Measurement of the WZ boson pair production cross section at 13 TeV and confidence intervals on anomalous triple gauge couplings with the ATLAS detector

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On behalf of the ATLAS collaboration

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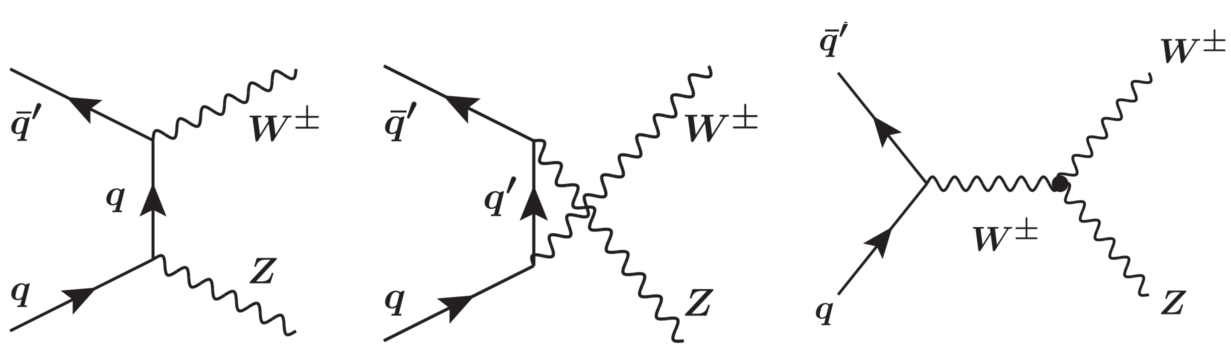
Outline

- Introduction - motivation
- Experimental signature and phase space definition
- Background estimation
- Event yields and control distributions
- Systematic Uncertainties
- Cross-section measurements
- Differential cross-sections
- aTGC confidence intervals
- Conclusions

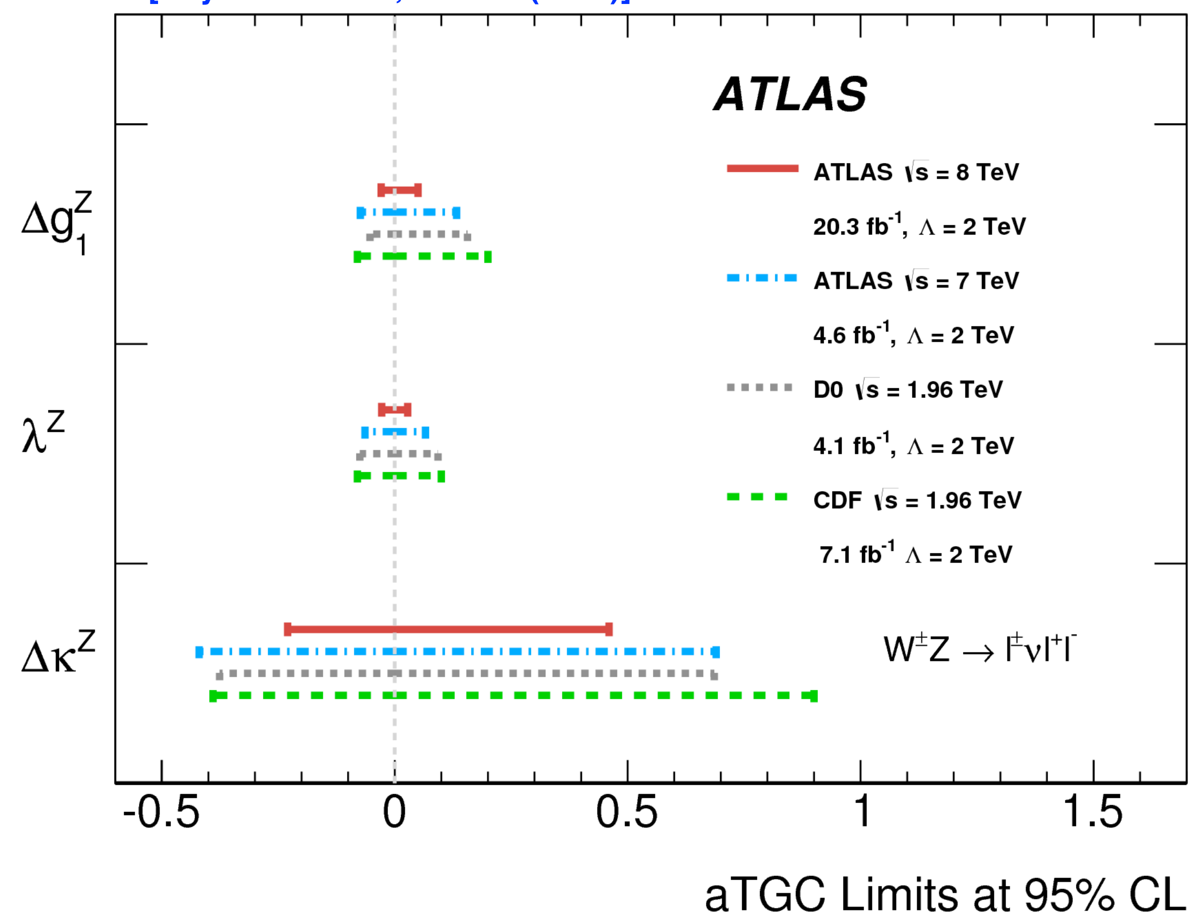
Introduction - motivation

- Test of pQCD as NNLO calculations become available
- The diboson processes are an excellent probe of the EW sector
- The WZ process has
  - higher production cross-section than ZZ
  - cleaner signature (experimentally) than WW
- Run-I: Observed discrepancy (~1.9σ) wrt NLO predictions
- First measurement at 13 TeV of
  - charged aTGC 95% CL intervals
  - differential cross-sections (Z_{pT}, m_T^{WZ})



WZ → lνll (LO)

[Phys. Rev. D 93, 092004 (2016)]

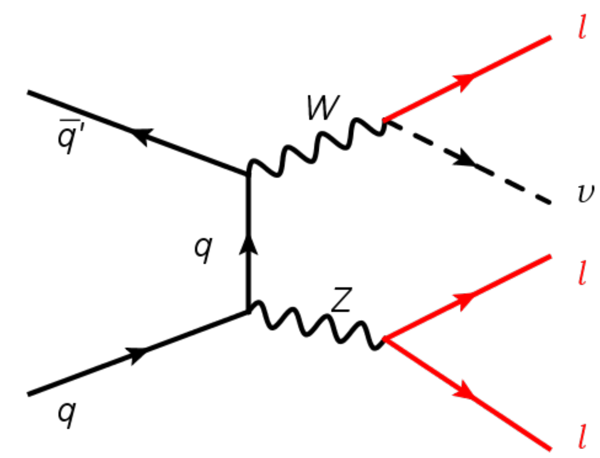


Experimental signature and analysis phase-space

- Study the purely leptonic decays of the W,Z bosons to electrons, muons
- 3 high-p_T, prompt, isolated leptons + missing E_T
- Invariant mass of 2 same flavour, opposite charge leptons consistent with Z-mass
- Transverse mass of 3rd lepton and missing E_T consistent with W-boson
- Four distinct final states:

eee, eμμ, μee, μμμ

Signal: 3 real leptons

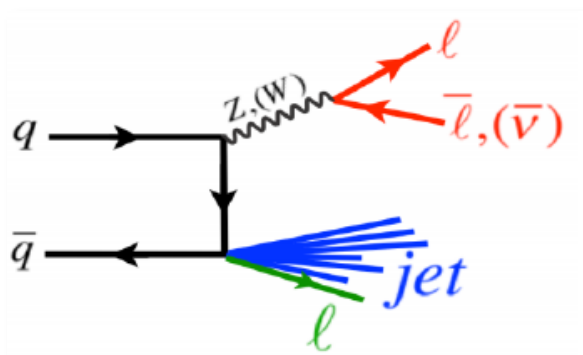


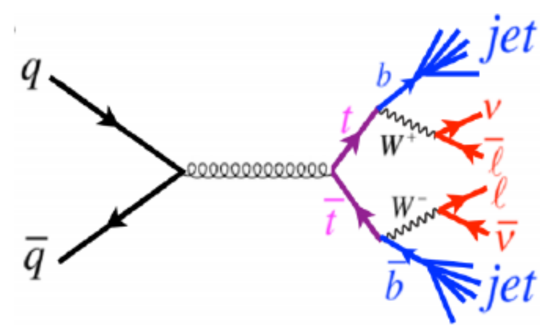
- Fiducial phase-space definition is kept identical to the 8 TeV WZ publication
- To compute the detector acceptance, utilise a user-defined algorithm (resonant shapes) that associates the generator-level leptons to the mother bosons
  - Can compare generators on an equal footing

