QCD measurements of vector-boson production with the ATLAS detector

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Run I results on vector-boson production

Standard Model Production Cross Section Measurements

Status: March 2015

Excellent agreement with theory

- Test of QCD calculations
- Sensitivity to PDFs
- Backgrounds for many BSM searches
- Jet multiplicities measured up to 7 jets
- Probe of pQCD calculations

Low mass DY at 7 TeV JHEP 06 (2014) 112

- Provides important information on the partonic structure of hadrons
- Allows to cover low partonic momentum fraction $x \sim 3 \times 10^{-4} - 1.7 \times 10^{-3}$ at $Q \simeq m_{ll} = 10 - 66$ GeV
- nominal analysis
 - 2011 data, $\mathcal{L} \simeq 1.6$ fb $^{-1}$
 - combined electron and muon channels
 - $26 \text{ GeV} < m_{ll} < 66 \text{ GeV}$
- low-mass extended analysis
 - 2010 data, $\mathcal{L} \simeq 35$ pb $^{-1}$
 - muon channel
 - $12 \text{ GeV} < m_{ll} < 66 \text{ GeV}$

Low mass DY at 7 TeV JHEP 06 (2014) 112

- FEWZ NLO calculations give poor description of data at low m_{ll}
- POWHEG NLO+LLPS and FEWZ NNLO describe data well

QCD analysis at NLO and NNLO

- fitting the PDFs to DIS data from HERA and the new measurements
- NLO fit unable to describe data
- NNLO results in a good fit

Z p_T at 7 TeV JHEP09(2014)145

- Sensitive to ISR and the intrinsic transverse momentum of the initial partons at low p_T^Z and pQCD at high p_T^Z
- Important for a precise measurement of W mass
- Probe of the gluon density of the proton

- Disagreement between data and FEWZ NNLO and DYNLO up to 10 % around 50 GeV; diverges at low p_T^Z due to the lack of resummation
- RESBOS (NLO+NNLL, NNLO+NNLL) agrees with the data within 5-7 %

Z p_T at 7 TeV JHEP09(2014)145

- PYTHIA and POWHEG agree best with the data
- MC@NLO, SHERPA and ALPGEN show discrepancies at low and high p_T^Z
- PYTHIA and POWHEG were tuned to determine sensitivity to parton shower model parameters in MC generators

- Tunes are performed for low p_T^Z < 26 GeV and $\phi_\eta^* < 0.29$ region, where parton shower dominates
- Final tune combines muon channel for p_T^Z and electron channel for ϕ_η^*
- Tuned predictions agree with the measured cross sections within 2 %

	PYTHIA8	POWHEG+PYTHIA8	Base tune
Tune Name	AZ	AZNLO	4C
Primordial k_T [GeV]	1.71 ± 0.03	1.75 ± 0.03	2.0
ISR $\alpha_S^{\text{ISR}}(m_Z)$	0.1237 ± 0.0002	0.118 (fixed)	0.137
ISR cut-off [GeV]	0.59 ± 0.08	1.92 ± 0.12	2.0
$\chi^2_{\text{min}}/\text{dof}$	45.4/32	46.0/33	-

W+jets at 7 TeV Eur. Phys. J. C (2015) 75:82

- Test of pQCD calculation in large kinematic range
- Background for many SM processes and BSM searches

- Differential cross-section studied for ~ 40 observables
- Measurements of W+($n \leq 7$) jets unfolded to particle level
- p_T of jet was explored up to 1 TeV
- Comparison to a variety of theoretical predictions done
- Overall reasonable agreement observed

W+jets/Z+jets at 7 TeV Eur. Phys. J. C (2014) 74: 3168

- Significantly increased precision in comparison to V+jet measurement, due to cancellation of many systematic effects
- Sensitivity to New Physics interfering W+jets or Z+jets production
- Probes the difference between kinematics of the jet system recoiling against W or Z bosons
- Differential cross-sections for ~ 20 observables studied
- Comparison with NLO pQCD calculation, LO ME Monte Carlo generators done

W+jets/Z+jets at 7 TeV Eur. Phys. J. C (2014) 74: 3168

- SHERPA prediction deviates by 1.5σ at high jet multiplicities
- Different behavior of the theoretical prediction at the lowest p_T observed, in particular in BLACKHAT+SHERPA
- At the lowest $\Delta R_{j1,2}$ predicted shapes are different from the measured

