



ATLAS Note

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

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

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59 List of contributions

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

62 **1 Changes and outstanding items**

63 **1.1 Changelog**

64 This is version 10

65 **1.1.1 Changes relative to v9**

- 66 • Reordered note to put fiducial region definition in the intro, tZ BDT before the event
67 selection
68 •

69 **1.1.2 Changes relative to v8**

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

77 **1.1.3 Changes relative to v7**

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

86 **1.1.4 Changes relative to v5**

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

93 **1.1.5 Changes relative to v4**

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

102 **1.1.6 Changes relative to v3**

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

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

122 **1.1.7 Changes relative to v2**

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

130 **1.1.8 Changes relative to v1**

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

136 **1.2 Outstanding Items**

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

139 2 Executive Summary

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

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

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

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

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

167 The result of the fit is used to extract the cross-section in this fiducial region for $WZ + b$ and
 168 $WZ + c$ with one associated jet, and $WZ + b$ and $WZ + c$ with two associated jets, where the
 169 number and flavor of the jets is determined at particle level. Events with both charm and b-jets
 170 are counted as $WZ + b$. The analysis reports a cross-section measurement of $WZ + b$ and $WZ +$
 171 c , along with their correlations, for both 1-jet and 2-jet exclusive regions. Normalization factors,
 172 representing how the MC prediction differs from the observed result, are also reported.

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

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

180 3 Data and Monte Carlo Samples

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

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

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

194 3.1 Data Samples

195 The study uses a sample of proton-proton collision data collected by the ATLAS detector from
 196 2015 through 2018 at an energy of $\sqrt{s} = 13$ TeV, which represents an integrated luminosity of
 197 139 fb^{-1} [2]. This data set was collected with a bunch-crossing rate of 25 ns. All data used in
 198 this analysis was verified by data quality checks [3], having been included in the following Good
 199 Run Lists:

- 200 • data15_13TeV.periodAllYear_DetStatus-v79-repro20-02_DQDefects-00-02-02
 201 _PHYS_StandardGRL_All_Good_25ns.xml
- 202 • data16_13TeV.periodAllYear_DetStatus-v88-pro20-21_DQDefects-00-02-04
 203 _PHYS_StandardGRL_All_Good_25ns.xml
- 204 • data17_13TeV.periodAllYear_DetStatus-v97-pro21-13_Uncknown_PHYS_StandardGRL
 205 _All_Good_25ns_Triggerno17e33prim.xml
- 206 • data18_13TeV.periodAllYear_DetStatus-v102-pro22-04_Uncknown_PHYS_StandardGRL
 207 _All_Good_25ns_Triggerno17e33prim.xml

208 Runs included from the AllYear period containers are included.

209 **3.2 Monte Carlo Samples**

210 Several different generators were used to produce Monte Carlo simulations of the signal and
 211 background processes. For all samples, the response of the ATLAS detector is simulated using
 212 **GEANT4** [4]. The WZ signal samples are simulated using **Sherpa 2.2.2** [5]. Signal events are
 213 generated using NNPDF30NNLO PDF set with up to one parton at NLO and 2 to 3 partons at
 214 LO [**Butterworth:2015oua**].

215 The tZ background is simulated at NLO with **MADGRAPH5_AMC@NLO**, with **PYTHIA8** used to
 216 perform parton showering and fragmentation. The NNPDF30NNLO PDF set is used.

217 Specific information about the Monte Carlo samples being used can be found in Table 1. A list
 218 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 [6]
tZ	MG5_AMC [7]	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
t̄tH	MG5_AMC (MG5_AMC)	NLO (NLO)	PYTHIA 8 (HERWIG++) [9]	NNPDF 3.0 NLO [8] (CT10 [6])
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
t̄t̄, t̄t̄t̄	MG5_AMC	LO	PYTHIA 8	NNPDF 2.3 LO [10]
t̄tW+W-	MG5_AMC	LO	PYTHIA 8	NNPDF 2.3 LO
t̄t	POWHEG-BOX v2 [11]	NLO	PYTHIA 8	NNPDF 3.0 NLO
t̄t̄γ	MG5_AMC	LO	PYTHIA 8	NNPDF 2.3 LO
s-, t-channel, Wt single top	POWHEG-BOX v1 [12]	NLO	PYTHIA 6	CT10
qqVV, VVV Z → l+l-	SHERPA 2.2.1	MEPS NLO	SHERPA	NNPDF 3.0 NLO

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

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

219 4 Object Reconstruction

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

223 4.1 Trigger

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

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

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

4.2 Light leptons

- 226 Electron candidates are reconstructed from energy clusters in the electromagnetic calorimeter
 227 that are associated with charged particle tracks reconstructed in the inner detector [13]. Electron
 228 candidates are required to have $p_T > 10$ GeV and $|\eta_{\text{cluster}}| < 2.47$. Muon candidates are
 229 reconstructed by combining inner detector tracks with track segments or full tracks in the muon
 230 spectrometer [14]. Muon candidates are required to have $p_T > 10$ GeV and $|\eta| < 2.5$. Candidates
 231 in the transition region between different electromagnetic calorimeter components, $1.37 <$
 232 $|\eta_{\text{cluster}}| < 1.52$, are rejected. A multivariate likelihood discriminant combining shower shape
 233 and track information is used to distinguish real electrons from hadronic showers (fake electrons).
 234 To further reduce the non-prompt electron contribution, the track is required to be consistent
 235 with originating from the primary vertex; requirements are imposed on the transverse impact
 236 parameter significance ($|d_0|/\sigma_{d_0} < 5$) and the longitudinal impact parameter ($|\Delta z_0 \sin \theta_\ell| < 0.5$
 237 mm). Electron candidates are required to pass TightLH identification.
- 238 Muon candidates are reconstructed by combining inner detector tracks with track segments or
 239 full tracks in the muon spectrometer [14]. Muon candidates are required to have $p_T > 10$ GeV
 240 and $|\eta| < 2.5$. The longitudinal impact parameter is the same for both electrons and muons, while
 241 muons are required to pass a slightly tighter transverse impact parameter, $|d_0|/\sigma_{d_0} < 3$. Muons
 242 are also required to pass Medium ID requirements.

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

247 **4.3 Jets**

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

256 **4.4 B-tagged Jets**

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

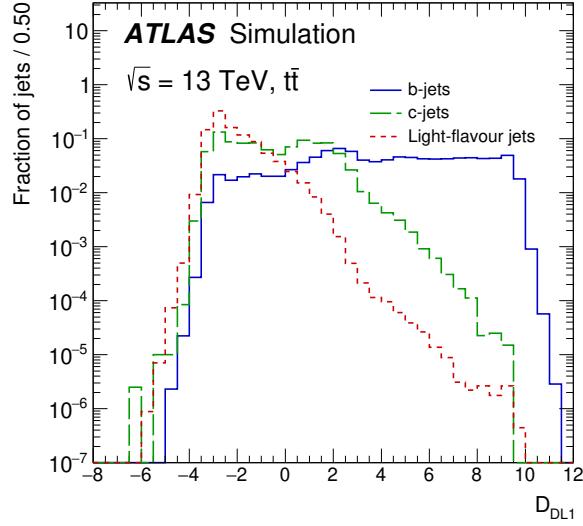


Figure 1: Output distribution of the DL1r algorithm for pure samples of b-jets, charm jets, and light jets, with each normalized to unity [19]

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

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

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

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

273 **4.5 Missing transverse energy**

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

280 **4.6 Overlap removal**

281 To avoid double counting objects and remove leptons originating from decays of hadrons, overlap
 282 removal is performed in the following order: any electron candidate within $\Delta R = 0.1$ of another
 283 electron candidate with higher p_T is removed; any electron candidate within $\Delta R = 0.1$ of a muon
 284 candidate is removed; any jet within $\Delta R = 0.2$ of an electron candidate is removed; if a muon
 285 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
 286 is kept and the muon is removed if the jet has at least three associated tracks, otherwise the jet is
 287 removed and the muon is kept.

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

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

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

290 **5 tZ Separation Multivariate Analysis**

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

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

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

299 **5.1 Top Mass Reconstruction**

300 The reconstruction of the top mass follows the procedure described in detail in section 6.1 of
 301 [21]. The mass of the top quark candidate is reconstructed from the jet, the lepton not included
 302 in the Z-candidate, and a reconstructed neutrino. In the case that there is one jet in the event,
 303 there is only possible b-jet candidate. For events with two jets, the jet with the highest DL1r
 304 score is used.

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

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

$$310 \quad (p_l + p_\nu)^2 = m_W^2$$

311 Expanding this out into components, this equation gives:

$$312 \quad \sqrt{p_{T\nu}^2 + p_{z\nu}^2} E_l = \frac{m_W^2 - m_l^2}{2} + p_{T\nu}(p_{lx}\cos\phi_\nu + p_{ly}\sin\phi_\nu) + p_{lz}p_{\nu z}$$

313 This equation gives two solutions for $p_{\nu z}$. For cases where only one of these solutions is real,
 314 that is taken as the value of $p_{\nu z}$. For instances with two real solutions, the one which is shown
 315 to be correct in the largest fraction of simulations is taken. For cases when no real solution is
 316 found, often because of detector effects, the value of E_T^{miss} is varied in decreasing increments of
 317 100 MeV until a real solution is found.

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

319 **5.2 tZ BDT**

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

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

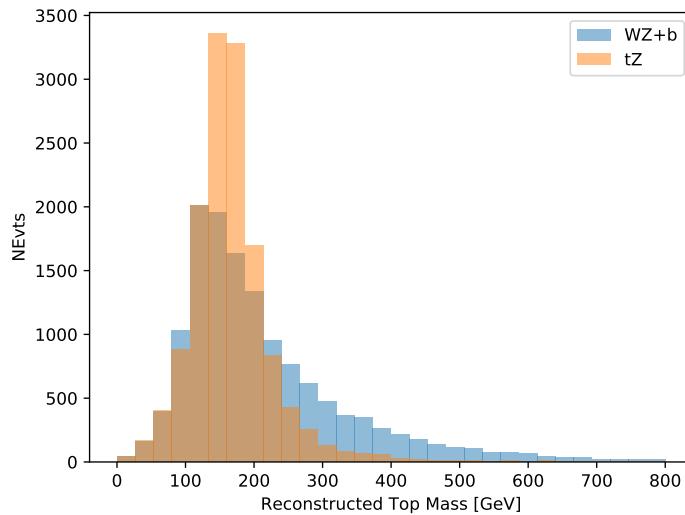


Figure 2: Reconstructed top mass distributions for tZ and WZ + b, measured in MeV.

325 • E_T^{miss}

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

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

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

331 The distributions of a few of these features for both signal and background is shown in figure
332 3.

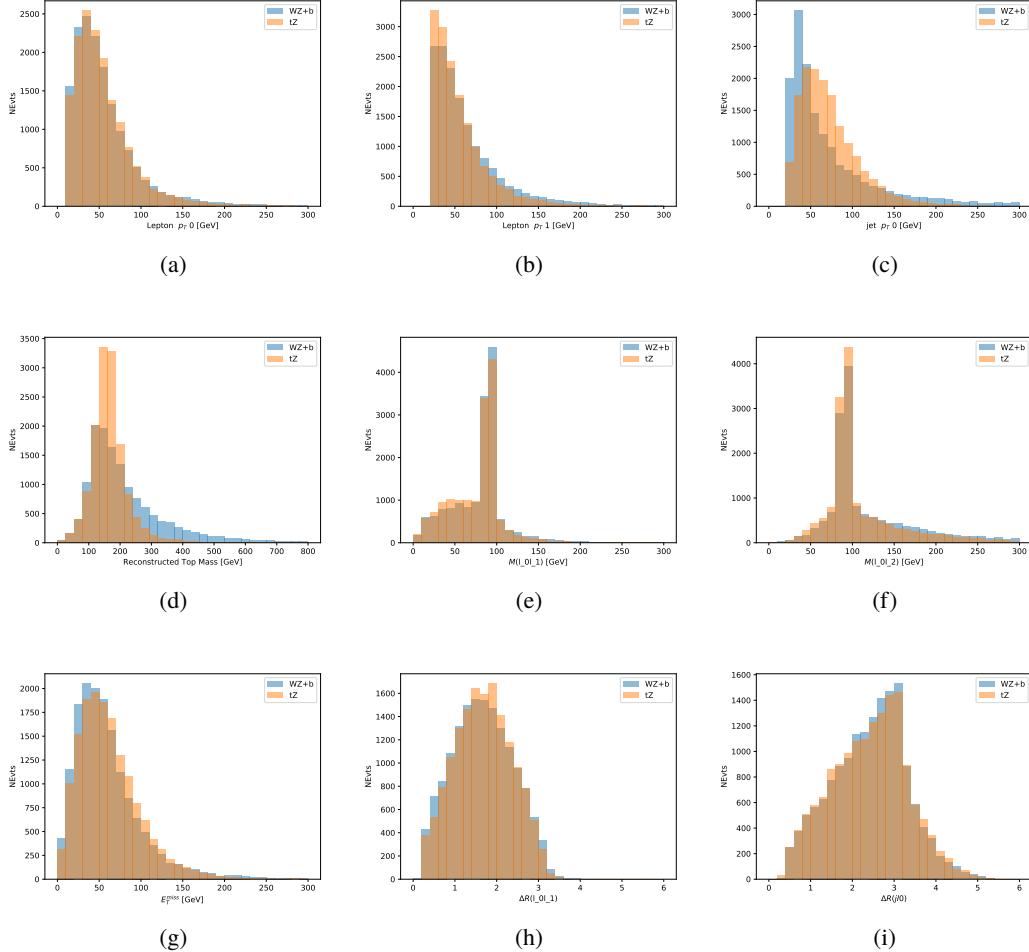


Figure 3: Distribution of input features of the BDT for signal (WZ) and background (tZ). Both are scaled to an equal number of events. (a), (b) and (c) show the p_T of lepton 0, lepton 1, and the jet, (d) show the reconstructed top mass, (e) and (f) show the invariant mass of leptons 0 and 1, leptons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

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

338 The results of the BDT training are shown in figure 4. The output scores for both signal and
 339 background events is shown on the left. The right shows the receiving operating characteristic
 340 (ROC) curve that results from the MVA. The ROC curve represents the background rejection
 341 as a function of signal efficiency, where each point on the curve represents a different response

342 score.

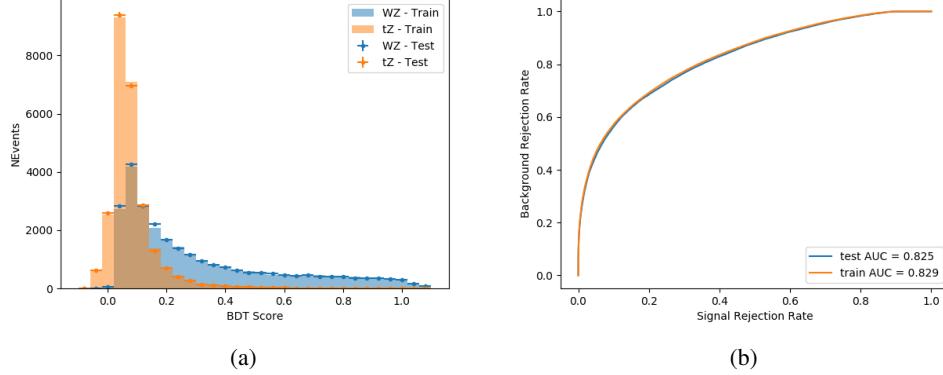


Figure 4: Distribution of the BDT response for signal and background events on the left, the ROC curve for the BDT on the right.

343 The relative important of each input feature in the model, measured by how often they appeared
344 in the decision trees, is shown in figure 5.

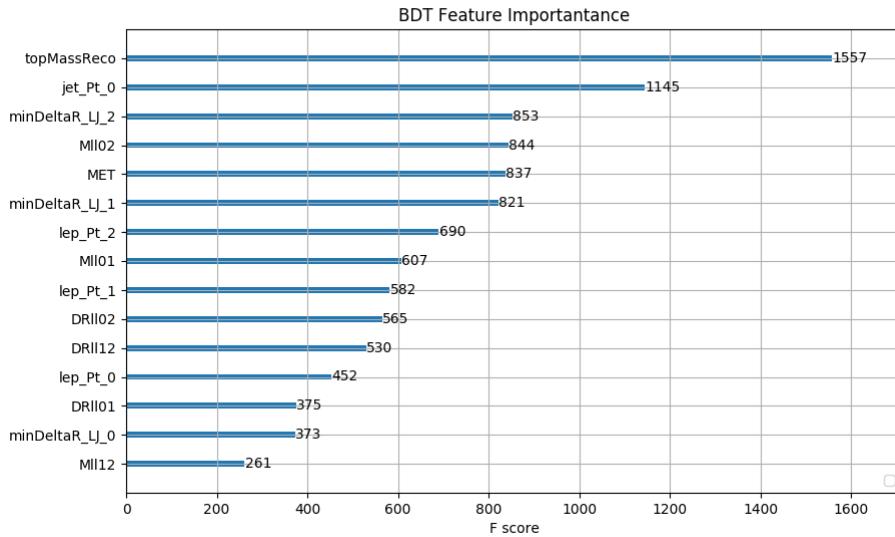


Figure 5: Relative importance of each input feature in the model.

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

347 of 0.12 is selected as a cutoff, where events with scores higher than this form a signal enriched
348 region, and events with scores lower than this form a tZ control region. This cutoff is selected by
349 varying the value of this cutoff in stat-only Asimov fits, and selecting the value that minimizes
350 the statistical uncertainty on WZ + b. A working point of 0.12 produces a background rejection
351 rate of 74%, compared to a signal acceptance of 78%.

352 **5.3 tZ Interference Studies**

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

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

363 MadGraph simulations of 10,000 tZ and 10,000 WZ + b-jet events are produced, along with
364 20,000 events where both are present, in the fiducial region where three leptons and at least one
365 jet are produced.

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

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

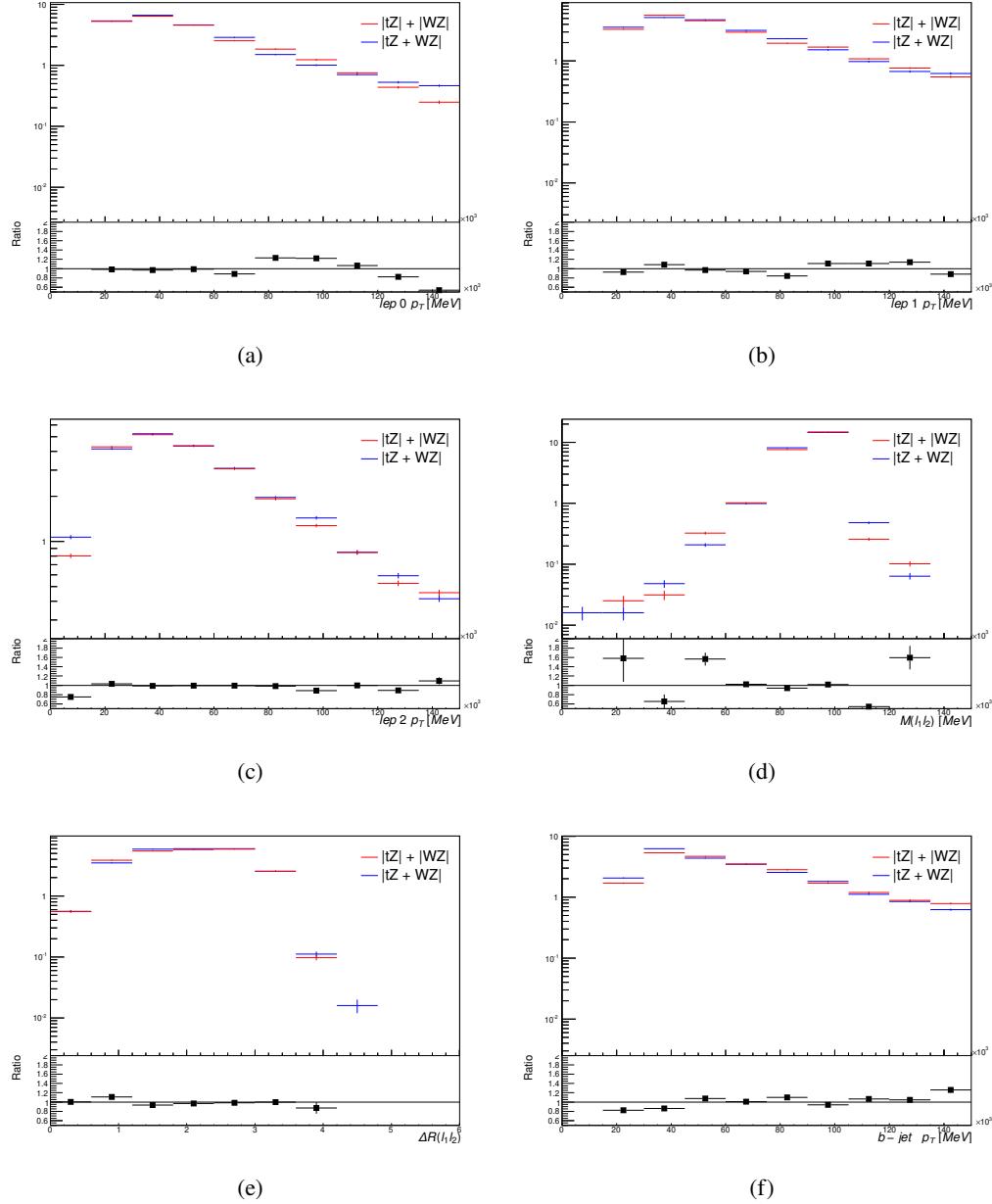


Figure 6: Comparisons between (a) the p_T of the lepton from the W, (b) and (c) show the p_T of the lepton from the Z, (d) the invariant mass of the Z-candidate, (e) ΔR of the leptons from the Z, and (f) the p_T of the b-jet, for WZ and tZ events generated with interference effects (blue) and without interference effects (red).

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

³⁷³ significantly impact the results.

³⁷⁴ 6 Event Selection and Signal Region Definitions

³⁷⁵ Event are required to pass a preselection described in Section 6.1 and summarized in Table 6.
³⁷⁶ Those that pass this preselection are divided into various fit regions described in Section 6.2,
³⁷⁷ based on the number of jets in the event, and the b-tag score of those jets.

³⁷⁸ 6.1 Event Preselection

³⁷⁹ Events are required to include exactly three reconstructed light leptons passing the requirement
³⁸⁰ described in 4.2, which have a total charge of ± 1 .

