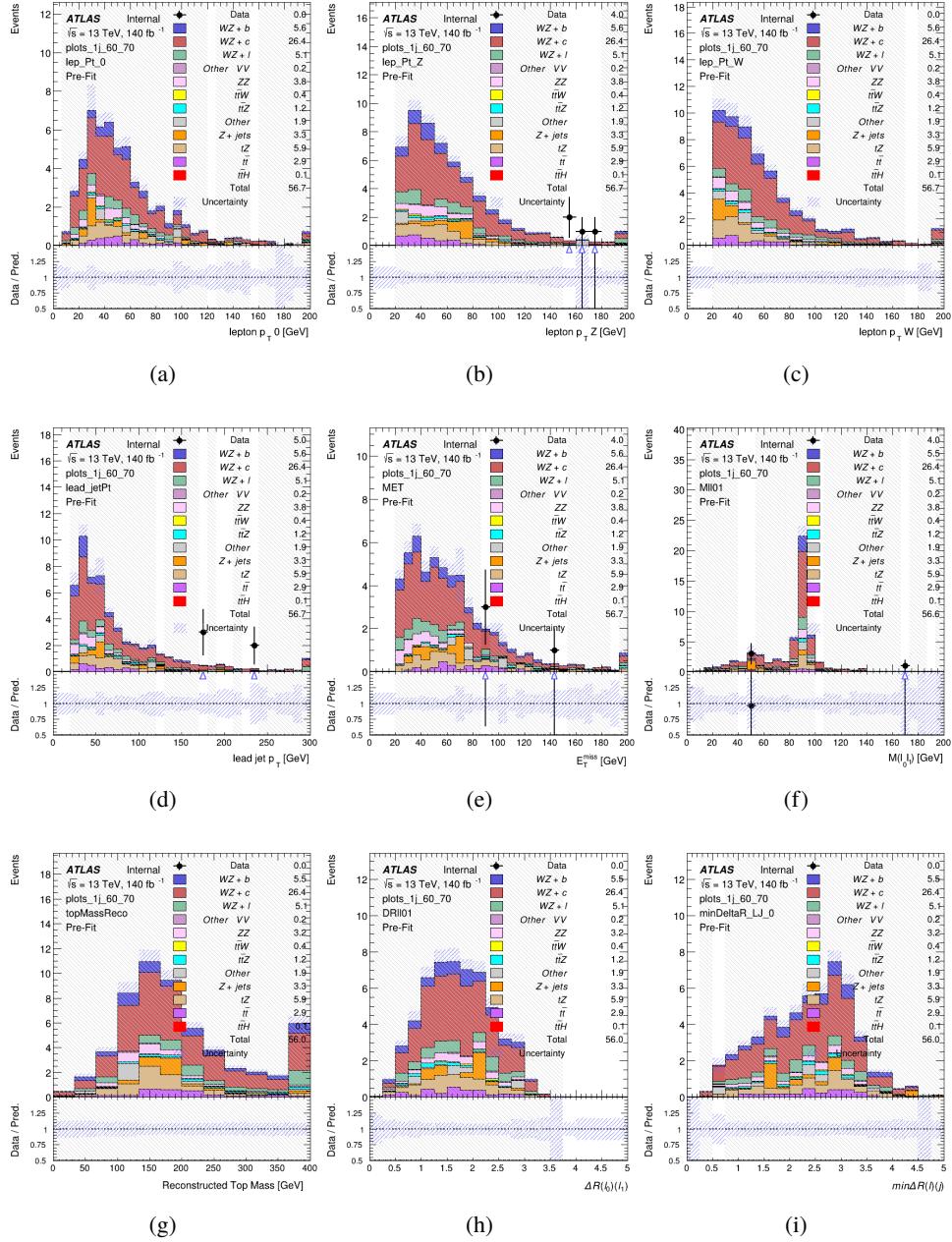


Figure 8: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$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

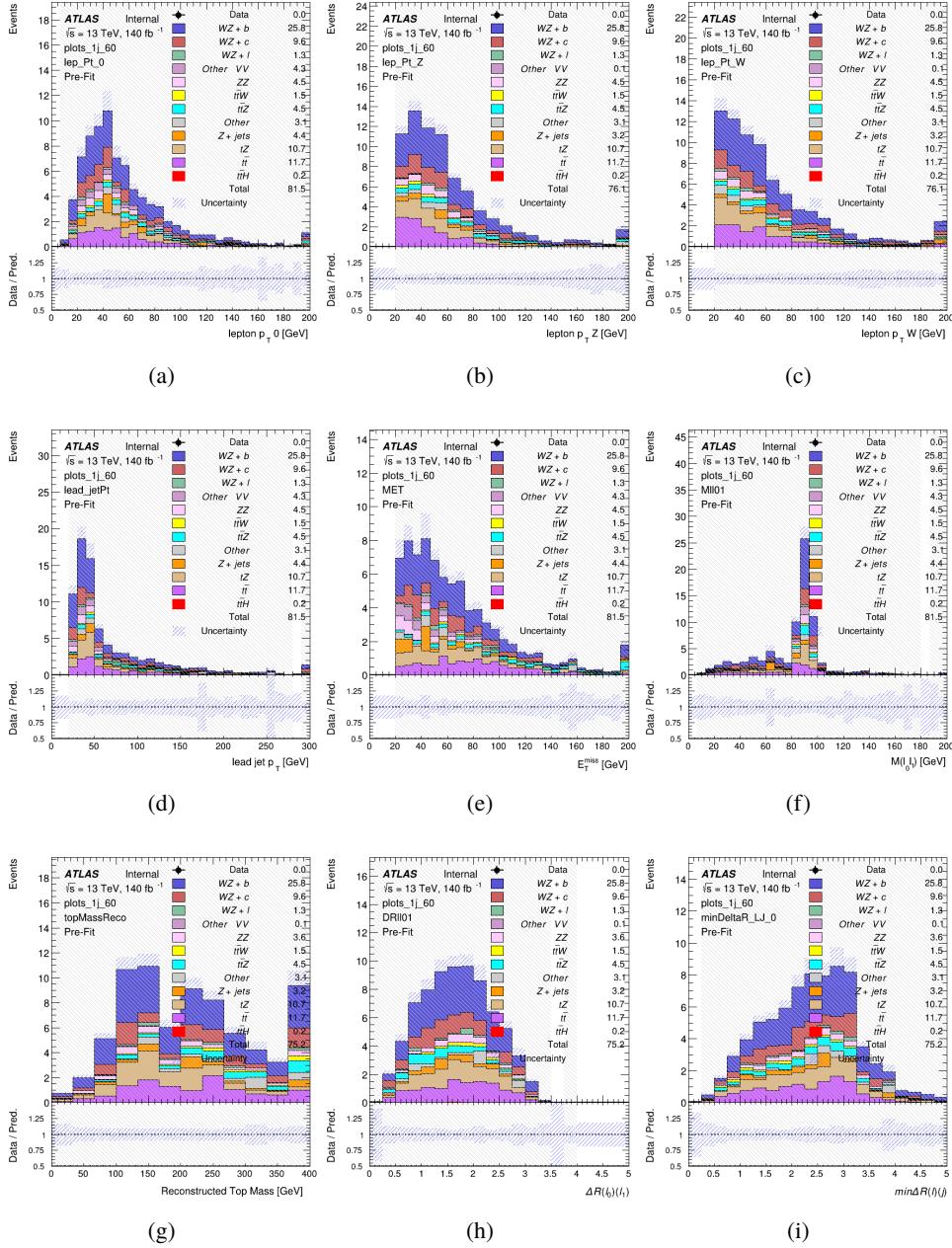


Figure 9: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$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

## WZ Fit Region - tZ-CR

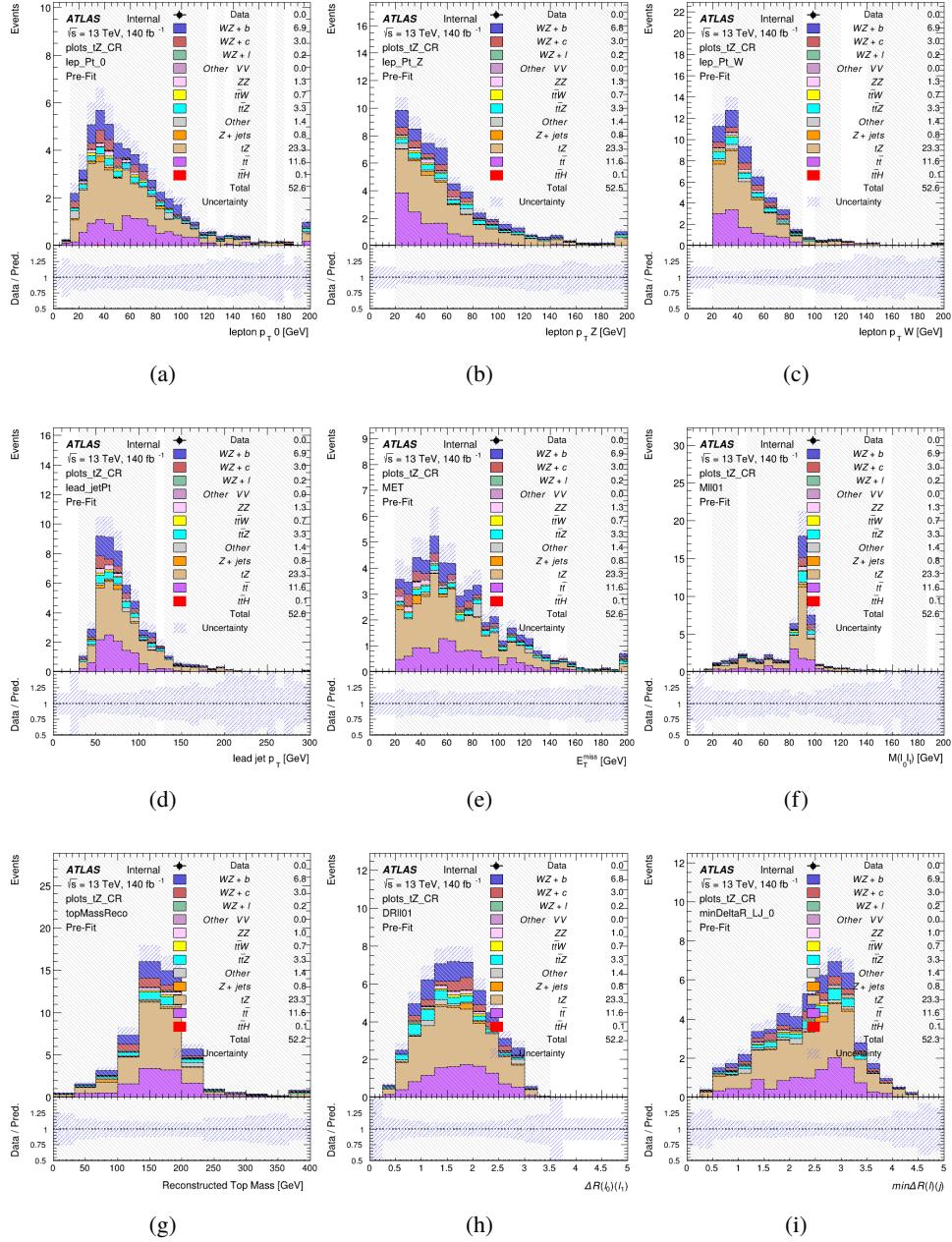


Figure 10: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$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

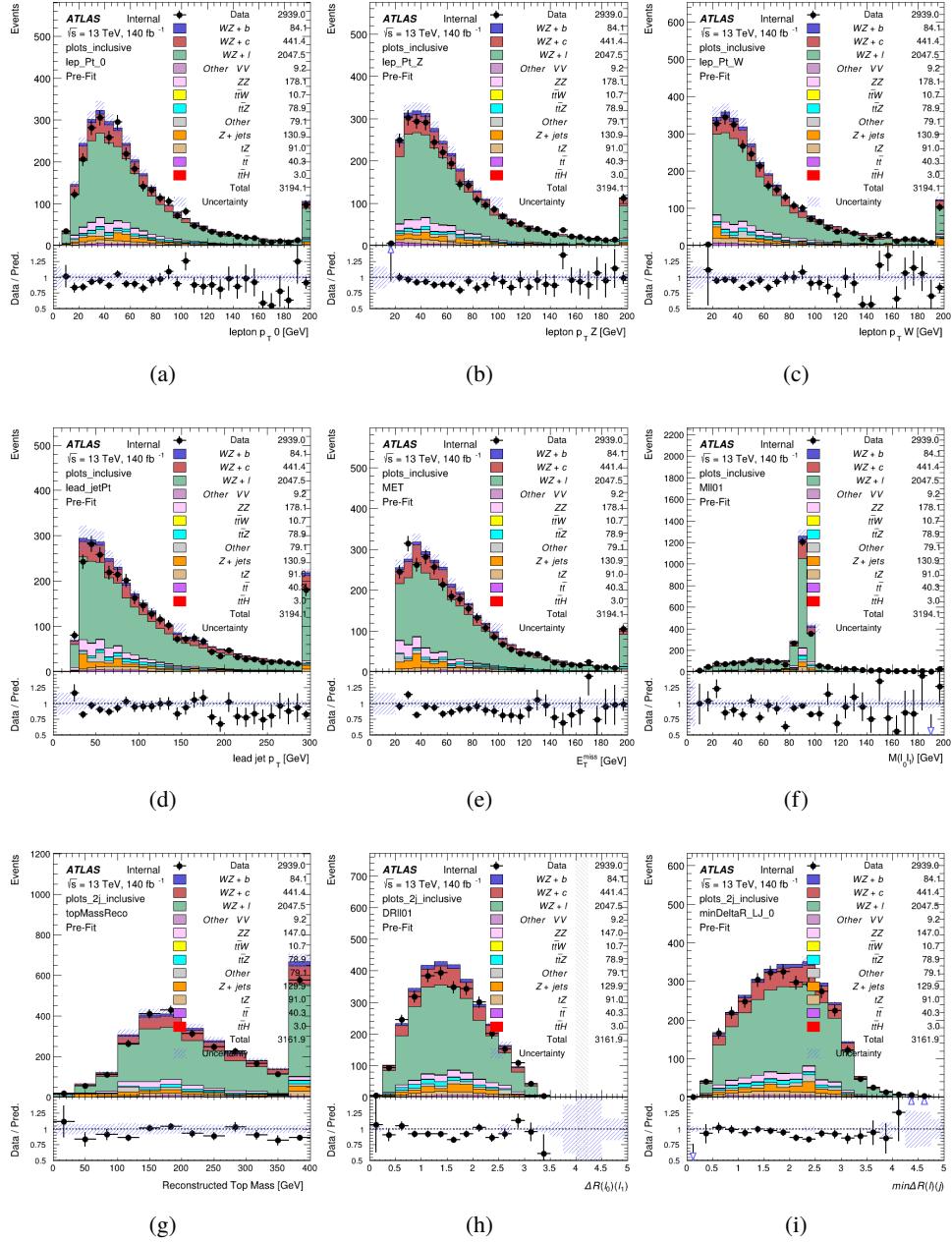


Figure 11: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$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