Z+b-jets at 7 TeV JHEP10(2014)141

- Important background to ZH with $H \rightarrow b\bar{b}$ and BSM signatures
- Two schemes in pQCD with heavy flavour quarks:
 - Four-flavour number scheme (4FNS) - four flavours in the initial state
 - Five-flavour number scheme (5FNS) - includes also b quark
- (a) exists only in 5FNS
 - Can be sensitive to b quark PDF

Z+b-jets at 7 TeV JHEP10(2014)141

- MCFM in five-flavour number scheme agrees with data within uncertainties
 - aMC@NLO 4FNS describes better $Z+\geq 2$ b-jets, while 5FNS describes better $Z+\geq 1$ b-jet
 - Shape of b-jet p_T well modeled
 - Discrepancies between MCFM and data in angular distributions for $Z+\geq 1$ b-jet
- At most two outgoing partons in association with the Z boson

Run II preview

- Measurements of the vector boson cross-sections with the new data can be used to constrain PDF uncertainties

- Run II at $\sqrt{s}=13$ TeV ongoing
- First measurements of the $W \rightarrow l\nu$ and $Z \rightarrow ll$ production cross sections corresponding to luminosity of 85 pb^{-1} are ready

arXiv:1507.00556

W, Z at 13 TeV ATLAS-CONF-2015-039

- Both electron and muon channels are used for the measurement
- Comparison with theoretical prediction from FEWZ and previous measurements done
- Cross sections increase following the expectations

W, Z at 13 TeV ATLAS-CONF-2015-039

- Ratios of measured cross sections benefit from uncertainties cancellations
- $R_{W^\pm/Z}$ constraints strange-quark distribution
- R_{W^+/W^-} sensitive to $u_v - d_v$ valence-quark distribution at low x
- $R_{W^\pm/Z}$ measurement agrees with different PDF predictions within uncertainties
- For R_{W^+/W^-} significant scatter of different PDF predictions observed, the measurement agrees with PDFs which include LHC measurements from Run I

Summary

- Vector boson (+jets) measurements:
 - test of pQCD
 - probe of PDFs
 - background for many SM processes and BSM searches
- Many Run I high precision measurements will be finalized soon
- Run II is already providing precise measurements which are able to distinguish among different PDF predictions
- First W, Z production cross sections at $\sqrt{s}=13$ TeV show agreement with NNLO QCD predictions

BACKUP

Low mass DY, systematic uncertainties, $Z \rightarrow ee$

m_{ee} [GeV]	Correlated						Uncorrelated					
	$\delta_{\text{cor}}^{\text{e.w.}}$ [%]	$\delta_{\text{cor}}^{\text{pTrw}}$ [%]	$\delta_{\text{cor1}}^{\text{id}}$ [%]	$\delta_{\text{cor2}}^{\text{id}}$ [%]	$\delta_{\text{cor}}^{\text{rec}}$ [%]	$\delta_{\text{cor}}^{\text{geant4}}$ [%]	δ^{trig} [%]	δ^{iso} [%]	$\delta_{\text{unf}}^{\text{res}}$ [%]	δ^{MC} [%]	$\delta_{\text{unc}}^{\text{id}}$ [%]	δ^{multijet} [%]
26–31	−0.4	0.7	1.0	0.4	2.3	−1.2	0.6	1.4	1.8	2.2	1.2	3.9
31–36	−0.4	0.7	0.8	0.3	2.0	−1.2	0.5	1.1	1.0	1.7	1.1	3.6
36–41	−0.5	0.6	0.5	0.2	1.7	−1.2	0.3	0.8	0.9	1.7	0.8	3.2
41–46	−0.7	1.2	0.3	0.2	1.4	−1.2	0.3	0.6	1.1	1.9	0.6	3.1
46–51	−0.9	0.1	0.2	0.1	0.8	−1.2	0.2	0.4	1.2	2.1	0.4	2.8
51–56	−1.0	0.8	0.2	0.1	0.5	−1.2	0.2	0.3	1.4	2.0	0.3	2.3
56–61	−0.8	0.2	0.1	0.1	0.4	−1.2	0.1	0.2	1.5	1.6	0.3	2.0
61–66	−0.8	−0.9	0.1	0.1	0.3	−1.2	0.1	0.2	1.1	1.0	0.2	1.6