³⁸¹ The leptons are ordered in the analysis code as 0, 1, and 2. Lepton 0 is the lepton whose charge
³⁸² is opposite the other two. Lepton 1 is the lepton closest to the opposite charge lepton, i.e. the
³⁸³ smallest ΔR , leaving lepton 2 as the lepton further from the opposite charge lepton. Lepton 0 is
³⁸⁴ required to have $p_T > 10$ GeV, as it is found to be prompt the vast majority of the time, while
³⁸⁵ the same sign leptons, 1 and 2, are required to have $p_T > 20$ GeV to reduce the contribution of
³⁸⁶ non-prompt leptons, as non-prompt leptons tend to be soft.

³⁸⁷ The invariant mass of at least one pair of opposite sign, same flavor leptons is required to fall
³⁸⁸ within 10 GeV of the mass of the Z boson, 91.2 GeV. Events where one of the opposite sign pairs
³⁸⁹ have an invariant mass less than 12 GeV are rejected in order to suppress low mass resonances.

³⁹⁰ An additional requirement is placed on the missing transverse energy, $E_T^{\text{miss}} > 20$ GeV, and the
³⁹¹ transverse mass of the W candidate, $m(E_T^{\text{miss}} + l_{\text{other}}) > 30$ GeV, defined as $\sqrt{2 p_T^{\text{lep}} E_T^{\text{miss}} * (1 - \cos(\phi_{\text{lep}} - \phi_{E_T^{\text{miss}}}))}$.
³⁹² Here E_T^{miss} is the missing transverse energy, and l_{other} is the lepton not included in the Z-
³⁹³ candidate.

³⁹⁴ Events are required to have one or two reconstructed jets passing the selection described in
³⁹⁵ Section 4.3. Events with more than two jets are rejected in order to reduce the contribution of
³⁹⁶ backgrounds such as $t\bar{t}Z$ and $t\bar{t}W$, which tend to have higher jet multiplicity.

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

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

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

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

Table 7: Event yields in the preselection region at 139.0 fb^{-1}

405 Here Other VV represents diboson processes other than WZ, and consists predominantly of
 406 $ZZ \rightarrow ll\bar{l}\bar{l}$ events where one of the leptons is not reconstructed.

407 Simulations are further validated by comparing the kinematic distributions of the Monte Carlo
 408 with data, which are shown in Figure 7. Here, bins with 5% or more WZ+b are blinded.

WZ Fit Region - Inclusive

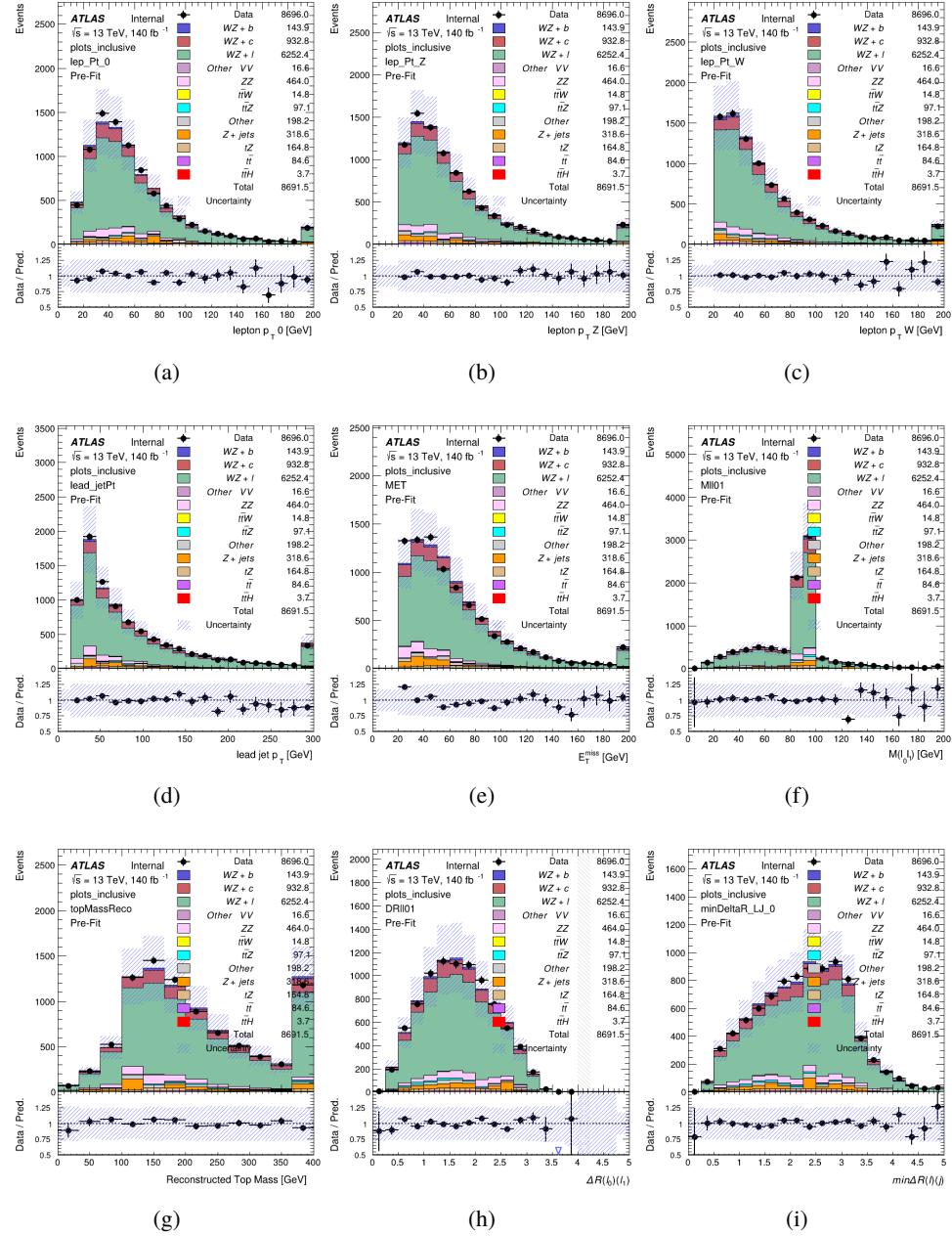


Figure 7: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant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

⁴⁰⁹ **6.2 Fit Regions**

⁴¹⁰ Once preselection has been applied, the remaining events are categorized into one of twelve
⁴¹¹ orthogonal regions. The regions used in the fit are summarized in Table 8.

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

Region	Selection
1j, <85%	$N_{\text{jets}} = 1, n_{\text{Jets_DL1r_85}} = 0$
1j, 85%-77%	$N_{\text{jets}} = 1, n_{\text{Jets_DL1r_85}} = 1, n_{\text{Jets_DL1r_77}} = 0$
1j, 77%-70%	$N_{\text{jets}} = 1, n_{\text{Jets_DL1r_77}} = 1, n_{\text{Jets_DL1r_70}} = 0$
1j, 70%-60%	$N_{\text{jets}} = 1, n_{\text{Jets_DL1r_70}} = 1, n_{\text{Jets_DL1r_60}} = 0$
1j, >60%	$N_{\text{jets}} = 1, n_{\text{Jets_DL1r_60}} = 1, tZ \text{ BDT} > 0.12$
1j tZ CR	$N_{\text{jets}} = 1, n_{\text{Jets_DL1r_60}} = 1, tZ \text{ BDT} < 0.12$
2j, <85%	$N_{\text{jets}} = 2, n_{\text{Jets_DL1r_85}} = 0$
2j, 85%-77%	$N_{\text{jets}} = 2, n_{\text{Jets_DL1r_85}} \geq 1, n_{\text{Jets_DL1r_77}} = 0$
2j, 77%-70%	$N_{\text{jets}} = 2, n_{\text{Jets_DL1r_77}} \geq 1, n_{\text{Jets_DL1r_70}} = 0$
2j, 70%-60%	$N_{\text{jets}} = 2, n_{\text{Jets_DL1r_70}} \geq 1, n_{\text{Jets_DL1r_60}} = 0$
2j, >60%	$N_{\text{jets}} = 2, n_{\text{Jets_DL1r_60}} \geq 1, tZ \text{ BDT} > 0.12$
2j tZ CR	$N_{\text{jets}} = 2, n_{\text{Jets_DL1r_60}} \geq 1, tZ \text{ BDT} < 0.12$

⁴¹² The working points discussed in Section 4.4 are used to separate events into fit regions based on
⁴¹³ the highest working point reached by a jet in each event. Because the background composition
⁴¹⁴ differs significantly based on the number of b-jets, events are further subdivided into 1-jet and
⁴¹⁵ 2-jet regions in order to minimize the impact of background uncertainties.

⁴¹⁶ An unfolding procedure is performed to account for differences in the number of reconstructed
⁴¹⁷ jets compared to the number of truth jets in each event. The `AntiKt4TruthDressedWZJets`
⁴¹⁸ truth jet collection is used to make this determination. In order to account for migration of
⁴¹⁹ WZ+1-jet and WZ+2-jet events between the 1-jet and 2-jet bins at reco level, the signal samples
⁴²⁰ are separated based on the number of truth jets. Events with 0 jets or more than 3 jets at truth
⁴²¹ level, yet fall within one of the categories listed in Table 8, are categorized as WZ + other, and
⁴²² treated as a background. The migration matrix in the number of jets at truth level versus reco
⁴²³ level is shown in Figure 8. The composition of the number of truth jets in each reco jet bin is
⁴²⁴ taken from MC, with uncertainties in these estimates described in detail in Section 7.

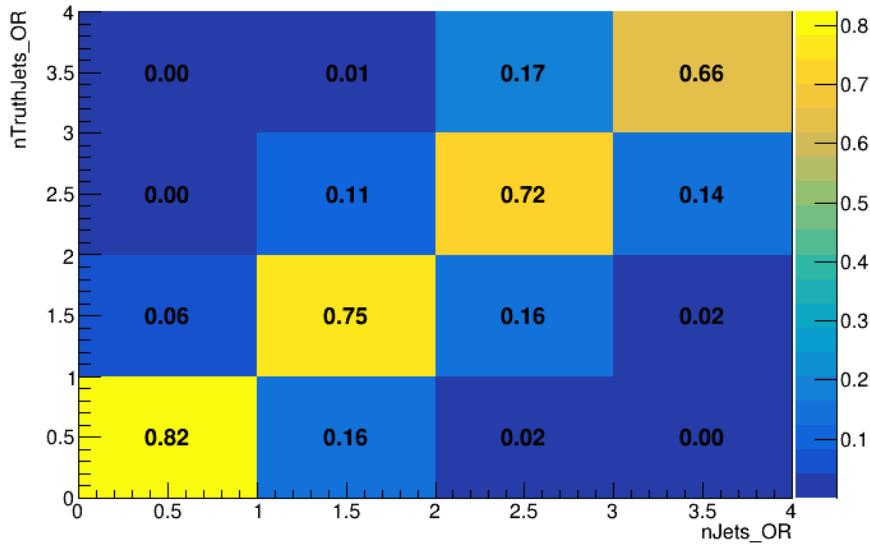


Figure 8: Number of truth jets compared to the number of reconstructed jets in each WZ event falling in the preselection region. Each row is normalized to unity.

- 425 An additional tZ control region is created based on the BDT described in Section 5. The region
 426 with 1-jet passing the 60% working point is split in two - a signal enriched region of events with
 427 a BDT score greater than 0.12, and a tZ control region including events with a score less than
 428 0.12. This cutoff is arrived at by performing a fit an Asimov dataset with a variety of cutoffs,
 429 and selecting the value that produces the highest significance for the measurement of WZ + b.
 430 The modeling in each region is validated by comparing data and MC predictions for various
 431 kinematic distributions. Events containing 5% or more WZ + b are blinded. These plot are
 432 shown in Figures 9-22.

WZ Fit Region - 1j Inclusive

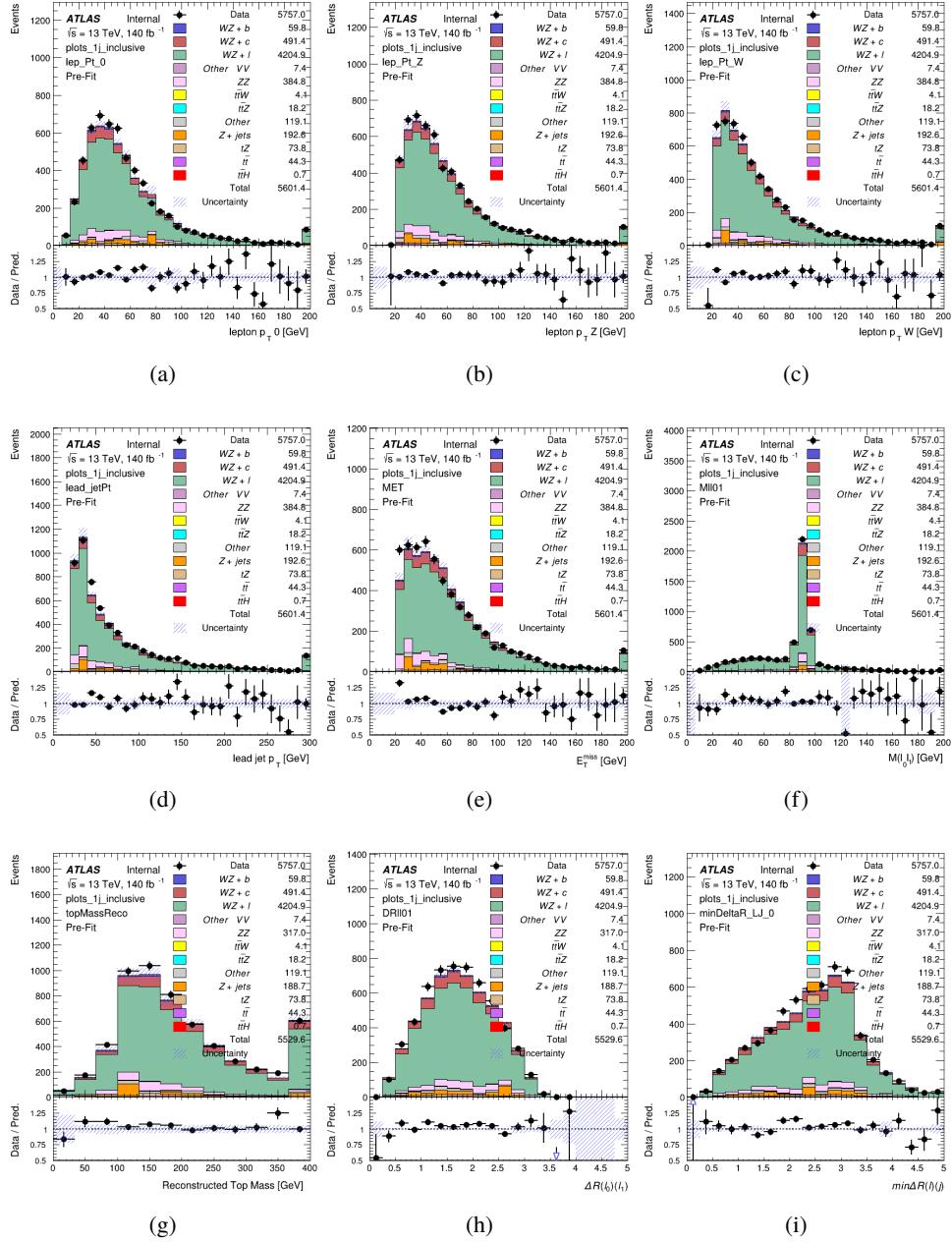


Figure 9: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant 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 < 85% WP

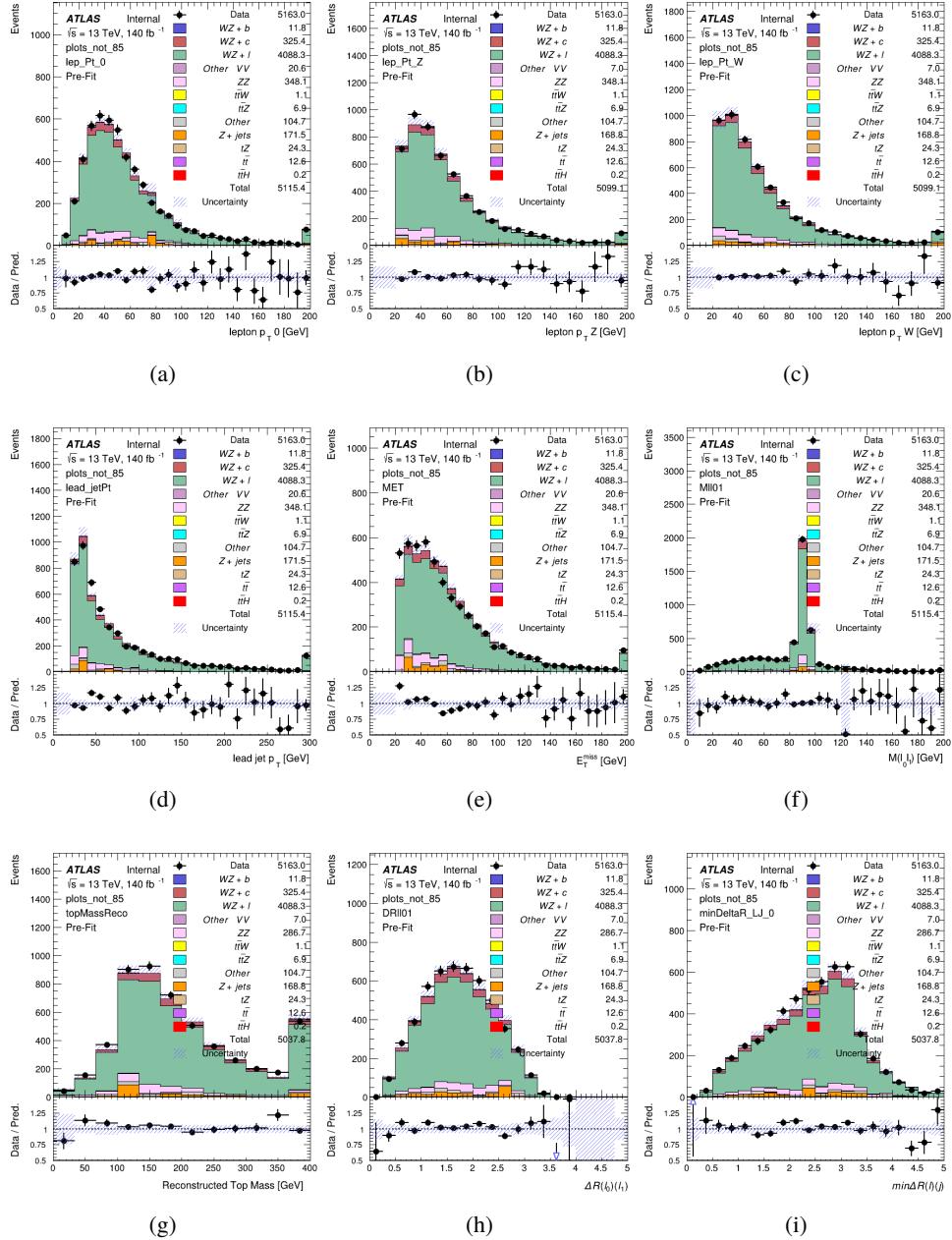


Figure 10: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant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

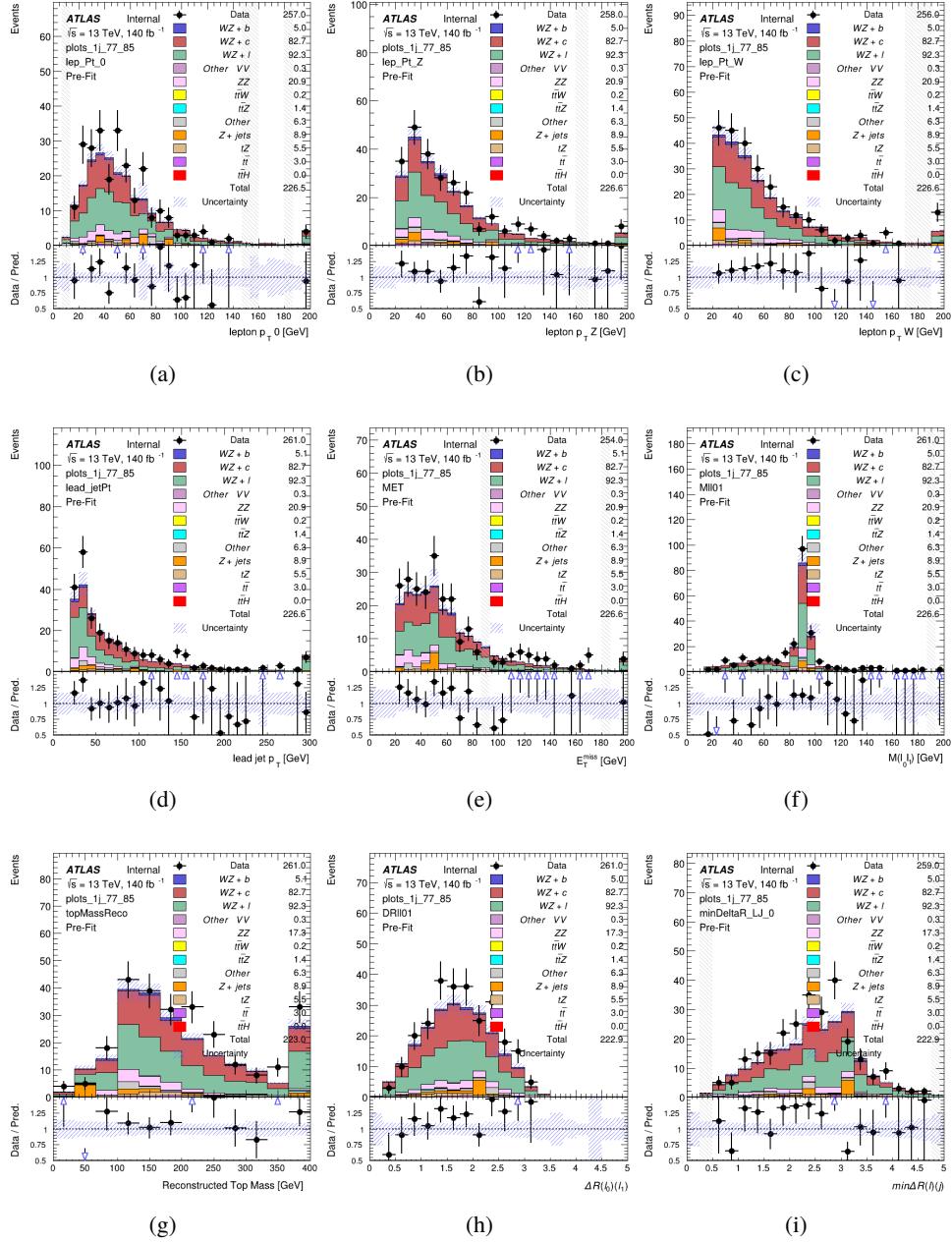


Figure 11: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant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

