Tests of the electroweak sector with diboson final states at the ATLAS Experiment

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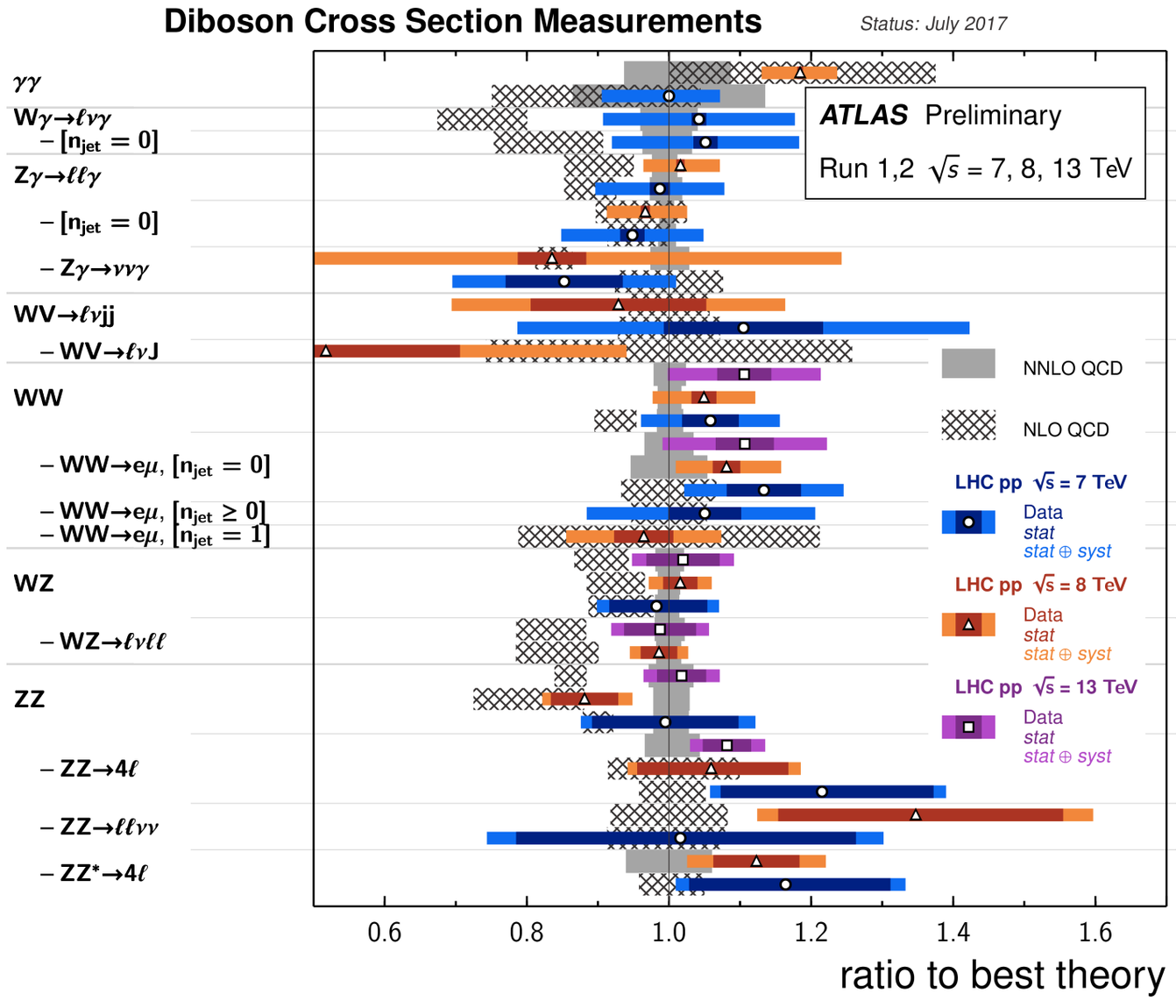
Lake Louise Winter Institute, 15th February 2019

Introduction

- Diboson production
  - Stringent test of the electroweak sector.
  - Model-independent means to search for new physics at the TeV scale.
- Vector boson scattering: diboson production in association with two jets.
  - Key process to investigate electroweak symmetry breaking.