- $\delta_{\text{cor}}^{\text{e.w.}}$ - from the uncertainty in the electroweak background contribution
- $\delta_{\text{cor}}^{\text{pTrw}}$ - from corrections to MC modelling of the Z/γ^* p_T spectra
- $\delta_{\text{cor1}}^{\text{id}}, \delta_{\text{cor2}}^{\text{id}}$ - from the electron identification efficiency
- $\delta_{\text{cor}}^{\text{rec}}$ - from the electron reconstruction efficiency
- $\delta_{\text{cor}}^{\text{geant4}}$ - from the Geant4 simulation
- δ^{trig} - from trigger efficiency correction
- δ^{iso} - from isolation efficiency correction
- $\delta_{\text{unf}}^{\text{res}}$ - unfolding uncertainties
- δ^{MC} - from the statistical precision of the signal Monte Carlo
- $\delta_{\text{un}}^{\text{id}}$ - uncorrelated part of the electron identification efficiency uncertainty
- δ^{multijet} - from the normalisation of the multijet background

Low mass DY, systematic uncertainties, $Z \rightarrow \mu\mu$ nominal

$m_{\mu\mu}$ [GeV]	$\delta^{\text{e.w.}}$ [%]	$\delta^{p\text{Trw}}$ [%]	Correlated					$\delta^{p\text{T scale}}$ [%]	Uncorrelated				
			$\delta^{\text{reco}}_{\text{cor}}$ [%]	$\delta^{\text{trig}}_{\text{cor}}$ [%]	$\delta^{\text{iso}}_{\text{cor}}$ [%]	δ^{multijet} [%]	$\delta^{\text{trig}}_{\text{unc}}$ [%]		$\delta^{\text{iso}}_{\text{unc}}$ [%]	δ^{res} [%]	δ^{MC} [%]	$\delta^{\text{reco}}_{\text{unc}}$ [%]	
26-31	-0.1	-0.2	0.5	0.8	2.6	-1.1	-0.5	0.5	1.4	0.2	0.8	0.2	
31-36	-0.1	0.2	0.5	0.8	2.1	-1.0	-0.8	0.5	1.2	0.1	0.6	0.2	
36-41	-0.2	0.0	0.5	0.8	1.5	-0.8	-1.0	0.5	0.9	0.1	0.7	0.2	
41-46	-0.3	-0.3	0.5	0.8	1.1	-0.8	-0.4	0.4	0.7	0.2	0.8	0.2	
46-51	-0.4	-0.1	0.5	0.8	0.9	-0.5	-0.6	0.4	0.5	0.3	0.8	0.2	
51-56	-0.4	-0.2	0.5	0.7	0.7	-0.5	-0.0	0.3	0.5	0.2	0.9	0.2	
56-61	-0.4	-0.2	0.5	0.7	0.6	-0.4	-0.3	0.3	0.4	0.2	0.8	0.2	
61-66	-0.3	-0.3	0.5	0.6	0.5	-0.3	0.9	0.2	0.3	0.2	0.3	0.2	

- $\delta^{\text{e.w.}}_{\text{cor}}$ - from the uncertainty in the electroweak background contribution
- $\delta^{p\text{Trw}}_{\text{cor}}$ - from corrections to MC modelling of the Z/γ^* p_{T} spectra
- $\delta^{\text{reco}}_{\text{cor}}$ - from the muon reconstruction efficiency
- $\delta^{\text{trig}}_{\text{cor}}$ - from trigger efficiency correction
- $\delta^{\text{iso}}_{\text{cor}}$ - from isolation efficiency correction
- δ^{multijet} - from the normalisation of the multijet background
- $\delta^{p\text{T scale}}$ - the muon momentum scale uncertainty
- $\delta^{\text{trig}}_{\text{unc}}$ - uncorrelated part from trigger efficiency correction
- $\delta^{\text{iso}}_{\text{unc}}$ - uncorrelated part from isolation efficiency correction
- δ^{res} - from the muon resolution correction
- δ^{MC} - from the statistical precision of the signal Monte Carlo
- $\delta^{\text{reco}}_{\text{unc}}$ - due to corrections for the reconstruction