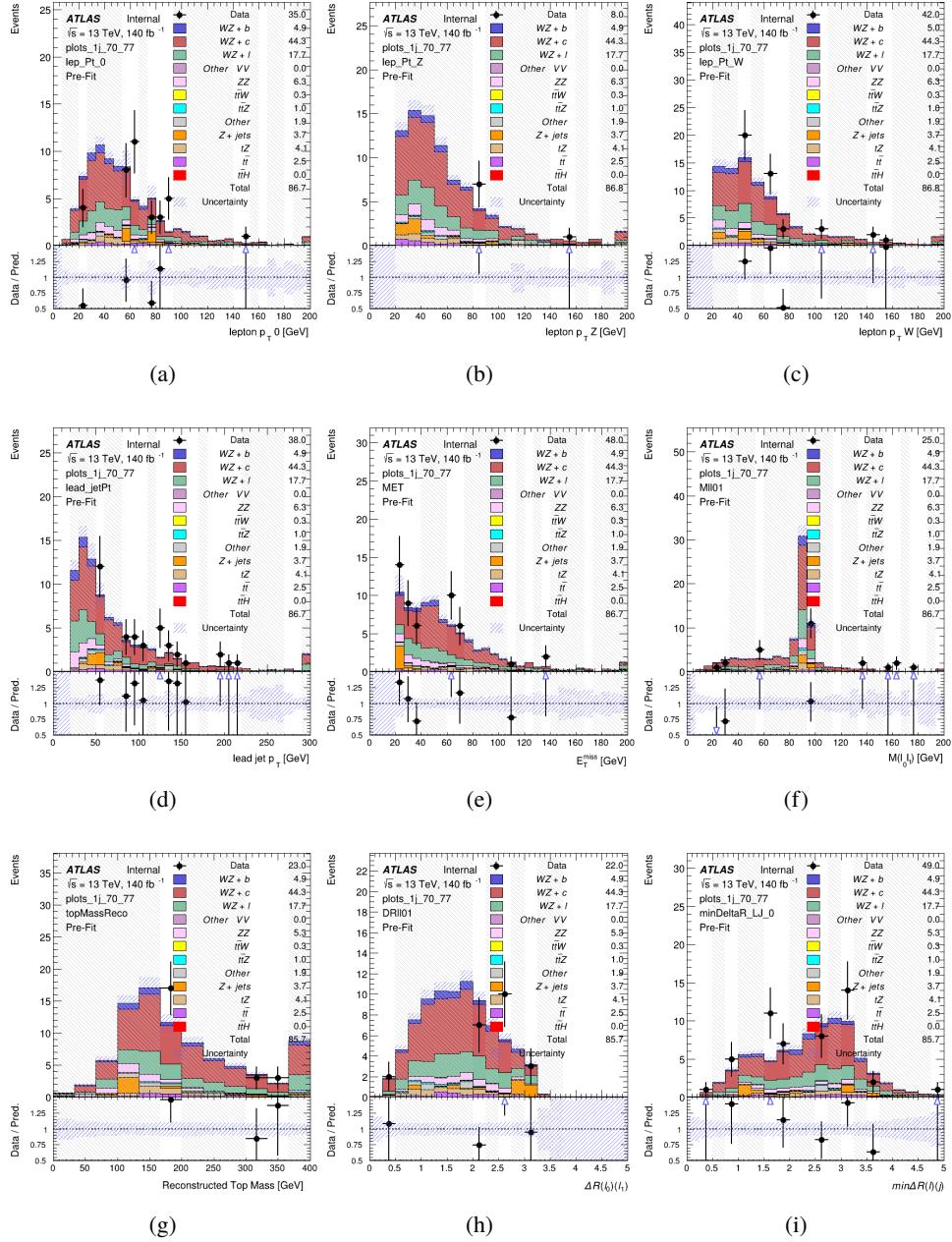


Figure 12: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant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

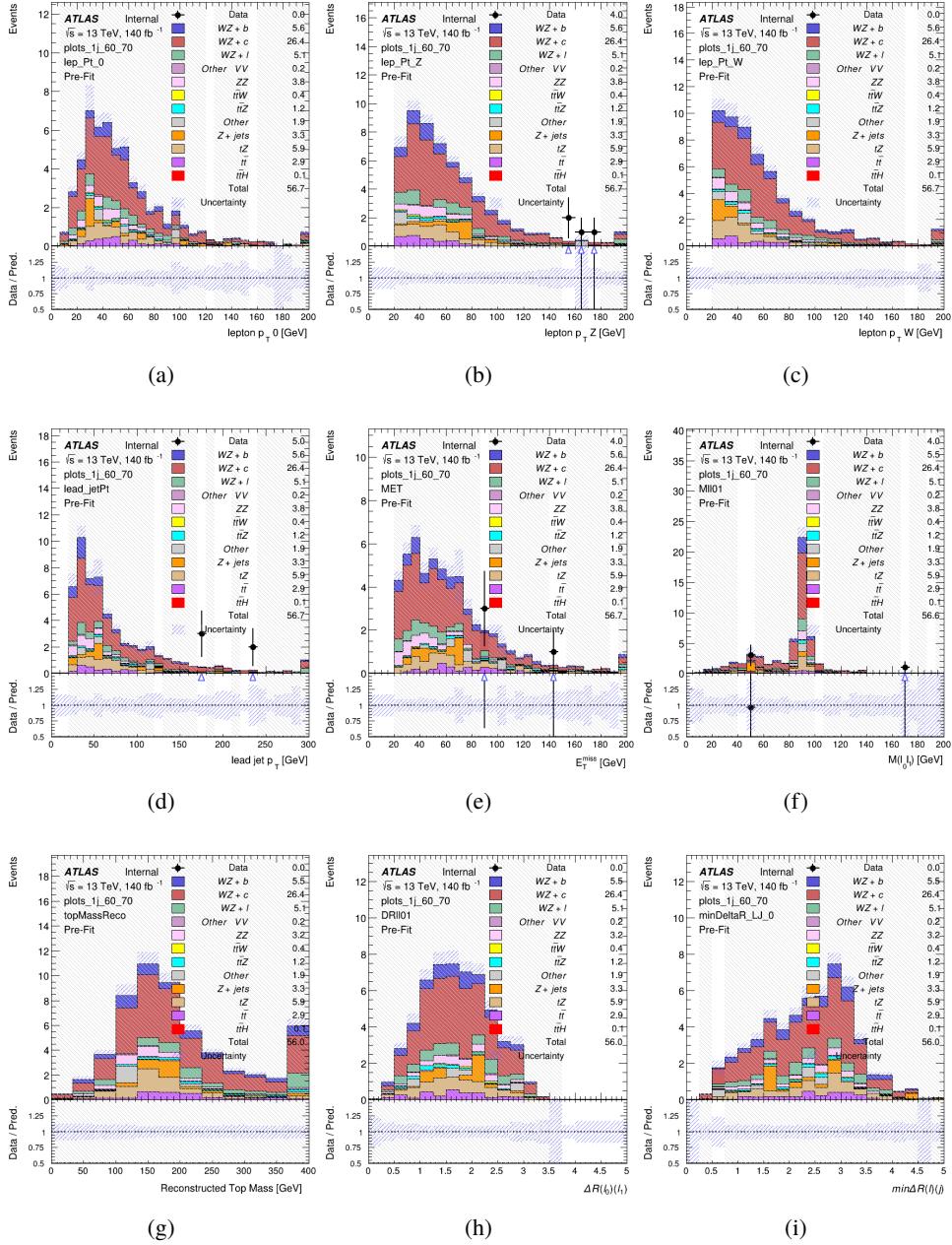


Figure 13: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant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

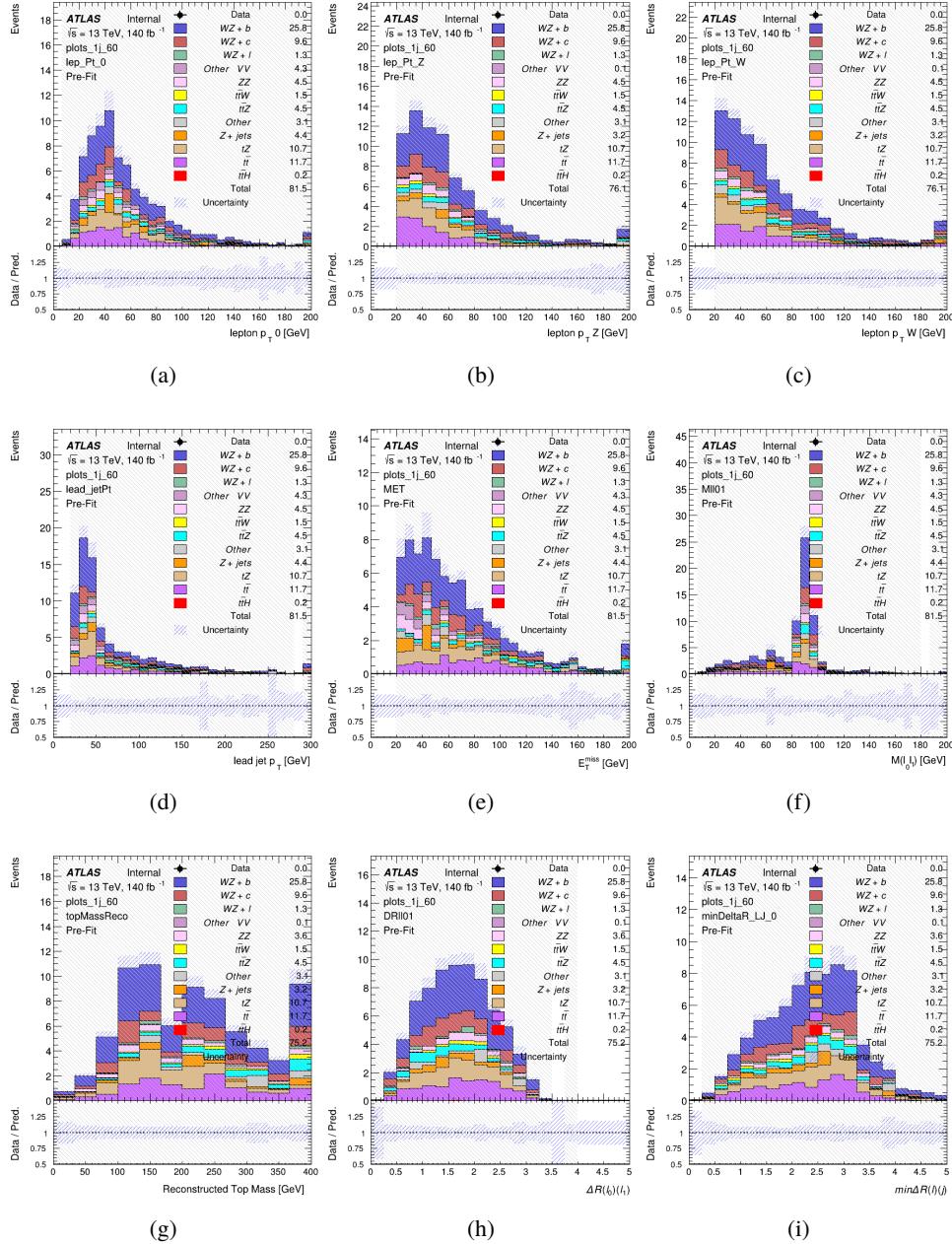


Figure 14: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant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

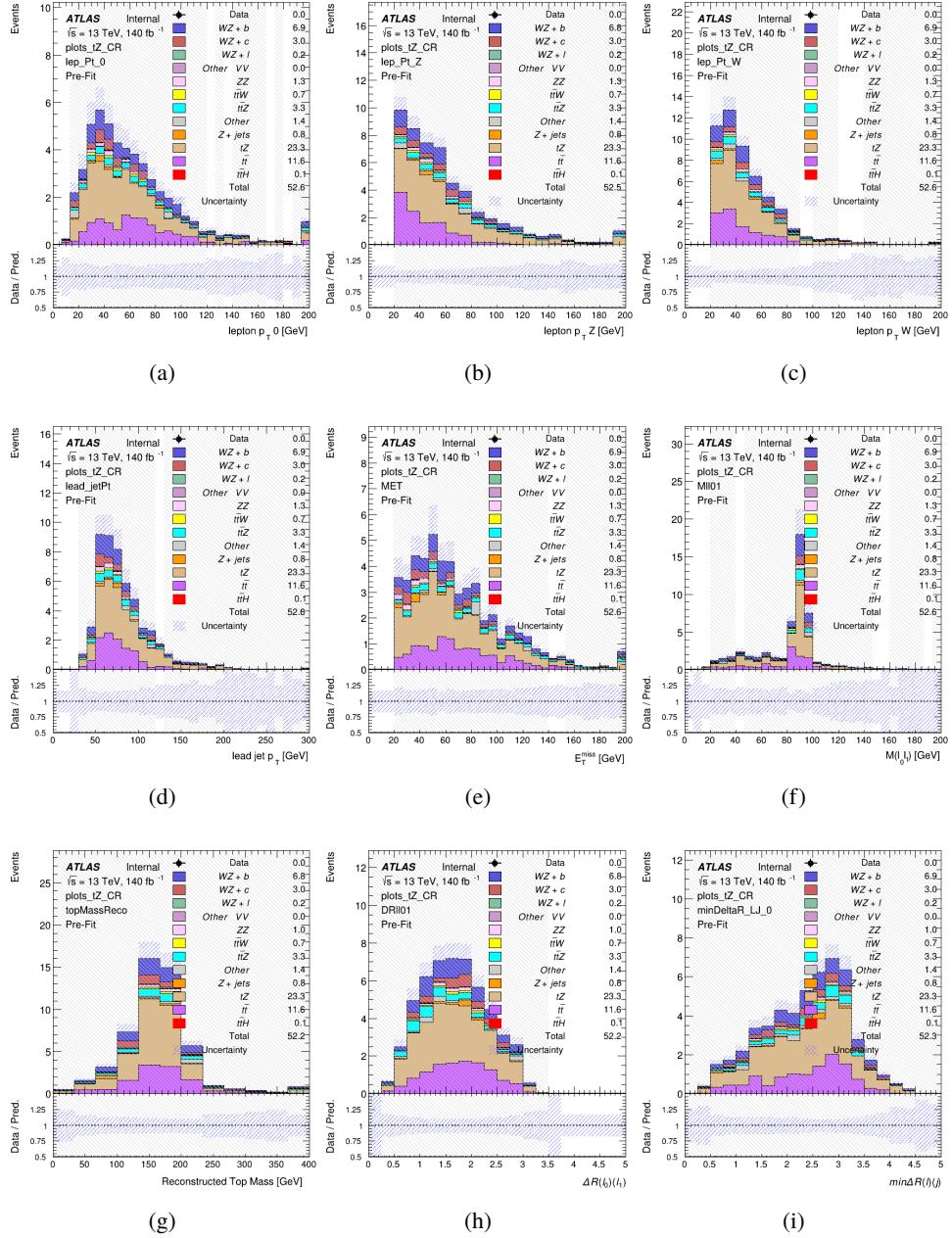


Figure 15: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant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

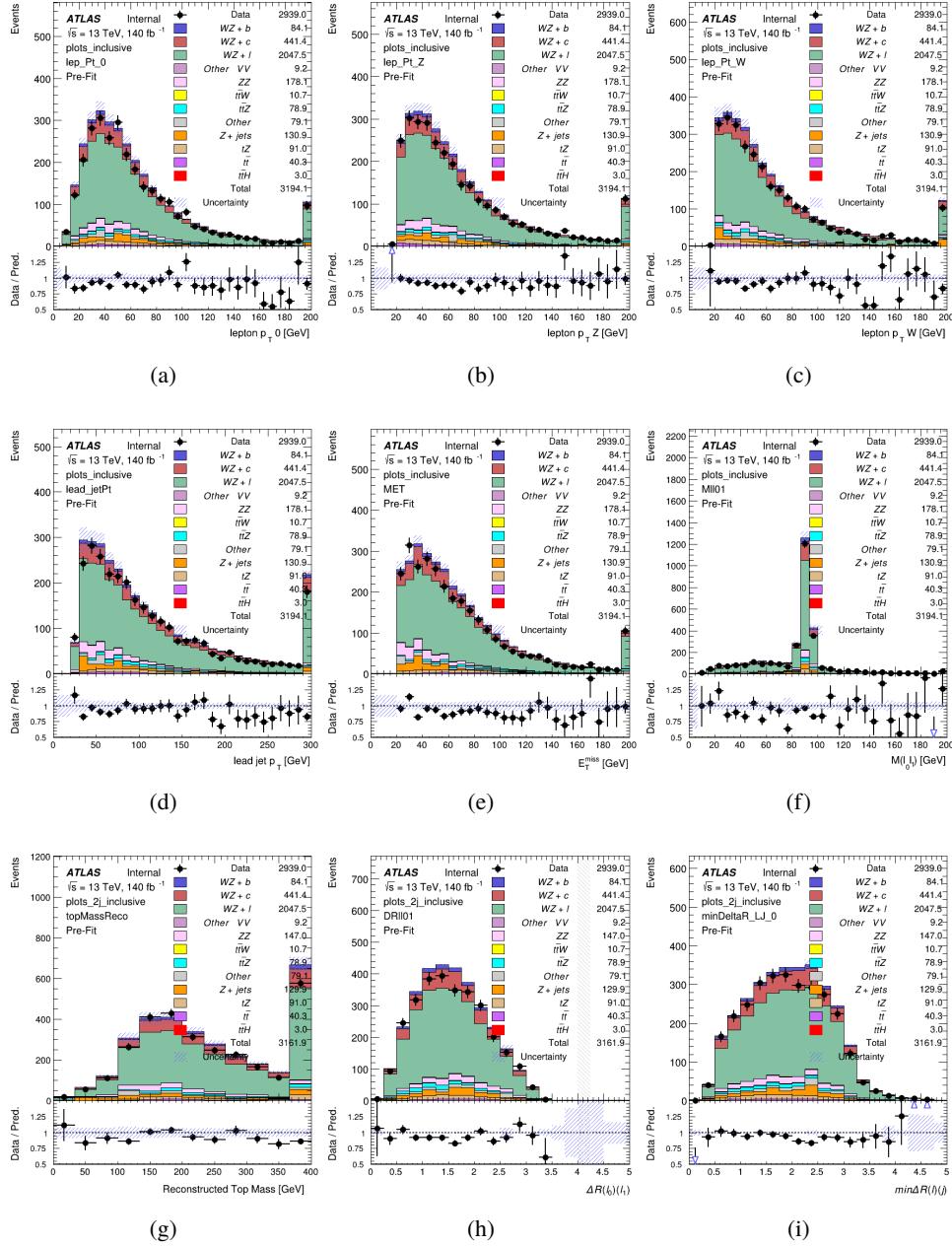


Figure 16: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant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

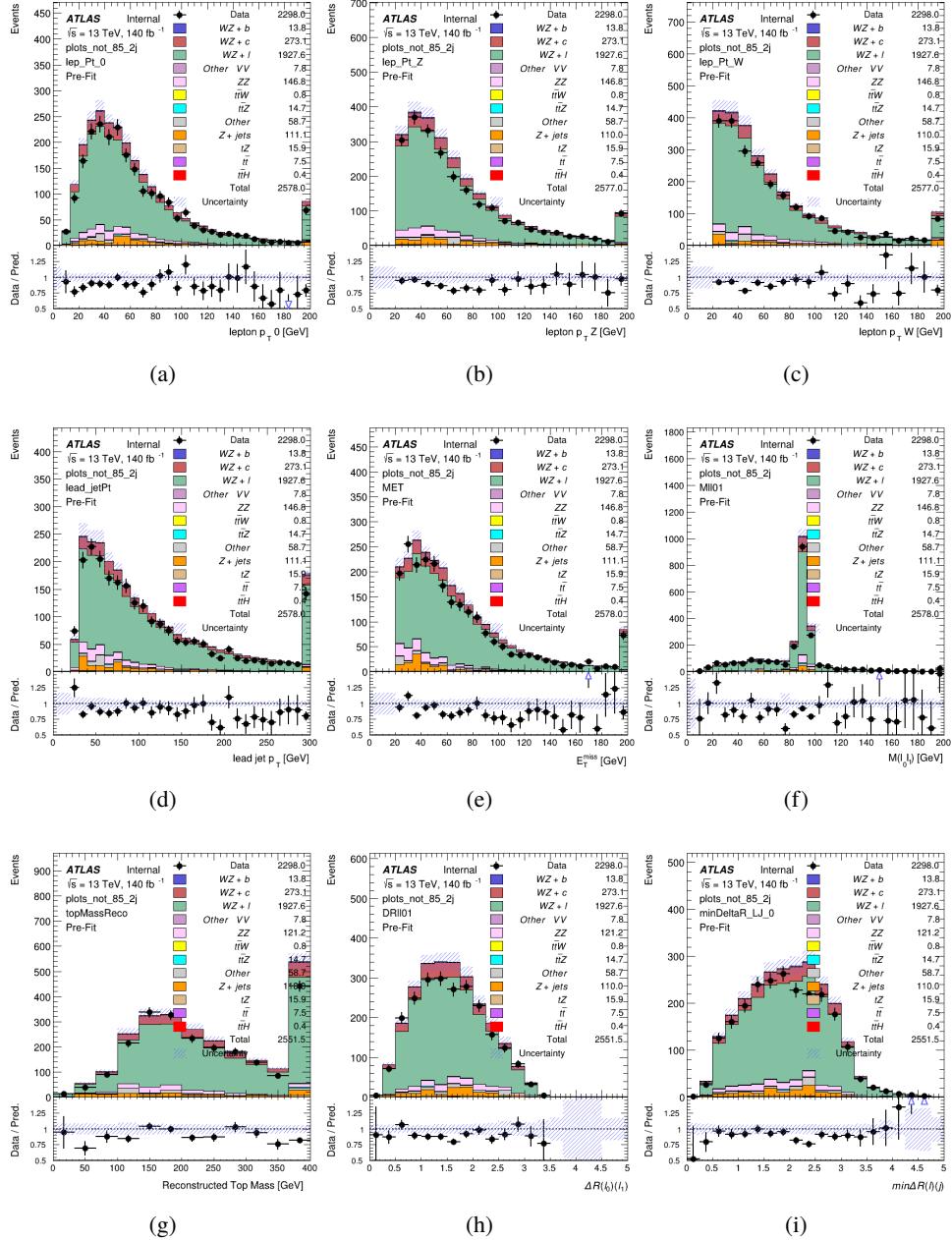
WZ Fit Region - $2j < 85\%$ WP

Figure 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^{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