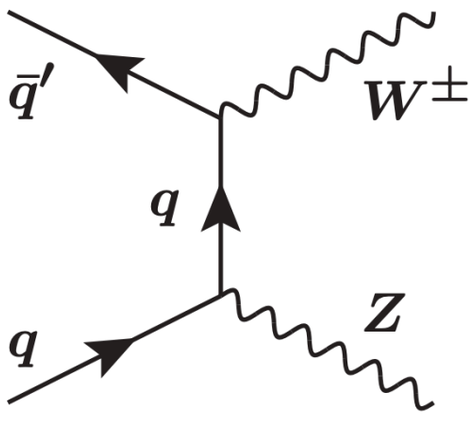
Overview

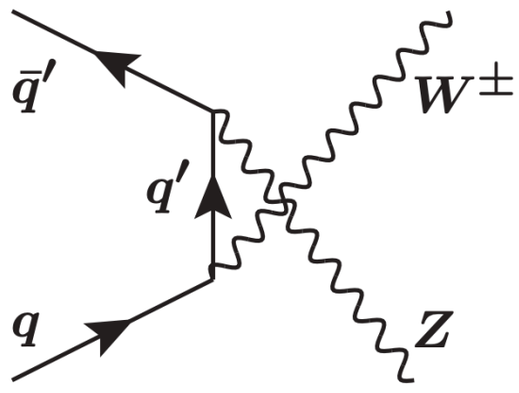
- In this talk I'll cover three analyses using 36.1 fb^{-1} of *pp* collision data recorded in 2015 and 2016 at $\sqrt{s}$=13 TeV:
  - Measurement of $W^{\pm}Z$ production cross sections and gauge boson polarisation ATLAS-CONF-2018-034

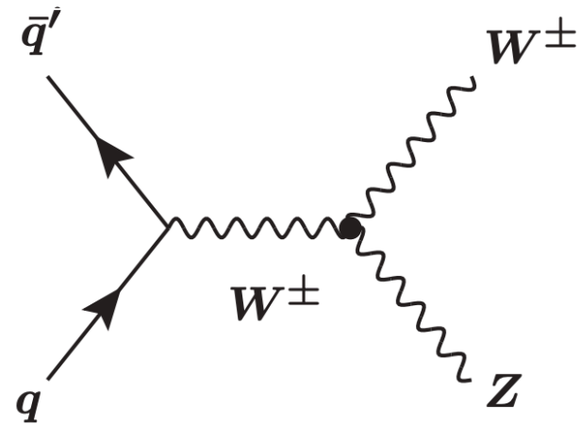
Paper submitted to EPJC today, will appear on arXiv on Monday STDM-2018-03

  - Observation of electroweak production of $W^{\pm}Z$ boson pair in association with two jets arXiv:1812.09740 [hep-ex]
  - Observation of electroweak production of a same-sign W boson pair in association with two jets ATLAS-CONF-2018-030
- New diboson results not covered:
  - Measurement of $Z\gamma \rightarrow \nu\nu\gamma$ cross-sections and limits on anomalous triple gauge-boson couplings JHEP 12 (2018) 010