Low mass DY, systematic uncertainties, $Z \rightarrow \mu\mu$ extended

$m_{\mu\mu}$ [GeV]	δ^{reco} [%]	δ^{trig} [%]	Correlated			Uncorrelated	
			δ^{iso} [%]	δ^{multijet} [%]	$\delta^{pT \text{ scale}}$ [%]	δ^{res} [%]	δ^{MC} [%]
12–17	2.5	4.0	11.3	−3.0	−0.2	0.5	0.6
17–22	1.4	3.7	11.3	−2.8	0.1	0.3	0.3
22–28	0.9	3.6	8.5	−1.8	0.0	0.1	0.4
28–36	0.7	3.6	6.2	−1.6	−0.1	0.2	0.4
36–46	0.7	3.6	4.2	−1.3	−0.1	0.1	0.5
46–66	0.6	3.6	3.6	−0.7	−0.0	0.1	0.5

- δ^{reco} - from the muon reconstruction efficiency
- δ^{trig} - from trigger efficiency correction
- δ^{iso} - from isolation efficiency correction
- δ^{multijet} - from the normalisation of the multijet background
- $\delta^{pT \text{ scale}}$ - the muon momentum scale uncertainty
- δ^{res} - from the muon resolution correction
- δ^{MC} - from the statistical precision of the signal Monte Carlo

$Z p_T$, systematic uncertainties

Z p_T, PS parameters tuning

Parameter	Variation Range	
	PYTHIA8 tune	PYTHIA8+POWHEG tune
Primordial k_T [GeV]	1.0–2.5	0.5–2.5
ISR $\alpha_S^{ISR}(m_Z)$	0.120–0.140	0.118
ISR cut-off [GeV]	0.5–2.5	0.5–3.0
ISR α_S order	LO	NLO
PYTHIA8 base tune	tune 4C	tune 4C
POWHEG cut-off [GeV ²]	-	4.0

- α_S^{ISR} - strong coupling constant used for the parton shower evolution; for POWHEG+PYTHIA8 tune $\alpha_S(M_Z)$ value used to calculate the QCD radiation in POWHEG should match α_S^{ISR} in PYTHIA 8
- ISR cut-off - the parton shower lower cut-off p_{T0} in the non-perturbative regime
- Primordial k_{T0} - the primordial transverse momentum of the partons initiating the hard scattering process
- POWHEG cut-off - the transverse momentum lowest threshold of the hardest (highest p_T) QCD radiation calculated by POWHEG; should match the upper limit of the PYTHIA 8 PS

$$Z \phi_{\eta}^*$$

$$\phi_{\eta}^* \equiv \tan(\phi_{\text{acop}}/2) \cdot \sin(\theta_{\eta}^*), \quad \phi_{\text{acop}} \equiv \pi - \Delta\phi$$

$$\cos(\theta_{\eta}^*) \equiv \tanh[(\eta^- - \eta^+)/2]$$

- partially correlated to p_T^Z
- depends on the direction of the two lepton tracks, which are measured better than their momenta

- interpreting ϕ_{η}^* as a probe of p_T^Z assumes that the lepton angular correlations are correctly modeled
- RESBOS reasonably describes data within 4 % in some of regions

Phys. Lett. B 720 (2013) 32-51, arXiv:1211.6899

W+jets at 7 TeV

Transverse momentum of the highest- p_T jet in $W+\leq 2$ jets

- BLACKHAT+SHERPA, MEPS@NLO and ALPGEN predictions agree well with data
- SHERPA deviates from data at high p_T
- HEJ predicts too hard jet spectrum

Angular separation of jets

- Well modeled by BLACKHAT+SHERPA
- All other predictions show discrepancies with data with different trends