Fiducial Phase-Space
$\lvert m_{\ell\ell} - m_Z \rvert < 10$ GeV
$m_{\mathrm{T}}^{W} > 30$ GeV
Z leptons: $p_{\mathrm{T}}^{\ell} > 15$ GeV
W lepton: $p_{\mathrm{T}}^{\ell} > 20$ GeV
$\lvert \eta_\ell \rvert < 2.5$ for all three leptons
$\Delta R(\ell, \ell) > 0.3$ between W and Z leptons
$\Delta R(\ell, \ell) > 0.2$ between Z leptons

Background estimation

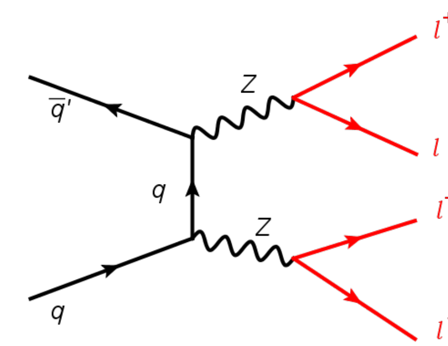
Reducible: at least 1 fake lepton





- Z+X, W+X, Z+γ, W+γ, ttbar, WW
- Fake leptons:
  - Heavy flavour decays
  - Jets misidentified as leptons
  - Photon conversions (electrons)
- Main source of total background (52%)
- Estimated using a data-driven method (matrix method)

Irreducible: at least 3 real leptons



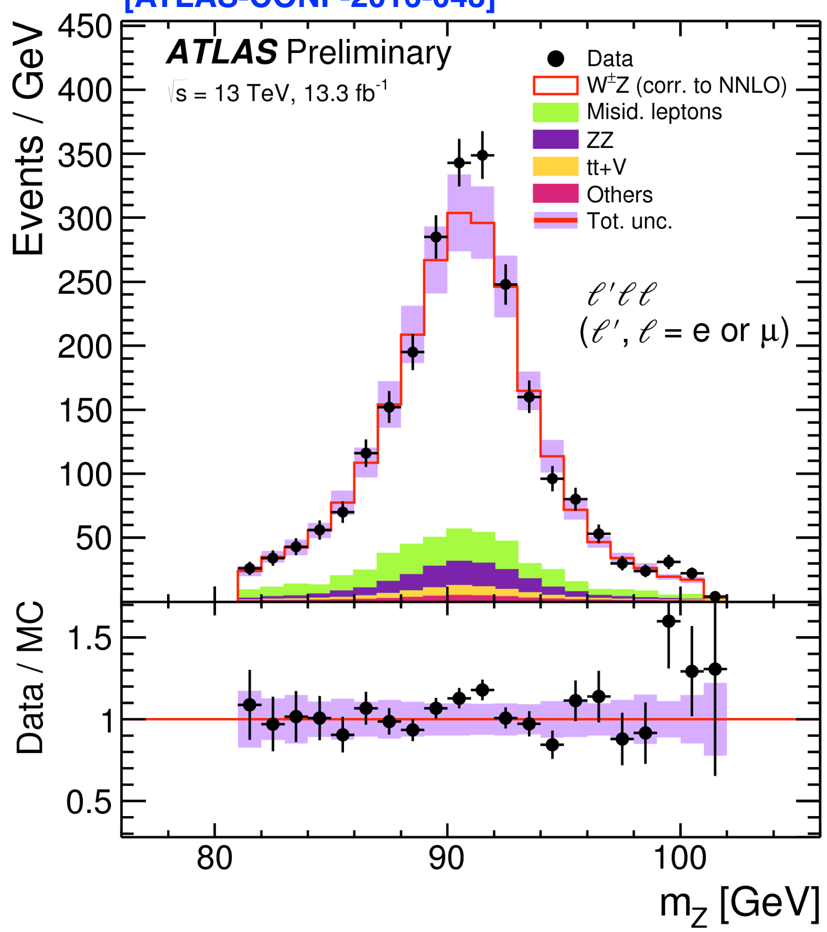
- ZZ, VVV, tZ, ttbarV
- Leptons from these processes, falling outside the detector acceptance or failing identification
- Main source: ZZ (30% of total background)
- Estimated using MC

Yields and control distributions

- Observed 2417 WZ events
- Only statistical uncertainties shown in the table
- Expected signal events scaled to match the recent NNLO calculations **[arXiv: 1604.08576]**

Channel	eee	μee	$e\mu\mu$	$\mu\mu\mu$	All
Data	516	537	612	752	2417
Total Expected	504 ± 7	588 ± 5	552 ± 6	671 ± 4	2315 ± 11
$W^{\pm}Z$	354.0 ± 2.5	442.7 ± 2.9	453.2 ± 2.9	581.1 ± 3.4	1831 ± 6
ZZ	27.7 ± 0.4	36.0 ± 0.5	32.9 ± 0.4	46.5 ± 0.5	143.2 ± 0.9
Misid. leptons	103 ± 7	87 ± 4	45 ± 6	17.9 ± 2.5	253 ± 10
$t\bar{t}$+V	12.8 ± 0.1	14.49 ± 0.13	13.50 ± 0.12	15.59 ± 0.13	56.41 ± 0.25
tZ	5.506 ± 0.029	6.674 ± 0.033	6.653 ± 0.032	8.22 ± 0.04	27.05 ± 0.07
VVV	0.974 ± 0.029	1.219 ± 0.034	1.166 ± 0.031	1.44 ± 0.04	4.80 ± 0.07

[ATLAS-CONF-2016-043]



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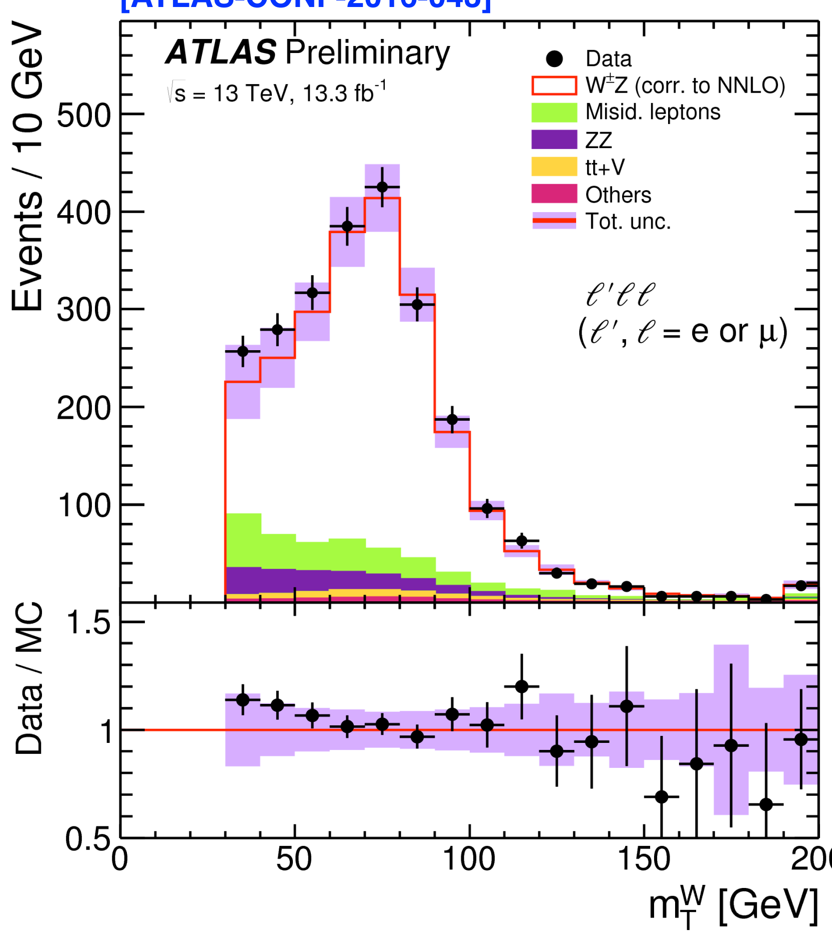
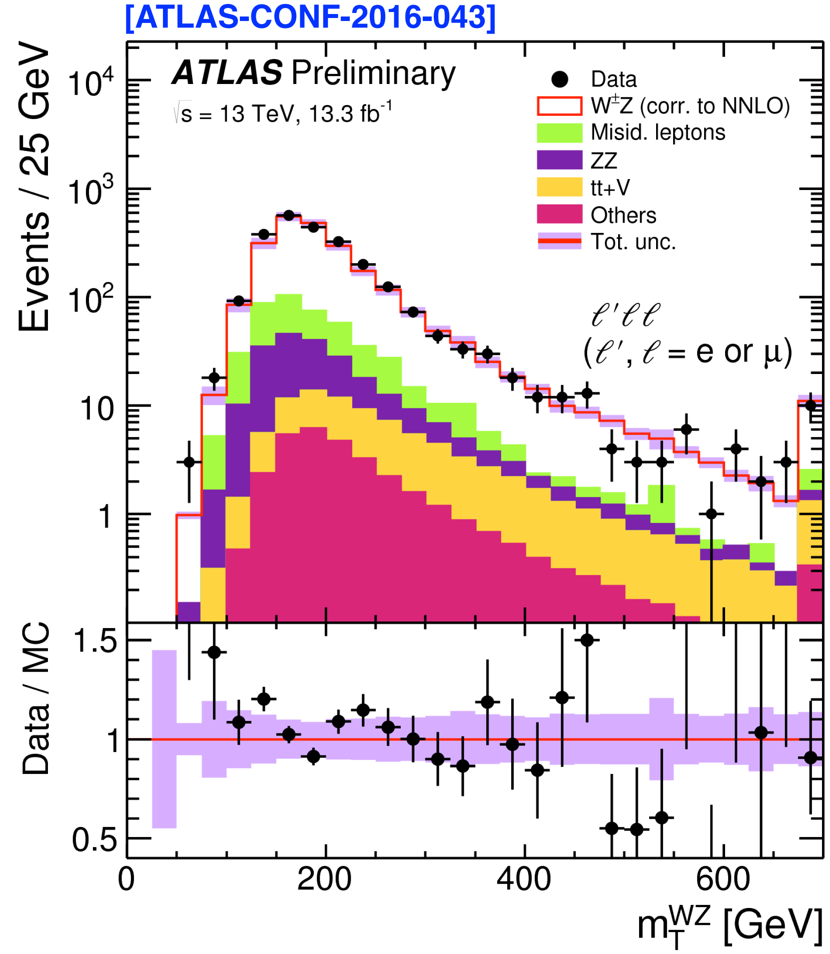