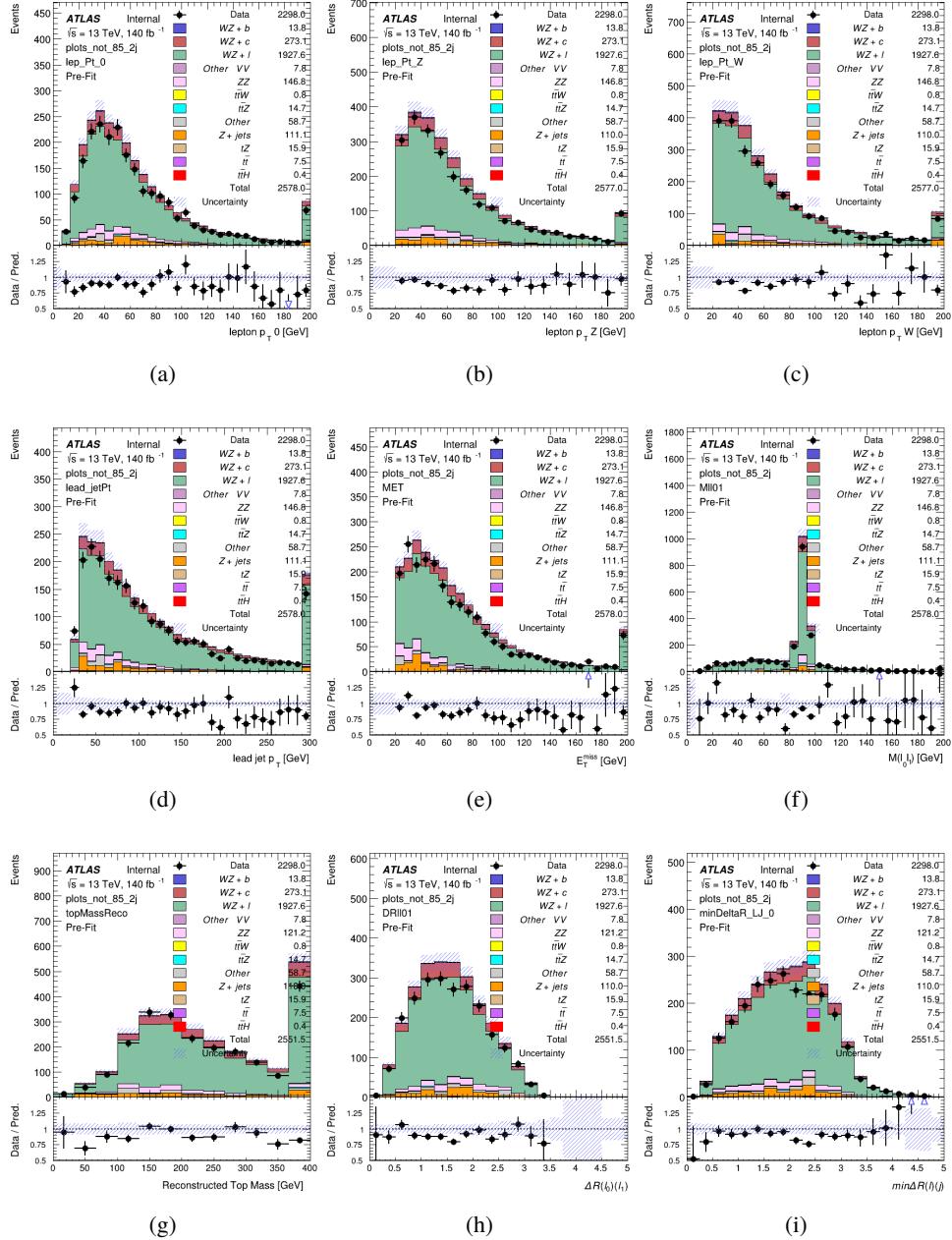
WZ Fit Region -  $2j < 85\%$  WP

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 - 2j 77-85% WP

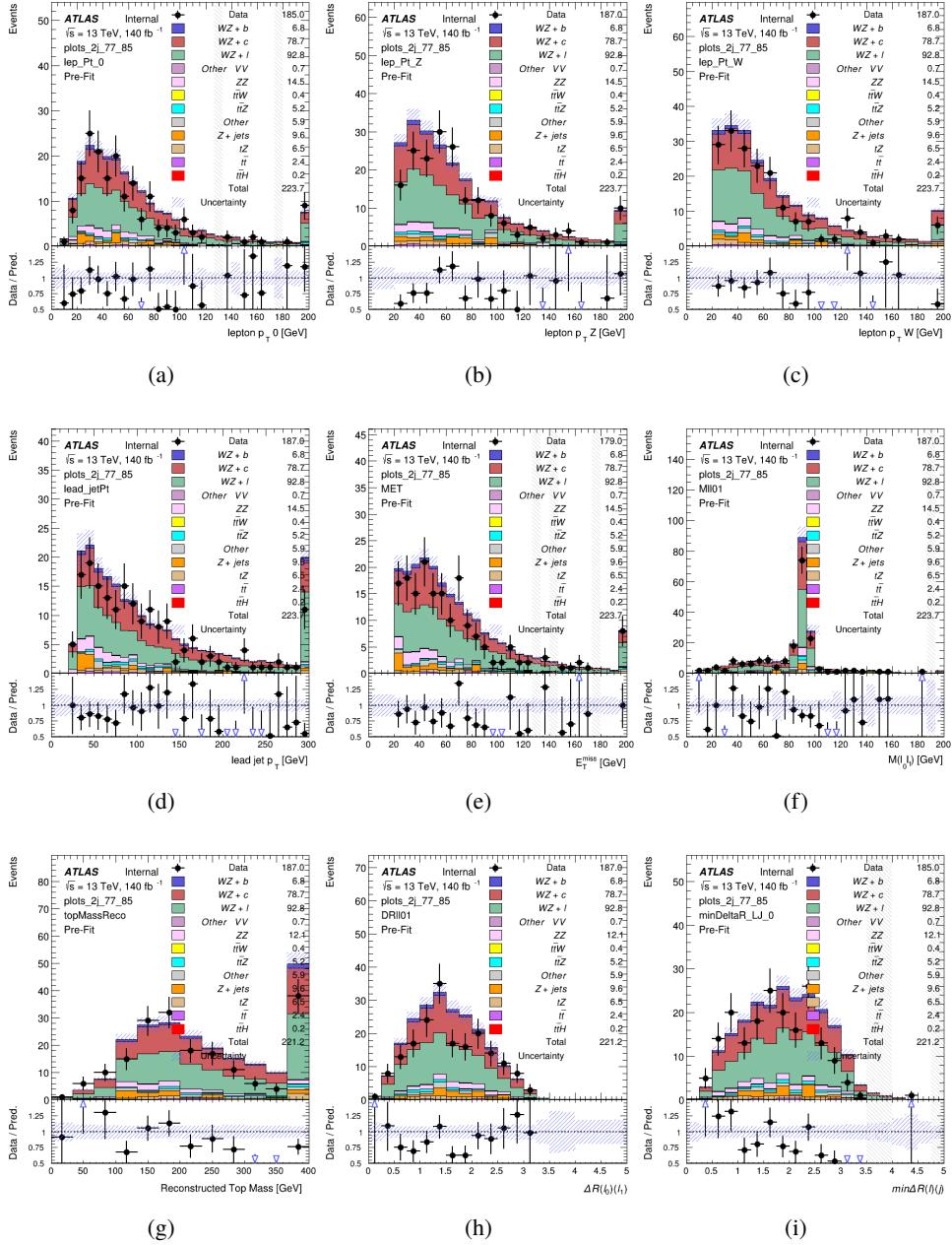


Figure 13: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , 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 - 2j 70-77% WP

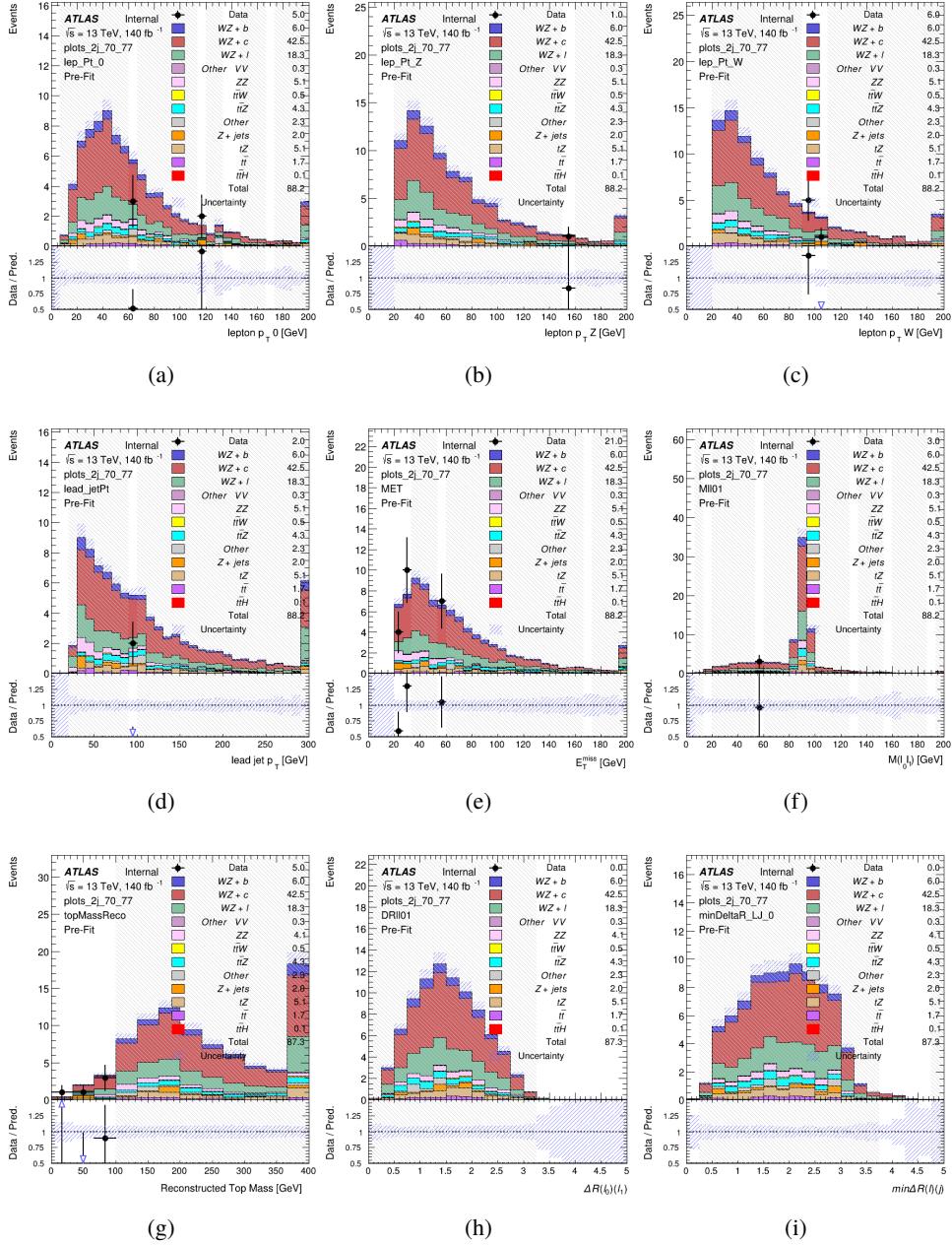


Figure 14: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the  $Z$  candidate, (c) the  $p_T$  of the lepton from the  $W$  candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , 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 - 2j 60-70% WP

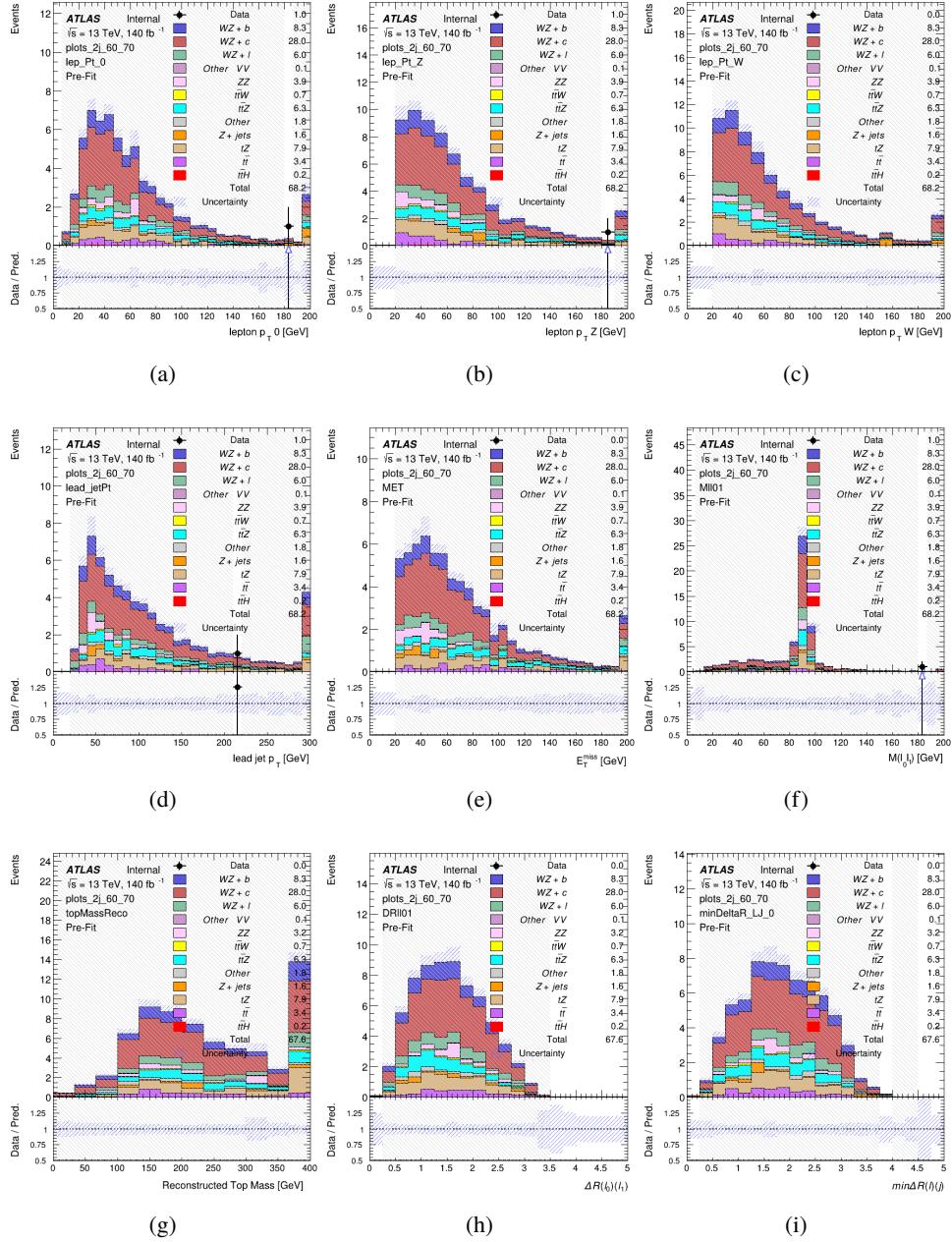


Figure 15: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , 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 - 2j 60% WP

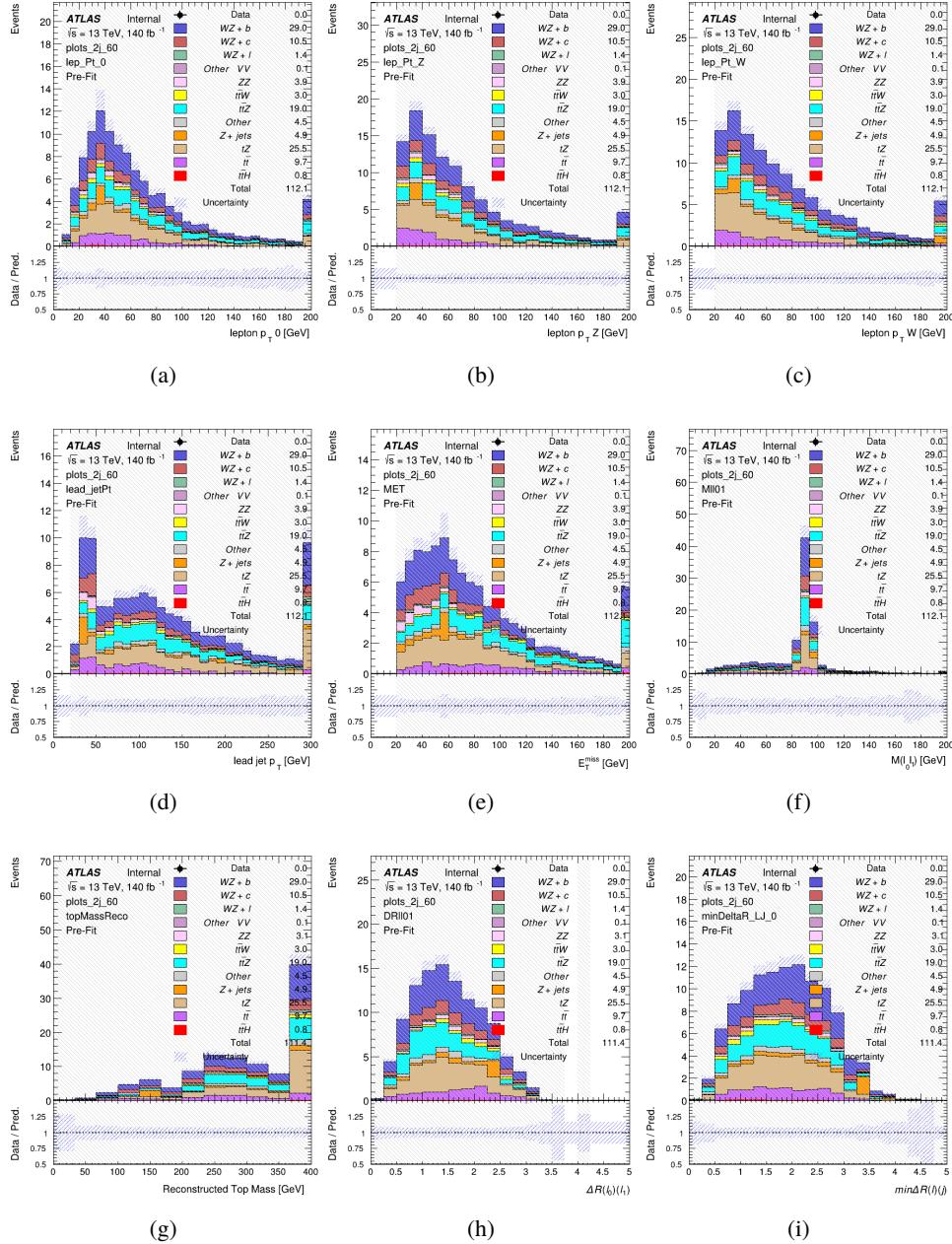


Figure 16: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , 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-2j