W+jets, background

N_{jet}	0	1	2	3	4	5	6	7
$W \rightarrow e\nu$								
$W \rightarrow e\nu$	94%	78%	73%	58%	37%	23%	14%	11%
<u>Multijet</u>	4%	<u>11%</u>	<u>12%</u>	<u>11%</u>	7%	6%	5%	4%
<u>$t\bar{t}$</u>	< 1%	< 1%	3%	<u>18%</u>	<u>46%</u>	<u>62%</u>	<u>76%</u>	<u>80%</u>
Single top	< 1%	< 1%	2%	3%	4%	3%	2%	2%
$W \rightarrow \tau\nu$, diboson	2%	3%	3%	3%	2%	1%	1%	1%
$Z \rightarrow ee$	< 1%	8%	7%	7%	5%	4%	3%	3%
Total Predicted	11 100 000 $\pm$ 640 000	1 510 000 $\pm$ 99 000	354 000 $\pm$ 23 000	89 500 $\pm$ 5600	28 200 $\pm$ 1400	8550 $\pm$ 440	2530 $\pm$ 200	572 $\pm$ 61
Data Observed	10 878 398	1 548 000	361 957	91 212	28 076	8514	2358	618
$W \rightarrow \mu\nu$								
$W \rightarrow \mu\nu$	93%	82%	78%	62%	40%	25%	17%	11%
<u>Multijet</u>	2%	<u>11%</u>	<u>10%</u>	<u>9%</u>	7%	5%	4%	3%
<u>$t\bar{t}$</u>	< 1%	< 1%	3%	<u>19%</u>	<u>46%</u>	<u>64%</u>	<u>75%</u>	<u>83%</u>
Single top	< 1%	< 1%	2%	3%	4%	3%	2%	2%
$W \rightarrow \tau\nu$, diboson	2%	3%	3%	3%	2%	1%	1%	< 1%
$Z \rightarrow \mu\mu$	3%	4%	3%	3%	2%	1%	1%	1%
Total Predicted	13 300 000 $\pm$ 770 000	1 710 000 $\pm$ 100 000	384 000 $\pm$ 24 000	96 700 $\pm$ 6100	30 100 $\pm$ 1600	8990 $\pm$ 480	2400 $\pm$ 180	627 $\pm$ 66
Data Observed	13 414 400	1 758 239	403 146	99 749	30 400	9325	2637	663

W+jets, systematics

$(W \rightarrow e\nu)$	Incl.	$N_{\text{jets}} \geq 1$	$N_{\text{jets}} \geq 2$	$N_{\text{jets}} \geq 3$	$N_{\text{jets}} \geq 4$	$N_{\text{jets}} \geq 5$	$N_{\text{jets}} \geq 6$	$N_{\text{jets}} \geq 7$
Electron	1.1%	1.3%	1.3%	1.2%	1.2%	1.3%	2.7%	3.4%
Jets	0.3%	<u>9%</u>	<u>11%</u>	<u>15%</u>	<u>20%</u>	<u>29%</u>	<u>42%</u>	<u>45%</u>
$t\bar{t}$ backgrounds	< 0.1%	0.2%	1.0%	4.8%	<u>13%</u>	<u>39%</u>	<u>100%</u>	<u>90%</u>
Multijet backgrounds	0.5%	1.5%	2.1%	2.1%	5%	15%	25%	25%
$E_{\text{T}}^{\text{miss}}$	0.2%	1.7%	1.2%	1.2%	1.0%	0.7%	1.7%	2.6%
Unfolding	0.2%	1.7%	0.9%	1.1%	1.2%	0.9%	5%	22%
Luminosity	1.9%	2.1%	2.1%	2.2%	2.3%	2.5%	2.6%	2.2%
Total Syst.	2.3%	10%	12%	16%	25%	50%	110%	110%

$(W \rightarrow \mu\nu)$	Incl.	$N_{\text{jets}} \geq 1$	$N_{\text{jets}} \geq 2$	$N_{\text{jets}} \geq 3$	$N_{\text{jets}} \geq 4$	$N_{\text{jets}} \geq 5$	$N_{\text{jets}} \geq 6$	$N_{\text{jets}} \geq 7$
Muon	1.5%	1.7%	1.7%	1.4%	1.5%	2.1%	3.7%	4.4%
Jets	0.1%	<u>8%</u>	<u>9%</u>	<u>13%</u>	<u>16%</u>	<u>20%</u>	<u>29%</u>	<u>60%</u>
$t\bar{t}$ backgrounds	< 0.1%	0.2%	0.9%	4.1%	11%	<u>26%</u>	<u>47%</u>	<u>60%</u>
Multijet backgrounds	0.1%	0.5%	0.8%	1.4%	2.2%	4.2%	4.6%	9%
$E_{\text{T}}^{\text{miss}}$	0.3%	1.0%	0.9%	1.0%	1.0%	0.6%	0.9%	1.1%
Unfolding	0.2%	1.7%	0.9%	1.0%	1.2%	1.3%	2.6%	11%
Luminosity	1.9%	2.0%	2.0%	2.1%	2.1%	2.1%	2.0%	2.0%
Total Syst.	2.5%	8%	10%	14%	20%	34%	60%	80%