Systematic uncertainties

- Comparable contributions:
  - statistical
  - luminosity
- Dominant systematics:
  - fake background estimation
  - electron, muon identification

[ATLAS-CONF-2016-043]



	eee	μee	$e\mu\mu$	$\mu\mu\mu$	combined
Relative uncertainties [%]					
e energy scale	0.3	0.2	0.2	0.0	0.1
e id. efficiency	4.6	2.7	1.9	0.0	1.3
μ momentum scale	0.0	0.1	0.1	0.2	0.1
μ id. efficiency	0.0	1.3	2.6	3.7	2.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ and jets	0.5	0.4	0.8	0.9	0.8
Trigger	0.1	0.1	0.1	0.2	0.1
Pileup	0.5	1.2	1.4	1.1	1.1
Misid. leptons background	11.9	5.6	11.9	1.7	3.1
ZZ background	0.6	0.7	0.6	0.6	0.6
Other Irr. backgrounds	0.5	0.5	0.4	0.3	0.4
Uncorrelated	10.6	9.2	6.2	3.6	2.9
Total systematics	16.6	11.3	13.9	5.7	5.5
Luminosity	3.3	3.3	3.2	3.2	3.2
Statistics	6.2	5.3	5.3	4.1	2.7
Total	18.1	12.9	15.2	7.7	6.9

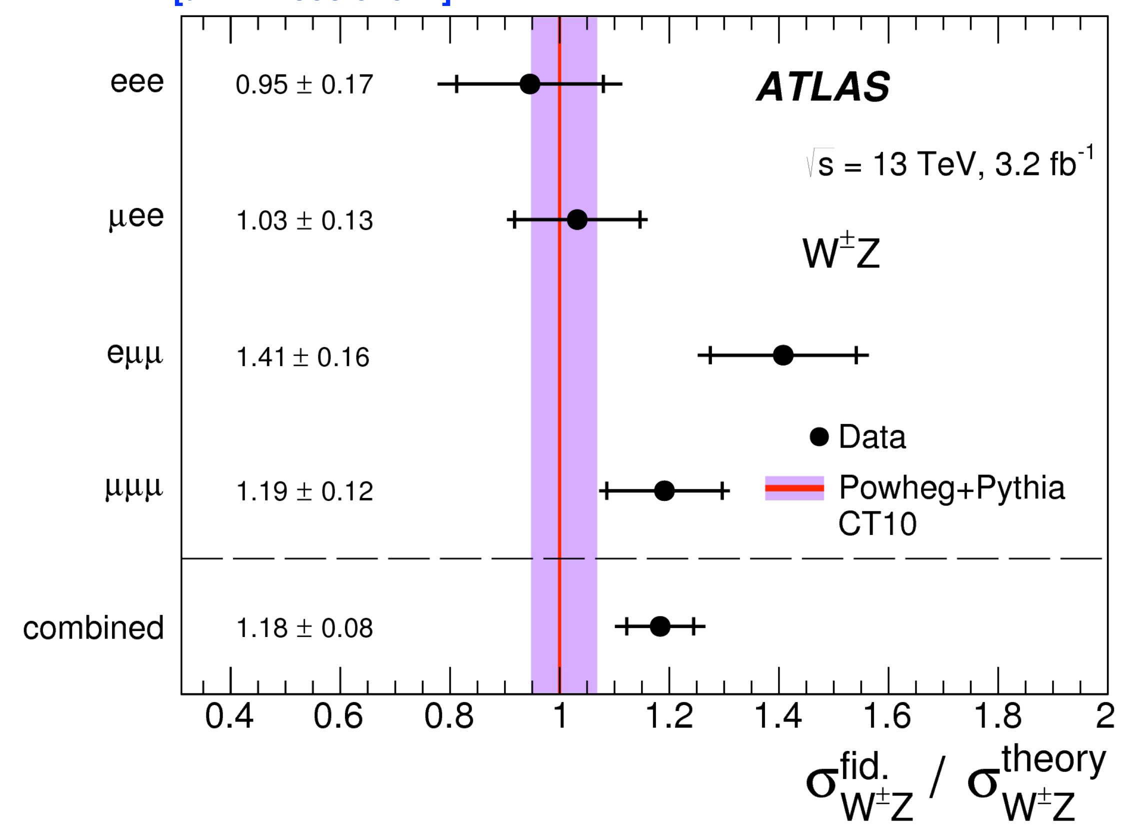
data2015: Fiducial and total cross-sections

- Combination of 4 channels using a χ^2 minimisation
- NLO SM prediction: POWHEG+PYTHIA ($\mu_R = m_{WZ/2}$, CT10 PDF)
- Same deviation (~1.7σ) from NLO prediction as observed in Run-I

$$\sigma^{\text{fid.}}_{W^\pm Z \to \ell' \nu \ell\ell} = 63.2 \pm 3.2\,(\text{stat.}) \pm 2.6\,(\text{sys.}) \pm 1.5\,(\text{lumi.})\ \text{fb}$$

$$\sigma^{fid}_{NLO,POWHEG+PYTHIA} = 53.4^{+3.6}_{-2.8}\ fb$$

[arXiv:1606.04017]



- Fiducial cross-section extrapolated to the total PS (defined by 66 < m_Z < 116 GeV)
- Theoretical uncertainties include PDF, scale and parton shower model (A_{WZ})