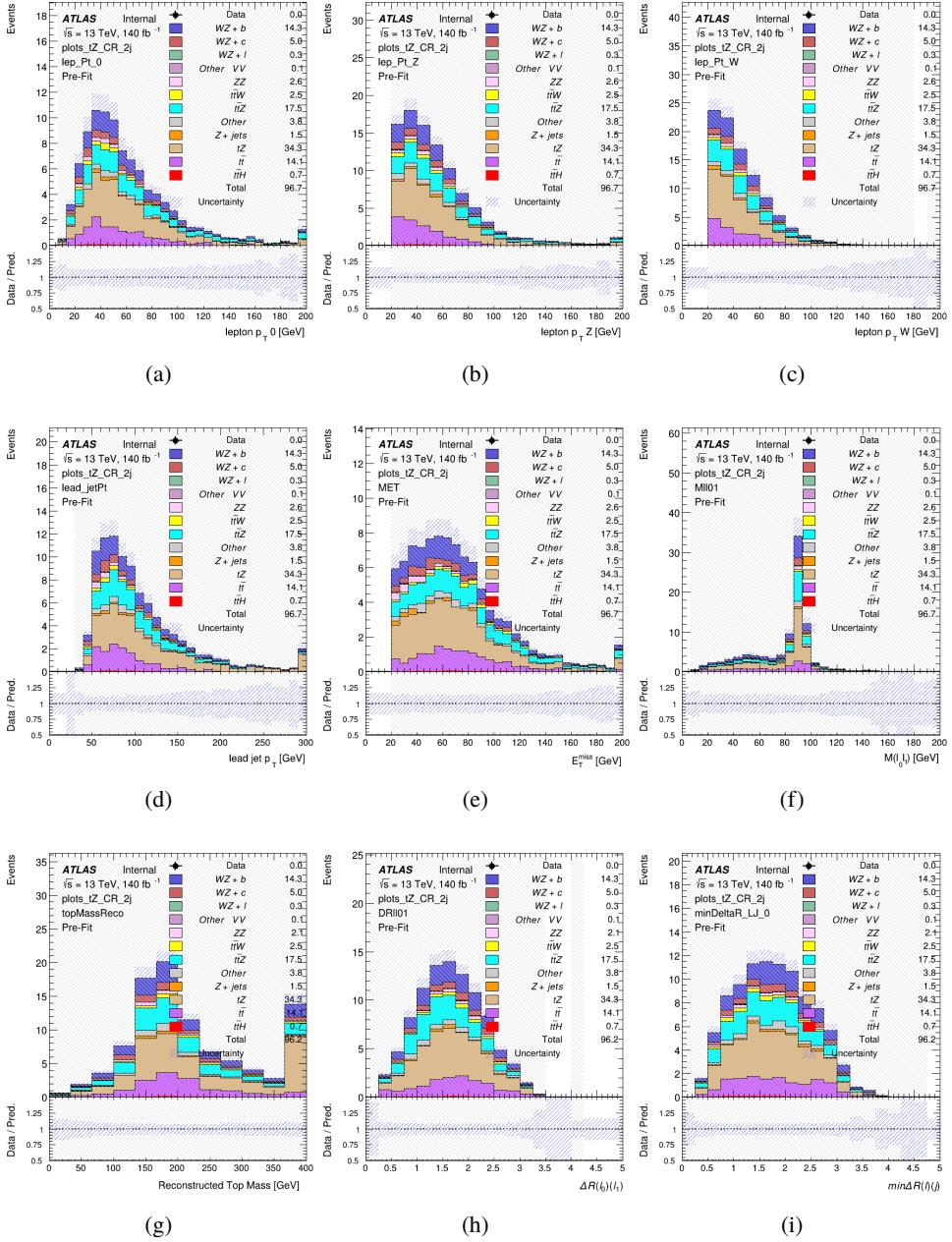


Figure 17: Comparisons between the data and MC distributions in the preselection region for (a) the  $p_T$  of the opposite sign lepton, (b) the  $p_T$  of the other lepton from the Z candidate, (c) the  $p_T$  of the lepton from the W candidate, (d) the leading jet  $p_T$ , (e) the  $E_T^{\text{miss}}$ , 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.

335 **5.3 Non-Prompt Lepton Estimation**

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

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

343 **5.3.1  $t\bar{t}$  Validation**

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

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

354 Further, because the jet multiplicity of  $t\bar{t}$  events tends to be higher than WZ, the number of jets  
 355 in each event is required to be greater than 1. As b-jets are almost invariably produced from top  
 356 decays, at least one b-tagged jet passing the 70% DL1r WP in each event is required. Various  
 357 kinematic plots of this region are shown in Figure 18.

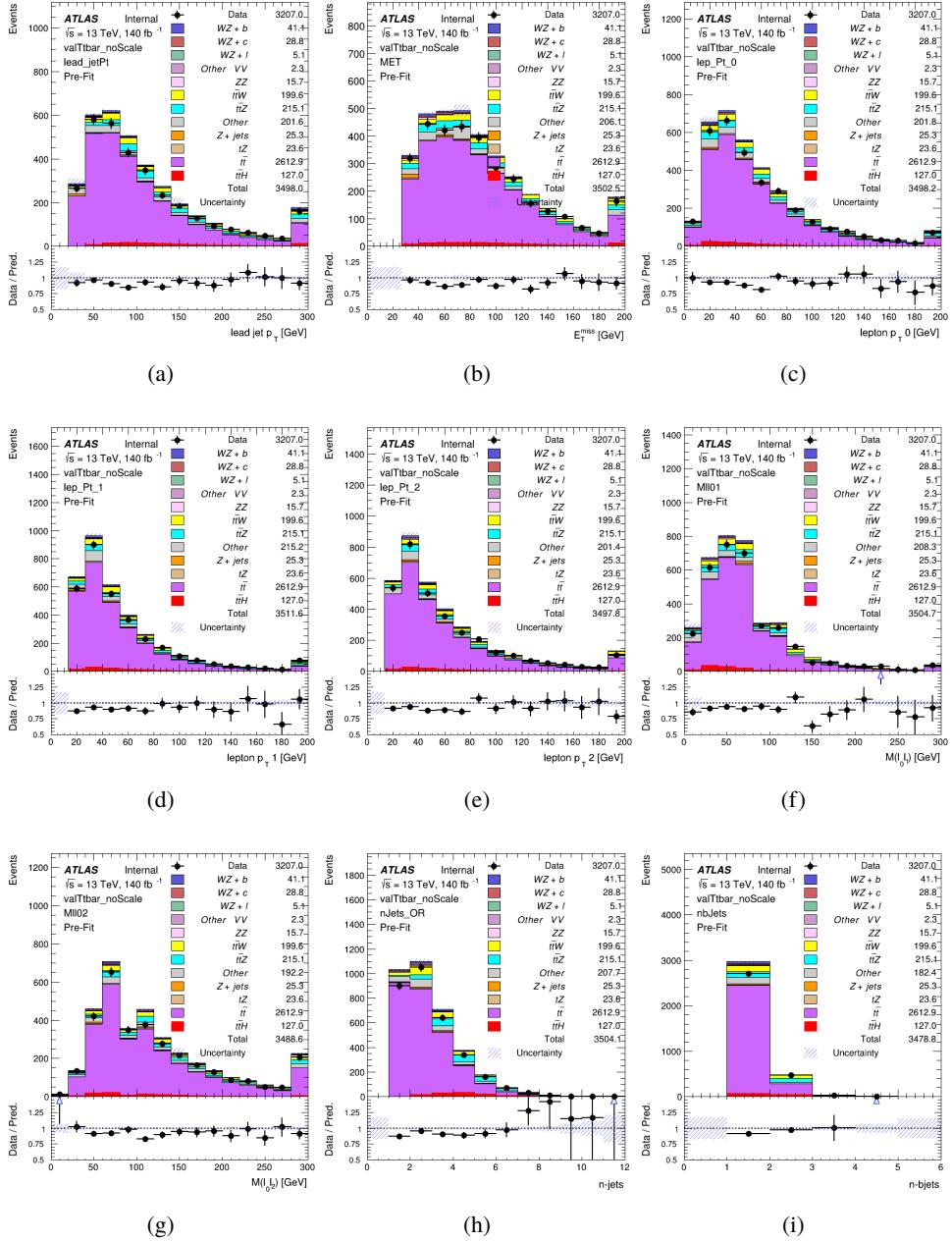


Figure 18: Comparisons between the data and MC distributions in the  $t\bar{t}$  control region for (a) the  $p_T$  of the leading jet, (b) the missing transverse energy, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of lepton 1, (e)  $p_T$  of lepton 2, (f) the invariant mass of leptons 0 and 1, (g) the invariant mass of leptons 0 and 2, (h) the number of jets, (i) the number of b-tagged jets.

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

360 MC prediction. Plots showing the kinematics of the  $t\bar{t}$  VR after this correction factor has been  
361 applied are shown in Figure 19.

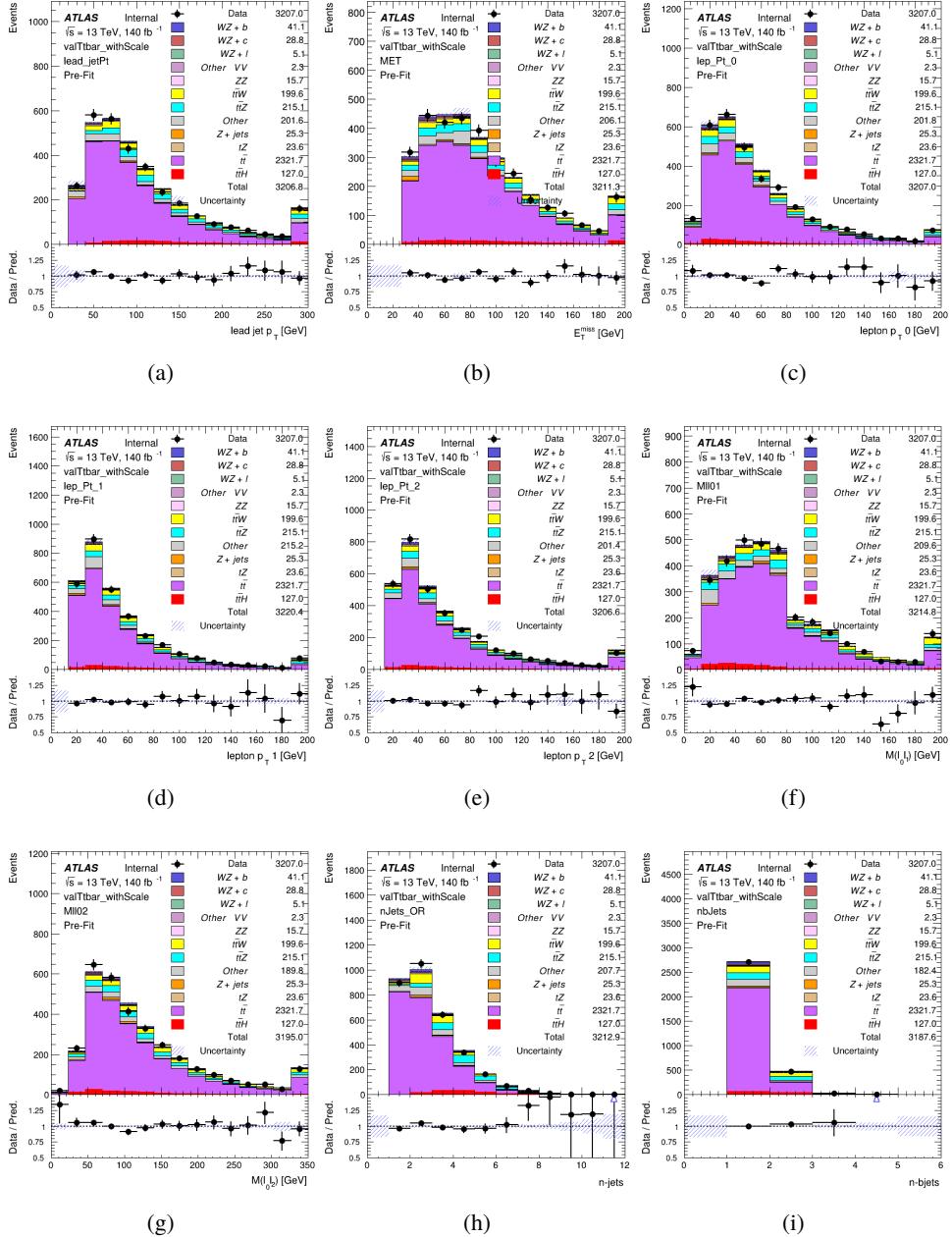


Figure 19: Comparisons between the data and MC distributions in the  $t\bar{t}$  control region after the correction factor has been applied for (a) the  $p_T$  of the leading jet, (b) the missing transverse energy, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of lepton 1, (e)  $p_T$  of lepton 2, (f) the 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.

362 The modeling is further validated by looking at the yield in the  $t\bar{t}$  VR for each DL1r WP, giving  
 363 a clearer correspondence to the signal regions used in the fit. Each region shown in Figure 20  
 364 requires one or more jets pass the listed WP, with no jets passing the next highest WP.

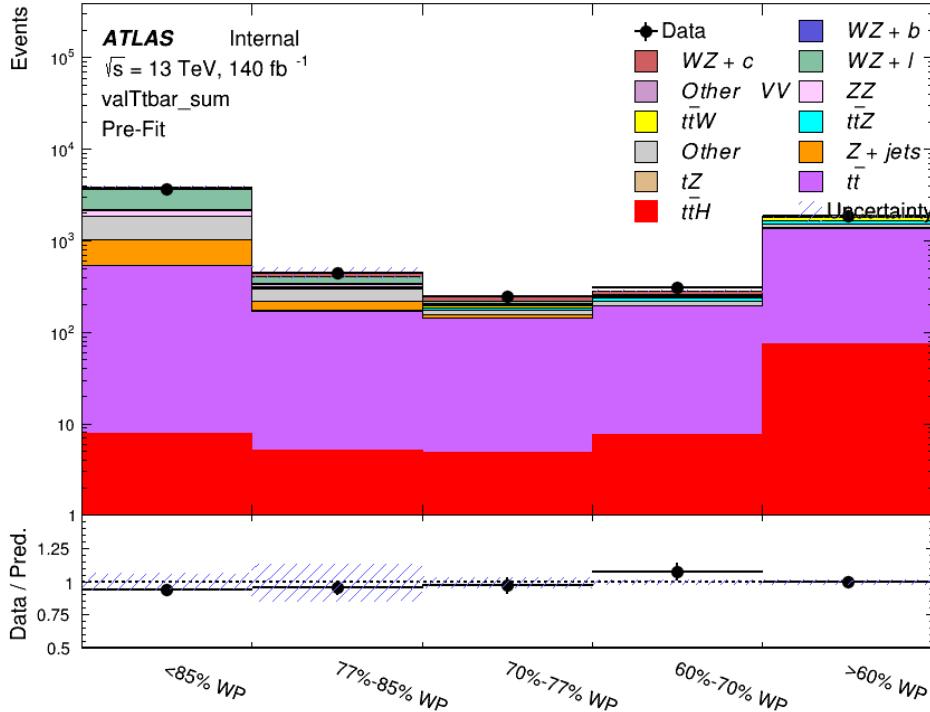


Figure 20: Data and MC comparisons for each DL1r WP for both 1-jet and 2-jet regions, after the  $t\bar{t}$  VR selection and correction factor have been applied