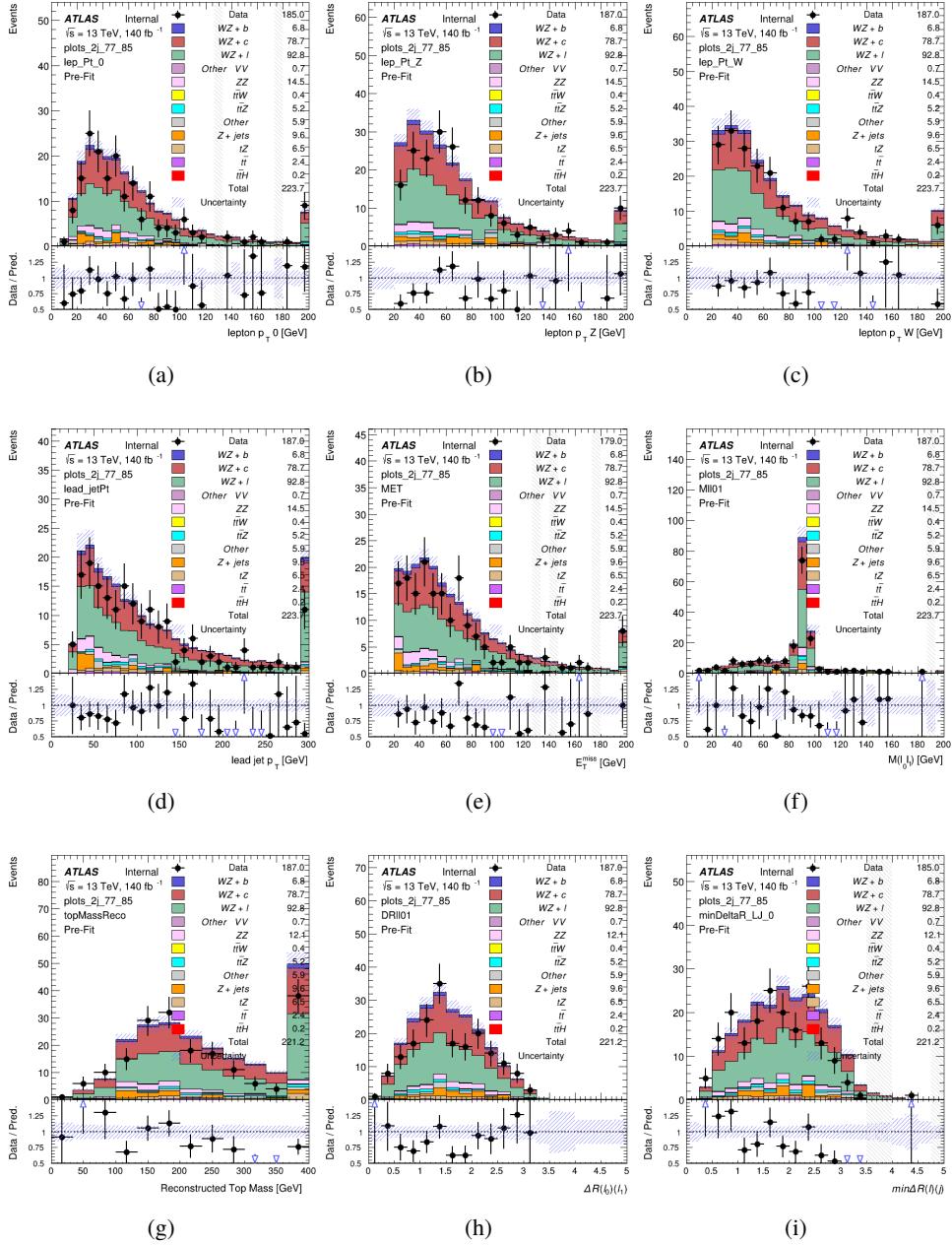


Figure 18: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant 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

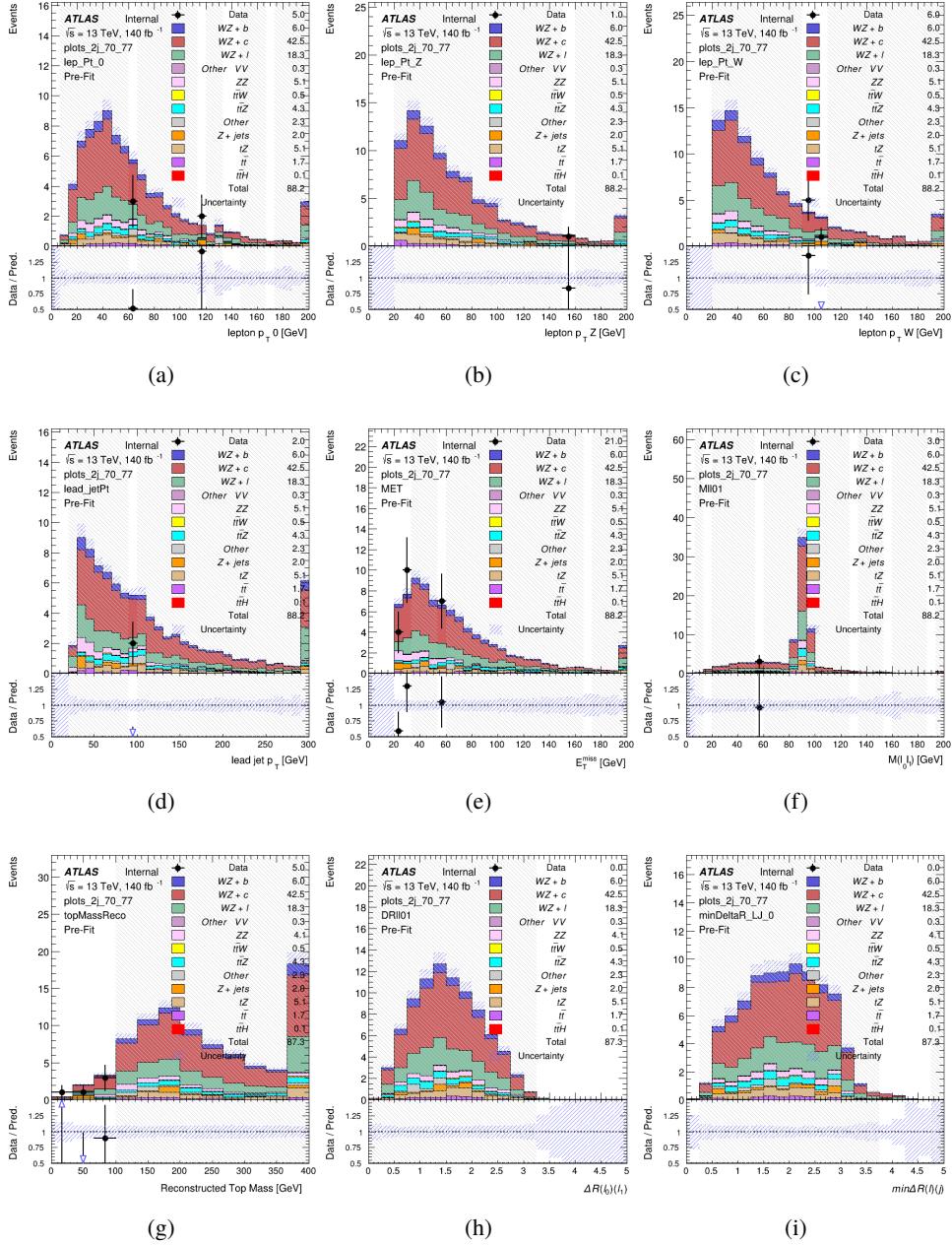


Figure 19: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant 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

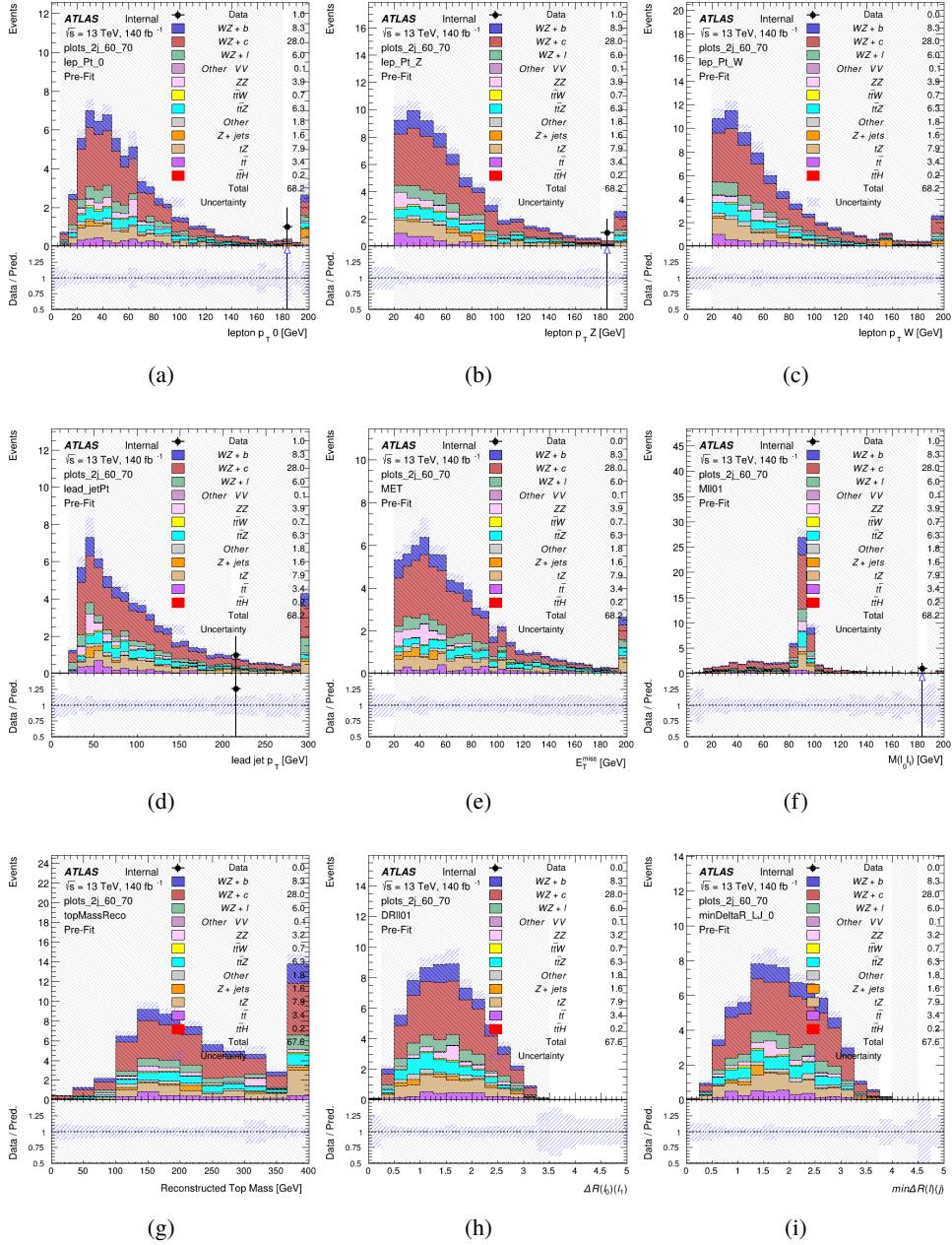


Figure 20: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant 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

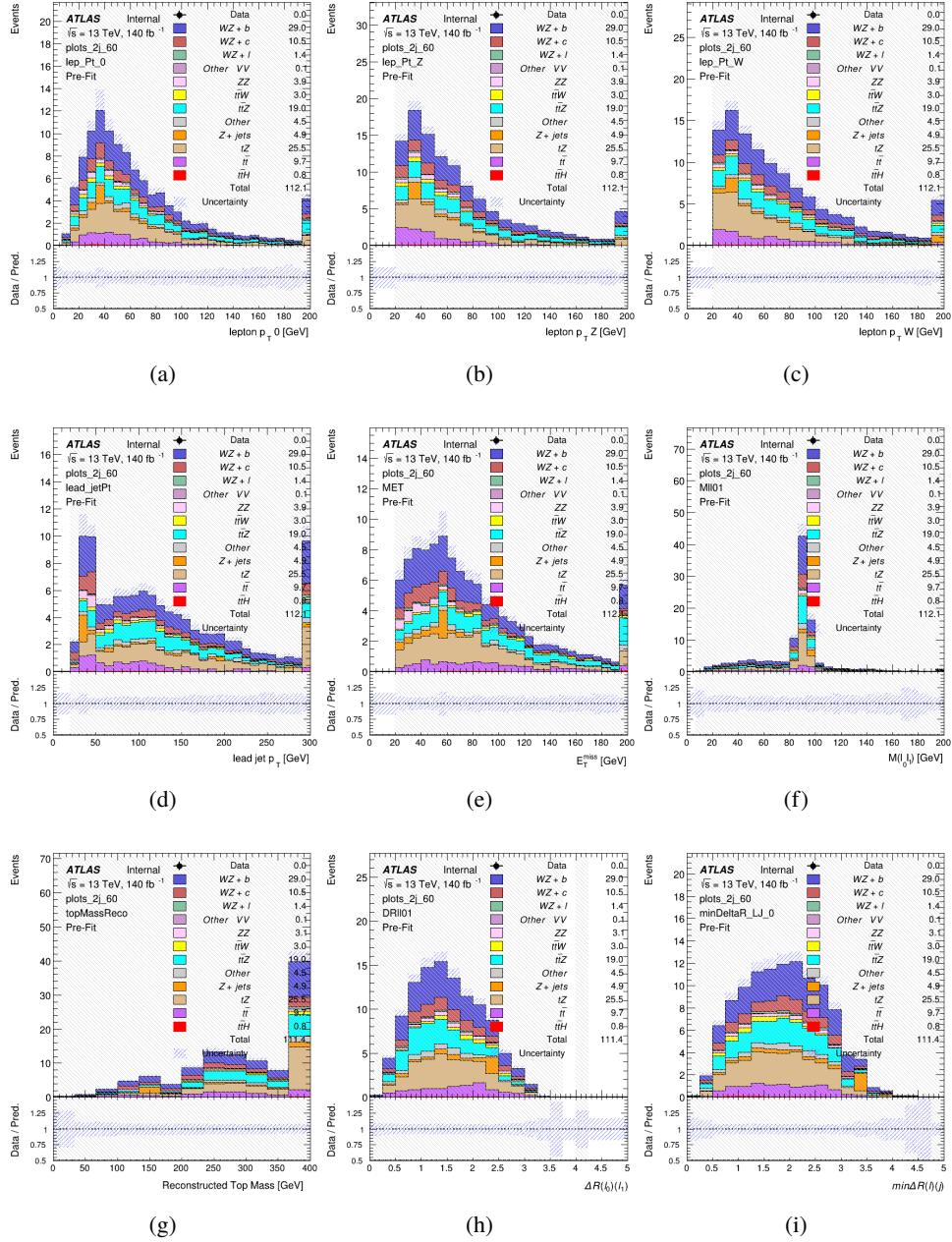


Figure 21: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant 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

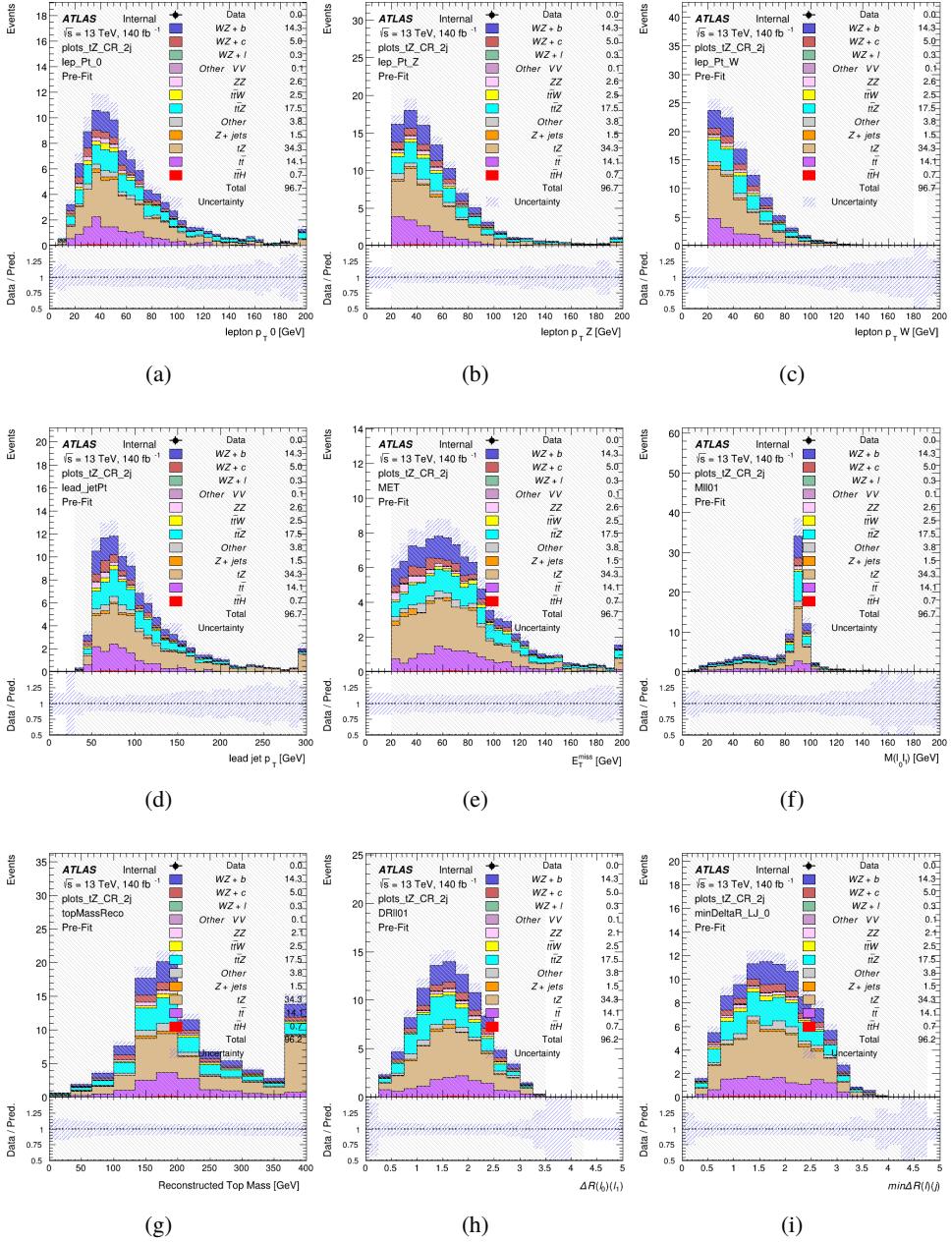


Figure 22: Comparisons between the data and MC distributions in the preselection region for (a) the p_T of the opposite sign lepton, (b) the p_T of the other lepton from the Z candidate, (c) the p_T of the lepton from the W candidate, (d) the leading jet p_T , (e) the E_T^{miss} , and (f) the invariant 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.

433 **6.3 Non-Prompt Lepton Estimation**

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

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

441 **6.3.1 $t\bar{t}$ Validation**

442 $t\bar{t}$ events can produce two prompt leptons from the decay of each of the tops. These top decays
 443 produce two b-quarks, the decay of which can produce additional non-prompt leptons, which
 444 occasionally pass the event preselection. In order to validate that the Monte Carlo accurately
 445 simulates this process accurately, the MC prediction in a non-prompt $t\bar{t}$ enriched validation
 446 region is compared to data.

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

452 Further, because the jet multiplicity of $t\bar{t}$ events tends to be higher than WZ + jets, the number
 453 of jets in each event is required to be greater than 1. As b-jets are almost invariably produced
 454 from top decays, at least one b-tagged jet passing the 70% DL1r WP in each event is required.
 455 Various kinematic plots of this region are shown in Figure 23.

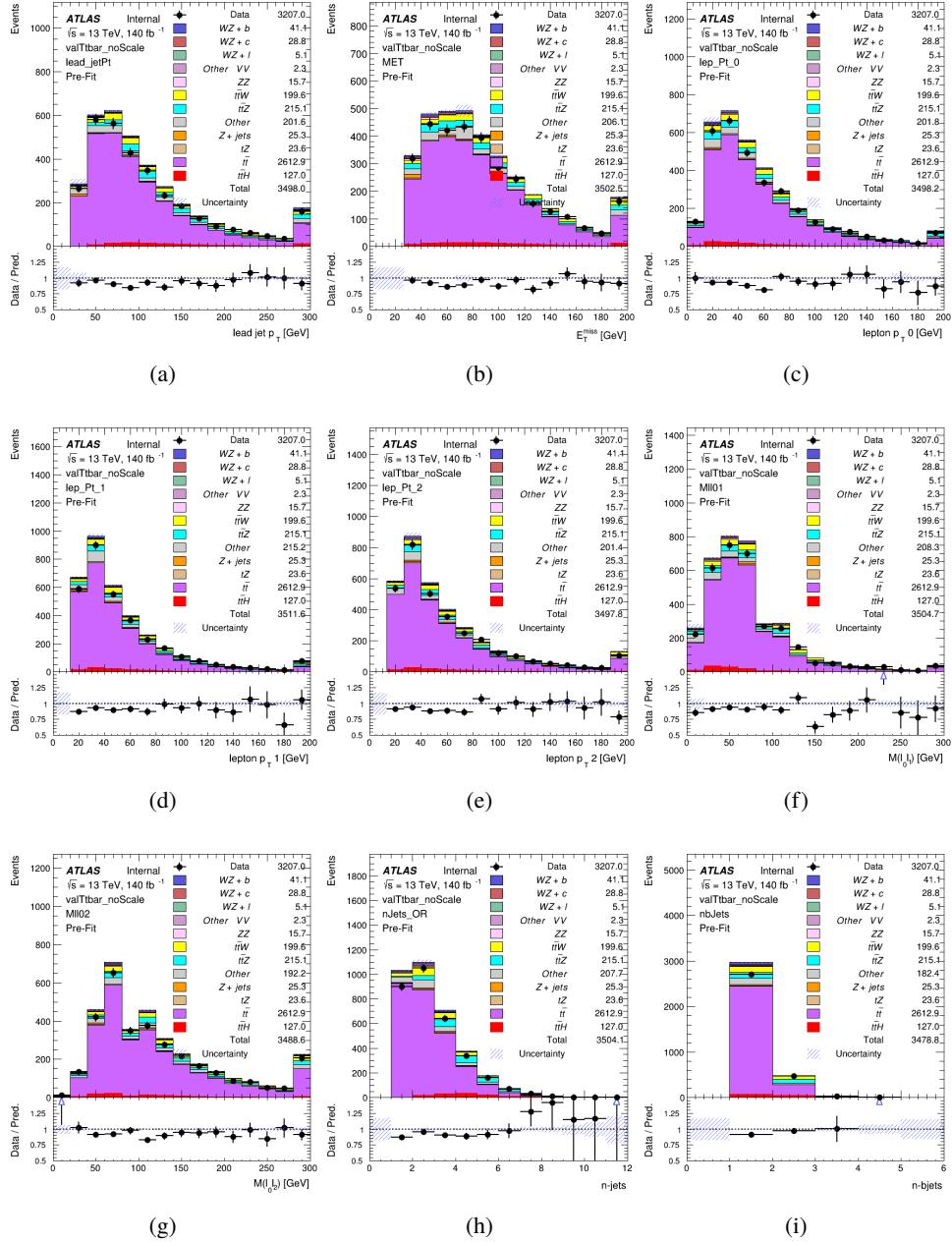


Figure 23: Comparisons between the data and MC distributions in the $t\bar{t}$ validation region for (a) the p_T of the leading jet, (b) the missing transverse energy, (c) the p_T of lepton 0, (d) p_T of lepton 1, (e) p_T of lepton 2, (f) the invariant mass of leptons 0 and 1, (g) the invariant mass of leptons 0 and 2, (h) the number of jets, (i) the number of b-tagged jets.