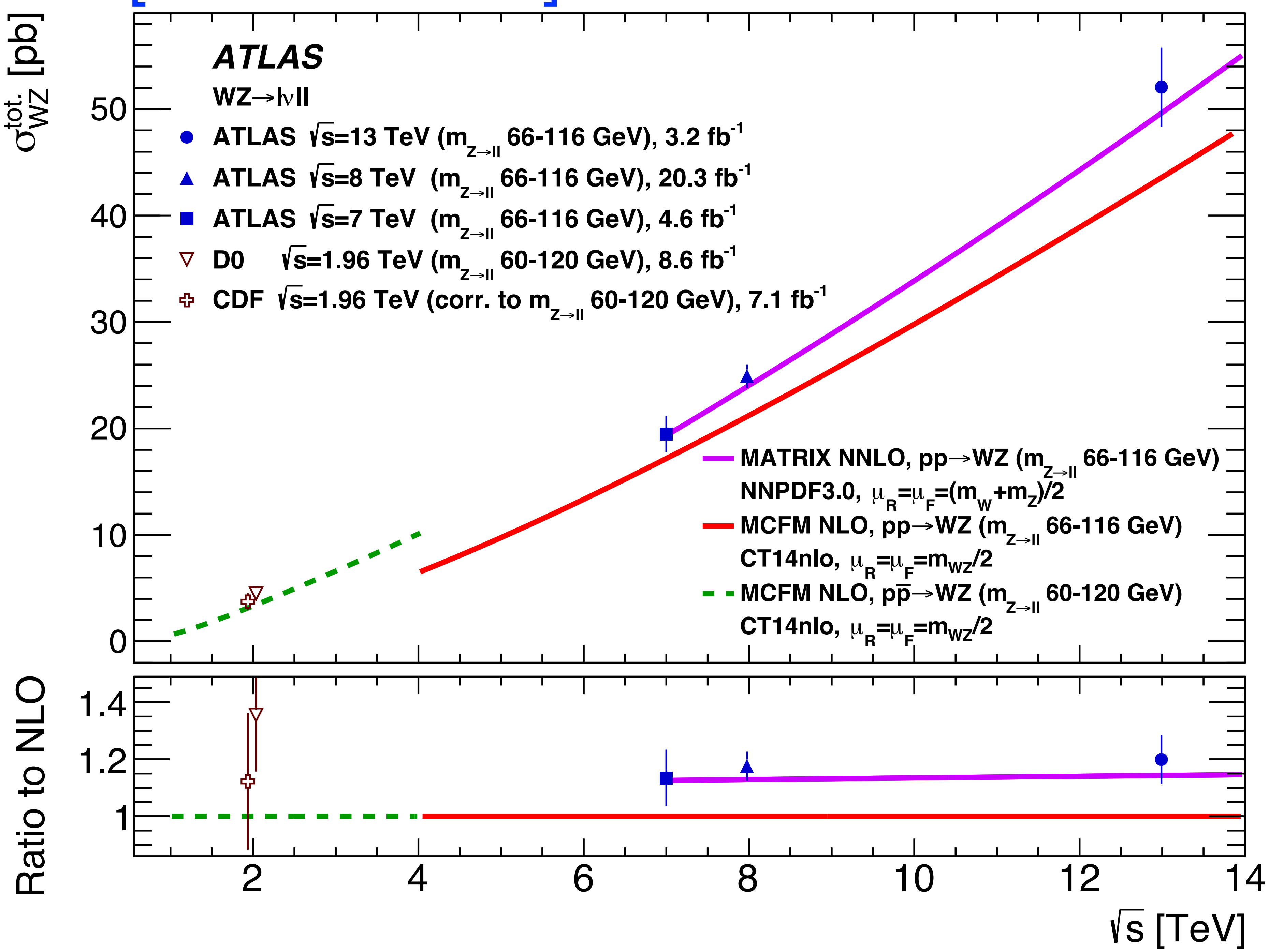
$$\sigma^{\text{tot.}}_{W^\pm Z} = 50.6 \pm 2.6\,(\text{stat.}) \pm 2.0\,(\text{sys.}) \pm 0.9\,(\text{th.}) \pm 1.2\,(\text{lumi.})\ \text{pb}$$

$$\sigma^{tot}_{NLO,POWHEG} = 42.4 \pm 0.3(stat.) \pm 0.8(PDF) \pm 1.6(scale)\,pb$$

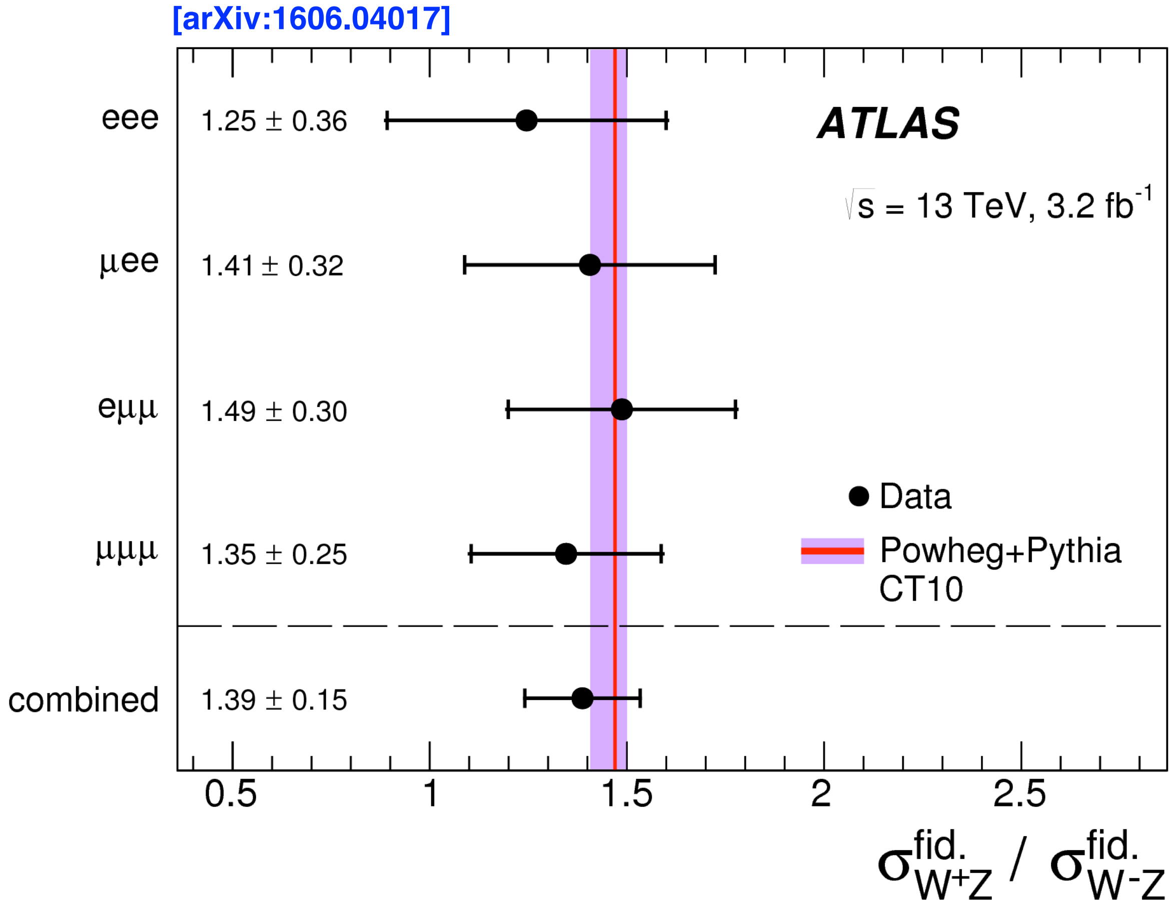
$$\sigma^{tot}_{NNLO,MATRIX} = 48.2^{+1.1}_{-1.0}\,(pb)$$

data2015: Fiducial and total cross-sections

[arXiv:1606.04017]



data2015: Charged and energies ratios



$\sigma^{\mathrm{fid}}_{W^+Z}/\sigma^{\mathrm{fid}}_{W^-Z}$:

$$\frac{\sigma^{\mathrm{fid.}}_{W^+Z\to\ell'\nu\ell\ell}}{\sigma^{\mathrm{fid.}}_{W^-Z\to\ell'\nu\ell\ell}} = 1.39 \pm 0.14\,(\mathrm{stat.}) \pm 0.03\,(\mathrm{sys.})$$

SM NLO prediction (POWHEG+PYTHIA): $1.47^{+0.03}_{-0.06}$

13TeV/8TeV:

$$\frac{\sigma^{\mathrm{fid.,13\ TeV}}_{W^\pm Z}}{\sigma^{\mathrm{fid.,8\ TeV}}_{W^\pm Z}} = 1.80 \pm 0.10\ (\mathrm{stat.}) \pm 0.08\ (\mathrm{sys.}) \pm 0.06\ (\mathrm{lumi.}).$$