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

### 367 5.3.2 Z+jets Validation

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

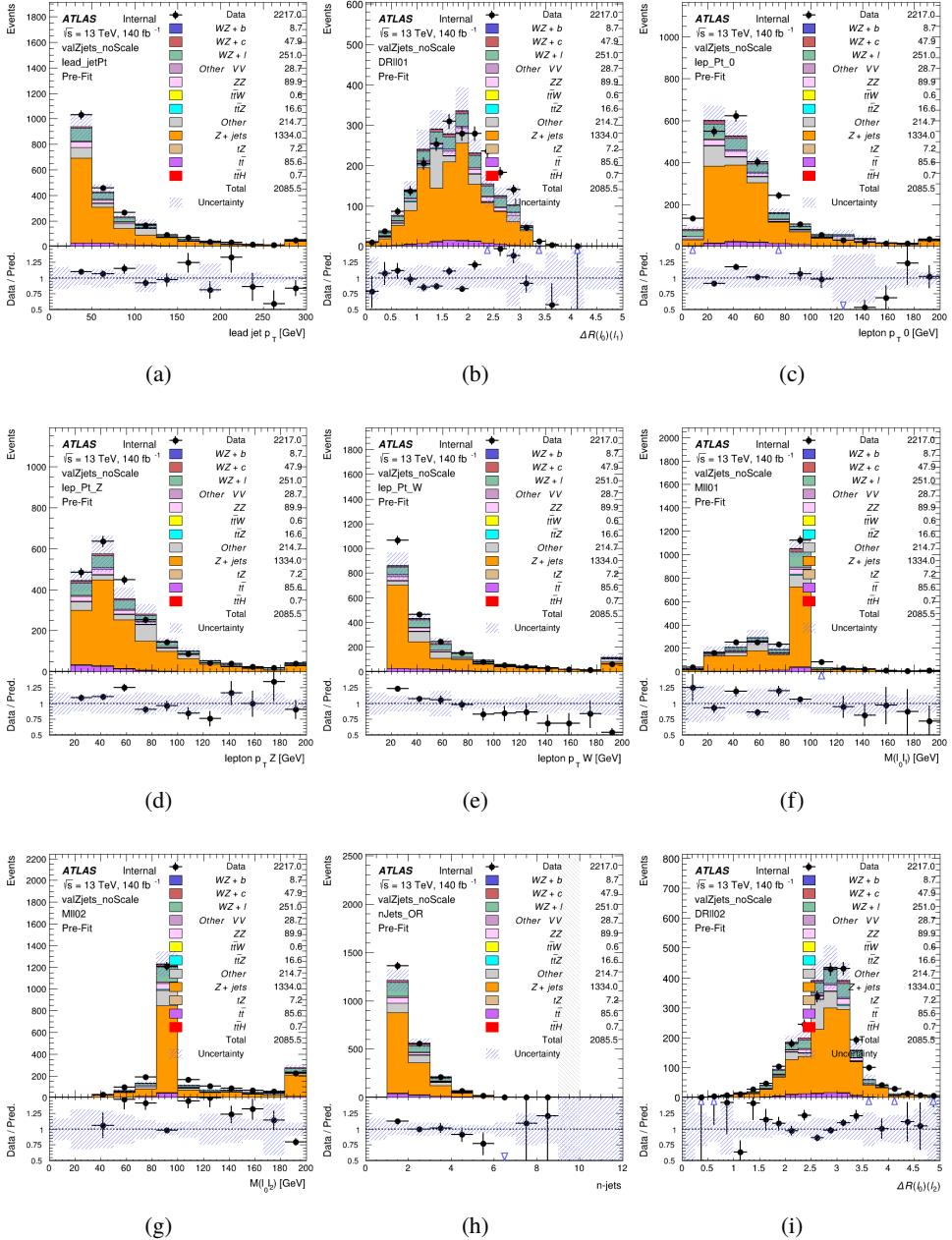


Figure 21: Comparisons between the data and MC distributions in the Z+jets control region for (a) the  $p_T$  of the leading jet, (b)  $\Delta R$  between leptons 0 and 1, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of SS lepton from the Z candidate, (e)  $p_T$  of the SS lepton from the W candidate, (f) 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

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

<sup>376</sup> of the  $p_T$  spectrum of the lepton from the W is found to differ. To account for this discrepancy,  
<sup>377</sup> a variable correction factor is applied to Z+jets.  $\chi^2$  minimization of the lepton 2  $p_T$  spectrum  
<sup>378</sup> is performed to derive a correction factor of  $1.53 - 6.6 * 10^{-6}(\text{lep\_Pt\_W})$ . Kinematic plots of  
<sup>379</sup> the Z + jets control region after this correction factor has been aplied are shown in Figure 22.

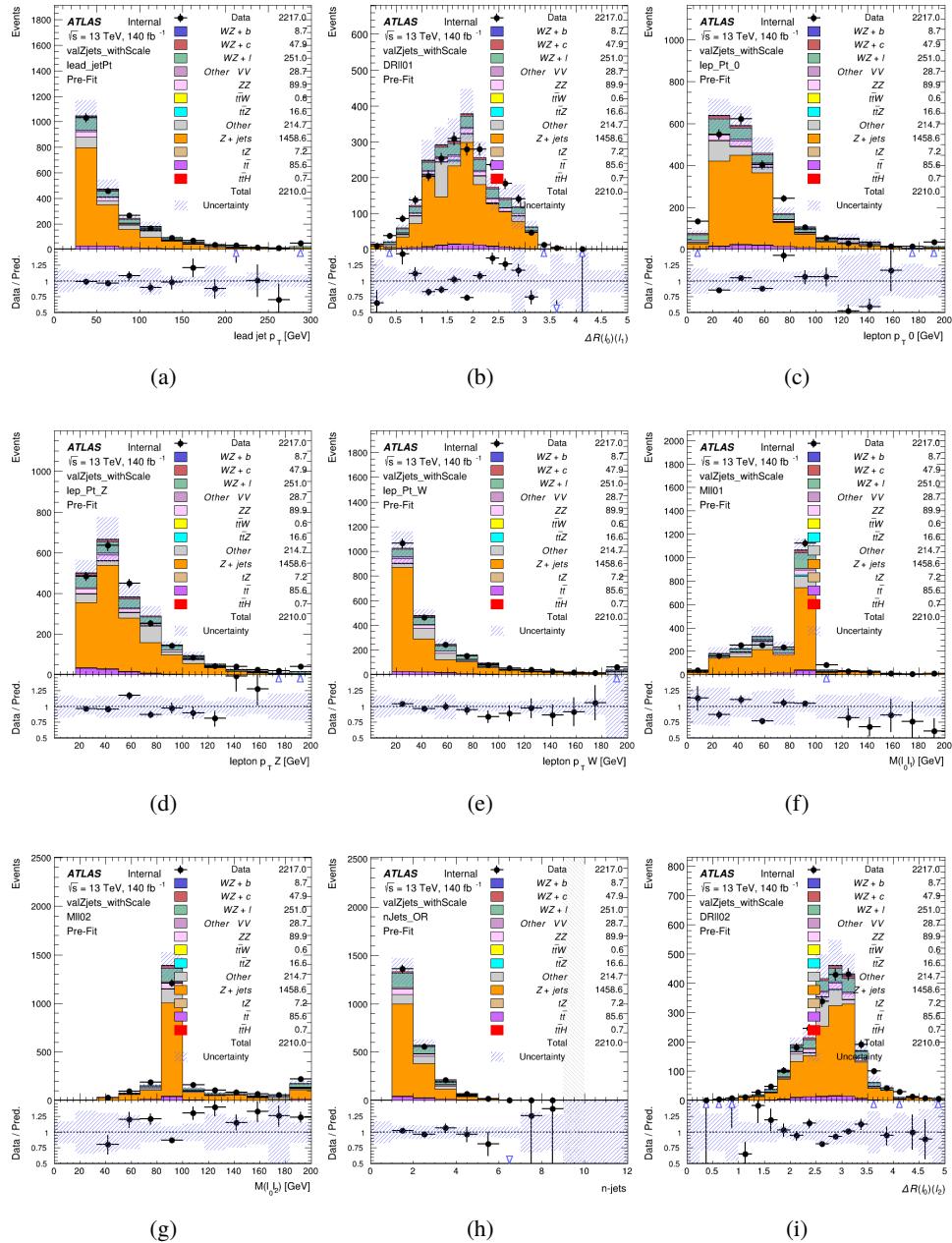


Figure 22: Comparisons between the data and MC distributions in the Z+jets control region after the correction factor has been applied for (a) the  $p_T$  of the leading jet, (b)  $\Delta R$  between leptons 0 and 1, (c) the  $p_T$  of lepton 0, (d)  $p_T$  of SS lepton from the Z candidate, (e)  $p_T$  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

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

381 giving a clearer correspondence to the signal regions used in the fit. Each region shown in Figure  
 382 23 requires one or more jets pass the listed WP, with no jets passing the next highest WP.

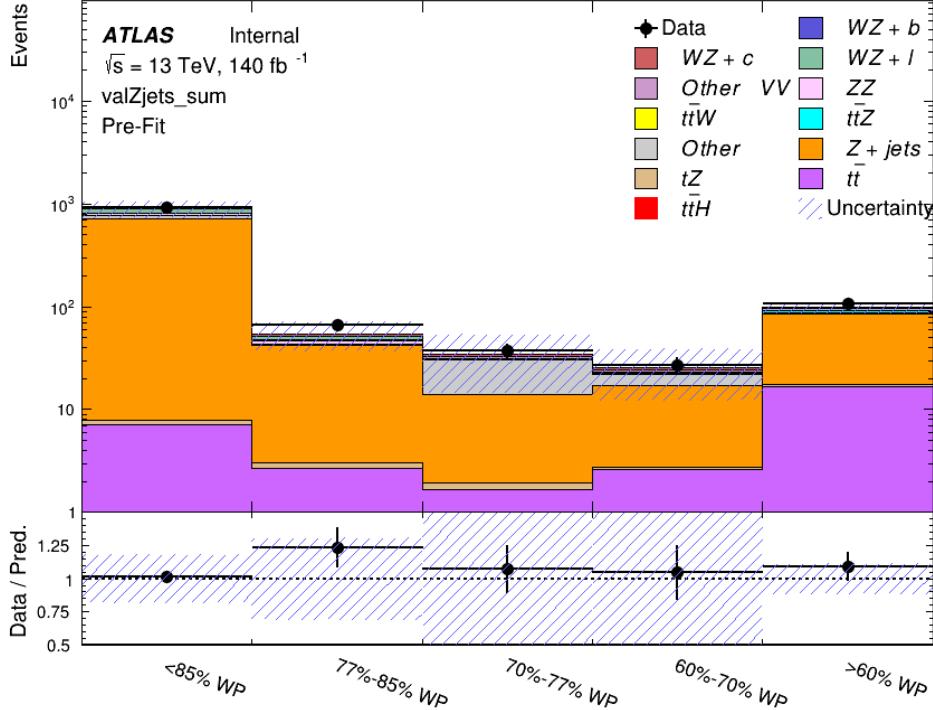


Figure 23: Data and MC comparisons for each DL1r WP for both 1-jet and 2-jet regions, after the Z+jets VR selection and correction factor have been applied

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

## 386 6 tZ Separation Multivariate Analysis

387 Because tZ produces a final state identical to signal, it represents a predominant background in  
 388 the most signal enriched regions. That is, the region with one jet passing the 60% DL1r WP.  
 389 Therefore, a boosted decision tree (BDT) algorithm is trained using TMVA [16] to separate WZ  
 390 + heavy flavor from tZ.

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

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

396 **6.1 Top Mass Reconstruction**

397 The reconstruction of the top mass follows the procedure described in detail in section 6.1 of  
 398 [17]. The mass of the top quark candidate is reconstructed from the jet, the lepton not included  
 399 in the Z-candidate, and a reconstructed neutrino. In the case that there is one jet in the event,  
 400 there is only possible b-jet candidate. For events with two jets, the jet with the highest DL1r  
 401 score is used.

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

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

$$407 \quad (p_l + p_\nu)^2 = m_W^2$$

408 Expanding this out into components, this equation gives:

$$409 \quad \sqrt{p_{T\nu}^2 + p_{z\nu}^2} E_l = \frac{m_w^2 - m_l^2}{2} + p_{T\nu}(p_{lx}\cos\phi_\nu + p_{ly}\sin\phi_\nu) + p_{lz}p_{\nu z}$$

410 This equation gives two solutions for  $p_{\nu z}$ . For cases where only one of these solutions is real,  
 411 that is taken as the value of  $p_{\nu z}$ . For instances with two real solutions, the one which is shown  
 412 to be correct in the largest fraction of simulations is taken. For cases when no real solution is  
 413 found, often because of detector effects, the value of  $E_T^{\text{miss}}$  is varied in decreasing increments of  
 414 100 MeV until a real solution is found.

415 The reconstructed top mass distribution for tZ and WZ + b can be seen in figure 24.

416 **6.2 tZ BDT**

417 A Boosted Decision Tree (BDT), specifically XGBoost [18], is used to provide separation between  
 418 tZ and WZ+b. The following kinematic variables are used as inputs:

- 419 • The invariant mass of the reconstructed top candidate
- 420 •  $p_T$  of each of the leptons, jet
- 421 • The invariant mass of each combination of lepton pairs,  $M(l\bar{l})$
- 422 •  $E_T^{\text{miss}}$

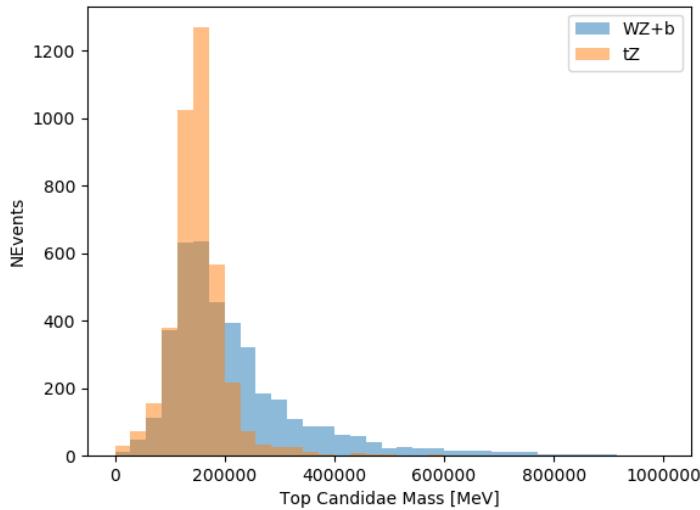


Figure 24: Reconstructed top mass distributions for tZ and WZ + b, measured in MeV.

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

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

The distributions of a few of these features for both signal and background is shown in figure 25.

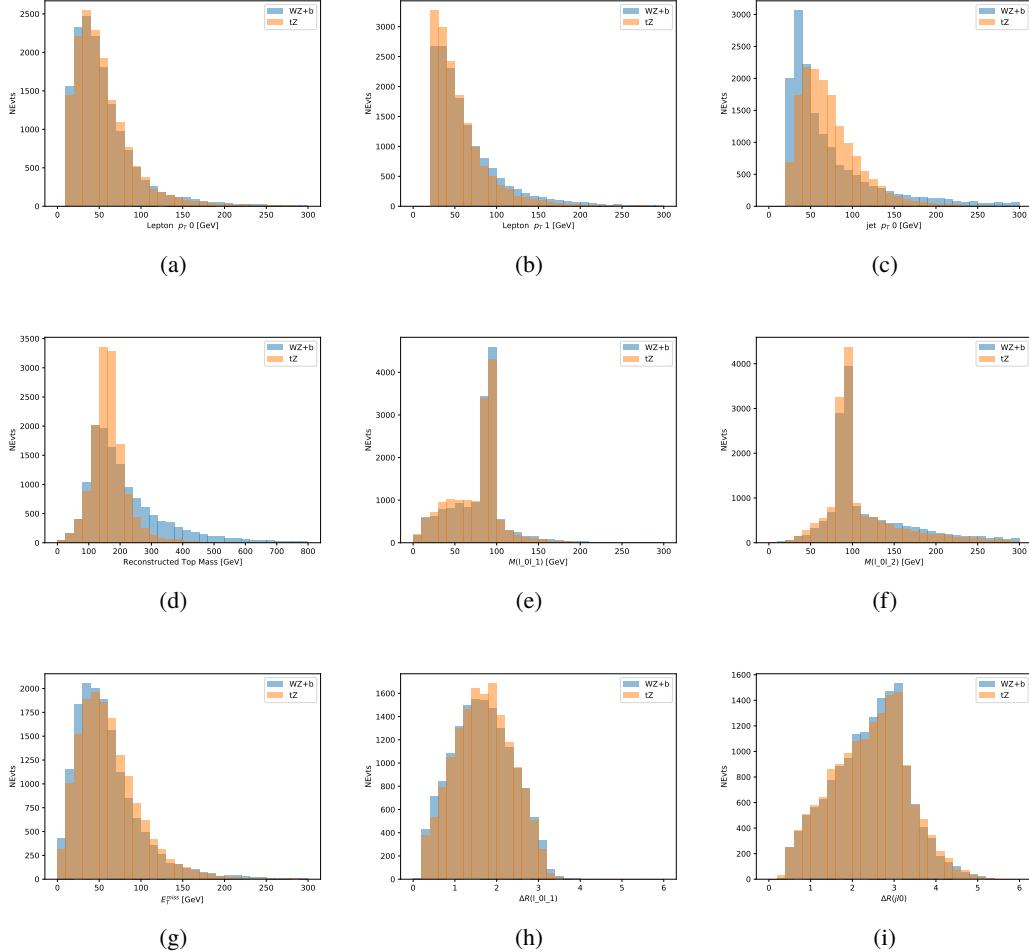


Figure 25: Distribution of input features of the BDT for signal (WZ) and background (tZ). Both are scaled to an equal number of events. (a), (b) and (c) show the  $p_T$  of lepton 0, lepton 1, and the jet, (d) show the reconstructed top mass, (e) and (f) show the invariant mass of leptons 0 and 1, leptons 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.

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

435 The results of the BDT training are shown in figure 26. The output scores for both signal and  
 436 background events is shown on the left. The right shows the receiving operating characteristic  
 437 (ROC) curve that results from the MVA. The ROC curve represents the background rejection  
 438 as a function of signal efficiency, where each point on the curve represents a different response

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

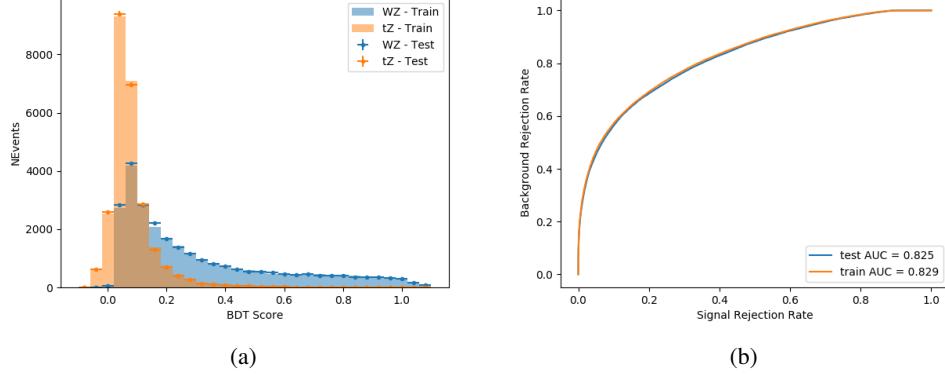


Figure 26: Distribution of the BDT response for signal and background events on the left, the ROC curve for the BDT on the right.