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

458 MC prediction. Plots showing the kinematics of the $t\bar{t}$ VR after this correction factor has been
459 applied are shown in Figure 24.

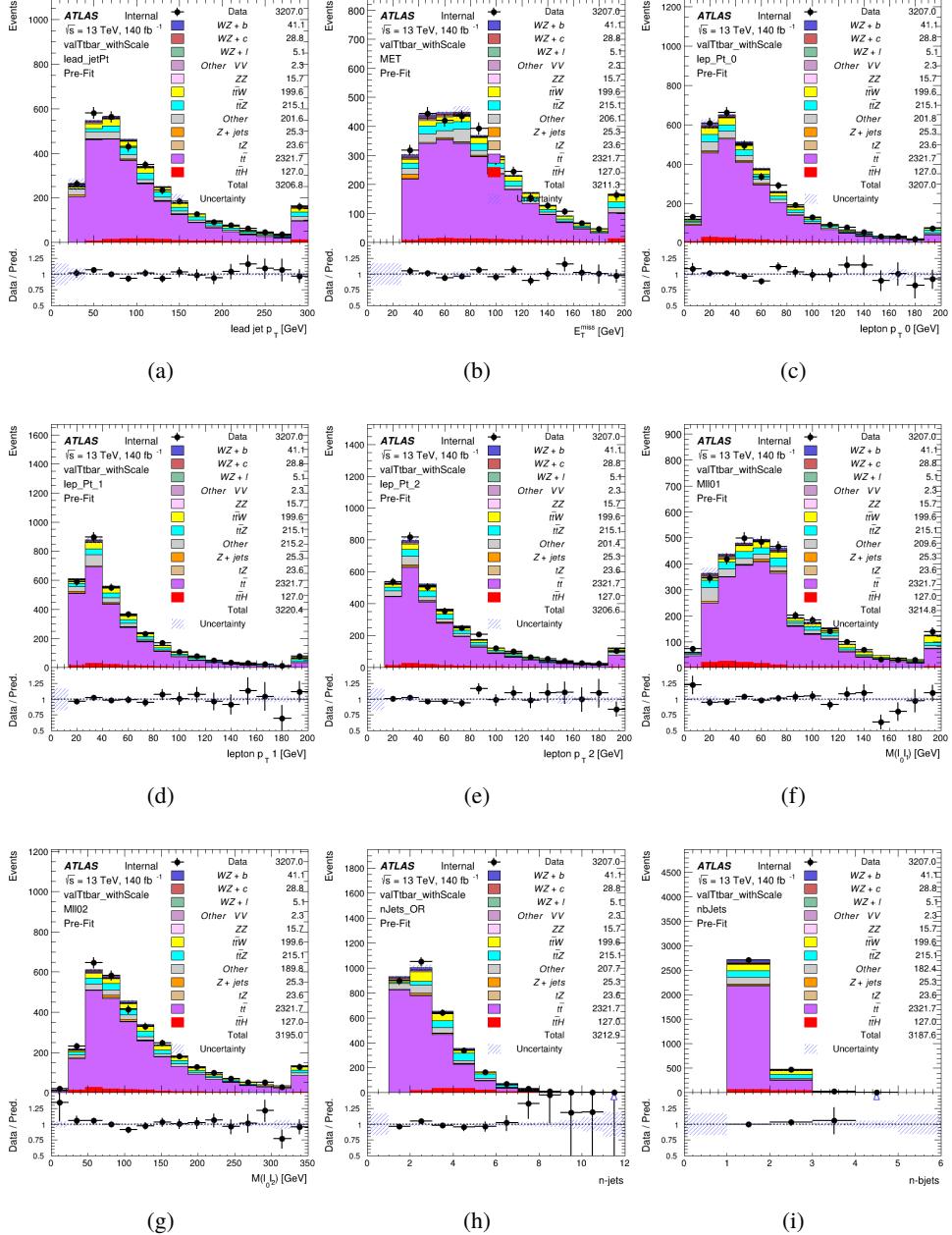


Figure 24: Comparisons between the data and MC distributions in the $t\bar{t}$ validation region after the correction factor has been applied for (a) the p_T of the leading jet, (b) the missing transverse energy, (c) the p_T of lepton 0, (d) p_T of lepton 1, (e) p_T of lepton 2, (f) the invariant mass of leptons 0 and 1, (g) the invariant mass of leptons 0 and 2, (h) the number of jets, (i) the number of b-tagged jets.

460 The modeling is further validated by looking at the yield in the $t\bar{t}$ VR for each DL1r WP, giving
 461 a clearer correspondence to the signal regions used in the fit. For these plots, the requirement
 462 that each event contain at least one b-tagged jet is removed. Each region shown in Figure 25
 463 requires one or more jets pass the listed WP, with no jets passing the next highest WP.

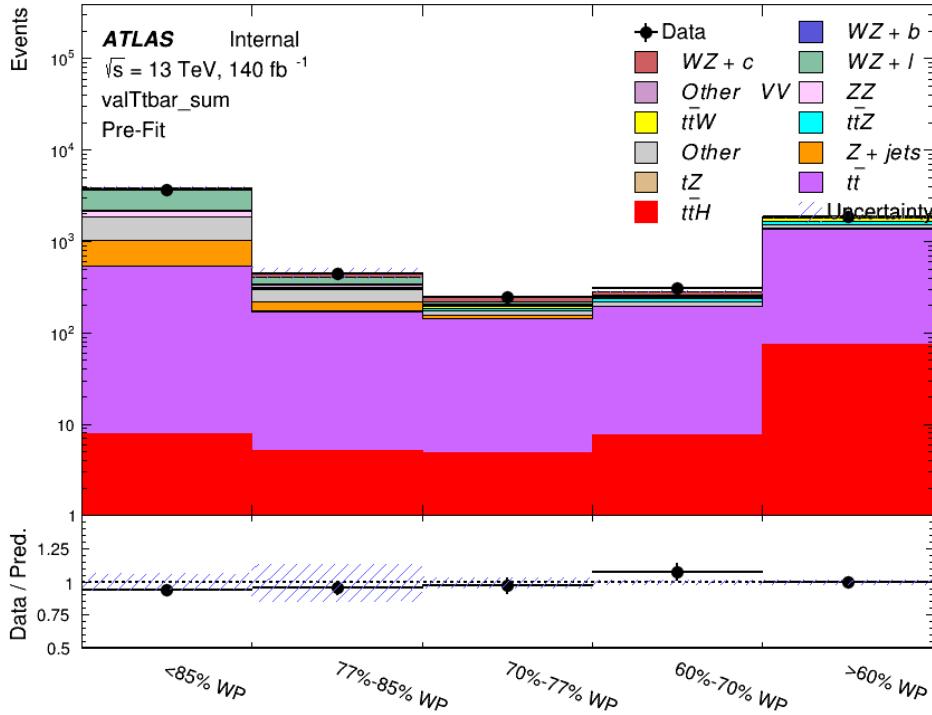


Figure 25: Data and MC comparisons for each DL1r WP for both 1-jet and 2-jet regions, after the $t\bar{t}$ VR selection and correction factor have been applied

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

466 6.3.2 Z+jets Validation

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

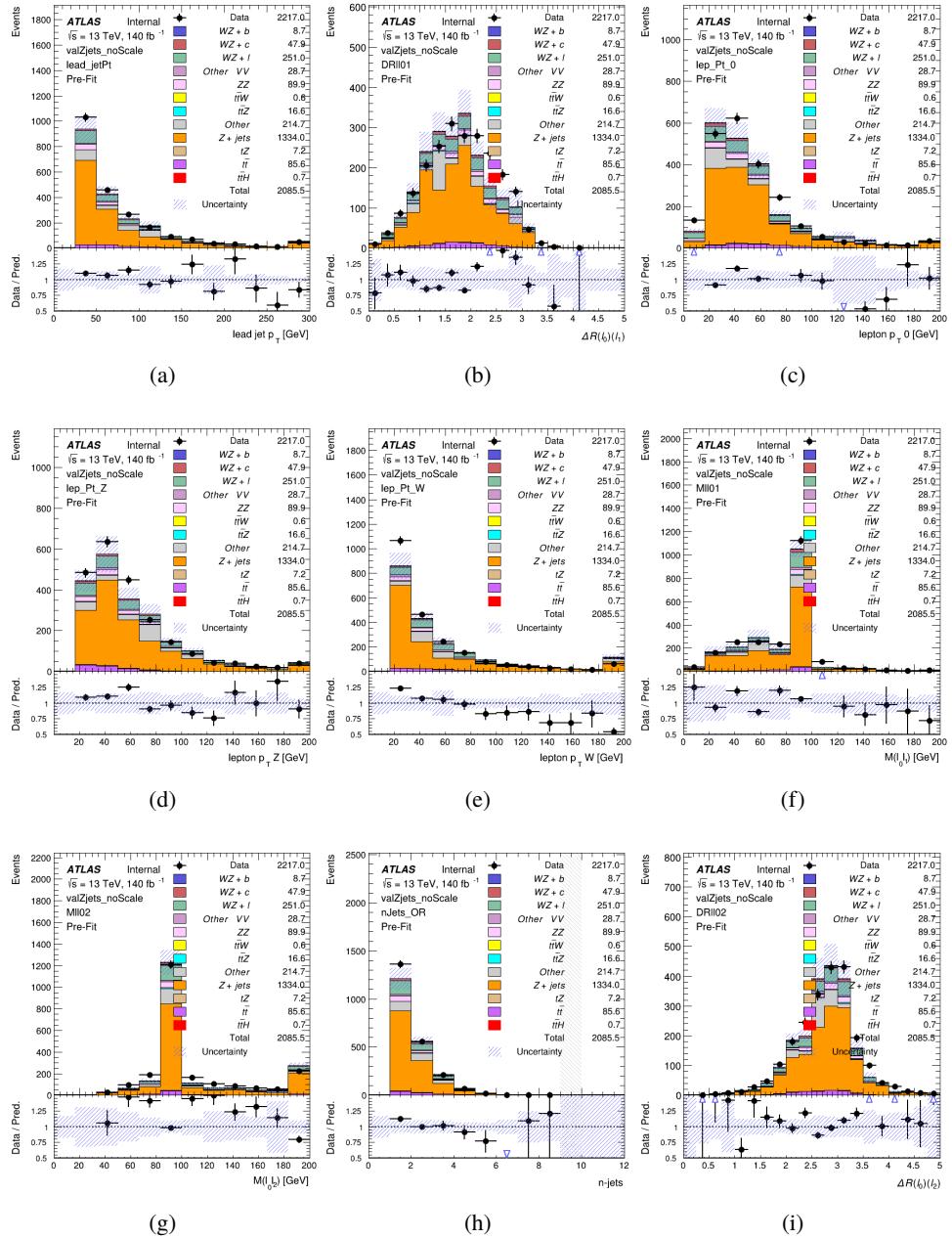


Figure 26: Comparisons between the data and MC distributions in the Z+jets validation region for (a) the p_T of the leading jet, (b) ΔR between leptons 0 and 1, (c) the p_T of lepton 0, (d) p_T of SS lepton from the Z candidate, (e) p_T of the SS lepton from the W candidate, (f) the invariant mass of leptons 0 and 1, (g) the invariant mass of leptons 0 and 2, (h) the number of jets, (i) ΔR between leptons 0 and 2. Includes only statistical uncertainties

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

of the p_T spectrum of the lepton from the W candidate is found to differ. As this is the lepton not included in the Z-candidate, in the case of Z+jets, this lepton is most often the non-prompt lepton. A similar effect is seen for both non-prompt muons and electrons in the Z+jets validation region, as shown in Figure 27.

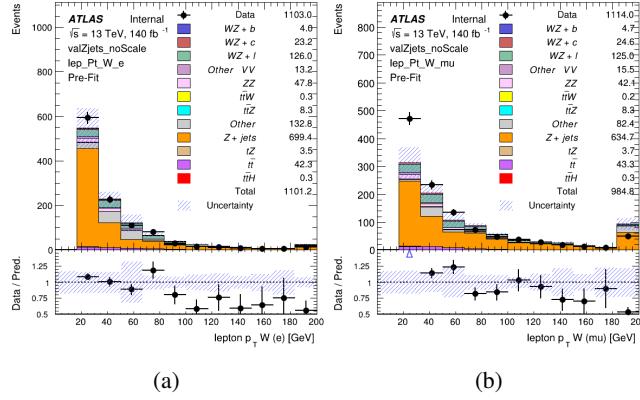


Figure 27: p_T spectrum of the lepton from the W candidate for (a) electrons and (b) muons

To account for this discrepancy, a variable correction factor is applied to Z+jets. χ^2 minimization of the W lepton p_T spectrum is performed to derive a correction factor as a function of this p_T . Kinematic plots of the Z + jets validation region after this correction factor has been applied are shown in Figure 28.

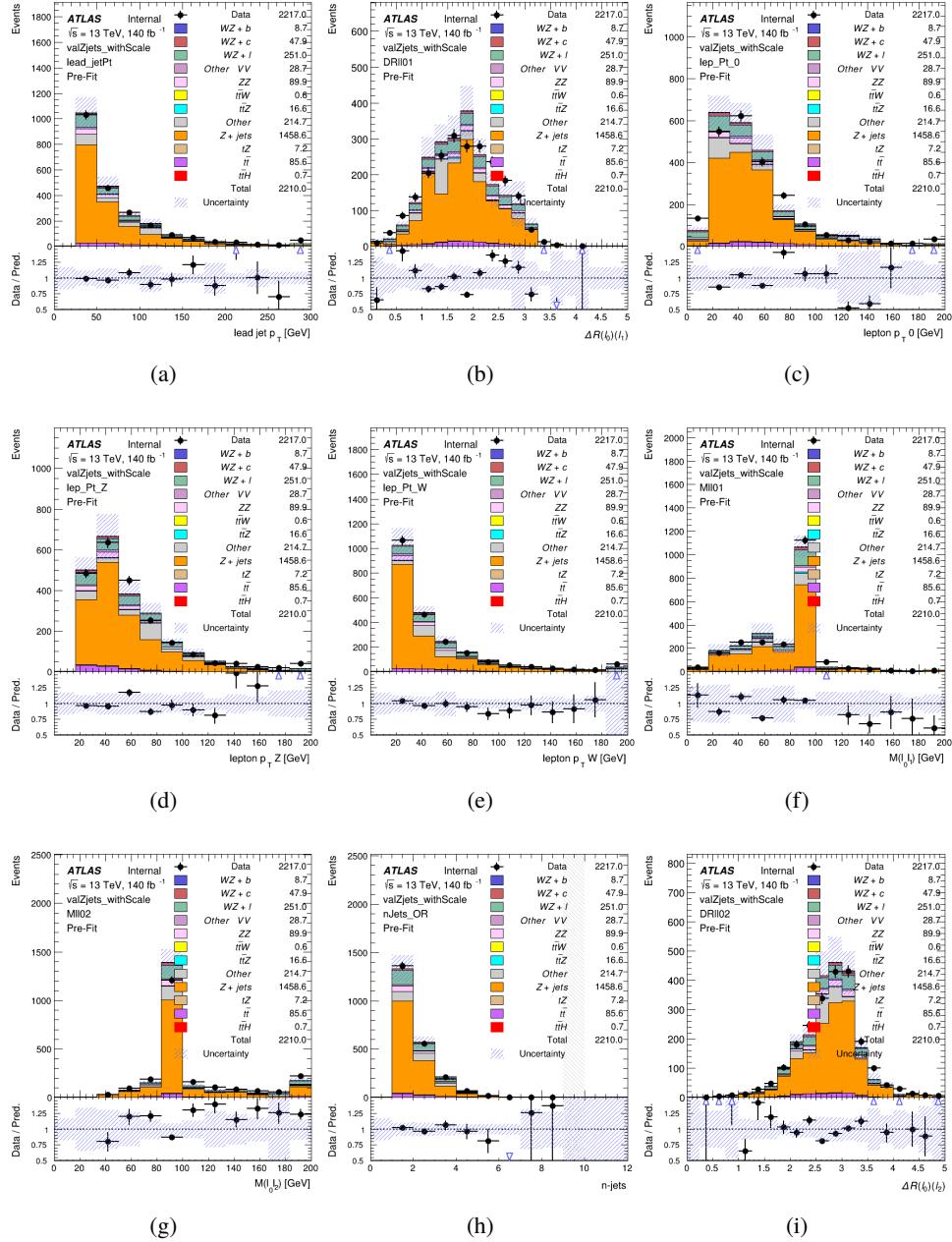


Figure 28: Comparisons between the data and MC distributions in the Z+jets validation region after the correction factor has been applied for (a) the p_T of the leading jet, (b) ΔR between leptons 0 and 1, (c) the p_T of lepton 0, (d) p_T of SS lepton from the Z candidate, (e) p_T of the SS lepton from 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) ΔR between leptons 0 and 2

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

484 giving a clearer correspondence to the signal regions used in the fit. Each region shown in Figure
 485 29 requires one or more jets pass the listed WP, with no jets passing the next highest WP.

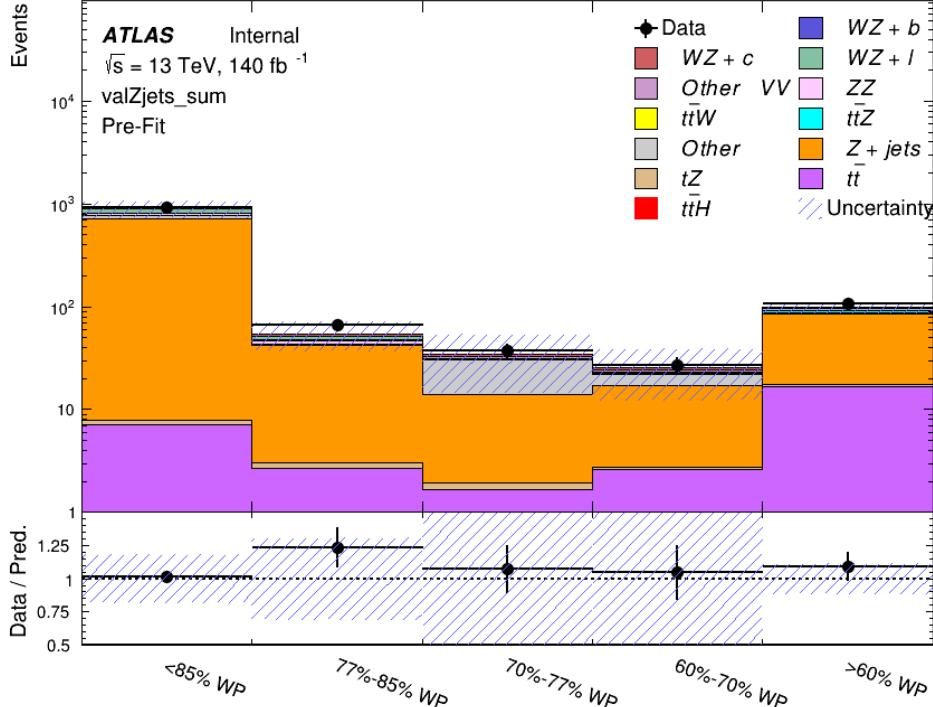


Figure 29: Data and MC comparisons for each DL1r WP for both 1-jet and 2-jet regions, after the Z+jets VR selection and correction factor have been applied

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

489 7 Systematic Uncertainties

490 The systematic uncertainties that are considered are summarized in Table 9. These are imple-
 491 mented in the fit either as a normalization factors or as a shape variation or both in the signal
 492 and background estimations. The numerical impact of each of these uncertainties is outlined in
 493 Section 8.

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

Systematic uncertainty	Components
Luminosity	1
Pileup reweighting	1
Physics Objects	
Electron	6
Muon	15
Jet energy scale	28
Jet energy resolution	8
Jet vertex fraction	1
Jet flavor tagging	131
E_T^{miss}	3
Total (Experimental)	194
Signal Modeling	
Shape modelling	3
Renormalization and factorization scales	5
nJet Migration	5
Background Modeling	
Cross section	15
Renormalization and factorization scales	12
Parton shower and hadronization model	2
Shower tune	4
Total (Signal and background modeling)	41
Total (Overall)	236

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

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

501 The sources which contribute to the uncertainty in the jet energy scale (JES) [28] are decom-
 502 posed into uncorrelated components and treated as independent sources in the analysis. The
 503 CategoryReduction model is used to account for JES uncertainties, which decomposes the uncer-
 504 tainties into 30 nuisance parameters included in the fit. The SimpleJER model is used to account
 505 for jet energy resolution (JER) uncertainties, and 8 JER uncertainty components included as NPs
 506 in the fit.

507 The uncertainties in the b-tagging efficiencies measured in dedicated calibration analyses
 508 [19] are also decomposed into uncorrelated components. The large number of components for
 509 b-tagging is due to the calibration of the distribution of the MVA discriminant.

510 The full list of systematic uncertainties considered in the analysis is summarized in Tables 10,
 511 11 and 12.

512

Experimental Systematics on Leptons and E_T^{miss}			
Type	Description	Systematics Name	Application
Trigger			
Scale Factors	Trigger Efficiency	lepSFTrigTight_MU(EL)_SF_Trigger_STAT(SYST)	Event Weight
Muons			
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
Electrons			
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
E_T^{miss}			
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^{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
	η 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, η 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 η	DL1r_Continuous_EventWeight_B0-29
	DL1r b-tagger efficiency on c originated jets in bins of η	DL1r_Continuous_EventWeight_C0-19
	DL1r b-tagger efficiency on light flavoured originated jets in bins of η 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.