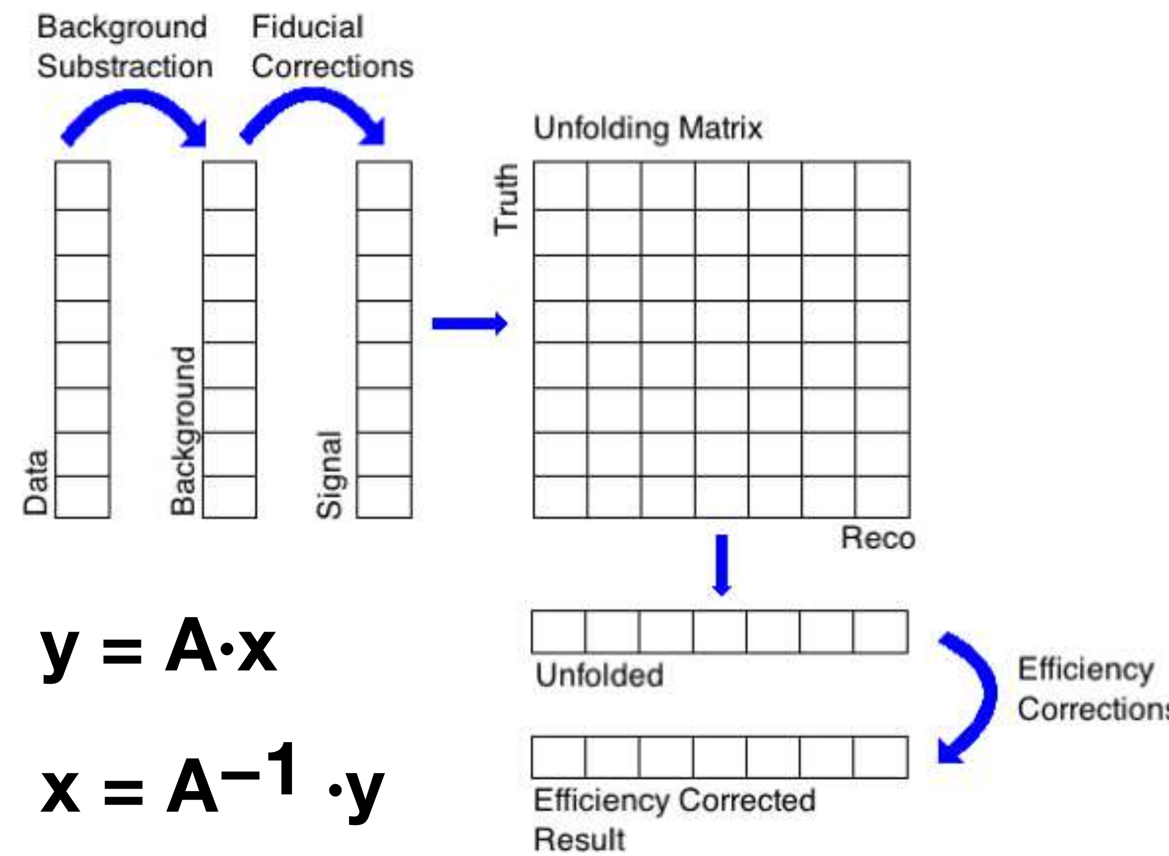
SM NLO prediction (POWHEG+PYTHIA): 1.78±0.03

Unfolding of the differential distribution

- Unfold differential distributions to remove detector effects, namely:
  - Limited acceptance
  - Imperfect detector efficiency
  - Finite resolution

- Response matrix: constructed using signal MC, contains the migrations from generated to reconstructed bins

- d'Agostini's Bayesian iterative **arXiv:1010.0632**



$$\mathbf{y} = \mathbf{A}\cdot\mathbf{x}$$

$$\mathbf{x} = \mathbf{A}^{-1}\cdot\mathbf{y}$$

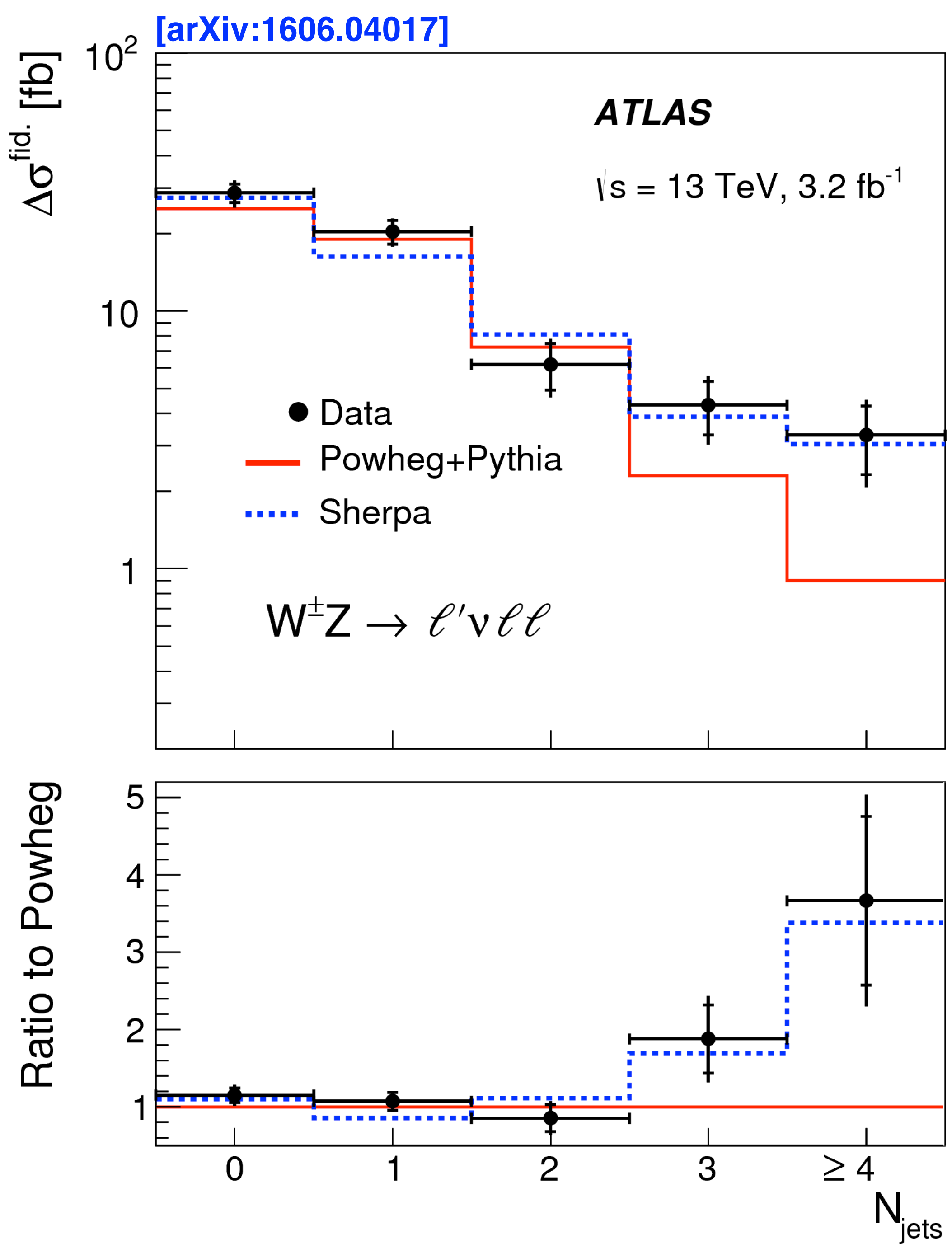
y: Measured distribution of observable
x: "True" distribution

More on Silvia Biondi's talk:
Experience with using unfolding procedures in ATLAS
https://indico.cern.ch/event/353906/contributions/2219987/

data2015:Differential cross-section vs N_{jets}

- All 4 channels added together
- Jets with p_T > 25 GeV, $|\eta|$<4.5
- Bayesian iterative, 3 iterations
- Dominant systematic: Prior uncertainty