$W^{\pm}Z$ production



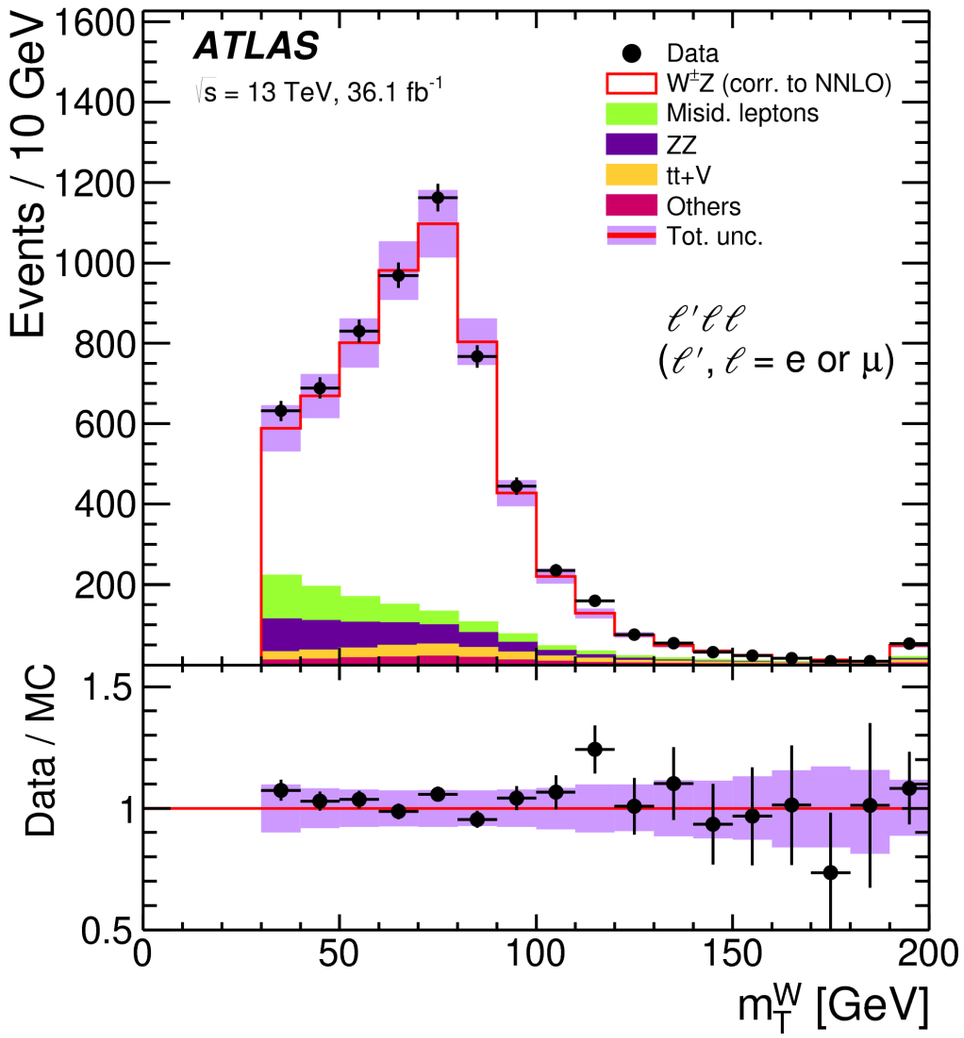




- Use leptonic (e, mu) decay modes of the gauge bosons.
- 3 isolated well reconstructed e and μ, veto fourth lepton to suppress ZZ.
- Fiducial phase space:
  - $Z \rightarrow ll$: $p_T^l > 15$ GeV, $|\eta^l| < 2.5$, $|m_{ll} - m_Z| < 10$ GeV.
  - $W \rightarrow l'\nu$: $p_T^{l'} > 20$ GeV, $|\eta^l| < 2.5$, transverse mass $m_T^W > 30$ GeV.
  - $\Delta R(l,l') > 0.3$, $\Delta R(l,l) > 0.2$.
  - Anti-k_T with R=0.4 particle-level jets: $p_T > 25$ GeV and $|\eta^l| < 4.5$.

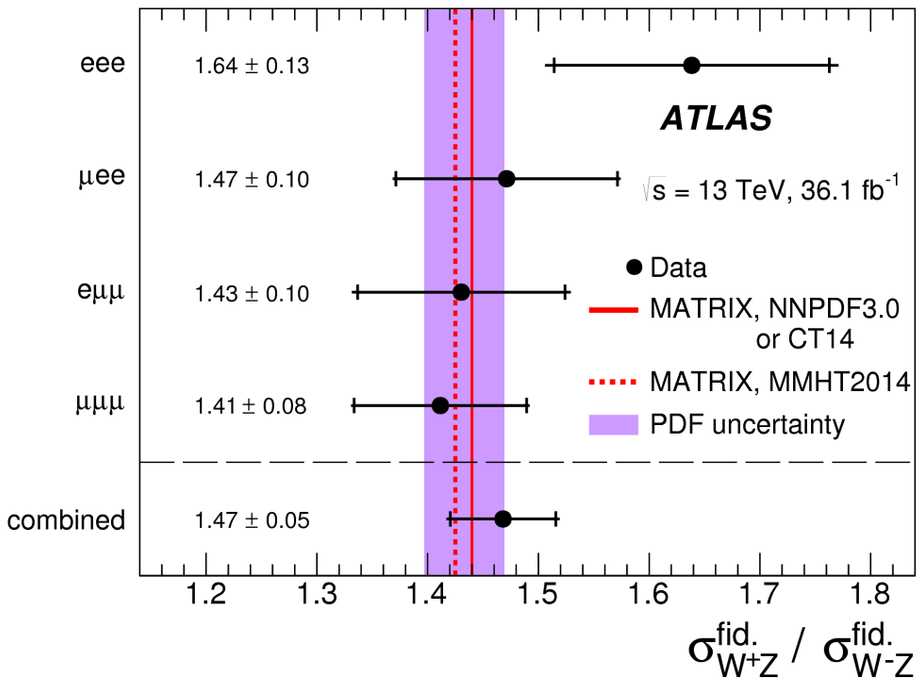
$W^{\pm}Z$ production

- Signal: generated with Powheg-Box at NLO in QCD, shower with Pythia 8.210
- Background:
  - Reducible: Fake lepton (measured in data)
  - Irreducible: ZZ, ttV, tZ, VVV (MC normalised to data CR)
- Systematics: dominated by the uncertainty on reducible background, followed by luminosity.