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

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

525 The theory uncertainties applied to the predominate background estimates are summarized in
 526 Table 13.

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

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

527 Due to its importance as a background, additional modelling uncertainties are considered for tZ.
 528 Alternative tZ samples with variations in scale (DSID 412064-5) and shower modelling (DSID
 529 501046) are included as systematics..

530 The fit involves varying the overall normalization of signal templates over the regions de-
 531 scribed in Section 6.2, which are defined by the flavor and number of associated jets at truth-
 532 level. The modelling of these template shapes therefore significantly impacts the final result.
 533 Additional signal uncertainties, probing the shape of the signal templates as well as the rate of
 534 migrations between the number of truth-jets and reconstructed jets, are estimated by comparing
 535 estimates from the nominal Sherpa WZ samples with alternative WZ samples generated with
 536 POWHEG+PYTHIA8 (DSID 361601). Separate systematics are included in the fit for WZ + b, WZ
 537 + c and WZ + light, where the distribution among each of the fit regions is varied based on the
 538 prediction of the Powheg sample.

539 The variations in the signal templates are shown in Figures 30 and 31. Each of these plots are
 540 normalized to unity in order to capture the relevant differences in shape.

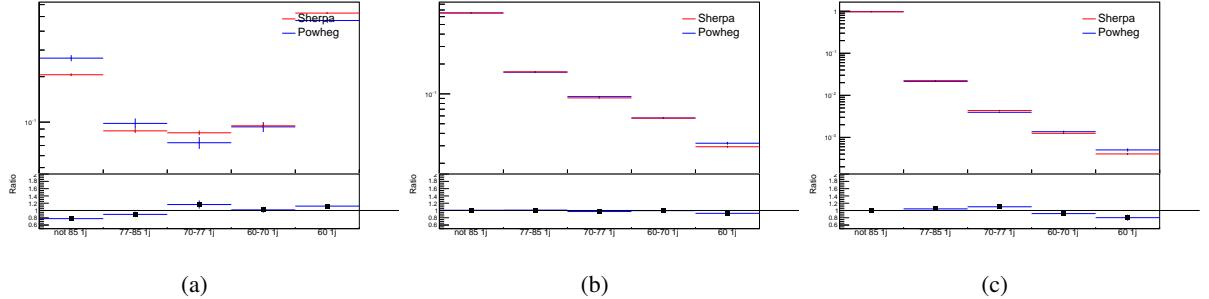


Figure 30: Comparison between Sherpa and Powheg predictions of the distribution of (a) WZ + b, (b) WZ + charm, and (c) WZ + light among the various b-tag WPs used in the 1-jet fit.

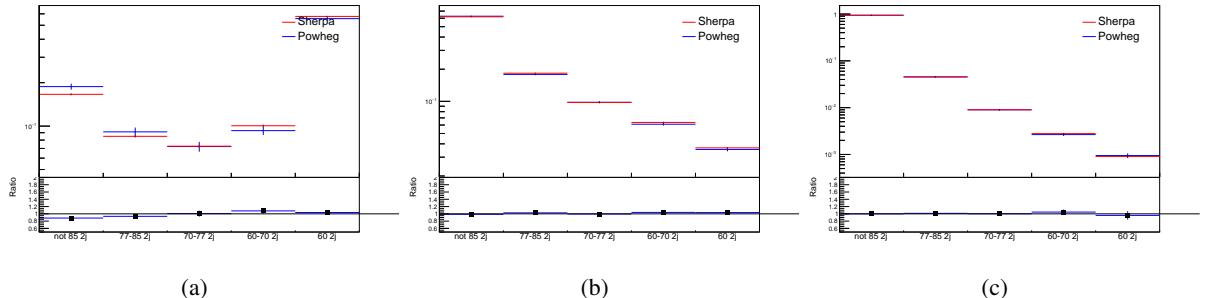


Figure 31: Comparison between Sherpa and Powheg predictions of the distribution of (a) WZ + b, (b) WZ + charm, and (c) WZ + light among the various b-tag WPs used in the 2-jet fit.

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

544 A similar approach is taken to account for uncertainties in migrations between the number of
 545 reco and truth jets. The fraction of events with 1 truth jet which fall into the 1 jet bin versus the
 546 2 jet bin at reco level is compared for Sherpa and Powheg. The same is done for events with 2
 547 truth jets. This comparison is shown in figure 32.

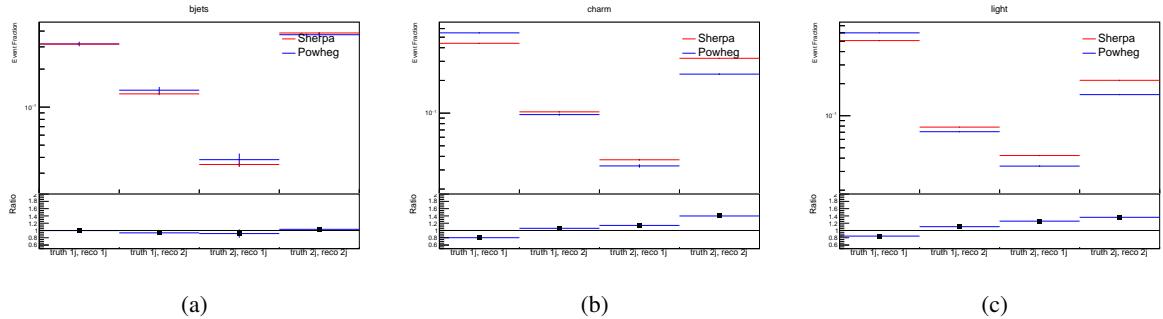


Figure 32: Comparison between Sherpa and Powheg predictions for truth jet migrations between the 1 and 2 jet reco bins for (a) WZ + b, (b) WZ + charm, and (c) WZ + light

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

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

555 The number of WZ events with 0-jets and $>=3$ -jets in the reconstructed 1-jet and 2-jet regions
 556 are compared for Sherpa and Powheg, as seen in figure 33. These differences are taken as separate
 557 normalization systematics on the yield of WZ+0-jet and WZ+ $>=3$ -jet events.

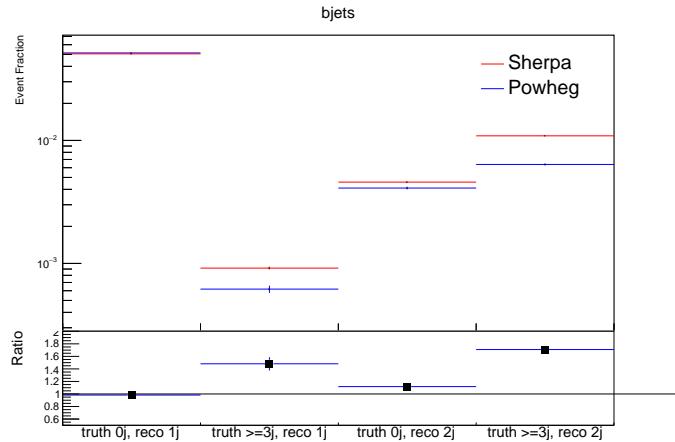


Figure 33: Comparison between Sherpa and Powheg predictions for 0 and $>=3$ truth jet contributions in the 1 and 2 jet reco bins

558 8 Results

559 8.1 Fit Procedure

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

563 Because the fit regions are defined by the number of associated jets at reco-level, an unfolding
 564 procedure is applied to the signal in order to account for differences in the number of truth jets
 565 compared to the number of reco-jets. The WZ + b, WZ + charm and WZ + light contributions
 566 are separated into independent samples based on the number of truth jets in each event. WZ + 1
 567 truth-jet and WZ + 2 truth-jets are treated as signal samples, while WZ + 0 truth-jets and WZ +
 568 >=3 truth-jets are treated as an additional background.

569 A maximum likelihood fit to data is performed simultaneously in the regions described in Section
 570 6, summarized in figure 34. The six signal templates, which include WZ+b 1-jet, WZ+c 1-jet,
 571 WZ+l 1-jet, WZ+b 2-jets, WZ+c 2-jets, WZ+l 2-jets, are allowed to float, while the remaining
 572 background contributions are held fixed. The parameters $\mu_{WZ+b-1-jet}$, $\mu_{WZ+charm1-jet}$,
 573 $\mu_{WZ+light-1-jet}$, $\mu_{WZ+b-2-jet}$, $\mu_{WZ+charm2-jet}$, $\mu_{WZ+light-2-jet}$, where $\mu = \sigma_{\text{observed}}/\sigma_{\text{SM}}$,
 574 are extracted from the fit. A simultaneous fit is performed over all 1-jet and 2-jet regions.

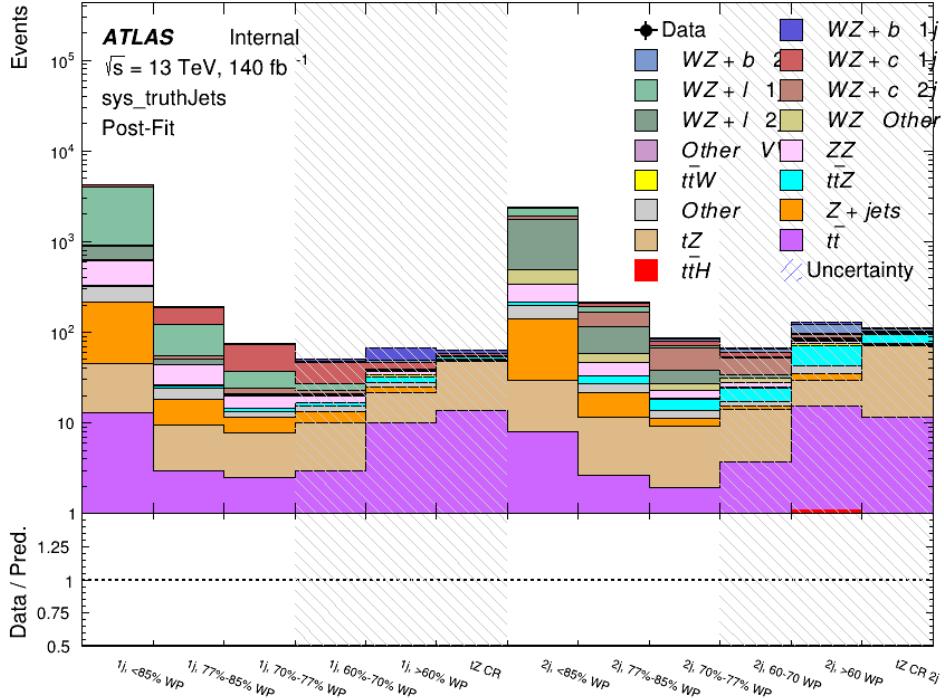


Figure 34: Post-fit summary of the fit regions.

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

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

8.2 Results of the Simultaneous Fit

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

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

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

592 For 2-jet events, the fit gives an expected μ value of $1.00^{+0.53}_{-0.51}(\text{stat})^{+0.39}_{-0.34}(\text{sys})$ for WZ + b.
 593 The fitted cross-section modifiers for WZ + charm and WZ + light are $1.00 \pm 0.25 \pm 0.21$ and
 594 $1.00 \pm 0.06 \pm 0.16$, respectively.

595 The expected WZ + b cross-section in the fiducial region with 2 associated jets is $2.5^{+1.3}_{-1.3}(\text{stat})^{+0.95}_{-0.83}(\text{sys})$
 596 fb with an expected significance of 1.7σ . The 2-jet expected cross-section of WZ + charm is
 597 $12.7 \pm 3.2(\text{stat}) \pm 2.7(\text{sys})$ fb, and the correlation between WZ + charm and WZ + b is -0.22.

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

599

	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

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

601

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

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

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

604

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

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

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

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

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

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

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

609 The ranking and impact of those nuisance parameters with the largest contribution to the overall
 610 uncertainty is shown in Figure 35.

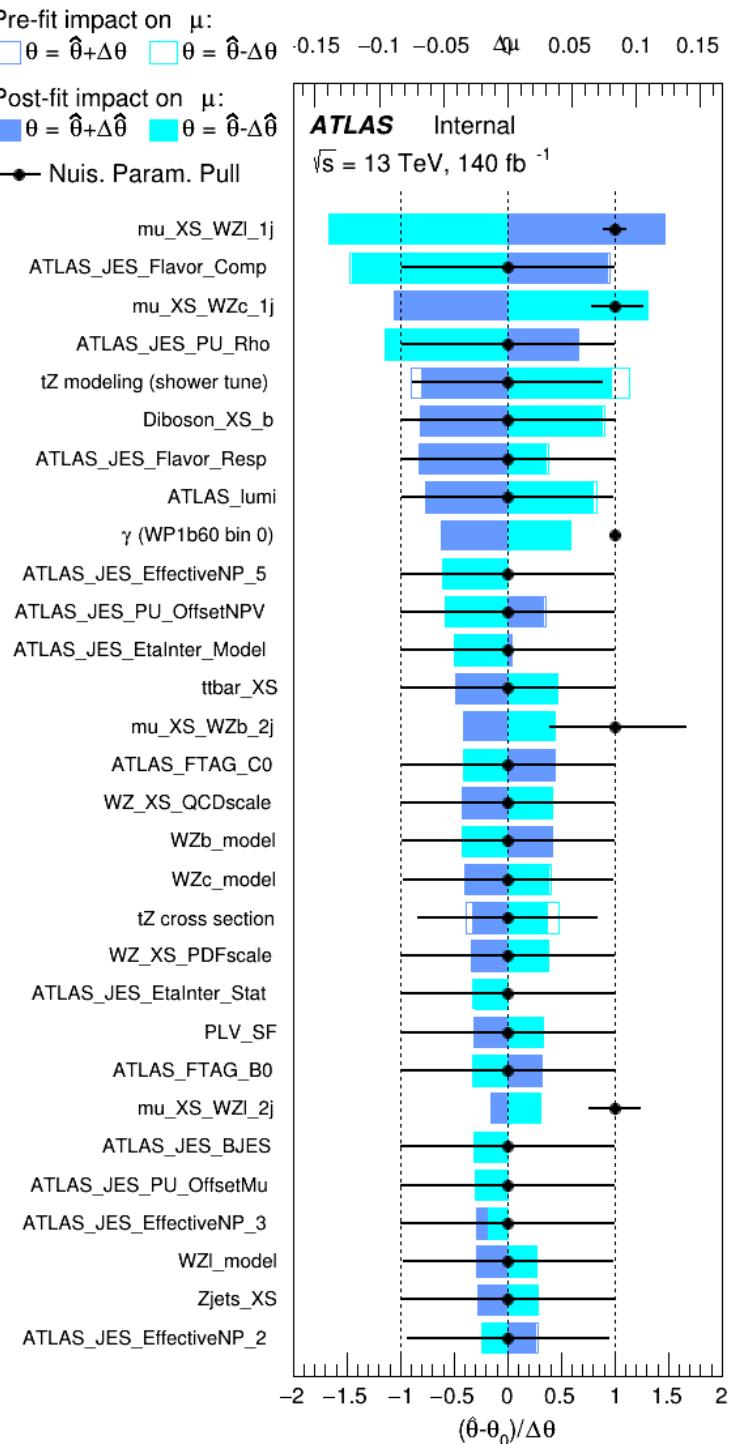


Figure 35: Impact of systematic uncertainties on the signal-strength of $WZ + b$ for events with exactly one jet

⁶¹¹ The large impact of the Jet Energy Scale and Jet Flavor Tagging is unsurprising, as the definition
⁶¹² of the fit regions depends heavily on the modeling of the jets. The other major sources of
⁶¹³ uncertainty come from background modelling and cross-section uncertainty.

⁶¹⁴ Pre-fit yields in each of the 2-jet fit are shown in Table 19.

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

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

⁶¹⁵ The post-fit yields in each region are summarized in Table 20.

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

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

⁶¹⁶ The same set of systematic uncertainties consider for the 1-jet fit are included in the 2-jet fit as
⁶¹⁷ well. The impact of the most significant systematic uncertainties is summarized in Table 21.

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

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

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

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

⁶¹⁸ The ranking and impact of those nuisance parameters with the largest contribution to the overall
⁶¹⁹ uncertainty is shown in Figure 36.

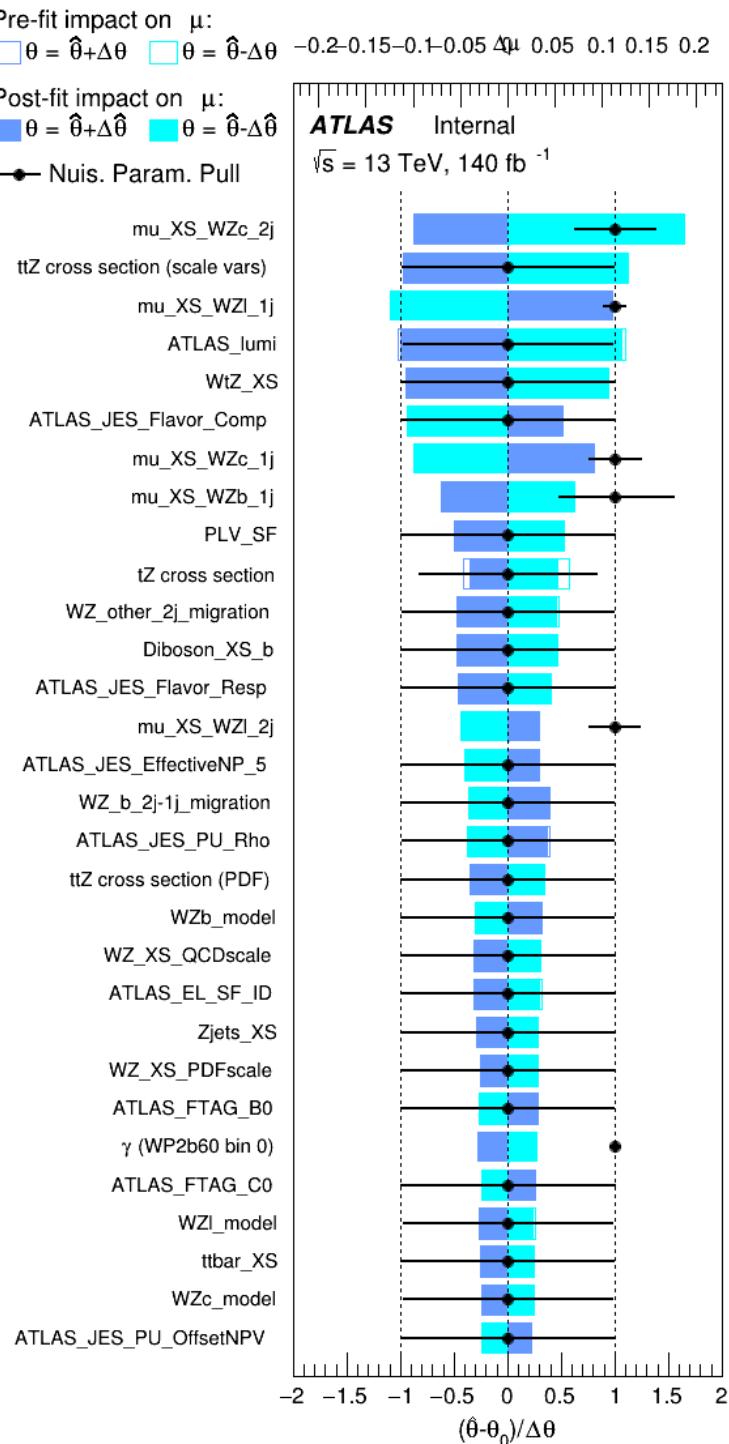


Figure 36: Impact of systematic uncertainties on the signal-strength of $WZ + b$ in 2-jet events.

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

623 **8.3 Inclusive 1+2 Jet Fit**

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

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

631 The measured μ value for WZ + b is $\mu = 1.00^{+0.30}_{-0.29}(\text{stat})^{+0.25}_{-23}(\text{sys})$, with a significance of 2.8σ ,
632 and the uncertainty on WZ + charm is $\mu = 1.00 \pm 0.12(\text{stat}) \pm 0.13(\text{sys})$. This is compared to
633 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
634 are measured separately and then combined.

635 A post-fit summary plot of the fit regions is shown in Figure 37:

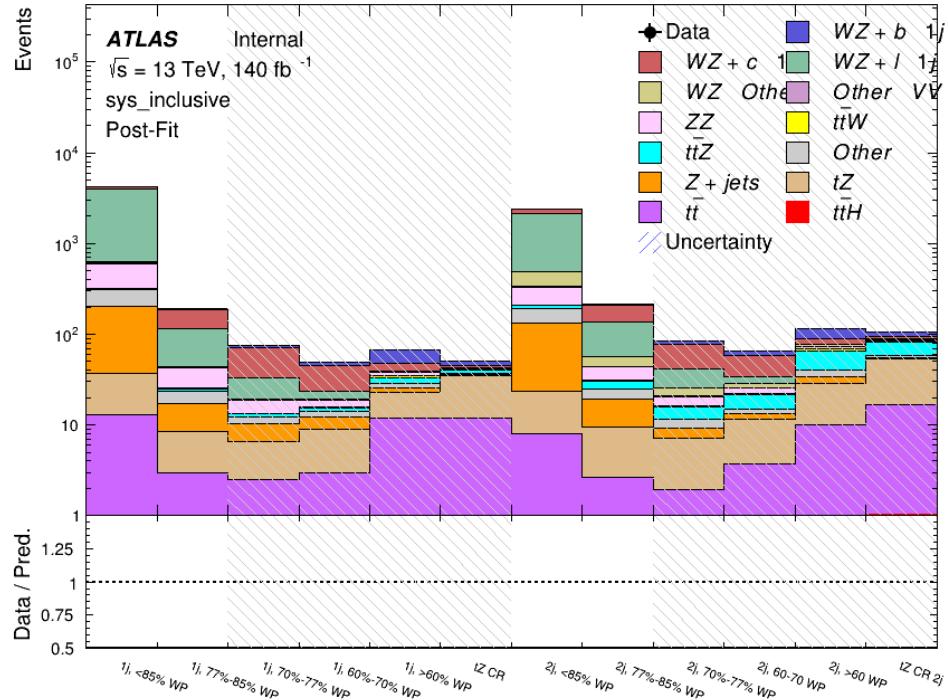


Figure 37: Post-fit summary of the 1-jet fit regions.

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

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

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

⁶³⁸ The ranking and impact of those nuisance parameters with the largest contribution to the overall
⁶³⁹ uncertainty is shown in Figure 38.