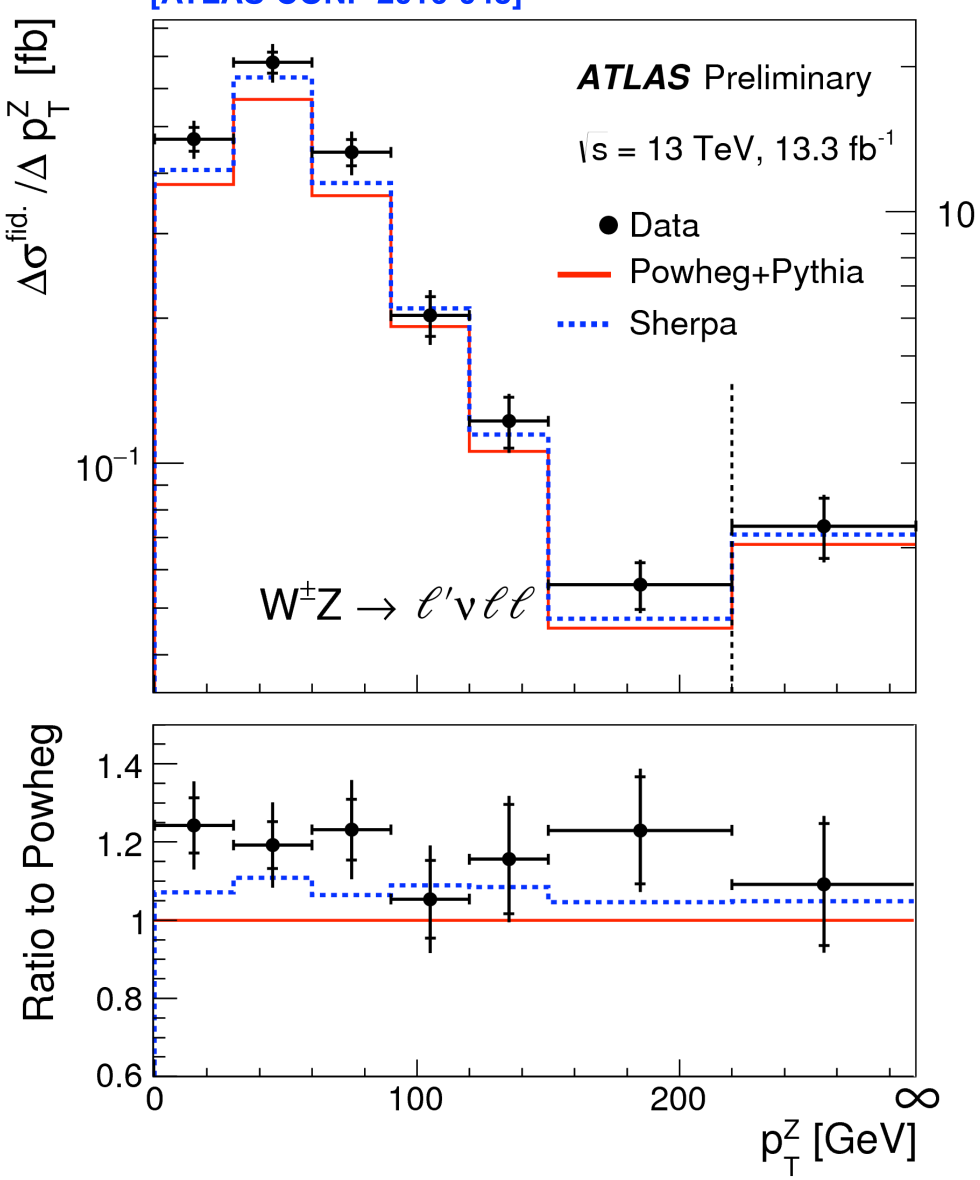
N_{jets}	0	1	2	3	≥ 4
$\Delta\sigma^{\text{fid.}}_{W^\pm Z}$ [fb]	28.7	20.3	6.2	4.3	3.3
Relative Uncertainties [%]					
Statistics	8.1	10.5	20.4	23.5	29.7
All systematics	8.7	6.2	15.2	18.1	22.4
Luminosity	2.3	2.4	2.8	2.8	3.1
Total	12.1	12.4	25.6	29.8	37.3
Prediction from Powheg+Pythia					
$\Delta\sigma^{\text{fid.}}_{W^\pm Z}$ [fb]	24.5	18.6	7.1	2.3	0.9
Prediction from Sherpa					
$\Delta\sigma^{\text{fid.}}_{W^\pm Z}$ [fb]	27.0	16.0	8.0	3.8	3.0



data2015+2016: Differential cross-section vs Z_{pT}, m_T^{WZ}

- All 4 channels added together; Z_{pT}, m_TWZ differential cross-sections reported for the first time in this energy regime
- Bayesian iterative: 3 iterations for Z_{pT}, 2 for m_T^{WZ}; Dominant systematic: Prior uncertainty

[ATLAS-CONF-2016-043]



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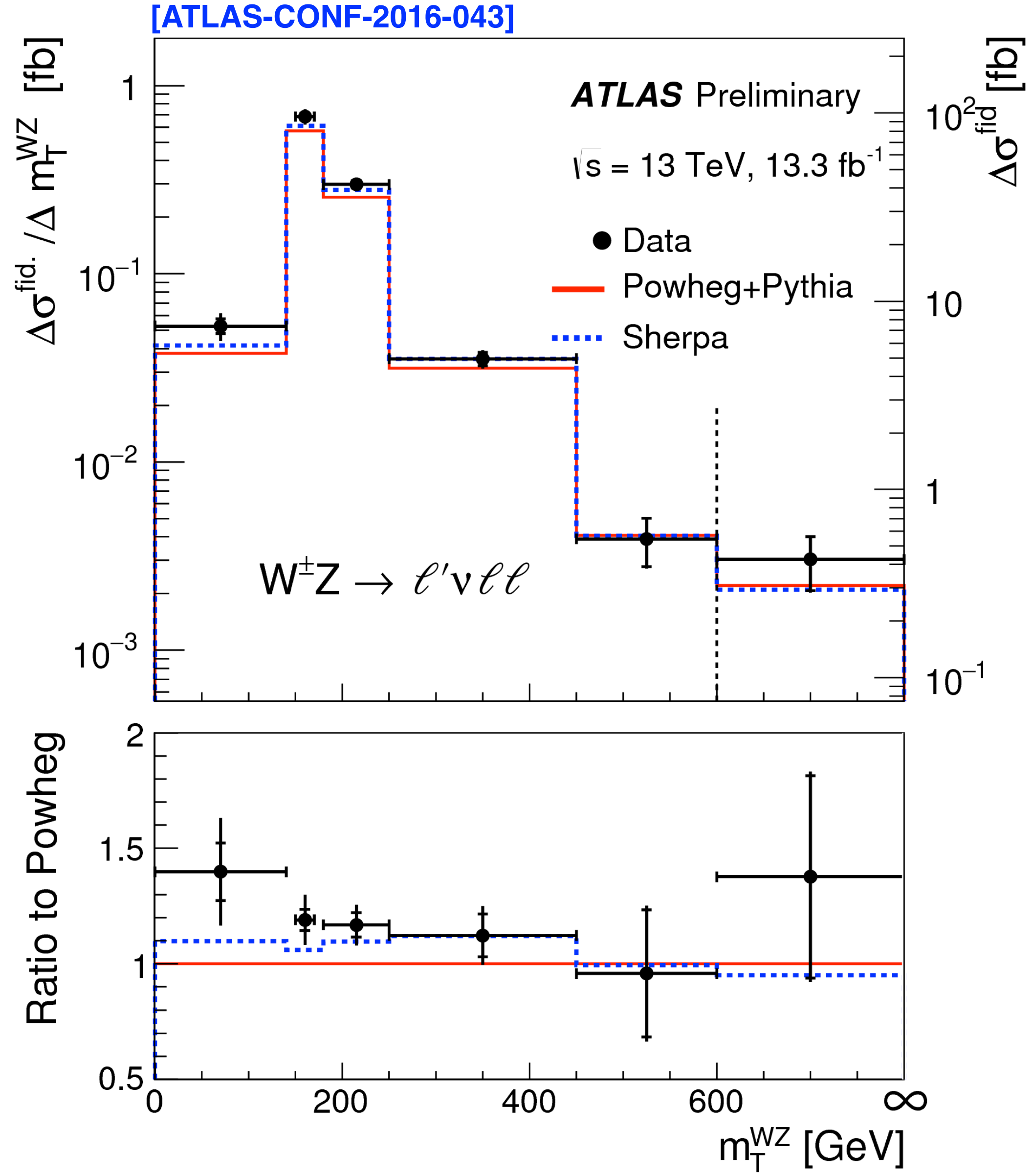