441 The relative important of each input feature in the model, measured by how often they appeared  
 442 in the decision trees, is shown in figure 27.

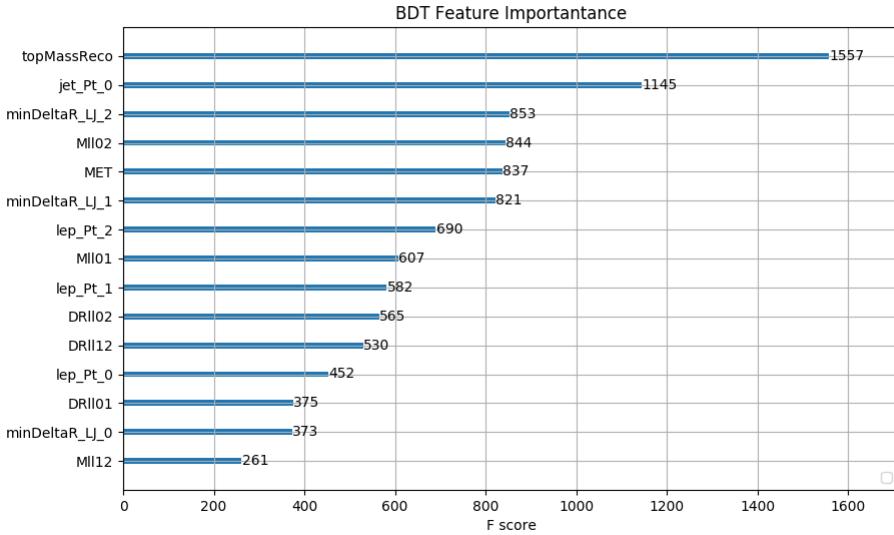


Figure 27: Relative importance of each input feature in the model.

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

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

## 449 7 Systematic Uncertainties

450 The systematic uncertainties that are considered are summarized in Table 9. These are imple-  
 451 mented in the fit either as a normalization factors or as a shape variation or both in the signal  
 452 and background estimations. The numerical impact of each of these uncertainties is outlined in  
 453 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	6
Muon	15
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
Total (Signal and background modeling)	35
Total (Overall)	230

454 The uncertainty in the combined integrated luminosity is derived from a calibration of the  
 455 luminosity scale performed for 13 TeV proton-proton collisions [19], [20].

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

461     The sources which contribute to the uncertainty in the jet energy scale (JES) [21] are decom-  
462     posed into uncorrelated components and treated as independent sources in the analysis. The  
463     CategoryReduction model is used to account for JES uncertainties, which decomposes the uncer-  
464     tainties into 30 nuisance parameters included in the fit. The SimpleJER model is used to account  
465     for jet energy resolution (JER) uncertainties, and 8 JER uncertainty components unclued as  
466     NPs in the fit.

467     The uncertainties in the b-tagging efficiencies measured in dedicated calibration analyses  
468     [22] are also decomposed into uncorrelated components. The large number of components for  
469     b-tagging is due to the calibration of the distribution of the MVA discriminant.

470     The full list of systematic uncertainties considered in the analysis is summarized in Tables 10,  
471     11 and 12.

472

<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_ JET_EffectiveNP_1-19	$p_T$ Correction $p_T$ Correction
	$\eta$ inter-calibration	JET_EtaIntercalibration_Modelling JET_EtaIntercalibration_NonClosure JET_EtaIntercalibration_TotalStat	$p_T$ Correction $p_T$ Correction $p_T$ Correction
	High $p_T$ jets	JET_SingleParticle_HighPt	$p_T$ Correction
	Pile-Up	JET_Pileup_OffsetNPV JET_Pileup_OffsetMu JET_Pileup_PtTerm JET_Pileup_RhoTopology	$p_T$ Correction $p_T$ Correction $p_T$ Correction $p_T$ Correction
	Non Closure	JET_PunchThrough_MC15	$p_T$ Correction
	Flavour	JET_Flavor_Response JET_BJES_Response JET_Flavor_Composition	$p_T$ Correction $p_T$ Correction $p_T$ Correction
Resolution		JET_JER_SINGLE_NP	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 on b originated jets in bins of $\eta$	DL1r_Continuous_EventWeight_B0-29
	DL1r b-tagger efficiency on c originated jets in bins of $\eta$	DL1r_Continuous_EventWeight_C0-19
	DL1r b-tagger efficiency on light flavoured originated jets in bins of $\eta$ and $p_T$	DL1r_Continuous_EventWeight_Light0-79
	DL1r b-tagger extrapolation efficiency	DL1r_Continuous_EventWeight_extrapolation 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.

473     Theoretical uncertainties applied to MC predictions, including cross section, PDF, and scale  
 474     uncertainties are taken from theory calculations, with the exception of non-prompt and diboson  
 475     backgrounds. The cross-section uncertainty on tZ is taken from [23]. Derivation of the non-  
 476     prompt background uncertainties, Z+jets and tt}, are explained in detail in Section 5.3. These  
 477     normalization uncertainties are chosen so as to account for the complete uncertainty in the  
 478     non-prompt contribution, and therefore no additional modelling uncertainties are considered for  
 479     Z+jets and tt}.

480     The other VV + heavy flavor processes (namely VV+b and VV+charm, which primarily consist  
 481     of ZZ events) are also poorly understood, because these processes involve the same physics as  
 482     WZ + heavy flavor, and have also not been measured. Therefore, a conservative 50% uncertainty  
 483     is applied to those samples. While this uncertainty is large, it is found to have little impact on  
 484     the significance of the final result.

485     The theory uncertainties applied to the predominate background estimates are summarized in  
 486     Table 13.

Process	X-section [%]
tZ	X-sec: $\pm 15.2$ QCD Scale: $^{+5.2}_{-1.3}$ PDF( $+\alpha_S$ ): $\pm 1.2$
t̄t H (aMC@NLO+Pythia8)	QCD Scale: $^{+5.8}_{-9.2}$ PDF( $+\alpha_S$ ): $\pm 3.6$
t̄t Z (aMC@NLO+Pythia8)	QCD Scale: $^{+9.6}_{-11.3}$ PDF( $+\alpha_S$ ): $\pm 4$
t̄t W (aMC@NLO+Pythia8)	QCD Scale: $^{+12.9}_{-11.5}$ PDF( $+\alpha_S$ ): $\pm 3.4$
VV + b/charm (Sherpa 2.2.1)	$\pm 50$
VV + light (Sherpa 2.2.1)	$\pm 6$
t̄t	$\pm 20$
Z + jets	$\pm 25$
Others	$\pm 50$

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

487 Additional signal uncertainties are estimated by comparing estimates from the nominal Sherpa  
 488 WZ samples with alternate WZ samples generated with Powheg+PYTHIA8 (DSID 361601).  
 489 MC/MC scale factors are applied to make these comparisons. The shape of the templates used  
 490 in the fit are compared between these two samples for WZ + b, WZ + charm and WZ + light,  
 491 as shown in Figures 28 and 29. Each of these plots are normalized to unity in order to capture  
 492 differences in shape.

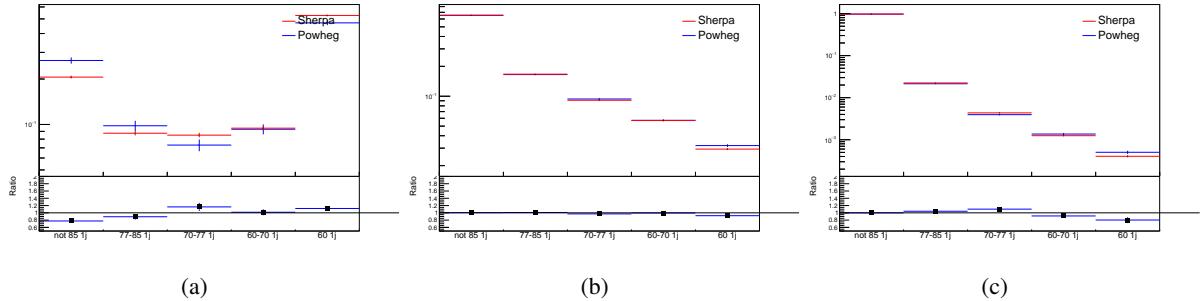


Figure 28: Comparison between Sherpa and Powheg predictions of the distribution of (a) WZ + b, (b) WZ + charm, and (c) WZ + light among the various b-tag WPs used in the 1-jet fit.

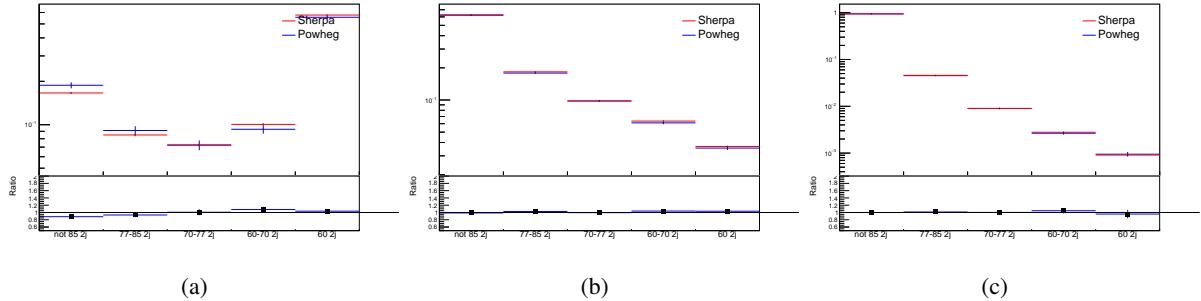


Figure 29: Comparison between Sherpa and Powheg predictions of the distribution of (a) WZ + b, (b) WZ + charm, and (c) WZ + light among the various b-tag WPs used in the 2-jet fit.

<sup>493</sup> Separate systematics are included in the fit for WZ + b, WZ + charm and WZ + light, where  
<sup>494</sup> the distribution among each of the fit regions is varied based on the prediction of the Powheg  
<sup>495</sup> sample.

496 A similar approach is taken to account for uncertainties in migrations between the number of  
 497 reco and truth jets. The fraction of events with 1 truth jet which fall into the 1 jet bin versus the  
 498 2 jet bin at reco level is compared for Sherpa and Powheg. The same is done for events with 2  
 499 truth jets. This comparison is shown in figure 30.

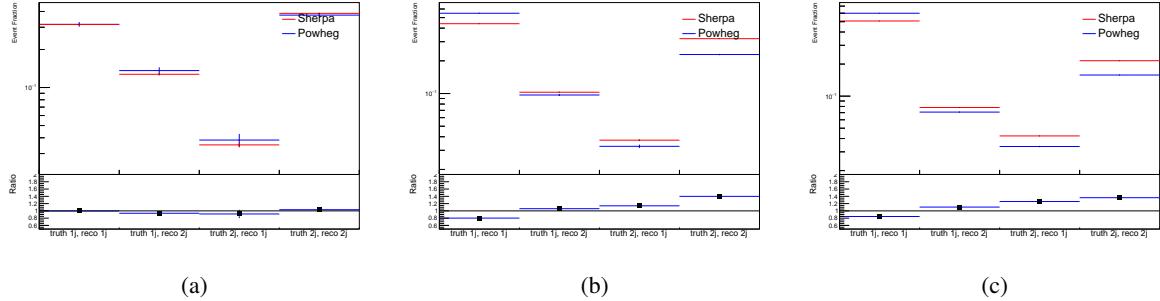


Figure 30: Comparison between Sherpa and Powheg predictions for truth jet migrations between the 1 and 2 jet reco bins for (a) WZ + b, (b) WZ + charm, and (c) WZ + light

500 A systematic is included where events are shifted between the 1-jet and 2-jet regions based on  
 501 the differences between these two shapes. This is done independently for each of the WZ + b,  
 502 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

505 outside the scope of this measurement, these events are included as a background. As such, a  
 506 normalization, rather than a shape, uncertainty is applied for this background.

507 The number of WZ events with 0-jets and  $>=3$ -jets in the reconstructed 1-jet and 2-jet regions  
 508 are compared for Sherpa and Powheg, as seen in figure 31. These differences are taken as separate  
 509 normalization systematics on the yield of WZ+0-jet and WZ+ $>=3$ -jet events.

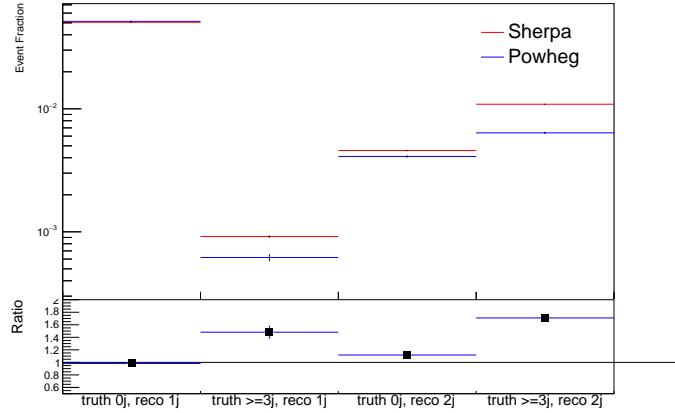


Figure 31: Comparison between Sherpa and Powheg predictions for 0 and  $>=3$  truth jet contributions in the 1 and 2 jet reco bins

## 510 8 Results

### 511 8.1 Fit Procedure

512 A maximum-likelihood fit is performed over the various fit regions described in Section 5 in  
 513 order to extract the best-fit value of the WZ + b-jet and WZ + charm jet contributions for events  
 514 with both 1 and 2 associated jets.

515 Because the fit regions are defined by the number of associated jets at reco-level, an unfolding  
 516 procedure is applied to the signal in order to account for differences in the number of truth jets  
 517 compared to the number of reco-jets. The WZ + b, WZ + charm and WZ + light contributions  
 518 are separated into independent samples based on the number of truth jets in each event. WZ + 1  
 519 truth-jet and WZ + 2 truth-jets are treated as signal samples, while WZ + 0 truth-jets and WZ +  
 520  $>=3$  truth-jets are treated as an additional background.

521 A maximum likelihood fit to data is performed simultaneously in the regions described in Section  
 522 5, summarized in figure 32. The six signal templates, which include WZ+b 1-jet, WZ+c 1-jet,  
 523 WZ+l 1-jet, WZ+b 2-jets, WZ+c 2-jets, WZ+l 2-jets, are allowed to float, while the remaining  
 524 background contributions are held fixed. The parameters  $\mu_{WZ+b-1-jet}$ ,  $\mu_{WZ+charm1-jet}$ ,

525  $\mu_{WZ+\text{light-}1\text{-jet}}$ ,  $\mu_{WZ+\text{b-}2\text{-jet}}$ ,  $\mu_{WZ+\text{charm2-jet}}$ ,  $\mu_{WZ+\text{light-}2\text{-jet}}$ , where  $\mu = \sigma_{\text{observed}}/\sigma_{\text{SM}}$ ,  
 526 are extracted from the fit. A simultaneous fit is performed over all 1-jet and 2-jet regions.

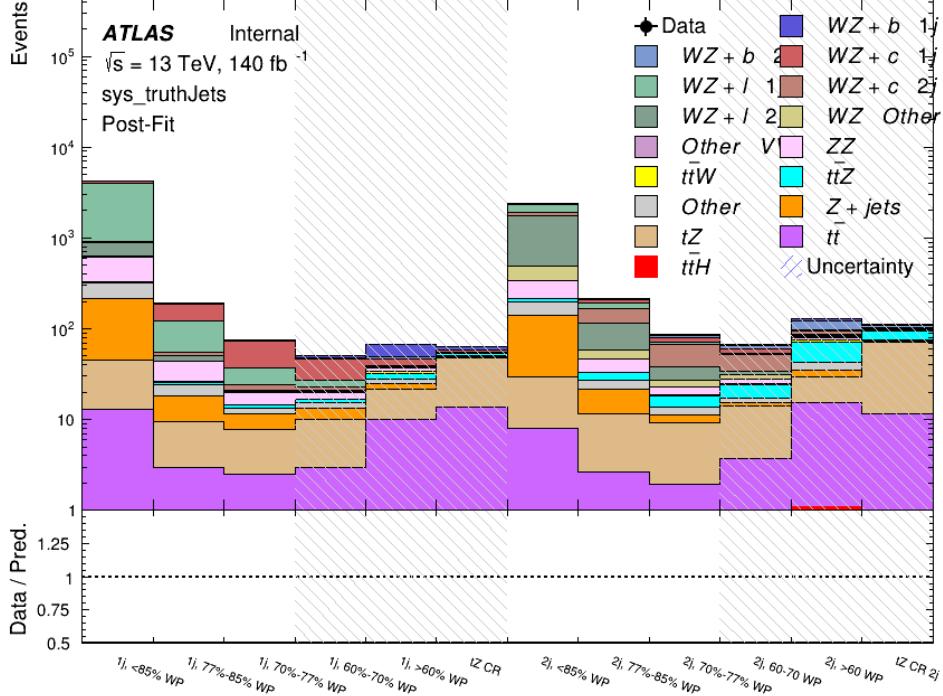


Figure 32: Post-fit summary of the fit regions.