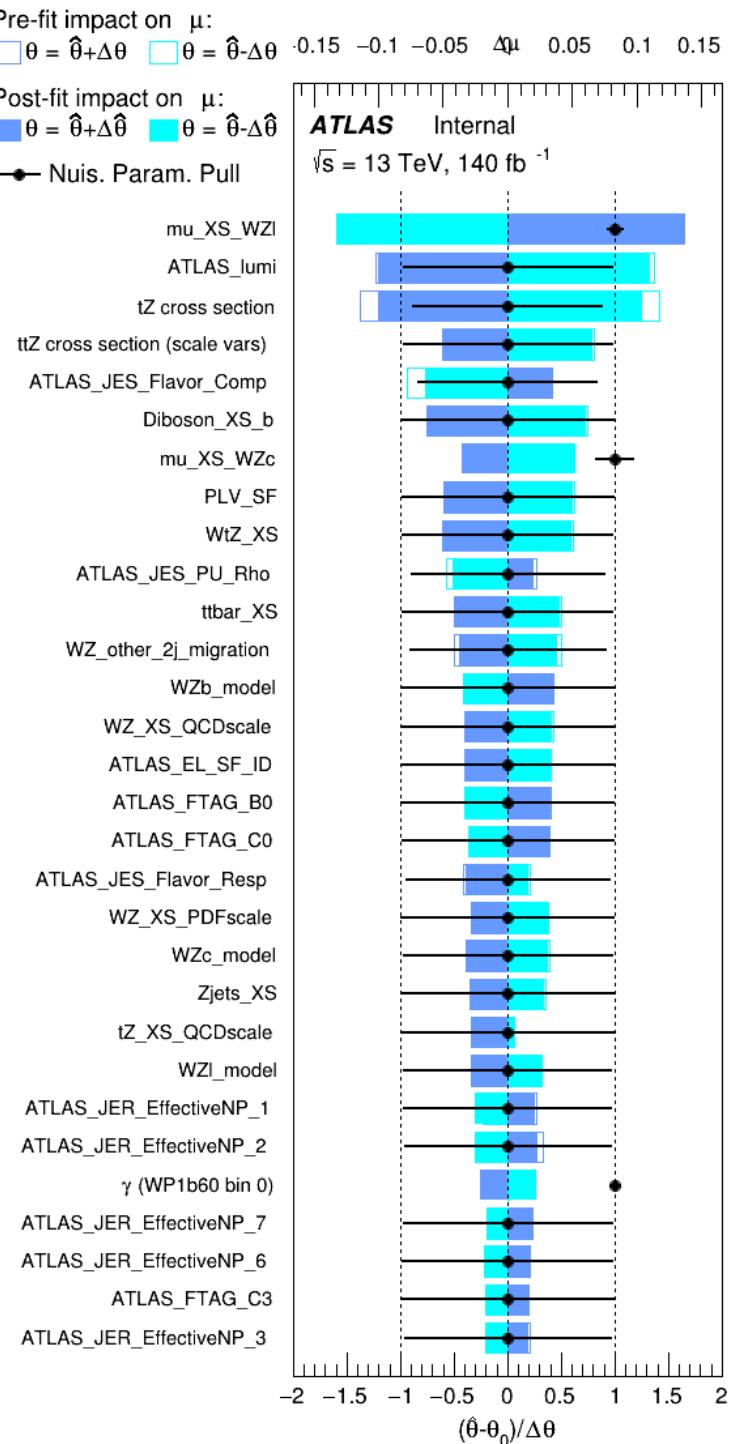


Figure 38: Impact of systematic uncertainties on the signal-strength of $WZ + b$ for events with one or two jets

640 **8.4 Alternate tZ Inclusive Fit**

641 **8.4.1 tZ Inclusive Fit**

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

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

649 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
650 an expected significance of 4.0σ .

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

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

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

652 **8.4.2 Floating tZ**

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

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

659 9 Conclusion

660 A measurement of WZ + heavy flavor is performed using 140 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ proton-
 661 proton collision data collected by the ATLAS detector at the LHC. The expected cross-section
 662 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
 663 + charm, with a correlation of -0.22 between them. An expected significance of 2.0 is observed
 664 for WZ + b in this region.

665 For the 2-jet regions, an expected significance of 1.7 is observed for WZ + b, with an ex-
 666 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
 667 $12.7 \pm 3.2(\text{stat}) \pm 2.7(\text{sys}) \text{ fb}$ is expected for 2-jet events. A correlation of -0.26 is observed
 668 for WZ+b and WZ + charm.

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

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- 763

763 **A Appendices**

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

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

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

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

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

788 `PromptLeptonVeto` is a gradient boosted BDT. The training of the BDT is performed on leptons
 789 selected from the Powheg+Pythia6 non-allhad t̄t MC sample. Eight variables are used to train
 790 the BDT in order to discriminate between prompt and non-prompt leptons. The track jets that
 791 are matched to the non-prompt leptons correspond to jets initiated by b or c quarks, and may
 792 contain a displaced vertex. Consequently, three of the selected variables are used to identify
 793 b-tag jets by standard ATLAS flavour tagging algorithms. Two variables use the relationship
 794 between the track jet and lepton: the ratio of the lepton p_T with respect to the track jet p_T and
 795 ΔR between the lepton and the track jet axis. Finally three additional variables test whether the
 796 reconstructed lepton is isolated: the number of tracks collected by the track jet and the lepton
 797 track and calorimeter isolation variables. Table 25 describes the variables used to train the BDT
 798 algorithm. The choice of input variables has been extensively discussed with Egamma, Muon,
 799 Tracking, and Flavour Tagging CP groups.

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

Variable	Description
N_{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_{TrkAtVtx} SV + JF	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
$\Delta R(\text{lepton}, \text{track jet})$	ΔR between the lepton and the track jet axis
$p_T^{\text{VarCone30}}/p_T$	Lepton track isolation, with track collecting radius of $\Delta R < 0.3$
$E_T^{\text{TopoCone30}}/p_T$	Lepton calorimeter isolation, with topological cluster collecting radius of $\Delta R < 0.3$

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

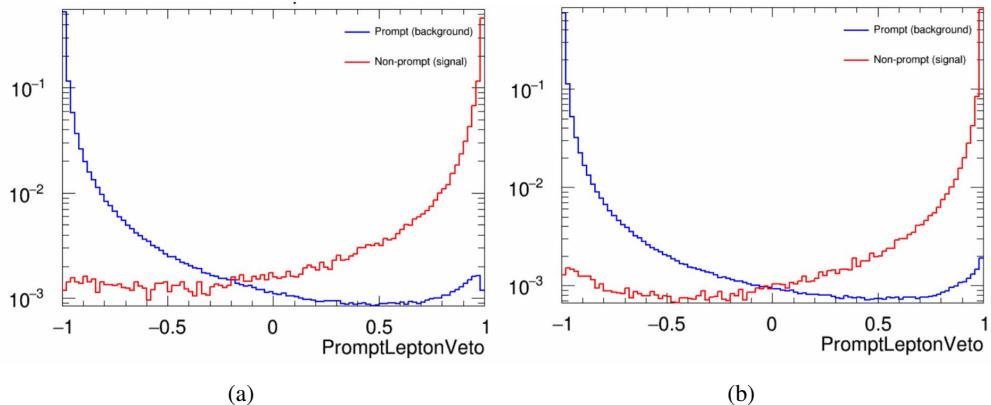


Figure 39: Distribution of the PLV BDT discriminant for (a) electrons and (b) muons.

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

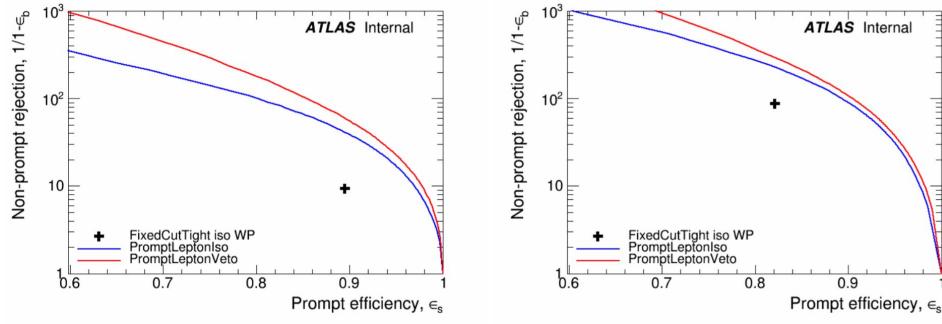


Figure 40: ROC curves for the PLV as well as the performance of the standard FixedCutTight WP for (left) electrons and (right) muons. Plot also includes curves for PROMPTLEPTONIso, which is not considered in this analysis.

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

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

814 **A.2 Non-prompt CR Modelling**

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

818 In the case of the Z+jets CR, the p_T spectrum of the lepton originating from the W candidate is
 819 shown, as this is the distribution used to extract the scale factor applied to Z+jets. These plots
 820 are shown in Figures 41 and 42.

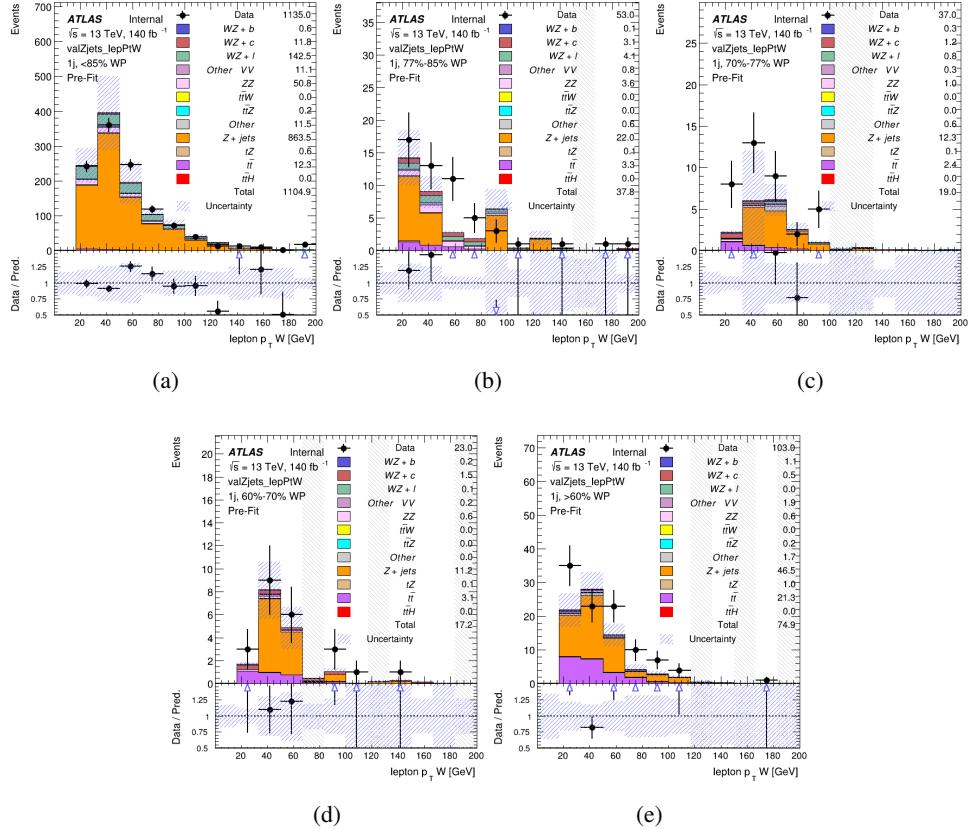


Figure 41: Comparisons between the data and MC distributions of the p_T of the lepton originating from the W-candidate in the Z+jets CR for each of the 1-jet b-tag working point regions

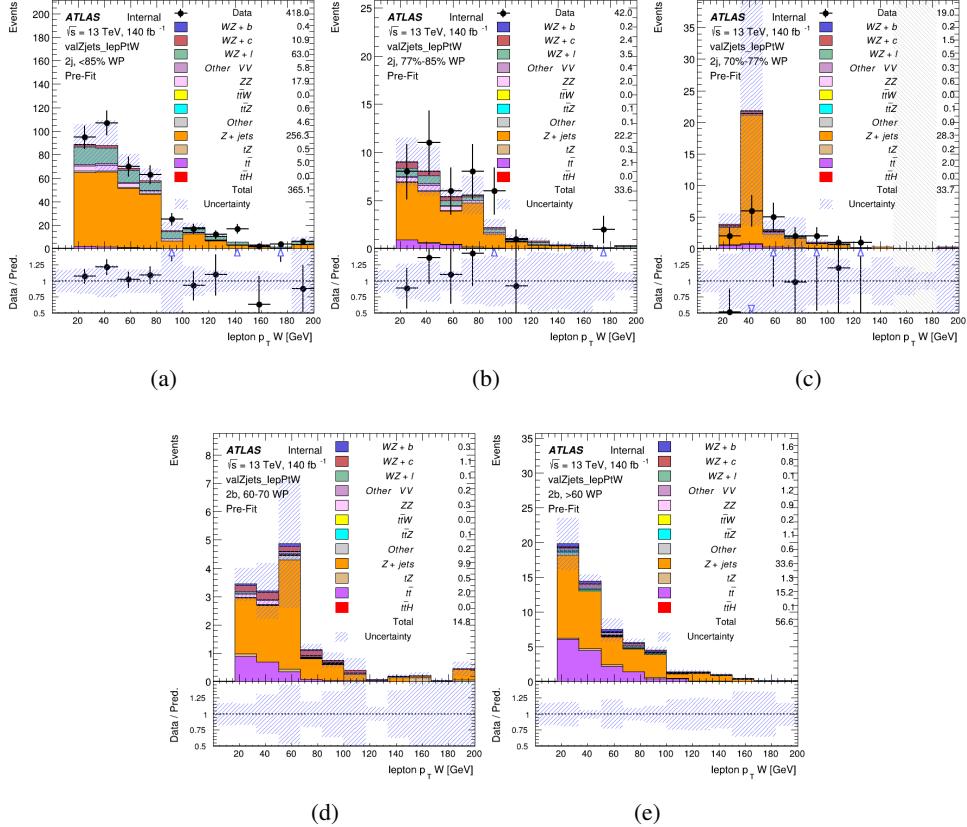


Figure 42: Comparisons between the data and MC distributions of the p_T of the lepton originating from the W-candidate in the Z+jets CR for each of the 2-jet b-tag working point regions

821 The same is shown for the $t\bar{t}$ CR, but the p_T of the OS lepton is used instead as a representation
 822 of the modeling, as the lepton from the W is not well defined for $t\bar{t}$ events. These plots are shown
 823 in Figures 43 and 44.

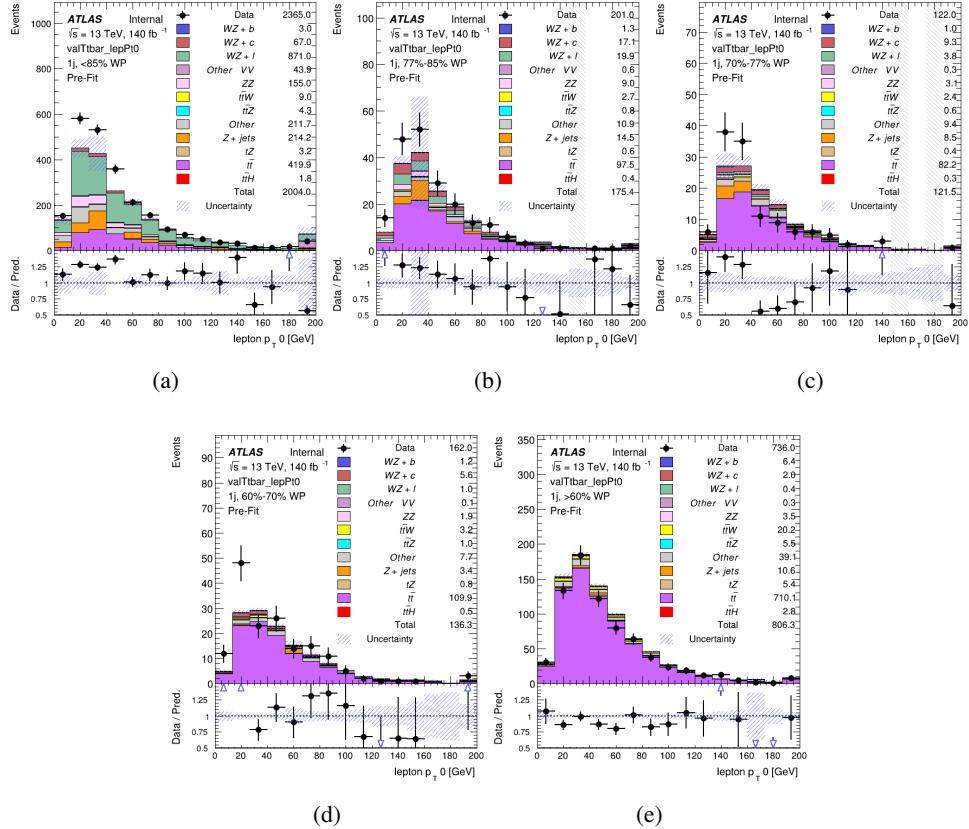


Figure 43: Comparisons between the data and MC distributions of the p_T of the OS lepton in the $t\bar{t}$ CR for each of the 1-jet b-tag working point regions

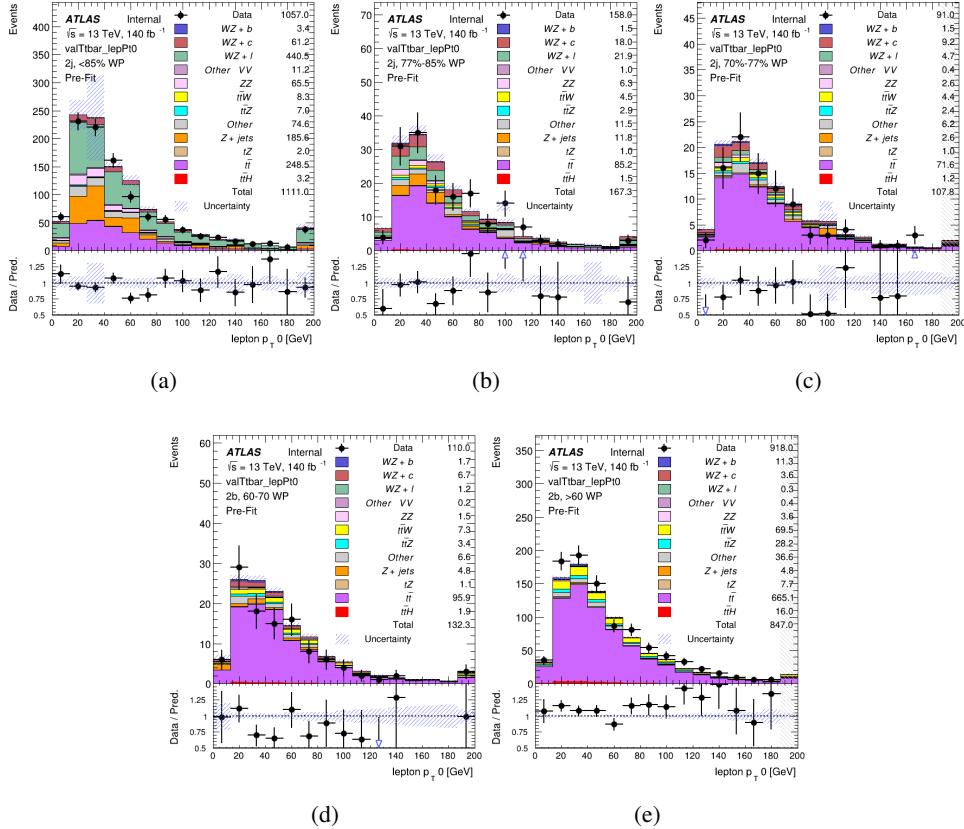


Figure 44: Comparisons between the data and MC distributions of the p_T of the OS lepton in the $t\bar{t}$ CR for each of the 2-jet b-tag working point regions