W+jets, theoretical predictions

Program	Max. number of partons at			Parton/Particle level
	approx. NNLO ($\alpha_s^{N_{\text{jets}}+2}$)	NLO ($\alpha_s^{N_{\text{jets}}+1}$)	LO ($\alpha_s^{N_{\text{jets}}}$)	
LoopSim	1	2	3	parton level with corrections
BLACKHAT+SHERPA	–	5	6	parton level with corrections
BLACKHAT+SHERPA exclusive sums	1	2	3	parton level with corrections
HEJ	all orders, resummation			parton level
MEPS@NLO	–	2	4	particle level
ALPGEN	–	–	5	particle level
SHERPA	–	–	4	particle level

W+jets/Z+jets, background

N_{jets}	0	1	2	3	4
Fraction [%]	$W(\rightarrow e\nu) + \text{jets}$				
$W \rightarrow e\nu$	94	78	73	58	37
$Z \rightarrow ee$	0.30	7.5	6.6	6.8	5.4
$t\bar{t}$	< 0.1	0.30	3.4	18	46
Multi-jet	4	11	12	11	6.9
Electroweak (without $Z \rightarrow ee$)	1.9	2.6	3.3	3	1.9
Single top	< 0.1	0.30	1.7	3.5	3.9
Total Predicted	11 100 000 $\pm$ 640 000	1 510 000 $\pm$ 99 000	354 000 $\pm$ 23 000	89 500 $\pm$ 5600	28 200 $\pm$ 1400
Data Observed	10 878 398	1 548 000	361 957	91 212	28 076
Fraction [%]	$Z(\rightarrow ee) + \text{jets}$				
$Z \rightarrow ee$	100	99	96	93	90
$W \rightarrow e\nu$	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
$t\bar{t}$	< 0.1	0.20	1.9	4.6	7.8
Multi-jet	0.20	0.20	0.40	0.50	0.50
Electroweak (without $W \rightarrow e\nu$)	0.10	0.50	1.3	1.4	1.2
Single top	< 0.1	< 0.1	0.10	0.20	0.10
Total Predicted	754 000 $\pm$ 47 000	96 500 $\pm$ 6900	22 100 $\pm$ 1700	4700 $\pm$ 930	1010 $\pm$ 93
Data Observed	761 280	99 991	22 471	4 729	1050

W+jets/Z+jets, background

N_{jets}	0	1	2	3	4
Fraction [%]	$W(\rightarrow \mu\nu) + \text{jets}$				
$W \rightarrow \mu\nu$	93	82	78	62	40
$Z \rightarrow \mu\mu$	3.4	3.5	3.5	3	2
$t\bar{t}$	< 0.1	0.20	3.1	19	46
Multi-jet	1.5	11	10	9.5	6.8
Electroweak (without $Z \rightarrow \mu\mu$)	1.9	2.7	3.4	2.9	1.9
Single top	< 0.1	0.20	1.7	3.4	3.8
Total Predicted	13 300 000 $\pm$ 770 000	1 710 000 $\pm$ 100 000	384 000 $\pm$ 24 000	96 700 $\pm$ 6100	30 100 $\pm$ 1600
Data Observed	13 414 400	1 758 239	403 146	99 749	30 400
Fraction [%]	$Z(\rightarrow \mu\mu) + \text{jets}$				
$Z \rightarrow \mu\mu$	100	99	96	91	84
$W \rightarrow \mu\nu$	< 0.1	0.10	0.10	0.20	0.20
$t\bar{t}$	< 0.1	0.30	2.2	6.1	13
Multi-jet	0.30	0.50	0.90	1.1	1.7
Electroweak (without $W \rightarrow \mu\nu$)	0.10	0.50	1.3	1.4	1.1
Single top	< 0.1	< 0.1	0.10	0.20	0.20
Total Predicted	1 300 000 $\pm$ 79 000	168 000 $\pm$ 12 000	37 800 $\pm$ 2800	8100 $\pm$ 660	1750 $\pm$ 160
Data Observed	1 302 010	171 200	38 618	8397	1864

W+jets/Z+jets, systematics

N_{jets}	$(W \rightarrow e\nu)/(Z \rightarrow ee)$				
	≥ 0	≥ 1	≥ 2	≥ 3	≥ 4
Electron	0.89	0.92	0.93	0.97	1.0
JES	0.094	2.0	2.0	3.5	5.7
JER	0.25	2.4	3.5	4.3	6.4
E_T^{miss}	0.19	1.7	1.2	1.2	1.0
$t\bar{t}$	0.024	0.23	1.0	4.9	14
Multi-jet	0.81	1.6	1.5	2.2	6.2
Other backgrounds	0.12	0.57	0.58	0.76	1.0
Unfolding	0.20	0.56	0.86	1.2	1.4
Luminosity	0.062	0.26	0.27	0.34	0.44
Total	1.3	4.1	4.8	8.2	18