527 As described in Section 7, there are 230 systematic uncertainties that are considered as NPs in  
 528 the fit. These NPs are constrained by Gaussian or log-normal probability density functions. The  
 529 latter are used for normalisation factors to ensure that they are always positive. The expected  
 530 number of signal and background events are functions of the likelihood. The prior for each NP  
 531 is added as a penalty term, decreasing the likelihood as it is shifted away from its nominal value.  
 532 The correlations between these nuisance parameters are summarized in Figure 33.

533 Several alternate fit strategies are documented in Appendices A.4-A.5.1. These include a mea-  
 534 surement of  $WZ + 1$  or  $2$  jets inclusively, a fit where  $tZ$  is allowed to float, and a case where  $tZ$  is  
 535 included as part of the signal.

## 536 8.2 Fiducial Region Definition

537 The fiducial volume at particle level is defined based on the number of stable leptons and jets in  
 538 each event. Three light leptons with total charge  $\pm 1$  and one or two associated jets are required.  
 539 This is separated into four observations based on the number and flavor of associated jets.

540 Only leptons which do not originate from hadron or  $\tau$  decays are considered. The phase space  
 541 definitions use dressed kinematics of the final state particles. Leptons are dressed by summing the  
 542 momentum of photons within a cone of  $\Delta R < 0.1$  of the lepton to correct the leptons energy.

543 Particle level jets are reconstructed using the anti- $k_t$  algorithm with a radius of  $R = 0.4$ .  
 544 Specifically, the `AntiKt4TruthDressedWZJets` collection is used to define the jets, and their  
 545 truth flavor is determined by `HadronConeExclTruthLabelID`.

546 The kinematic selection used at particle level closely follows the selection used at reconstructed  
 547 level. Three light leptons with total charge  $\pm 1$  and one or two associated jets Leptons and jets  
 548 are required to have  $|\eta| < 2.5$ , with the transition region included. The OS leptons is required to  
 549 have  $p_T > 10$  GeV, while the SS leptons are required to have  $p_T > 20$  GeV. Jets are required to  
 550 have  $p_T > 25$  GeV. The base fiducial region definition is summarized below:

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

555 The result of the fit is used to extract the cross-section in this fiducial region for WZ + b and WZ  
 556 + charm with one associated jet, and WZ + b and WZ + charm with two associated jets, where  
 557 the number and flavor of the jets is determined at particle level. Events with both charm and  
 558 b-jets are counted as WZ + b.

### 559 8.3 Results of the Simultaneous Fit

560 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  
 561 + b. The fitted cross-section modifiers for WZ + charm and WZ + light are  $1.00 \pm 0.17 \pm 0.17$   
 562 and  $1.00 \pm 0.06 \pm 0.14$ , respectively.

563 The expected cross-section of WZ+b with 1-jet is  $1.74^{+0.82}_{-0.75}(\text{stat})^{+0.53}_{-0.48}(\text{sys})$  fb, and  $14.6 \pm$   
 564  $2.5(\text{stat}) \pm 2.3(\text{sys})$  fb for WZ + charm, with a correlation of -0.15 between them. An expected  
 565 significance of 2.0 is observed for WZ + b in this region.

566 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.  
 567 The fitted cross-section modifiers for WZ + charm and WZ + light are  $1.00 \pm 0.25 \pm 0.21$  and  
 568  $1.00 \pm 0.06 \pm 0.16$ , respectively.

569 The expected WZ + b cross-section in the 2-jet region is  $2.5^{+1.3}_{-1.3}(\text{stat})^{+0.95}_{-0.83}(\text{sys})$  fb with an  
 570 expected significance of  $1.7\sigma$ . The 2-jet expected cross-section of WZ + charm is  $12.7 \pm$   
 571  $3.2(\text{stat}) \pm 2.7(\text{sys})$  fb, and the correlation between WZ + charm and WZ + b is -0.22.

572 A summary of the correlation between the various WZ components is summarized in Table 14.

573

	WZ + b - 1-jet	WZ + c - 1-jet	WZ + l - 1-jet	WZ + b - 2-jet	WZ + c - 2-jet	WZ + l - 2-jet
WZ + b - 1-jet	1.00	-0.15	0.28	-0.13	-0.22	0.17
WZ + c - 1-jet	-	1.00	0.36	0.13	-0.14	-0.16
WZ + l - 1-jet	-	-	1.00	0.10	-0.20	-0.39
WZ + b - 2-jet	-	-	-	1.00	-0.22	0.17
WZ + c - 2-jet	-	-	-	-	1.00	0.23
WZ + l - 2-jet	-	-	-	-	-	1.00

Table 14: Correlations between the various components of WZ

<sup>574</sup> The correlations between the all of the nuisance parameters considered in the fit are summarized  
<sup>575</sup> in Figure 33.a

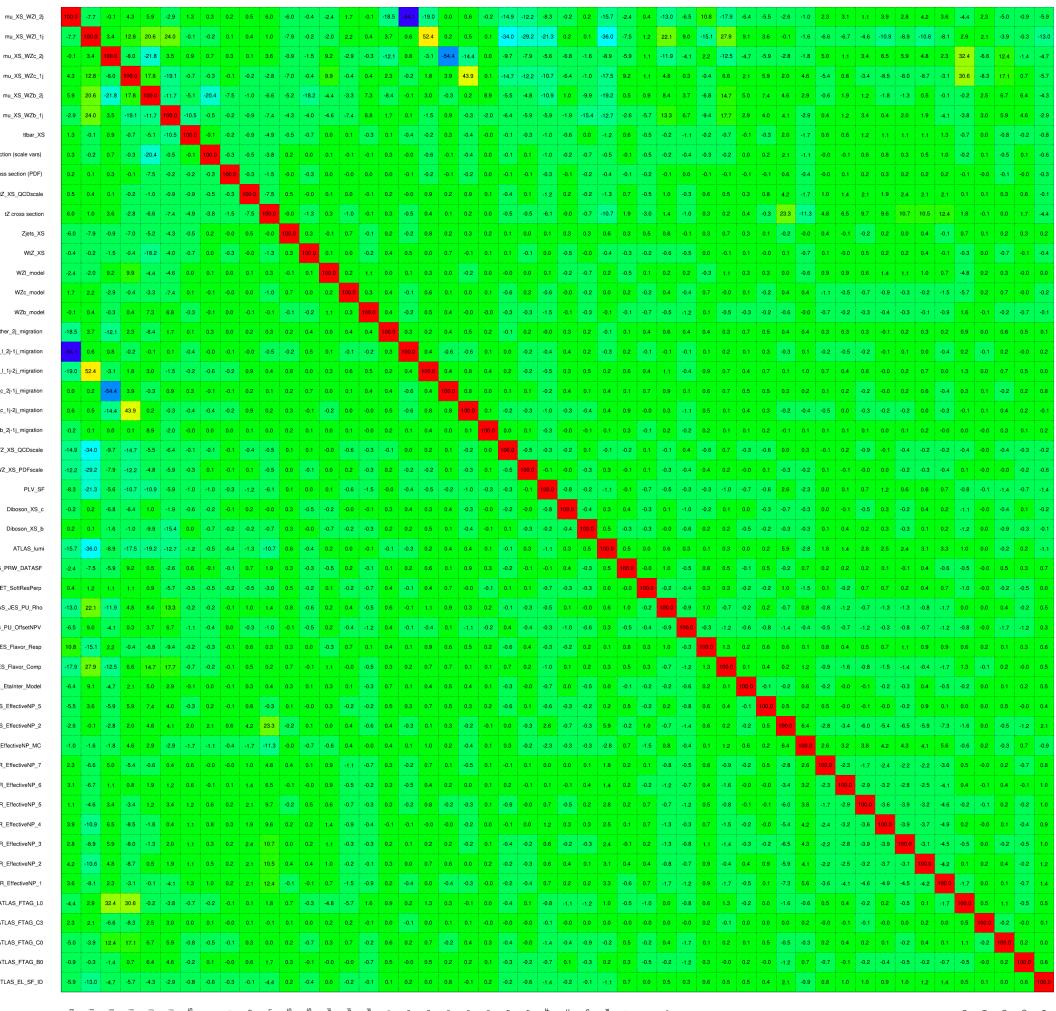


Figure 33: Correlations between nuisance parameters

576 The pre-fit yields in each of the 1-jet regions used in the fit are shown in Table 8.3.

577

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>578</sup> The post-fit yields in each region are summarized in Figure 8.3.

<sup>579</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	$346 \pm 57$	$19 \pm 5$	$4.3 \pm 0.8$	$2.7 \pm 0.5$	$2.4 \pm 0.1$	$2.1 \pm 0.6$
t̄W	$1.09 \pm 0.21$	$0.2 \pm 0.1$	$0.1 \pm 0.1$	$0.4 \pm 0.1$	$1.5 \pm 0.3$	$0.1 \pm 0.2$
t̄Z	$6.8 \pm 1.2$	$1.4 \pm 0.3$	$1.0 \pm 0.2$	$1.2 \pm 0.2$	$4.4 \pm 0.7$	$3.2 \pm 0.5$
rare Top	$0.14 \pm 0.04$	$0.04 \pm 0.02$	$0.04 \pm 0.0$	$0.1 \pm 0.03$	$0.14 \pm 0.04$	$0.15 \pm 0.05$
t̄WW	$0.04 \pm 0.03$	$0.01 \pm 0.02$	$0.01 \pm 0.01$	$0.01 \pm 0.01$	$0.01 \pm 0.02$	$0.01 \pm 0.01$
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.

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

Uncertainty Source	$\Delta\mu$	
WZ + 1-jet light XS	0.13	-0.18
WZ + charm cross-section	-0.10	0.12
Jet Energy Scale	0.1	-0.13
tZ cross-section	-0.10	0.10
WZ 1-jet/2-jet Migration	0.08	-0.07
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
t <bar>t} cross-section</bar>	-0.05	0.05
Total Systematic Uncertainty	0.29	0.34

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

<sup>584</sup> The ranking and impact of those nuisance parameters with the largest contribution to the overall  
<sup>585</sup> uncertainty is shown in Figure 34.

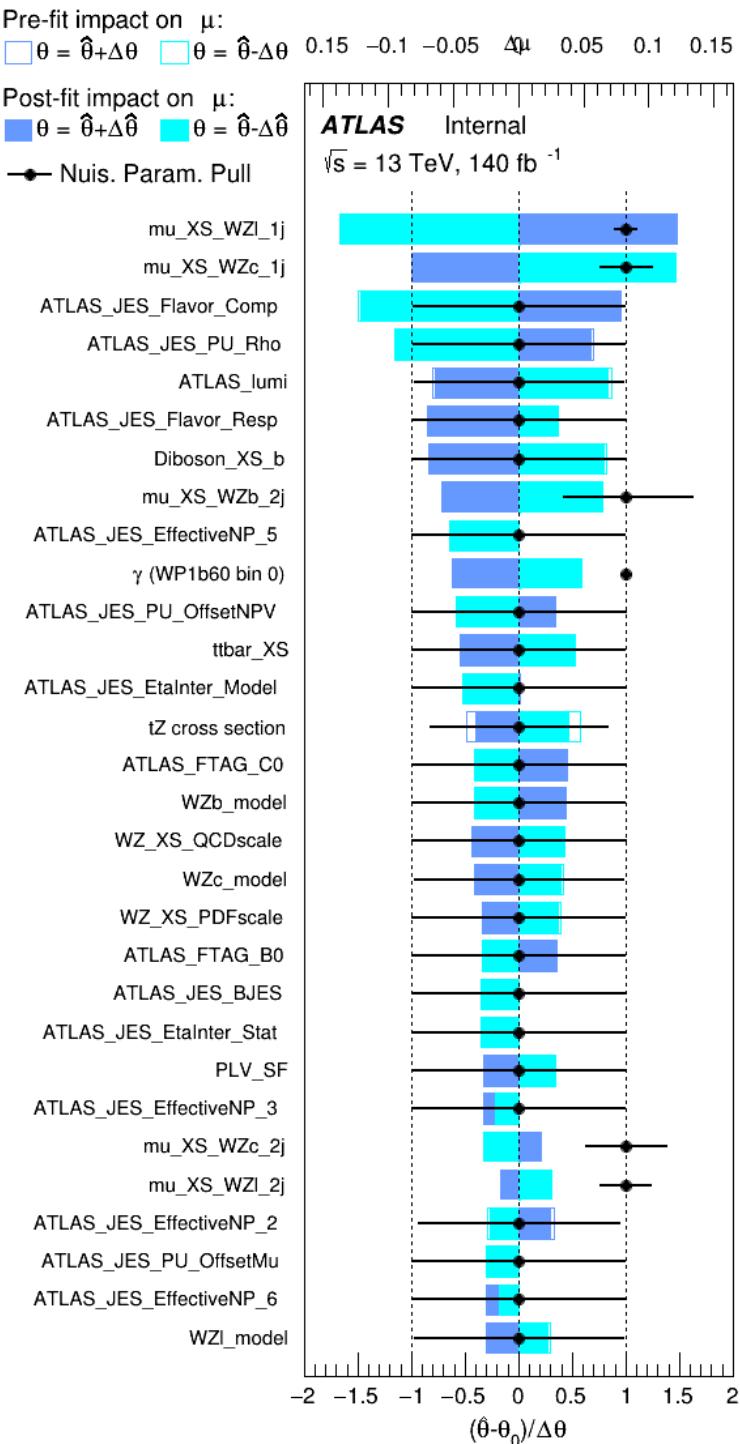


Figure 34: Impact of systematic uncertainties on the signal-strength of  $WZ + b$  for events with exactly one jet

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

589 Pre-fit yields in each of the 2-jet fit are shown in Figure 8.3.

	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	$135 \pm 20$	$14.1 \pm 3.2$	$4.7 \pm 0.8$	$4.0 \pm 0.6$	$4.1 \pm 0.7$	$3.1 \pm 0.5$
t̄W	$0.8 \pm 0.2$	$0.4 \pm 0.1$	$0.5 \pm 0.1$	$0.7 \pm 0.2$	$4.3 \pm 0.6$	$3.9 \pm 0.6$
t̄Z	$14.7 \pm 2.2$	$5.6 \pm 0.8$	$4.5 \pm 0.7$	$6.5 \pm 1.1$	$25.4 \pm 4.0$	$21.9 \pm 3.4$
rare Top	$0.14 \pm 0.04$	$0.07 \pm 0.03$	$0.03 \pm 0.02$	$0.09 \pm 0.03$	$0.37 \pm 0.07$	$0.6 \pm 0.1$
t̄WW	$0.04 \pm 0.03$	$0.02 \pm 0.02$	$0.01 \pm 0.01$	$0.01 \pm 0.00$	$0.03 \pm 0.03$	$0.01 \pm 0.01$
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 + γ	$25 \pm 18$	$0.5 \pm 0.2$	$0.1 \pm 0.1$	$0.1 \pm 0.1$	$0.0 \pm 0.02$	$0.05 \pm 0.07$
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	$19.5 \pm 4.2$	$2.8 \pm 1.6$	$0.7 \pm 0.7$	$0.1 \pm 0.2$	$0.0 \pm 0.0$	$0.0 \pm 0.0$
t̄t	$0.7 \pm 0.4$	$0.1 \pm 0.1$	$0.05 \pm 0.06$	$0.15 \pm 0.13$	$0.8 \pm 0.5$	$2.3 \pm 1.2$
t̄t̄	$6.8 \pm 1.0$	$2.4 \pm 0.5$	$1.8 \pm 0.4$	$3.3 \pm 0.6$	$8.4 \pm 1.2$	$13.6 \pm 1.7$
t̄tH	$0.4 \pm 0.1$	$0.2 \pm 0.1$	$0.16 \pm 0.02$	$0.23 \pm 0.03$	$0.94 \pm 0.11$	$1.03 \pm 0.12$
Total	$2580 \pm 160$	$229 \pm 24$	$89 \pm 13$	$69 \pm 11$	$120 \pm 15$	$108 \pm 11$

Table 18: Pre-fit yields in each of the 2-jet regions.

590 The post-fit yields in each region are summarized in Figure 8.3.

	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	$145 \pm 30$	$11.3 \pm 4.4$	$2.7 \pm 1.6$	$1.0 \pm 0.3$	$4.0 \pm 0.1$	$2.4 \pm 0.1$
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 + $\gamma$	$25 \pm 19$	$0.5 \pm 0.2$	$0.1 \pm 0.1$	$0.13 \pm 0.14$	$0.0 \pm 0.02$	$0.05 \pm 0.07$
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 19: Post-fit yields in each of the 2-jet regions.