824 A.3 DSID list

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 mc16_13TeV.364108.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV140_280_BFilter.deriv.DAOD_HIGG8D1.e5271_s3126_r9364_r9315_p4133
 mc16_13TeV.364109.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV280_500_CVetoBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r9364_r9315_p4133
 mc16_13TeV.364110.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV280_500_CFilterBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r9364_r9315_p4133
 mc16_13TeV.364111.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV280_500_BFilter.deriv.DAOD_HIGG8D1.e5271_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.364111.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV280_500_BFilter.deriv.DAOD_HIGG8D1.e5271_s3126_r9364_r9315_p4133
 mc16_13TeV.364112.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV500_1000.deriv.DAOD_HIGG8D1.e5271_s3126_r9364_r9315_p4133
 mc16_13TeV.364113.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV1000_E_CMS.deriv.DAOD_HIGG8D1.e5271_s3126_r9364_r9315_p4133
 mc16_13TeV.364114.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV0_70_CVetoBVeto.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364115.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV0_70_CFilterBVeto.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364116.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV0_70_BFilter.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364117.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV70_140_CVetoBVeto.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364118.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV70_140_CFilterBVeto.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364119.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV70_140_BFilter.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364120.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV140_280_CVetoBVeto.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364121.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV140_280_CFilterBVeto.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
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 mc16_13TeV.364123.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV280_500_CVetoBVeto.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364124.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV280_500_CFilterBVeto.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364125.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV280_500_BFilter.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364126.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV280_500_BFilter.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364127.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV1000_E_CMS.deriv.DAOD_HIGG8D1.e5299_s3126_r9364_r9315_p4133
 mc16_13TeV.364128.Sherpa_221_NNPDF30NNLO_Ztautau_MAXHTPTV0_70_CVetoBVeto.deriv.DAOD_HIGG8D1.e5307_s3126_r9364_r9315_p4133
 mc16_13TeV.364129.Sherpa_221_NNPDF30NNLO_Ztautau_MAXHTPTV0_70_CFilterBVeto.deriv.DAOD_HIGG8D1.e5307_s3126_r9364_r9315_p4133
 mc16_13TeV.364130.Sherpa_221_NNPDF30NNLO_Ztautau_MAXHTPTV0_70_BFilter.deriv.DAOD_HIGG8D1.e5307_s3126_r9364_r9315_p4133
 mc16_13TeV.364131.Sherpa_221_NNPDF30NNLO_Ztautau_MAXHTPTV70_140_CVetoBVeto.deriv.DAOD_HIGG8D1.e5307_s3126_r9364_r9315_p4133
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 mc16_13TeV.364133.Sherpa_221_NNPDF30NNLO_Ztautau_MAXHTPTV70_140_BFilter.deriv.DAOD_HIGG8D1.e5307_s3126_r9364_r9315_p4133
 mc16_13TeV.364134.Sherpa_221_NNPDF30NNLO_Ztautau_MAXHTPTV140_280_CVetoBVeto.deriv.DAOD_HIGG8D1.e5307_s3126_r9364_r9315_p4133
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 mc16_13TeV.364136.Sherpa_221_NNPDF30NNLO_Ztautau_MAXHTPTV140_280_BFilter.deriv.DAOD_HIGG8D1.e5307_s3126_r9364_r9315_p4133
 mc16_13TeV.364137.Sherpa_221_NNPDF30NNLO_Ztautau_MAXHTPTV280_500_CVetoBVeto.deriv.DAOD_HIGG8D1.e5307_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.364138.Sherpa_221_NNPDF30NNLO_Ztautau_MAXHTPTV280_500_CFilterBVeto.deriv.DAOD_HIGG8D1.e5313_s3126_r9364_r9315_p4133

mc16_13TeV.364189.Sherpa_221_NNPDF30NNLO_Wtaunu_MAXHTPTV70_140_BFilter.deriv.DAOD_HIGG8D1.e5340_s3126_r9364_r9315_p4133
 mc16_13TeV.364190.Sherpa_221_NNPDF30NNLO_Wtaunu_MAXHTPTV140_280_CVetoBVeto.deriv.DAOD_HIGG8D1.e5340_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.364190.Sherpa_221_NNPDF30NNLO_Wtaunu_MAXHTPTV140_280_CVetoBVeto.deriv.DAOD_HIGG8D1.e5340_s3126_r9364_r9315_p4133
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 mc16_13TeV.364191.Sherpa_221_NNPDF30NNLO_Wtaunu_MAXHTPTV140_280_CFilterBVeto.deriv.DAOD_HIGG8D1.e5340_e5984_s3126_s3136_r9364_r9315_p4133
 mc16_13TeV.364192.Sherpa_221_NNPDF30NNLO_Wtaunu_MAXHTPTV140_280_BFilter.deriv.DAOD_HIGG8D1.e5340_s3126_r9364_r9315_p4133
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 mc16_13TeV.364193.Sherpa_221_NNPDF30NNLO_Wtaunu_MAXHTPTV280_500_CVetoBVeto.deriv.DAOD_HIGG8D1.e5340_e5984_s3126_s3136_r9364_r9315_p4133
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 mc16_13TeV.364196.Sherpa_221_NNPDF30NNLO_Wtaunu_MAXHTPTV500_1000.deriv.DAOD_HIGG8D1.e5340_s3126_r9364_r9315_p4133
 mc16_13TeV.364197.Sherpa_221_NNPDF30NNLO_Wtaunu_MAXHTPTV1000_E_CMS.deriv.DAOD_HIGG8D1.e5340_s3126_r9364_r9315_p4133
 mc16_13TeV.364500.Sherpa_222_NNPDF30NNLO_eegamma_pty_7_15.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.364501.Sherpa_222_NNPDF30NNLO_eegamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.364502.Sherpa_222_NNPDF30NNLO_eegamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r9364_r9315_p4133
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 mc16_13TeV.364510.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_7_15.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364511.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364512.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364513.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_70_140.deriv.DAOD_HIGG8D1.e5982_s3126_r9364_r9315_p4133
 mc16_13TeV.364514.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364521.Sherpa_222_NNPDF30NNLO_enugamma_pty_7_15.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364522.Sherpa_222_NNPDF30NNLO_enugamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364523.Sherpa_222_NNPDF30NNLO_enugamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364524.Sherpa_222_NNPDF30NNLO_enugamma_pty_70_140.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364525.Sherpa_222_NNPDF30NNLO_enugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364525.Sherpa_222_NNPDF30NNLO_enugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.364526.Sherpa_222_NNPDF30NNLO_munugamma_pty_7_15.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364527.Sherpa_222_NNPDF30NNLO_munugamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364528.Sherpa_222_NNPDF30NNLO_munugamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
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 mc16_13TeV.364530.Sherpa_222_NNPDF30NNLO_munugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.364531.Sherpa_222_NNPDF30NNLO_taunugamma_pty_7_15.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364532.Sherpa_222_NNPDF30NNLO_taunugamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364533.Sherpa_222_NNPDF30NNLO_taunugamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
 mc16_13TeV.364534.Sherpa_222_NNPDF30NNLO_taunugamma_pty_70_140.deriv.DAOD_HIGG8D1.e5928_s3126_r9364_r9315_p4133
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 mc16_13TeV.364535.Sherpa_222_NNPDF30NNLO_taunugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.410560.MadGraphPythia8EvtGen_A14_Z_4fl_tchan_noAllHad.deriv.DAOD_HIGG8D1.e5803_s3126_r9364_r9315_p4133
 mc16_13TeV.410013.PowhegPythiaEvtGen_P2012_Wt_inclusive_top.deriv.DAOD_HIGG8D1.e3753_s3126_r9364_r9315_p4133
 mc16_13TeV.410014.PowhegPythiaEvtGen_P2012_Wt_inclusive_antitop.deriv.DAOD_HIGG8D1.e3753_s3126_r9364_r9315_p4133
 mc16_13TeV.410408.aMcAtNloPythia8EvtGen_tWZ_Tzoll_minDR1.deriv.DAOD_HIGG8D1.e6423_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.364242.Sherpa_222_NNPDF30NNLO_WWW_31v_EW6.deriv.DAOD_HIGG8D1.e5887_s3126_r9364_r9315_p4133
 mc16_13TeV.364243.Sherpa_222_NNPDF30NNLO_WWW_412v_EW6.deriv.DAOD_HIGG8D1.e5887_s3126_r9364_r9315_p4133
 mc16_13TeV.364244.Sherpa_222_NNPDF30NNLO_WWW_214v_EW6.deriv.DAOD_HIGG8D1.e5887_s3126_r9364_r9315_p4133
 mc16_13TeV.364245.Sherpa_222_NNPDF30NNLO_WZZ_51v_EW6.deriv.DAOD_HIGG8D1.e5887_s3126_r9364_r9315_p4133
 mc16_13TeV.364246.Sherpa_222_NNPDF30NNLO_WZZ_313v_EW6.deriv.DAOD_HIGG8D1.e5887_s3126_r9364_r9315_p4133
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 mc16_13TeV.364248.Sherpa_222_NNPDF30NNLO_ZZZ_412v_EW6.deriv.DAOD_HIGG8D1.e5887_s3126_r9364_r9315_p4133
 mc16_13TeV.364249.Sherpa_222_NNPDF30NNLO_ZZZ_214v_EW6.deriv.DAOD_HIGG8D1.e5887_s3126_r9364_r9315_p4133
 mc16_13TeV.342284.Pythia8EvtGen_A14NNPDF23LO_WH125_inc.deriv.DAOD_HIGG8D1.e4246_s3126_r9364_r9315_p4133
 mc16_13TeV.342285.Pythia8EvtGen_A14NNPDF23LO_ZH125_inc.deriv.DAOD_HIGG8D1.e4246_s3126_r9364_r9315_p4133
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 mc16_13TeV.410389.MadGraphPythia8EvtGen_A14NNPDF23_ttgamma_nonallhadronic.deriv.DAOD_HIGG8D1.e6155_e5984_s3126_r9364_r9315_p4133

mc16_13TeV.410470.PhPy8EG_A14_ttbar_hdamp258p75_nonallhad.deriv.DAOD_HIGG8D1.e6337_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.410472.PhPy8EG_A14_ttbar_hdamp258p75_dil.deriv.DAOD_HIGG8D1.e6348_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.346343.PhPy8EG_A14NNPDF23_NNPDF30ME_ttH125_allhad.deriv.DAOD_HIGG8D1.e7148_e5984_s3126_r9364_r9315_p4133
 mc16_13TeV.346344.PhPy8EG_A14NNPDF23_NNPDF30ME_ttH125_semilep.deriv.DAOD_HIGG8D1.e7148_e5984_s3126_r9364_r9315_p4133
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 mc16_13TeV.364250.Sherpa_222_NNPDF30NNLO_llll.deriv.DAOD_HIGG8D1.e5984_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364254.Sherpa_222_NNPDF30NNLO_llvv.deriv.DAOD_HIGG8D1.e5916_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364255.Sherpa_222_NNPDF30NNLO_lvvv.deriv.DAOD_HIGG8D1.e5916_e5984_s3126_r10201_r10210_p4133
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 mc16_13TeV.410397.MadGraphPythia8EvtGen_ttbar_wbee_MEN30LO_A14N23LO.deriv.DAOD_HIGG8D1.e6086_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.410398.MadGraphPythia8EvtGen_ttbar_wbmumu_MEN30LO_A14N23LO.deriv.DAOD_HIGG8D1.e6086_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.410399.MadGraphPythia8EvtGen_ttbar_wbtautau_MEN30LO_A14N23LO.deriv.DAOD_HIGG8D1.e6086_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.410658.PhPy8EG_A14_tchan_BW50_lept_top.deriv.DAOD_HIGG8D1.e6671_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.410659.PhPy8EG_A14_tchan_BW50_lept_antitop.deriv.DAOD_HIGG8D1.e6671_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.410644.PowhegPythia8EvtGen_A14_singletop_schan_lept_top.deriv.DAOD_HIGG8D1.e6527_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.410645.PowhegPythia8EvtGen_A14_singletop_schan_lept_antitop.deriv.DAOD_HIGG8D1.e6527_s3126_r10201_r10210_p4133
 mc16_13TeV.412063.aMcAtNloPythia8EvtGen_tllq_NNPDF30_nf4_A14.deriv.DAOD_TOPQ1.e7054_e5984_s3126_r10201_r10210_p4174
 mc16_13TeV.304014.MadGraphPythia8EvtGen_A14NNPDF23_3top_SM.deriv.DAOD_HIGG8D1.e4324_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.410080.MadGraphPythia8EvtGen_A14NNPDF23_4topSM.deriv.DAOD_HIGG8D1.e4111_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.410081.MadGraphPythia8EvtGen_A14NNPDF23_ttbarWW.deriv.DAOD_HIGG8D1.e4111_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364100.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV0_70_CVetoBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364101.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV0_70_CFilterBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364101.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV0_70_CFilterBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364102.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV0_70_BFilter.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364103.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV70_140_CVetoBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364104.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV70_140_CFilterBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364106.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV140_280_CVetoBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364107.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV140_280_CFilterBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364108.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV140_280_BFilter.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364108.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV140_280_BFilter.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364109.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV280_500_CVetoBVeto.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
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 mc16_13TeV.364112.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV280_500_BFilter.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364112.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV500_1000.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364113.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHTPTV1000_E_CMS.deriv.DAOD_HIGG8D1.e5271_s3126_r10201_r10210_p4133
 mc16_13TeV.364114.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV0_70_CVetoBVeto.deriv.DAOD_HIGG8D1.e5299_s3126_r10201_r10210_p4133
 mc16_13TeV.364115.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV0_70_CFilterBVeto.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364116.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV0_70_BFilter.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364117.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV70_140_CVetoBVeto.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364118.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV70_140_CFilterBVeto.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364119.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV70_140_BFilter.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364120.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV140_280_CVetoBVeto.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364121.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV140_280_CFilterBVeto.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364122.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV140_280_BFilter.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364123.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV280_500_CVetoBVeto.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364124.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV280_500_CFilterBVeto.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364125.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV280_500_BFilter.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133
 mc16_13TeV.364126.Sherpa_221_NNPDF30NNLO_Zee_MAXHTPTV500_1000.deriv.DAOD_HIGG8D1.e5299_e5984_s3126_r10201_r10210_p4133

mc16_13TeV.364506.Sherpa_222_NNPDF30NNLO_mumugamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364507.Sherpa_222_NNPDF30NNLO_mumugamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364508.Sherpa_222_NNPDF30NNLO_mumugamma_pty_70_140.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364509.Sherpa_222_NNPDF30NNLO_mumugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364510.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_7_15.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364511.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364512.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364513.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_70_140.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364513.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364514.Sherpa_222_NNPDF30NNLO_tautaugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364521.Sherpa_222_NNPDF30NNLO_enugamma_pty_7_15.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364522.Sherpa_222_NNPDF30NNLO_enugamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364523.Sherpa_222_NNPDF30NNLO_enugamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364524.Sherpa_222_NNPDF30NNLO_enugamma_pty_70_140.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364525.Sherpa_222_NNPDF30NNLO_enugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364526.Sherpa_222_NNPDF30NNLO_munugamma_pty_7_15.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364527.Sherpa_222_NNPDF30NNLO_munugamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364528.Sherpa_222_NNPDF30NNLO_munugamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364529.Sherpa_222_NNPDF30NNLO_munugamma_pty_70_140.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364530.Sherpa_222_NNPDF30NNLO_munugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364531.Sherpa_222_NNPDF30NNLO_taunugamma_pty_7_15.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364532.Sherpa_222_NNPDF30NNLO_taunugamma_pty_15_35.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364533.Sherpa_222_NNPDF30NNLO_taunugamma_pty_35_70.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364534.Sherpa_222_NNPDF30NNLO_taunugamma_pty_70_140.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364535.Sherpa_222_NNPDF30NNLO_taunugamma_pty_140_E_CMS.deriv.DAOD_HIGG8D1.e5928_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.410056.MadGraphPythiaEvtGen_A14_iZ_4fl_tchan_noAllHad.deriv.DAOD_HIGG8D1.e5803_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.410013.PowhegPythiaEvtGen_P2012_Wt_inclusive_top.deriv.DAOD_HIGG8D1.e3753_s3126_r10201_r10210_p4133
mc16_13TeV.410014.PowhegPythiaEvtGen_P2012_Wt_inclusive_antitop.deriv.DAOD_HIGG8D1.e3753_s3126_r10201_r10210_p4133
mc16_13TeV.410408.aMcAtNloPythia8EvtGen_tWZ_Ztoll_minDR1.deriv.DAOD_HIGG8D1.e6423_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364242.Sherpa_222_NNPDF30NNLO_WWW_313v_EW6.deriv.DAOD_HIGG8D1.e5887_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364243.Sherpa_222_NNPDF30NNLO_WWZ_412v_EW6.deriv.DAOD_HIGG8D1.e5887_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364244.Sherpa_222_NNPDF30NNLO_WWZ_214v_EW6.deriv.DAOD_HIGG8D1.e5887_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364245.Sherpa_222_NNPDF30NNLO_WZZ_511v_EW6.deriv.DAOD_HIGG8D1.e5887_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364246.Sherpa_222_NNPDF30NNLO_WZZ_313v_EW6.deriv.DAOD_HIGG8D1.e5887_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364247.Sherpa_222_NNPDF30NNLO_ZZZ_610v_EW6.deriv.DAOD_HIGG8D1.e5887_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364248.Sherpa_222_NNPDF30NNLO_ZZZ_412v_EW6.deriv.DAOD_HIGG8D1.e5887_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.364249.Sherpa_222_NNPDF30NNLO_ZZZ_214v_EW6.deriv.DAOD_HIGG8D1.e5887_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.342284.Pythia8EvtGen_A14NNPDF23LO_WH125_inc.deriv.DAOD_HIGG8D1.e4246_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.342285.Pythia8EvtGen_A14NNPDF23LO_ZH125_inc.deriv.DAOD_HIGG8D1.e4246_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.341998.aMcAtNloHppEG_UEEE5_CTEQ6L1_CT10ME_tWH125_gamgam_yt_plus1.deriv.DAOD_HIGG8D1.e4394_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.410470.PhPy8EG_A14_ttbar_hdamp258p75_nonallhad.deriv.DAOD_HIGG8D1.e6337_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.410472.PhPy8EG_A14_ttbar_hdamp258p75_dil.deriv.DAOD_HIGG8D1.e6348_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.346343.PhPy8EG_A14NNPDF23_NNPDF30ME_ttH125_allhad.deriv.DAOD_HIGG8D1.e7148_e5984_s3126_r10201_r10210_p4133
mc16_13TeV.346344.PhPy8EG_A14NNPDF23_NNPDF30ME_ttH125_semilep.deriv.DAOD_HIGG8D1.e7148_e5984_a875_r10201_r10210_p4133
mc16_13TeV.346345.PhPy8EG_A14NNPDF23_NNPDF30ME_ttH125_dilep.deriv.DAOD_HIGG8D1.e7148_e5984_a875_r10201_r10210_p4133

mc16e:

mc16_13TeV.361605.PowhegPy8EG_CT10nloME_AZNLOCTEQ6L1_ZZvvvv_mll4.deriv.DAOD_HIGG8D1.e4054_e5984_s3126_r10724_r10726_p4133
mc16_13TeV.361602.PowhegPy8EG_CT10nloME_AZNLOCTEQ6L1_WZlvvv_mll4.deriv.DAOD_HIGG8D1.e4054_e5984_s3126_r10724_r10726_p4133
mc16_13TeV.361601.PowhegPy8EG_CT10nloME_AZNLOCTEQ6L1_WZlavl_mll4.deriv.DAOD_HIGG8D1.e4475_e5984_s3126_r10724_r10726_p4133
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mc16_13TeV.361604.PowhegPy8EG_CT10nloME_AZNLOCTEQ6L1_ZZvvll_mll4.deriv.DAOD_HIGG8D1.e4475_e5984_s3126_r10724_r10726_p4133
mc16_13TeV.364288.Sherpa_222_NNPDF30NNLO_llll_lowMllPtComplement.deriv.DAOD_HIGG8D1.e6096_s3126_r10724_p3983 mc16_13TeV.364287.Sherpa_222_NNPDF30NNLO_llll_lowMllPtComplement.deriv.DAOD_HIGG8D1.e6096_s3126_r10724_p3983
mc16_13TeV.364285.Sherpa_222_NNPDF30NNLO_llvjj_EW6.deriv.DAOD_HIGG8D1.e6055_s3126_r10724_p3983
mc16_13TeV.364284.Sherpa_222_NNPDF30NNLO_llvjj_EW6.deriv.DAOD_HIGG8D1.e6055_s3126_r10724_p3983
mc16_13TeV.364283.Sherpa_222_NNPDF30NNLO_lllijj_EW6.deriv.DAOD_HIGG8D1.e6055_s3126_r10724_p3983
mc16_13TeV.364739.MGPy8EG_NNPDF30NLO_A14NNPDF23LO_lvjlljjEW6_OFMinus.deriv.DAOD_HIGG8D1.e7421_e5984_s3126_r10724_r10726_p4133
mc16_13TeV.364742.MGPy8EG_NNPDF30NLO_A14NNPDF23LO_lvjlljjEW6_SFPlus.deriv.DAOD_HIGG8D1.e7421_e5984_s3126_r10724_r10726_p4133
mc16_13TeV.364740.MGPy8EG_NNPDF30NLO_A14NNPDF23LO_lvjlljjEW6_OFPlus.deriv.DAOD_HIGG8D1.e7421_e5984_s3126_r10724_r10726_p4133
mc16_13TeV.364741.MGPy8EG_NNPDF30NLO_A14NNPDF23LO_lvjlljjEW6_SFMinus.deriv.DAOD_HIGG8D1.e7421_e5984_s3126_r10724_r10726_p4133
mc16_13TeV.364253.Sherpa_222_NNPDF30NNLO_llv.deriv.DAOD_HIGG8D1.e5916_e5984_s3126_r10724_r10726_p4133

mc16_13TeV.364250.Sherpa_222_NNPDF30NNLO_llll.deriv.DAOD_HIGG8D1.e5894_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.364254.Sherpa_222_NNPDF30NNLO_llvv.deriv.DAOD_HIGG8D1.e5916_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.364255.Sherpa_222_NNPDF30NNLO_lvvv.deriv.DAOD_HIGG8D1.e5916_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410155.aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttW.deriv.DAOD_HIGG8D1.e5070_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410156.aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttZnunu.deriv.DAOD_HIGG8D1.e5070_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410157.aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttZqq.deriv.DAOD_HIGG8D1.e5070_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410218.aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttee.deriv.DAOD_HIGG8D1.e5070_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410219.aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttmumu.deriv.DAOD_HIGG8D1.e5070_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410220.aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttautau.deriv.DAOD_HIGG8D1.e5070_e5984_s3126_r10724_r10726_p4133
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 mc16_13TeV.410278.aMcAtNloPythia8EvtGen_MEN30NLO_A14N23LO_ttautau_mll_1_5.deriv.DAOD_HIGG8D1.e6087_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410397.MadGraphPythia8EvtGen_ttbar_wbee_MEN30NLO_A14N23LO.deriv.DAOD_HIGG8D1.e6086_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410398.MadGraphPythia8EvtGen_ttbar_wbmumu_MEN30NLO_A14N23LO.deriv.DAOD_HIGG8D1.e6086_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410399.MadGraphPythia8EvtGen_ttbar_wbtautau_MEN30NLO_A14N23LO.deriv.DAOD_HIGG8D1.e6086_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410658.PhPy8EG_A14_tchan_BW50_lept_top.deriv.DAOD_HIGG8D1.e6671_e5984_s3126_s3136_r10724_r10726_p4133
 mc16_13TeV.410659.PhPy8EG_A14_tchan_BW50_lept_antitop.deriv.DAOD_HIGG8D1.e6671_e5984_s3126_s3136_r10724_r10726_p4133
 mc16_13TeV.410644.PowhegPythia8EvtGen_A14_singletop_schan_lept_top.deriv.DAOD_HIGG8D1.e6527_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410645.PowhegPythia8EvtGen_A14_singletop_schan_lept_antitop.deriv.DAOD_HIGG8D1.e6527_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.412063.aMcAtNloPythia8EvtGen_tllq_NNPDF30_nf4_A14.deriv.DAOD_TOPQ1.e7054_e5984_s3126_r10724_r10726_p4174
 mc16_13TeV.304014.MadGraphPythia8EvtGen_A14NNPDF23_3top_SM.deriv.DAOD_HIGG8D1.e4324_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410080.MadGraphPythia8EvtGen_A14NNPDF23_4topSM.deriv.DAOD_HIGG8D1.e4111_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.410081.MadGraphPythia8EvtGen_A14NNPDF23_ttbarWW.deriv.DAOD_HIGG8D1.e4111_e5984_s3126_r10724_r10726_p4133
 mc16_13TeV.364100.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHPTV0_70_CVetoBVeto.deriv.DAOD_HIGG8D1.e5271_e5984_s3126_s3136_r10724_r10726_p4133
 mc16_13TeV.364100.Sherpa_221_NNPDF30NNLO_Zmumu_MAXHPTV0_70_CVetoBVeto.deriv.DAOD_HIGG8D1.e5271_e5984_s3126_r10724_r10726_p4133
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 mc16_13TeV.364242.Sherpa_222_NNPDF30NNLO_WWW_3l3v_EW6.deriv.DAOD_HIGG8D1.e5887_e5984_s3126_r10724_r10726_p4133
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