N_{jets}	$(W \rightarrow \mu\nu)/(Z \rightarrow \mu\mu)$				
	≥ 0	≥ 1	≥ 2	≥ 3	≥ 4
Muon	1.1	1.2	1.1	0.86	0.87
JES	0.10	0.84	0.71	1.8	2.6
JER	0.094	1.6	1.8	2.6	4.2
E_T^{miss}	0.30	1.0	0.94	0.97	0.99
$t\bar{t}$	0.018	0.18	0.87	4.3	12
Multi-jet	0.20	0.60	1.1	1.7	2.7
Other backgrounds	0.21	0.24	0.28	0.42	0.60
Unfolding	0.22	0.59	0.90	1.2	1.2
Luminosity	0.10	0.12	0.11	0.088	0.023
Total	1.2	2.5	3.0	5.9	13

Z+b-jets, Z+light-/c-jets bkg extraction

- Neural network algorithm, JFComb, is used combining information about:
 - weak $b \rightarrow c$ cascade topologies
 - likelihood based on the impact parameter significance with respect to the PV of preselected tracks
- Output: pb, pc, and pu corresponding to the probability that a given jet is a b-jet, c-jet or light-jet, respectively
- Combination of these variables, $\text{CombNNc} = \ln(\text{pb}/\text{pc})$, $\text{CombNN} = \ln(\text{pb}/\text{pu})$, are used in maximum-likelihood fits to data

Analysis selection	Data yield	Fitted Components		Fixed Components	
		Z + b(b)-jets	[ALPGEN+HJ]	Z+[other]-jets	tt
$\sigma(Zb) \times N_{b,jet}$	49701	18010±210	[2470]	29780±230	1330
$\sigma^*(Zb) \times N_{b,jet}$	41243	15640±190	[10460]	23840±210	1230
$\sigma(Zb)$	47138	18610±200	[11410]	29290±220	930
$\sigma(Zb)$	2494	1170±60	[960]	860±50	305

Z+b-jets, systematic uncertainty

Source of uncertainty	$\sigma(Zb)$ [%]	$\sigma(Zbb)$ [%]
<u>b-jet tagging efficiency</u>	<u>3.4</u>	<u>9.8</u>
c-jet mistag rate	0.2	2.3
light-jet mistag rate	0.4	0.6
JES	2.9	4.7
JER	0.3	0.7
<u>b-jet template shape</u>	<u>4.8</u>	<u>4.8</u>
c-jet template shape	0.2	0.6
light-jet template shape	0.9	0.9
b-jet template scale factor	N/A	2.3
MPI	2.5	0.8
gluon splitting	1.2	1.5
background normalisation	1.1	3.6
$t\bar{t}$ modelling	0.0	2.9
MC sample size	1.0	1.4
lepton efficiency, scale and resolution	1.2	1.2
E_T^{miss}	0.1	0.6
luminosity	1.8	1.8
total	7.7	14.0

Z+ ≥ 1 b-jet

Z+ ≥ 2 b-jets

W, Z at 13 TeV, MC samples

Physics process	Generator	σ ($\cdot$ BR [pb])	Order	Reference
$W \rightarrow \ell \nu$ ($\ell = e, \mu, \tau$)	POWHEG +PYTHIA 8	$20400 \pm 5\%$	NNLO	[2,3,4,5]
$W^+ \rightarrow \ell^+ \nu$		$11770 \pm 5\%$	NNLO	[2,3,4,5]
$W^- \rightarrow \ell^- \bar{\nu}$		$8640 \pm 5\%$	NNLO	[2,3,4,5]
$Z \rightarrow \ell^+ \ell^-$ ($66 < m_{\ell\ell} < 116$ GeV)	POWHEG +PYTHIA 8	$1930 \pm 5\%$	NNLO	[2,3,4,5]
$t\bar{t}$ ($m_t = 172.5$ GeV)	POWHEG +PYTHIA 6	$830 \pm 6\%$	NNLO+NNLL	[27]
Dibosons	SHERPA	$99 \pm 6\%$	NLO	[31]
Dijet (e channel, $\hat{p}_T > 21$ GeV)	PYTHIA 8	180×10^3	LO	[13]
$b\bar{b}$ (μ channel, $\hat{p}_T > 15$ GeV)	PYTHIA 8	188	LO	[13]
$c\bar{c}$ (μ channel, $\hat{p}_T > 15$ GeV)	PYTHIA 8	58	LO	[13]