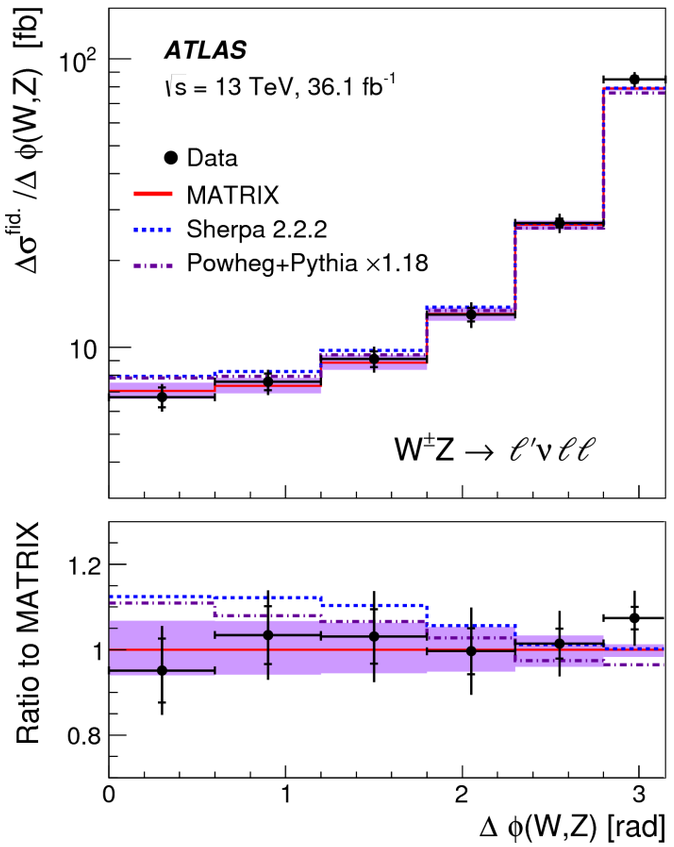
- $\sigma^{\text{fid.}}_{W^{\pm}Z \to l'\nu ll} = 63.7 \pm 1.0\,(\text{stat.}) \pm 2.3\,(\text{sys.}) \pm 0.3\,(\text{mod.}) \pm 1.5\,(\text{lumi.})$ fb
- NNLO prediction (MATRIX): $61.5\ ^{+1.4}_{-1.3}$ fb

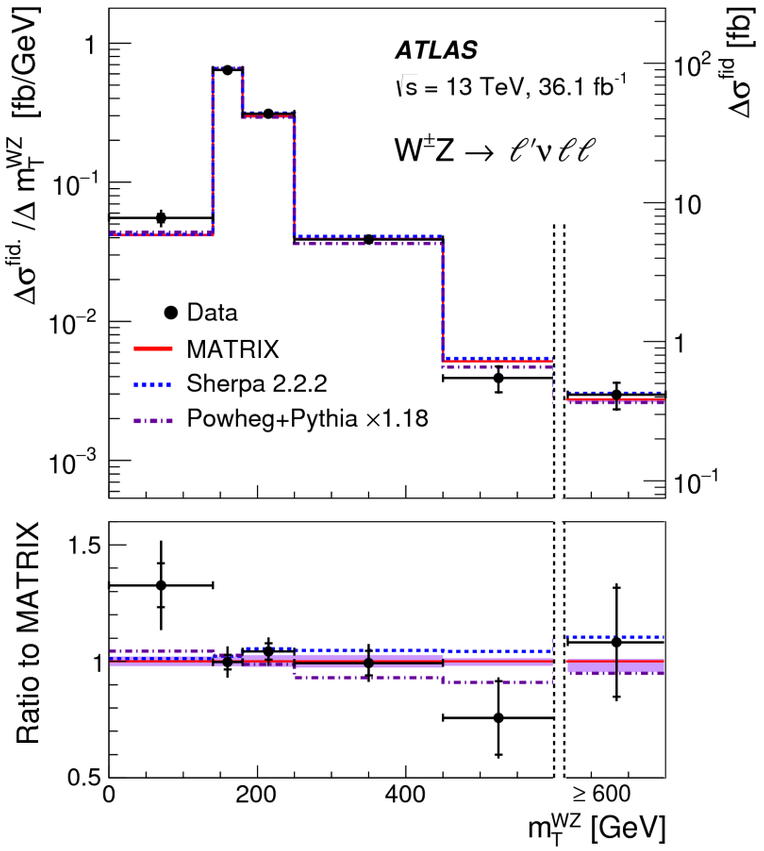
$W^{\pm}Z$ cross-sections



- Differential cross sections for $p_T^Z, p_T^W, m_T^{WZ}, \Delta\phi(W,Z), p_T^{\nu}, |y_Z - y_{l,W}|, N_{jets}, m_{jj}$