<sup>591</sup> The same set of systematic uncertainties consider for the 1-jet fit are included in the 2-jet fit as  
<sup>592</sup> well. The impact of the most significant systematic uncertainties is summarized in Table 20.

Uncertainty Source	$\Delta\mu$	
WZ + c 2-jet cross-section	0.19	0.15
WZ 0-jet, $>=3$ -jet cross-section	0.14	-0.14
Luminosity	-0.11	0.12
tZ cross-section	-0.11	0.11
Jet Energy Scale	-0.11	0.11
ttZ cross-section - QCD scale	-0.08	0.09
WZ + l cross-section	0.08	-0.07
WtZ cross-section	-0.07	0.07
Flavor tagging	0.05	0.05
Other VV + b cross-section	-0.05	0.05
Total	0.32	0.36

Table 20: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + b 2-jet events.

<sup>593</sup> The ranking and impact of those nuisance parameters with the largest contribution to the overall  
<sup>594</sup> uncertainty is shown in Figure 35.

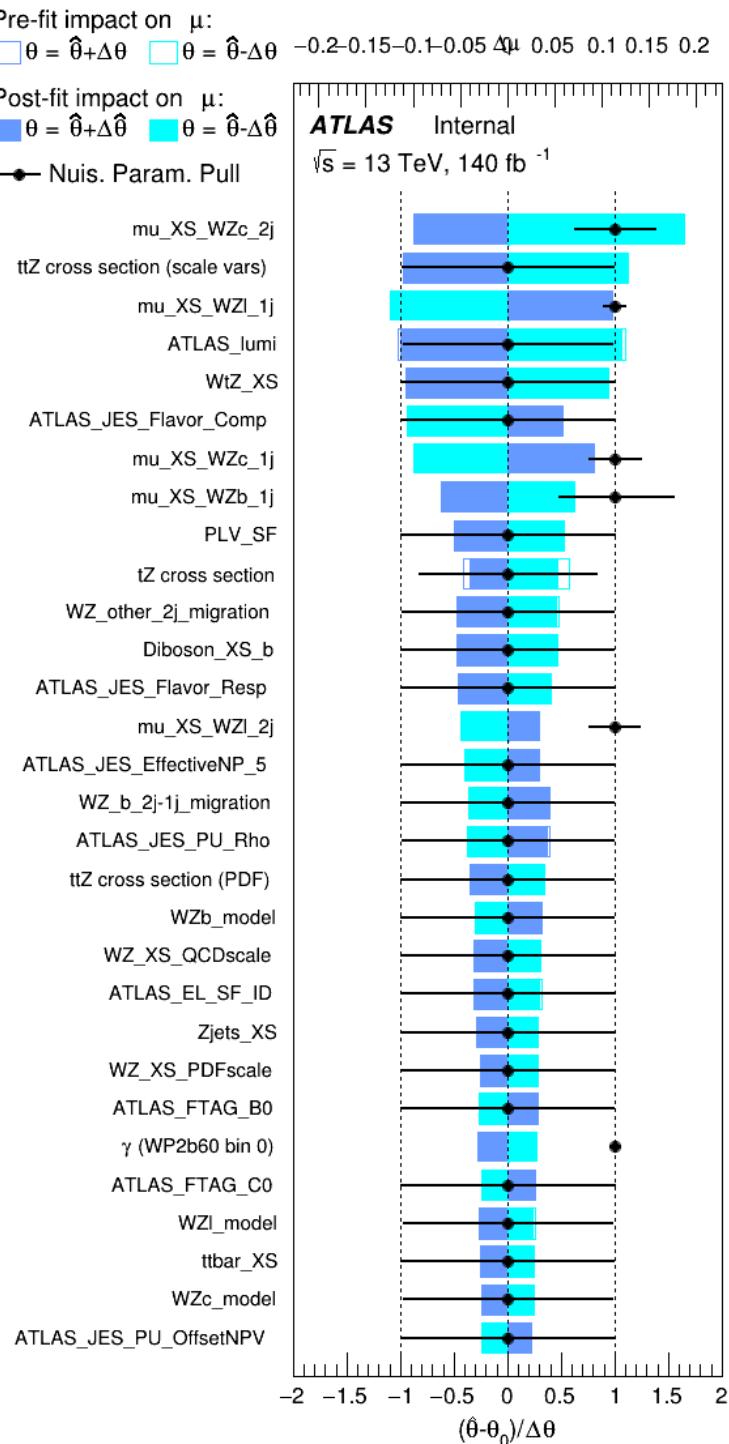


Figure 35: Impact of systematic uncertainties on the signal-strength of  $WZ + b$  in 2-jet events.

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

## 598 9 Conclusion

599 A measurement of  $WZ +$  heavy flavor is performed using  $140 \text{ fb}^{-1}$  of  $\sqrt{s} = 13 \text{ TeV}$  proton-  
 600 proton collision data collected by the ATLAS detector at the LHC. The expected cross-section  
 601 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  $WZ$   
 602 + charm, with a correlation of -0.22 between them. An expected significance of 2.0 is observed  
 603 for  $WZ + b$  in this region.

604 For the 2-jet regions, an expected significance of 1.7 is observed for  $WZ + b$ , with an ex-  
 605 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  
 606  $12.7 \pm 3.2(\text{stat}) \pm 2.7(\text{sys}) \text{ fb}$  is expected for 2-jet events. A correlation of -0.26 is observed  
 607 for  $WZ+b$  and  $WZ +$  charm.

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

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680 **A Appendices**

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

682 A lepton MVA has been developed to better reject non-prompt leptons than standard cut  
 683 based selections based upon impact parameter, isolation and PID. The name of this MVA is  
 684 `PromptLeptonIso`. The full set of studies and detailed explanation can be found in [9].

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

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

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

705 `PromptLeptonIso` is a gradient boosted BDT. The training of the BDT is performed on leptons  
 706 selected from the POWHEG+PYTHIA6 non-allhad t̄t MC sample. Eight variables are used to train  
 707 the BDT in order to discriminate between prompt and non-prompt leptons. The track jets that  
 708 are matched to the non-prompt leptons correspond to jets initiated by b or c quarks, and may  
 709 contain a displaced vertex. Consequently, three of the selected variables are used to identify  
 710 b-tag jets by standard ATLAS flavour tagging algorithms. Two variables use the relationship  
 711 between the track jet and lepton: the ratio of the lepton p<sub>T</sub> with respect to the track jet p<sub>T</sub> and  
 712 ΔR between the lepton and the track jet axis. Finally three additional variables test whether the  
 713 reconstructed lepton is isolated: the number of tracks collected by the track jet and the lepton  
 714 track and calorimeter isolation variables. Table 21 describes the variables used to train the BDT  
 715 algorithm. The choice of input variables has been extensively discussed with Egamma, Muon,  
 716 Tracking, and Flavour Tagging CP groups.

717 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
$N_{\text{TrkAtVtx}}$	Number of tracks used in the secondary vertex found by the SV1 algorithm 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 21: A table of the variables used in the training of `PromptLeptonIso`.

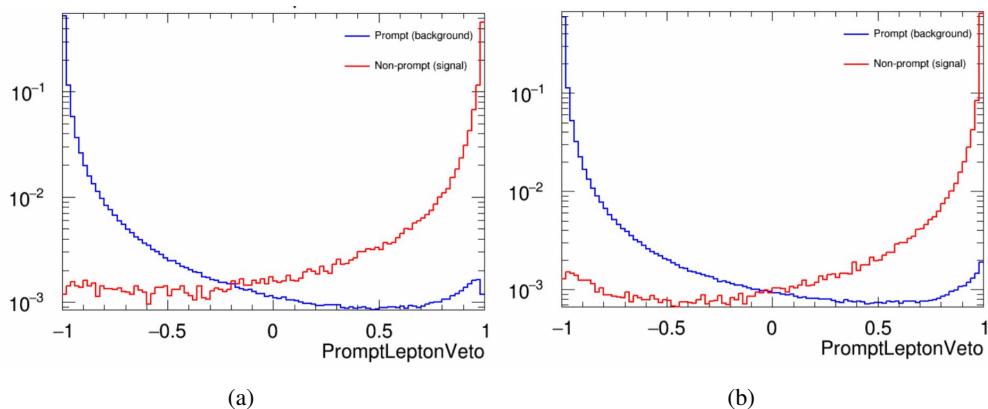


Figure 36: Distribution of the PLV BDT discriminant for (a) electrons and (b) muons

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

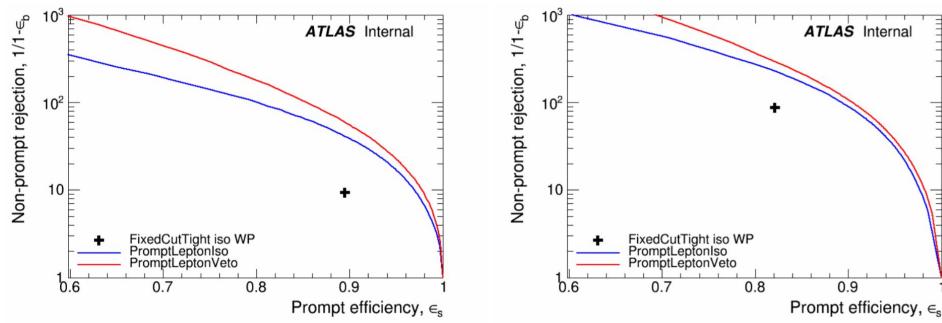


Figure 37: ROC curves for the PLV as well as the performance of the standard FixedCutTight WP for (left) electrons and (right) muons

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

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

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

732 In order to further validate the modeling in each of the non-prompt CRs, additional kinematic  
 733 plots are made in the Z+jets CR and  $t\bar{t}$  CR in each of the continuous b-tag regions, after the  
 734 correction factors detailed in Section 5.3 have been applied.

735 In the case of the Z+jets CR, the  $p_T$  spectrum of the lepton originating from the W candidate is  
 736 shown, as this is the distribution used to extract the scale factor applied to Z+jets. These plots  
 737 are shown in Figures 38 and 39.

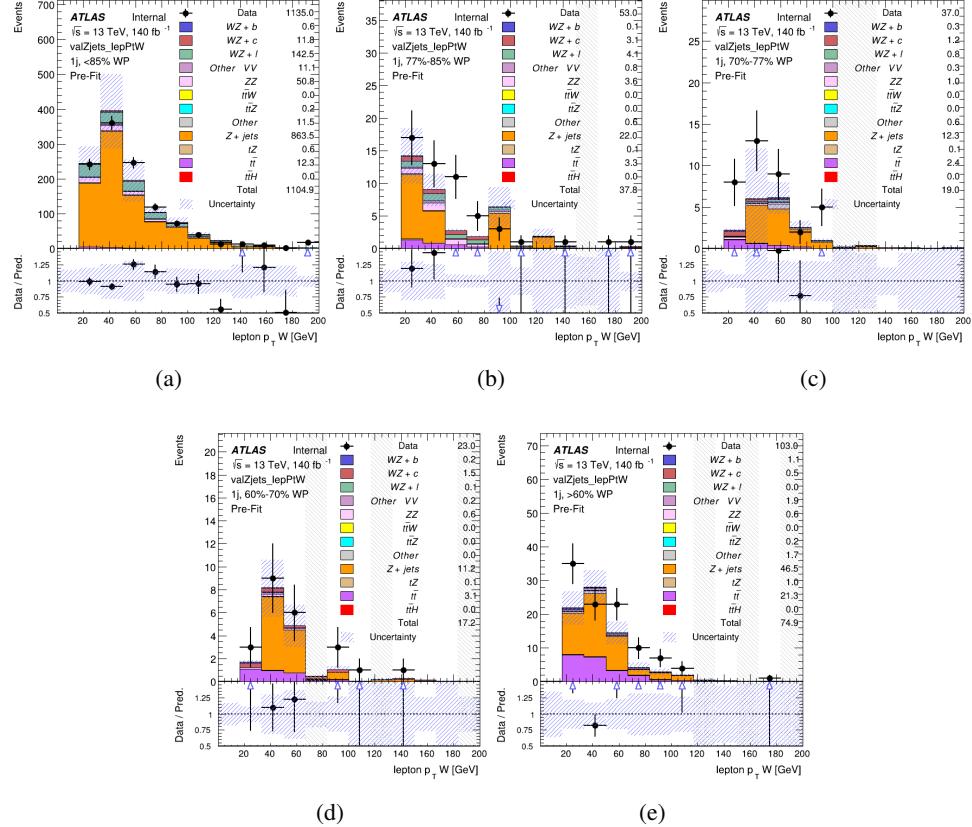


Figure 38: Comparisons between the data and MC distributions of the  $p_T$  of the lepton originating from the W-candidate in the Z+jets CR for each of the 1-jet b-tag working point regions

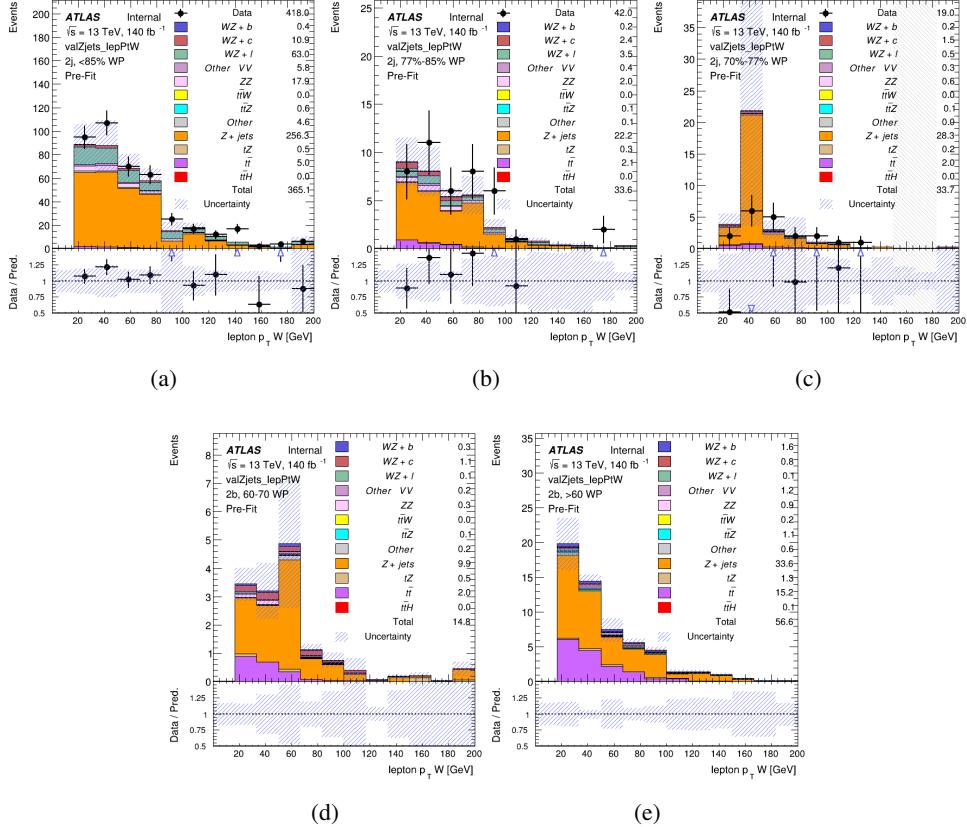


Figure 39: Comparisons between the data and MC distributions of the  $p_T$  of the lepton originating from the W-candidate in the Z+jets CR for each of the 2-jet b-tag working point regions

738 The same is shown for the  $t\bar{t}$  CR, but the  $p_T$  of the OS lepton is used instead as a representation  
 739 of the modeling, as the lepton from the W is not well defined for  $t\bar{t}$  events. These plots are shown  
 740 in Figures 40 and 41.