data2015+2016: aTGC confidence intervals

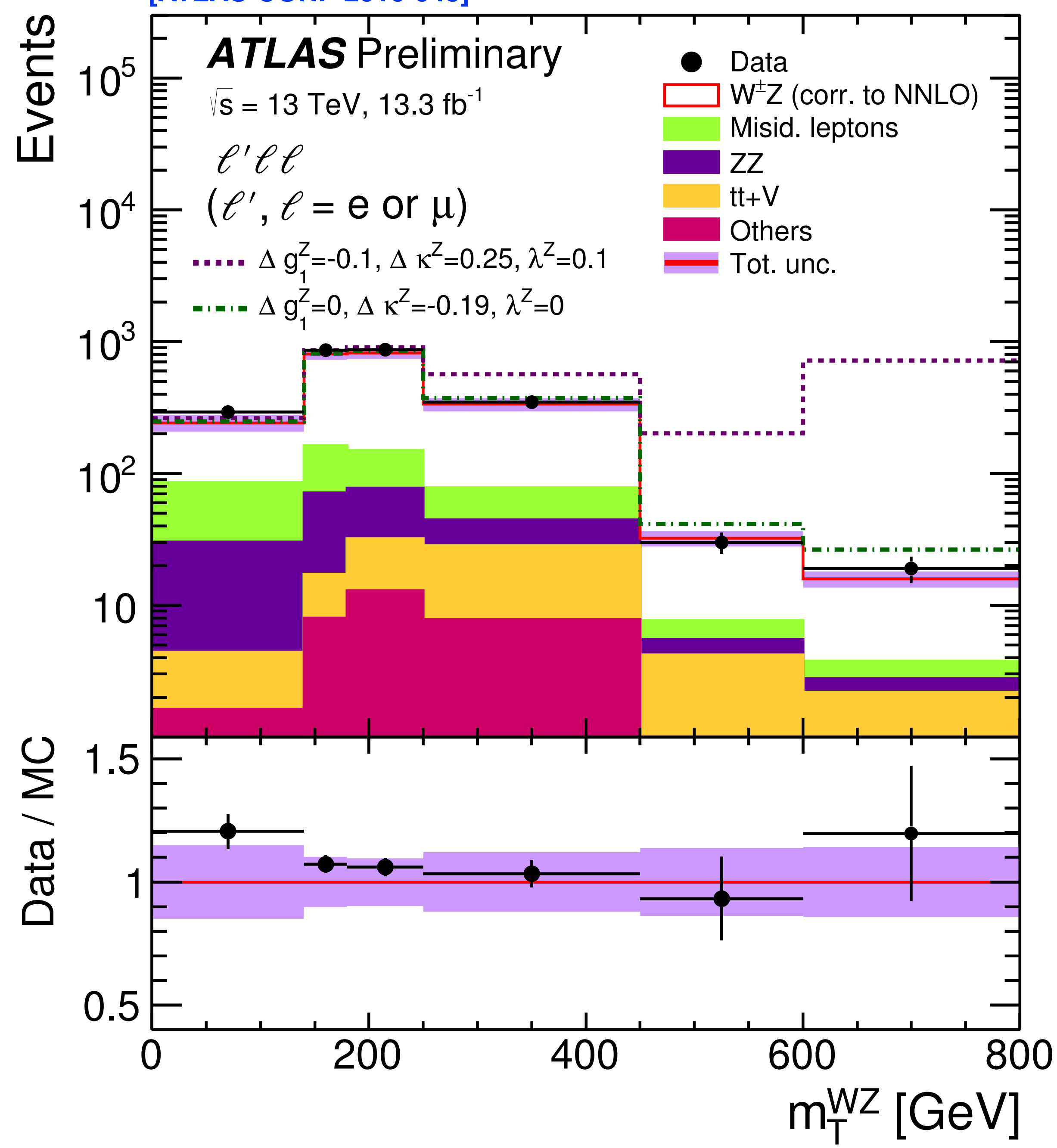
- Anomalous WWZ couplings are expected to increase the yield in the higher bins of differential distributions
- Two parametrisations used:
  - An effective Lagrangian describing the WWZ vertex that includes only CP-conserving terms: $\Delta\kappa^Z$, Δg^Z, λ^Z
  - An EFT parametrisation (alternatively to the generalised Lagrangian): c_{WWW}/Λ^2_{NP}, c_B/Λ^2_{NP}, c_W/Λ^2_{NP}
- m_T^{WZ} distribution used to extract limits

$$\frac{c_W}{\Lambda^2} = \frac{2}{m_Z^2}\Delta g_1^Z$$

$$\frac{c_B}{\Lambda^2} = \frac{2}{m_Z^2}(\Delta\kappa^\gamma - \Delta\kappa^Z)$$

$$\frac{c_{WWW}}{\Lambda^2} = \frac{2}{3g^2 m_W^2}\lambda$$

[ATLAS-CONF-2016-043]



Reconstructed signal MC scaled to match recent NNLO QCD calculations

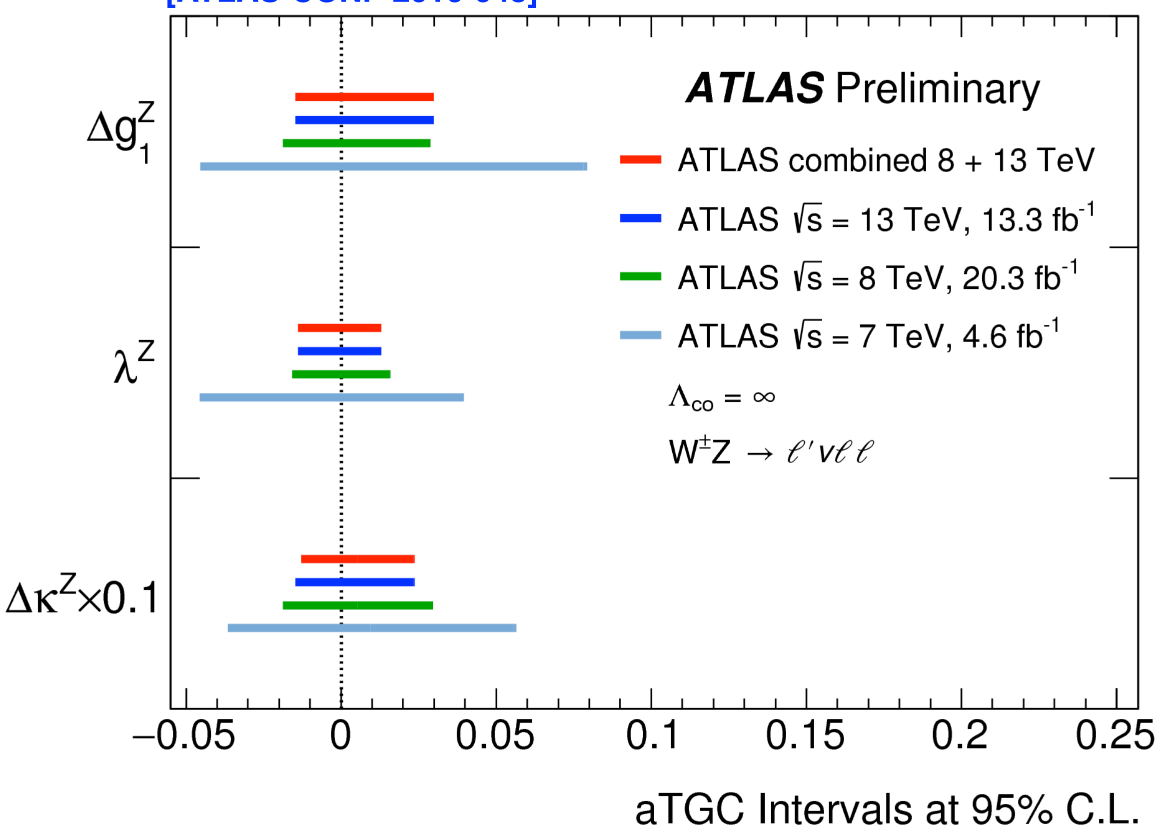
data2015+2016: aTGC confidence intervals results

- Extract the 95% CL intervals using a frequentist approach: Feldman-Cousins profile likelihood implementation
- Λ_∞ to extract CL intervals (unitarity constraints: Λ_{cutoff} > 10 TeV, form-factor ~ 1)
- The combination of 8 and 13 TeV data improves the CL intervals by as much as 20%

Dataset	Coupling	Expected	Observed
13 TeV	Δg_1^Z	[-0.017; 0.032]	[-0.016; 0.036]
	$\Delta\kappa_1^Z$	[-0.18; 0.24]	[-0.15; 0.26]
	λ^Z	[-0.015; 0.014]	[-0.016; 0.015]
8 and 13 TeV	Δg_1^Z	[-0.014; 0.029]	[-0.015; 0.030]
	$\Delta\kappa_1^Z$	[-0.15; 0.21]	[-0.13; 0.24]
	λ^Z	[-0.013; 0.012]	[-0.014; 0.013]

Generalised Lagrangian

[ATLAS-CONF-2016-043]



Dataset	Coupling	Expected [TeV^{-2}]	Observed [TeV^{-2}]
13 TeV	c_W/Λ^2_{NP}	[-4.1; 7.6]	[-3.8; 8.6]
	c_B/Λ^2_{NP}	[-261; 193]	[-280; 163]
	c_{WWW}/Λ^2_{NP}	[-3.6; 3.4]	[-3.9; 3.7]
8 and 13 TeV	c_W/Λ^2_{NP}	[-3.4; 6.9]	[-3.6; 7.3]
	c_B/Λ^2_{NP}	[-221; 166]	[-253; 136]
	c_{WWW}/Λ^2_{NP}	[-3.2; 3.0]	[-3.3; 3.2]

EFT

Most stringent CL intervals in the charged WWZ vertex!