W, Z at 13 TeV background

	Expected fraction in each channel			
	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$	$Z \rightarrow e^+e^-$	$Z \rightarrow \mu^+\mu^-$
$W \rightarrow \tau\nu$	1.8	2.0	–	–
$Z \rightarrow \tau^+\tau^-$	0.2	0.2	0.1	0.1
Diboson	–	–	0.1	0.1
$t\bar{t}$	1.2	1.1	0.5	0.5
$W \rightarrow e\nu$	95.6	–	0.1	–
$W \rightarrow \mu\nu$	–	92.0	–	0.1
$Z \rightarrow e^+e^-$	1.2	–	99.4	–
$Z \rightarrow \mu^+\mu^-$	–	4.7	–	99.4

Number of observed events in the $W \rightarrow l\nu$ channels

$\ell^\pm$	Observed candidates	Background (EW+top)	Background (Multijet)	Background-subtracted events N_W^{sig}
e^+	256923	10100 ± 600	$15200 \pm 300 \pm 6700$	$231600 \pm 500 \pm 6700$
e^-	206140	8900 ± 500	$15600 \pm 300 \pm 6900$	$181600 \pm 500 \pm 6900$
μ^+	272841	20420 ± 920	$12200 \pm 200 \pm 3500$	$240300 \pm 500 \pm 3600$
μ^-	214249	18210 ± 830	$11500 \pm 100 \pm 3100$	$184500 \pm 500 \pm 3200$

Number of observed events in the $Z \rightarrow l^+l^-$ channels

$\ell^\pm$	Observed candidates	Background (EW+top)	Background (Multijet)	Background-subtracted events N_Z^{sig}
$e^\pm$	34955	$229 \pm 1 \pm 24$	$< 0.1\%$	$34730 \pm 190 \pm 20$
$\mu^\pm$	44899	$296 \pm 2 \pm 31$	$< 0.1\%$	$44600 \pm 210 \pm 30$

W, Z at 13 TeV, systematics

Process $\delta C/C$ (%)	$Z \rightarrow \mu^+ \mu^-$	$W^+ \rightarrow \mu^+ \nu$	$W^- \rightarrow \mu^- \bar{\nu}$	$Z \rightarrow e^+ e^-$	$W^+ \rightarrow e^+ \nu$	$W^- \rightarrow e^- \bar{\nu}$
Electron Trigger	–	–	–	0.5	3.0	3.2
Electron Reconstruction, Identification	–	–	–	3.8	2.0	2.1
Electron Isolation	–	–	–	1.0	0.5	0.5
Electron Scale and Resolution	–	–	–	0.2	0.4	0.5
Charge Identification	–	–	–	0.8	0.1	0.1
Muon Trigger	1.0	2.0	2.0	–	–	–
Muon Reconstruction, Identification	0.9	0.4	0.4	–	–	–
Muon Isolation	0.5	0.3	0.3	–	–	–
Muon Scale and Resolution	0.1	0.1	0.1	–	–	–
JES and JER	–	1.5	1.5	–	1.9	1.8
MET Soft Term	–	0.1	0.1	–	0.1	0.1
Pileup Modeling	0.9	1.2	1.2	0.9	1.4	1.4
Total	1.7	2.8	2.8	4.1	4.4	4.5

W, Z at 13 TeV, cross section ratio

W, Z at 13 TeV, fiducial cross sections

W, Z at 13 TeV, total cross sections

PDF	A_{W^+}	A_{W^-}	$A_{W^\pm}$	A_Z
CT10NNLO	$0.396^{+0.003}_{-0.003}$	$0.399^{+0.003}_{-0.004}$	$0.397^{+0.003}_{-0.003}$	$0.399^{+0.003}_{-0.005}$
NNPDF3.0	0.396	0.404	0.399	0.398
MMHT14NNLO	0.394	0.406	0.399	0.398
ABM12LHC	0.395	0.408	0.401	0.402