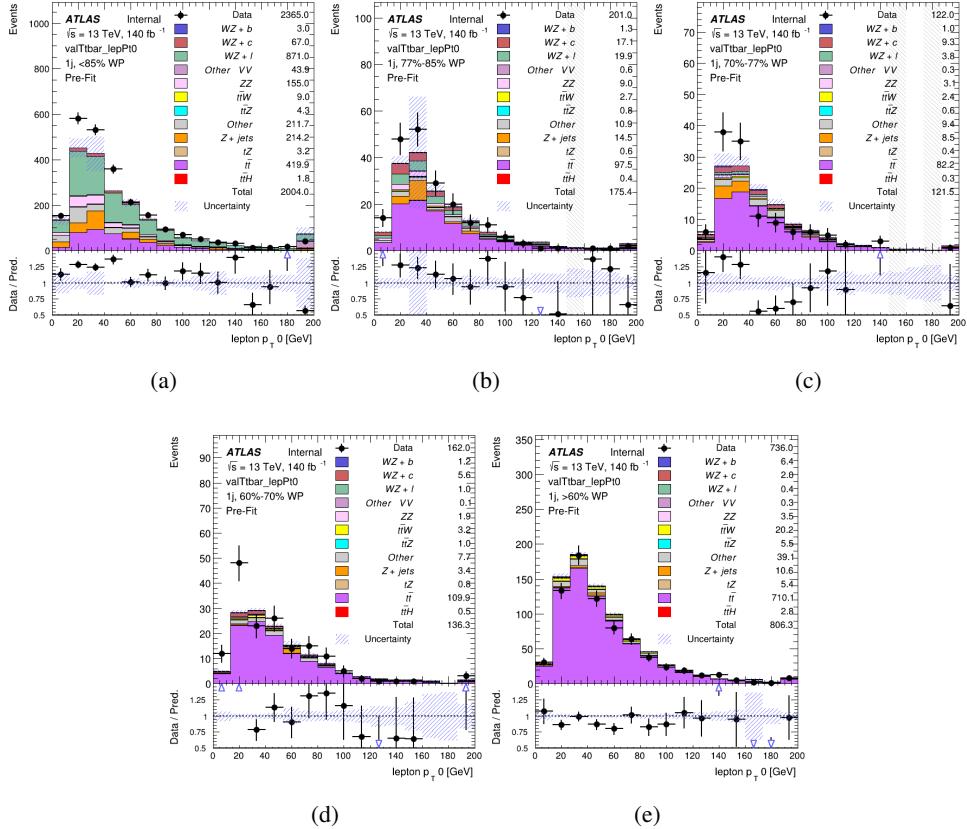


Figure 40: Comparisons between the data and MC distributions of the  $p_T$  of the OS lepton in the  $t\bar{t}$  CR for each of the 1-jet b-tag working point regions

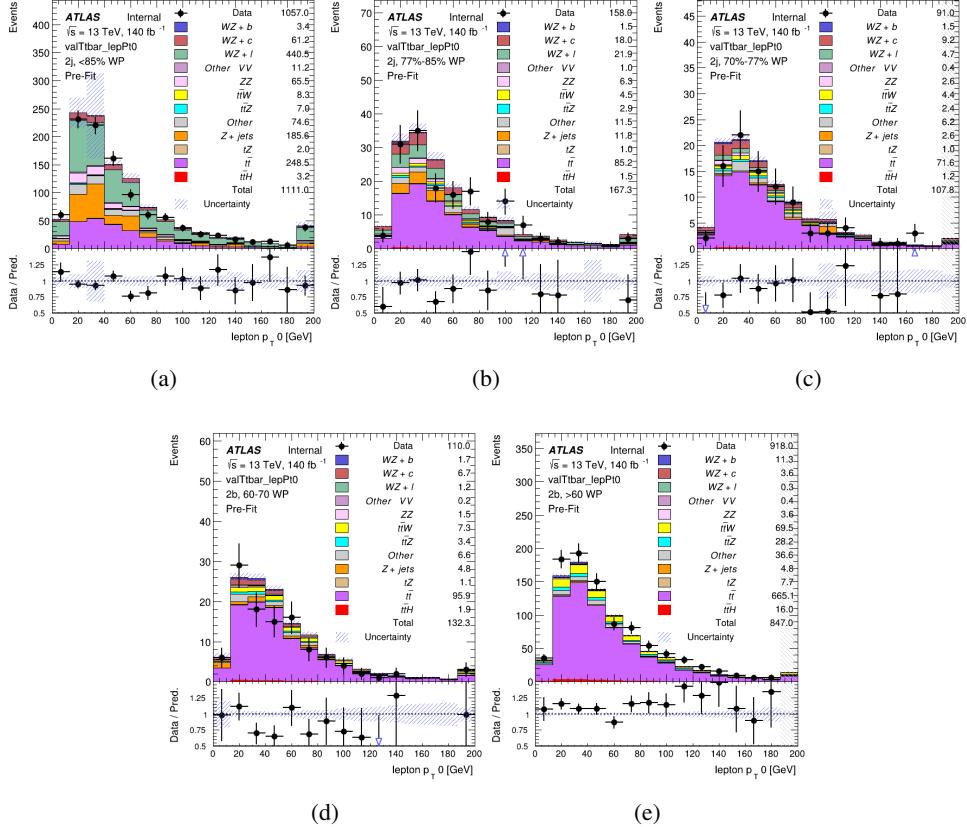


Figure 41: Comparisons between the data and MC distributions of the  $p_T$  of the OS lepton in the  $t\bar{t}$  CR for each of the 2-jet b-tag working point regions

### A.3 tZ Interference Studies

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

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

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

754 jet are produced.

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

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

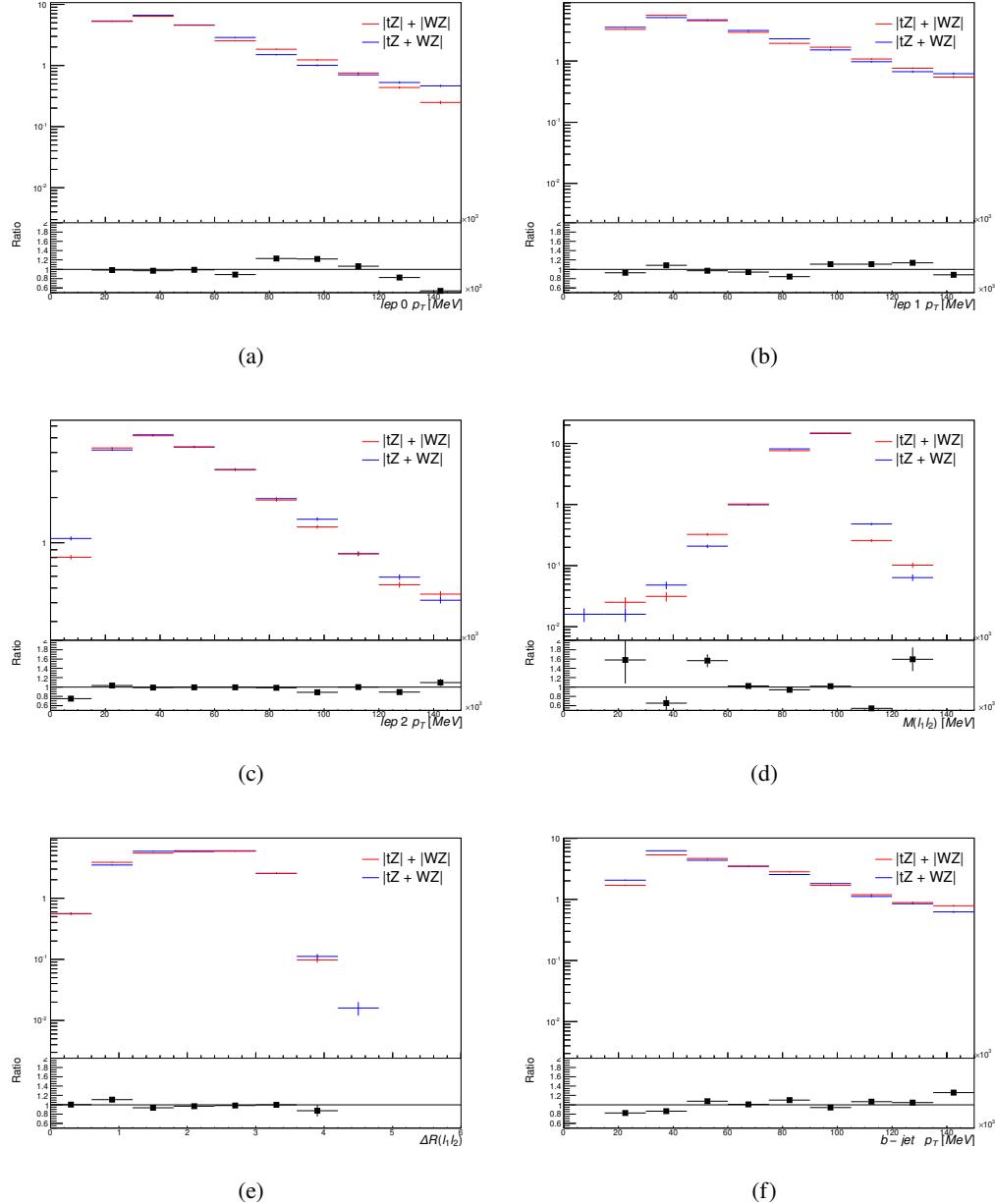


Figure 42: Comparisons between (a) the  $p_T$  of the lepton from the W, (b) and (c) show the  $p_T$  of the lepton from the Z, (d) the invariant mass of the Z-candidate, (e)  $\Delta R$  of the leptons from the Z, and (f) the  $p_T$  of the b-jet, for WZ and tZ events generated with interference effects (blue) and without interference effects (red).

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

762 significantly impact the results.

#### 763 A.4 Inclusive 1+2 Jet Cross Check

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

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

771 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  $2.8\sigma$ ,  
 772 and the uncertainty on WZ + charm is  $\mu = 1.00 \pm 0.12(\text{stat}) \pm 0.13(\text{sys})$ . This is compared to  
 773 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  
 774 are measured separately and then combined.

775 A post-fit summary plot of the fit regions is shown in Figure 43:

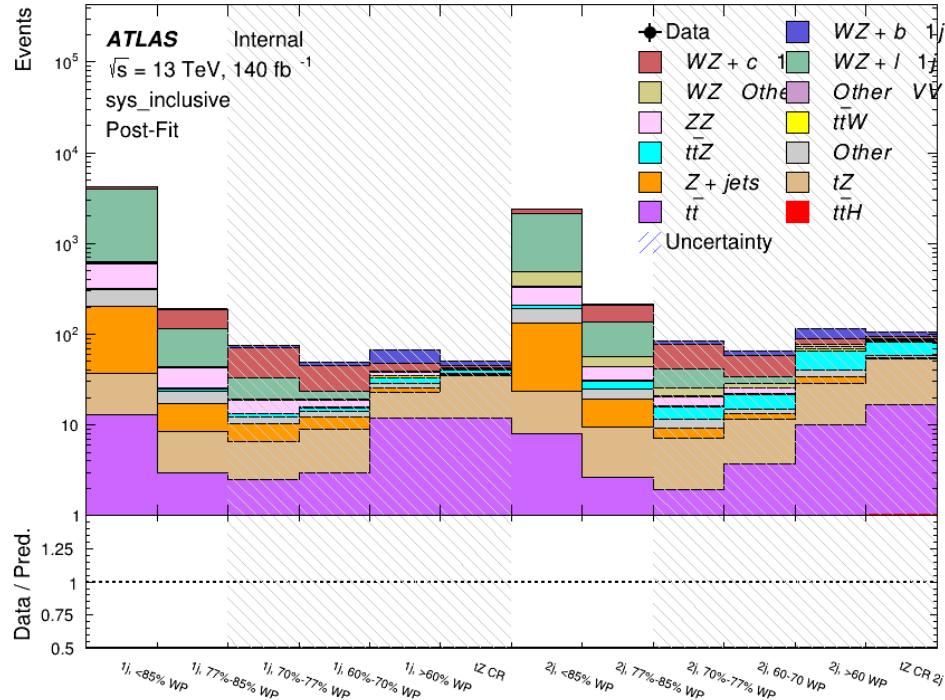


Figure 43: Post-fit summary of the 1-jet fit regions.

<sup>776</sup> The impact of the most significant sources of systematic uncertainties on the measurement of  
<sup>777</sup> WZ+b is summarized in Table 22.

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
t <bar>t} cross-section</bar>	-0.05	0.05
WZ cross-section - QCD scale	-0.04	0.03
Total Systematic Uncertainty	0.28	0.32

Table 22: Summary of the most significant sources of systematic uncertainty on the measurement of WZ + b with one or two associated jets.

<sup>778</sup> The ranking and impact of those nuisance parameters with the largest contribution to the overall  
<sup>779</sup> uncertainty is shown in Figure 44.

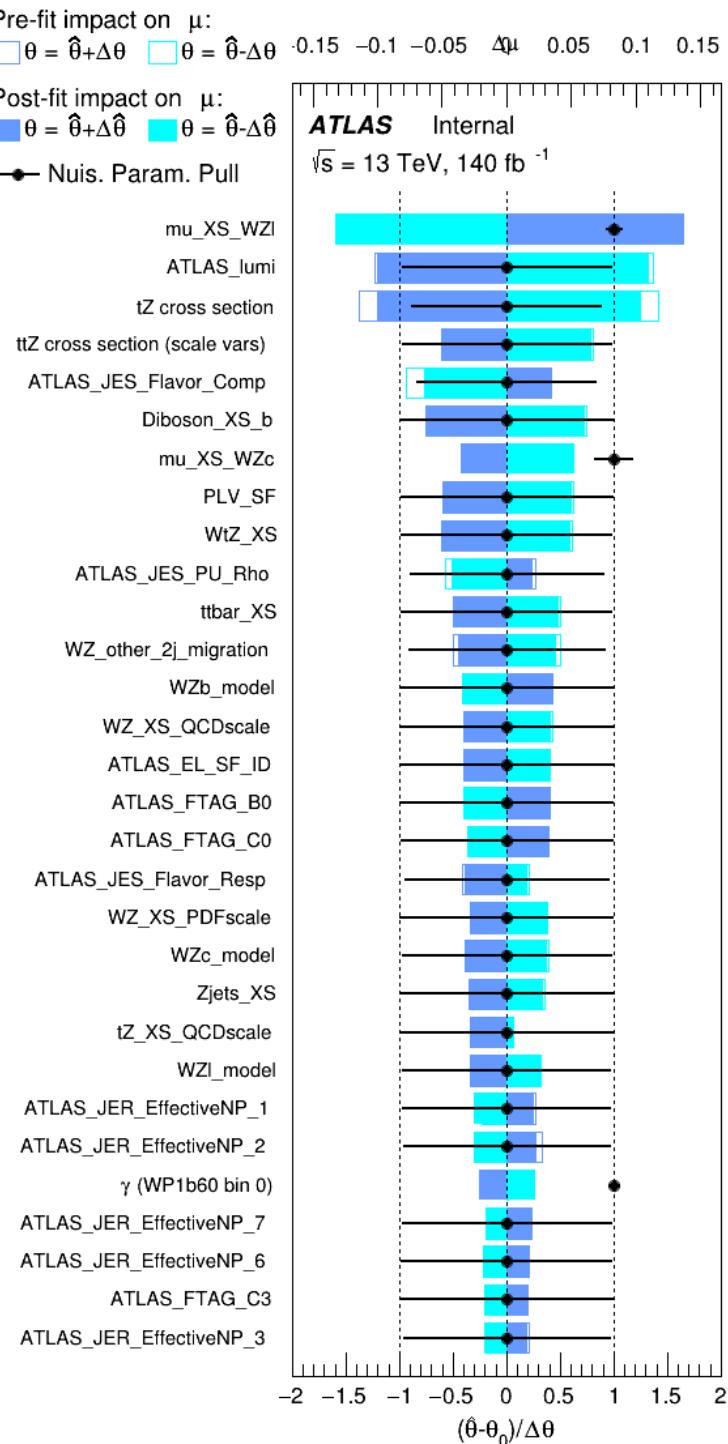


Figure 44: Impact of systematic uncertainties on the signal-strength of  $WZ + b$  for events with one or two jets

780 **A.5 Alternate tZ Inclusive Fit**

781 **A.5.1 tZ Inclusive Fit**

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

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

789 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  
 790 an expected significance of  $4.0\sigma$ .

791 The impact of the predominate systematics are summarized in Table 23.

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

792 **A.5.2 Floating tZ**

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

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

799 **A.6 DSID list**

Data:

```
data15_13TeV.AllYear.physics_Main.PhysCont.DAOD_HIGG8D1.grp15_v01_p4134
data16_13TeV.AllYear.physics_Main.PhysCont.DAOD_HIGG8D1.grp16_v01_p4134
data17_13TeV.AllYear.physics_Main.PhysCont.DAOD_HIGG8D1.grp17_v01_p4134
data18_13TeV.AllYear.physics_Main.PhysCont.DAOD_HIGG8D1.grp18_v01_p4134
```

mc16a:

```
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mc16d:

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mc16\_13TeV.364193.Sherpa\_221\_NNPDF30NNLO\_Wtaunu\_MAXHTPTV280\_500\_CVetoBVeto.deriv.DAOD\_HIGG8D1.e5340\_e5984\_s3126\_r10724\_r10726\_p4133  
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 mc16\_13TeV.364502.Sherpa\_222\_NNPDF30NNLO\_eegamma\_pty\_35\_70.deriv.DAOD\_HIGG8D1.e5928\_e5984\_s3126\_r10724\_r10726\_p4133  
 mc16\_13TeV.364503.Sherpa\_222\_NNPDF30NNLO\_eegamma\_pty\_70\_140.deriv.DAOD\_HIGG8D1.e5928\_e5984\_s3126\_r10724\_r10726\_p4133  
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 mc16\_13TeV.410408.aMcAtNloPythia8EvtGen\_tWZ\_Ztoll\_minDR1.deriv.DAOD\_HIGG8D1.e6423\_e5984\_s3126\_r10724\_r10726\_p4133  
 mc16\_13TeV.364242.Sherpa\_222\_NNPDF30NNLO\_WWW\_313v\_EW6.deriv.DAOD\_HIGG8D1.e5887\_e5984\_s3126\_r10724\_r10726\_p4133  
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 mc16\_13TeV.364247.Sherpa\_222\_NNPDF30NNLO\_ZZZ\_610v\_EW6.deriv.DAOD\_HIGG8D1.e5887\_e5984\_s3126\_r10724\_r10726\_p4133  
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