Conclusions

- The WZ diboson production is an excellent probe of the EWK sector
- No deviations from the SM prediction observed
- aTGC confidence intervals measured at 13 TeV and combined with 8 TeV. An up to ~20% improvement achieved over previous results
- NNLO calculations provide ~11% increase in total cross-section and describe much better the LHC data
- Theorists need to “compete” with the high experimental precision in the measurements
- On the experimental side, we need to improve on systematic uncertainties to profit from the high statistics
- One of the most “highlighted” precision measurements at ICHEP2016!

Back up

Object selection

Electrons

Selection	Baseline	Z	W
$p_T > 7$ GeV	✓	✓	✓
Electron object quality	✓	✓	✓
$\|\eta_{cluster}\| < 2.47$, $\|\eta\| < 2.5$	✓	✓	✓
LooseLH + BLayer identification	✓	✓	✓
$\sigma(d_0^{BL}) < 5$	✓	✓	✓
$\|\Delta z_0^{BL} \sin\theta\| < 0.5$ mm	✓	✓	✓
LooseTrackOnly isolation	✓	✓	✓
e-μ and e-e overlap removal	✓	✓	✓
e-jet Overlap Removal		✓	✓
$p_T > 15$ GeV		✓	✓
Exclude $1.37 < \|\eta_{cluster}\| < 1.52$		✓	✓
MediumLH identification		✓	✓
Gradient Loose isolation		✓	✓
$p_T > 20$ GeV			✓
TightLH identification			✓
Gradient isolation			✓

Muons

Selection	Baseline	Z	W
$p_T > 7$ GeV	✓	✓	✓
$\|\eta\| < 2.5$	✓	✓	✓
Loose quality	✓	✓	✓
$\sigma(d_0^{BL}) < 3$	✓	✓	✓
$\|\Delta z_0^{BL} \sin\theta\| < 0.5$ mm	✓	✓	✓
LooseTrackOnly isolation	✓	✓	✓
μ-jet Overlap Removal		✓	✓
$p_T > 15$ GeV		✓	✓
Medium quality		✓	✓
Gradient Loose isolation		✓	✓
$p_T > 20$ GeV			✓

Jets

AntiKt4EMTopoJets
$p_T > 25$ GeV
$\|\eta\| < 4.5$
JVT > 0.64, for jets with $p_T < 50$ GeV and $\|\eta\| < 2.4$

MET

Track soft term
Hard term: baseline leptons
Calo based MET with JVT cut

Unfolding N_{jet} uncertainties

N_{jets}	0	1	2	3	≥ 4
Prior uncertainty	0.1	2.2	10.0	14.9	8.8
Misid. leptons background	3.72	4.56	9.44	6.67	6.04
ZZ background	0.56	0.73	0.97	0.47	0.21
$WZ \to \tau$ background	0.30	0.36	0.49	0.22	0.12
tZ background	0.00	0.10	1.07	0.77	0.77
$t\bar{t}V$ background	0.00	0.00	0.19	1.3	4.7
Jet energy scale, EffectiveNP 1	-4.32	1.80	3.21	4.19	11.2
Jet energy scale, EffectiveNP 2	0.78	-0.42	-0.85	-0.92	-1.98
Jet energy scale, EffectiveNP 3	-0.23	0.17	0.37	0.45	0.59
Jet energy scale, EffectiveNP 4	0.10	-0.06	-0.18	-0.31	-0.00
Jet energy scale, EffectiveNP 5	-0.00	0.00	0.11	0.00	-0.09
Jet energy scale, EffectiveNP 6	-0.00	0.00	0.09	-0.07	-0.05
Jet η intercalibration, modelling	-2.21	0.84	2.04	3.03	5.46
Jet η intercalibration, total	-0.79	0.35	0.79	0.50	2.07
Jet flavor composition	-4.57	1.88	3.49	4.41	12.4
Jet flavor response	1.40	-0.58	-0.97	-1.59	-3.32
Jet pile-up, offset term, μ	0.26	-0.15	-0.20	-0.10	-0.68
Jet pile-up, offset term, number of primary vertexes	-0.06	-0.06	0.30	0.00	0.32
Jet pile-up, p_{T} term	-0.00	0.00	0.11	-0.13	0.00
Jet pile-up, ρ topology	-1.42	0.64	1.09	1.35	3.63
Jet punch through	-0.00	0.00	0.00	-0.00	0.00
Jet single particle, high p_{T}	0.00	0.00	0.00	0.00	0.00
Jet vertex tagger	-0.78	0.32	1.12	0.64	2.43
$E_{\text{T}}^{\text{miss}}$ track soft term scale	0.05	0.16	0.11	0.00	0.07
$E_{\text{T}}^{\text{miss}}$ track soft term resolution	0.12	0.16	0.09	0.15	0.15
Pile-up	2.88	0.44	0.36	1.24	2.79
Electron energy resolution, calorimeter material	0.00	0.00	0.00	0.00	0.14
Electron energy resolution, cryostat material	0.00	0.00	0.05	0.11	0.15
Electron energy resolution, gap	0.00	0.00	0.05	0.06	0.00
Electron energy resolution, ID material	0.00	0.00	0.10	0.08	0.09
Electron energy resolution, pile-up	0.00	0.00	0.07	0.00	0.06
Electron energy resolution, sampling term	0.05	0.00	0.06	0.10	0.12
Electron energy resolution, Z smearing	0.05	0.18	0.00	0.26	0.32
Electron energy scale, GEANT4	0.00	0.00	0.00	0.00	0.05
Electron energy scale, layer 1 gain	0.00	0.00	0.00	0.00	0.00
Electron energy scale, layer 2 gain	0.00	0.00	0.00	0.05	0.19
Electron energy scale, LAr E1/E2 relative calibration from muons	0.00	0.00	0.06	0.00	0.10
Electron energy scale, LAr E1/E2 electron calibration	0.00	0.00	0.00	0.00	0.00
Electron energy scale, LAr E1/E2 modelling differences between electrons and unconverted photons	0.00	0.06	0.07	0.08	0.11
Electron energy scale, LAr E1/E2 modelling for unconverted photons	0.00	0.00	0.00	0.00	0.09
Electron energy scale, calorimeter material	0.00	0.00	0.00	0.00	0.09
Electron energy scale, cryostat material	0.00	0.00	0.00	0.00	0.19
Electron energy scale, ID material	0.00	0.00	0.05	0.00	0.14
Electron energy scale, pedestal	0.00	0.00	0.00	0.00	0.00
Electron energy scale, presampler layer	0.00	0.00	0.00	0.00	0.09
Electron energy scale, E1/E2 ratio	0.00	0.00	0.00	0.00	0.06
Electron energy scale, $Z \to ee$ statistics	0.00	0.00	0.00	0.00	0.00
Electron energy scale, $Z \to ee$ systematics	0.18	0.15	0.11	0.24	0.26
Electron ID efficiency	1.10	1.20	1.32	1.48	1.56
Electron isolation efficiency	0.30	0.37	0.50	0.62	0.71
Electron reconstruction efficiency	0.49	0.55	0.59	0.64	0.66
Electron trigger efficiency	0.00	0.00	0.00	0.00	0.00
Muon reconstruction, ID	0.00	0.06	0.08	0.00	0.20
Muon reconstruction, MS	0.00	0.00	0.07	0.15	0.06
Muon scale	0.00	0.00	0.13	0.09	0.16
Muon ID efficiency, statistics	0.20	0.10	0.00	0.10	0.41
Muon ID efficiency, low p_{T} systematics	0.00	0.20	0.36	0.45	0.58
Muon ID efficiency, systematics	0.51	0.41	0.51	0.65	0.21
Muon trigger efficiency, statistics	0.09	0.09	0.08	0.08	0.08
Muon trigger efficiency, systematics	0.00	0.00	0.00	0.00	0.00
Muon isolation efficiency, statistics	0.06	0.07	0.08	0.08	0.10
Muon isolation efficiency, systematics	0.35	0.35	0.36	0.36	0.40
Muon track-to-vertex association efficiency, statistics	0.13	0.16	0.17	0.17	0.18
Muon track-to-vertex association efficiency, systematics	0.17	0.18	0.18	0.16	0.15

Unfolding N_{jets} prior uncertainty

- Perform nominal unfolding using Powheg+Pythia;
- Extract reweighing factors by comparing the unfolded data (result of step 1) distribution to the MC truth;
- The Powheg+Pythia MC WZ signal sample is reweighed with the factors (obtained from step 2);
- A reweighed response matrix is obtained (using the reweighed MC from step 3) and the unfolding procedure is repeated, with the role of data played by the reconstructed MC, under the no-background hypothesis (similar to a simple MC closure test);
- By comparing the unfolded reconstructed distribution (result of step 4) to the initial MC truth (step 1), the uncertainty per bin is estimated;