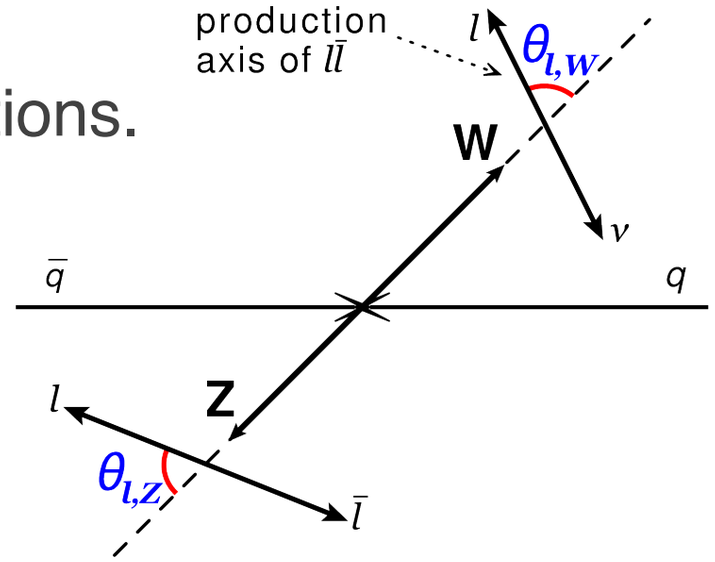
- Ratio of the W^+Z/W^-Z cross sections, which is sensitive to the PDF is also measured.
  - Most systematics cancelled in the ratio.

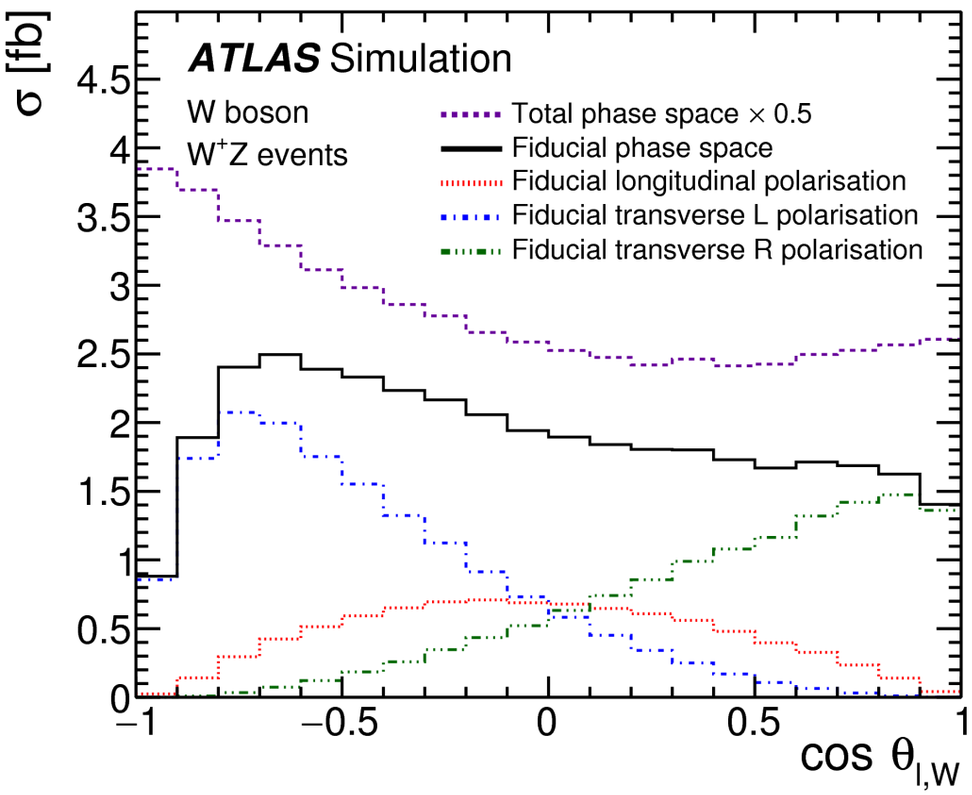


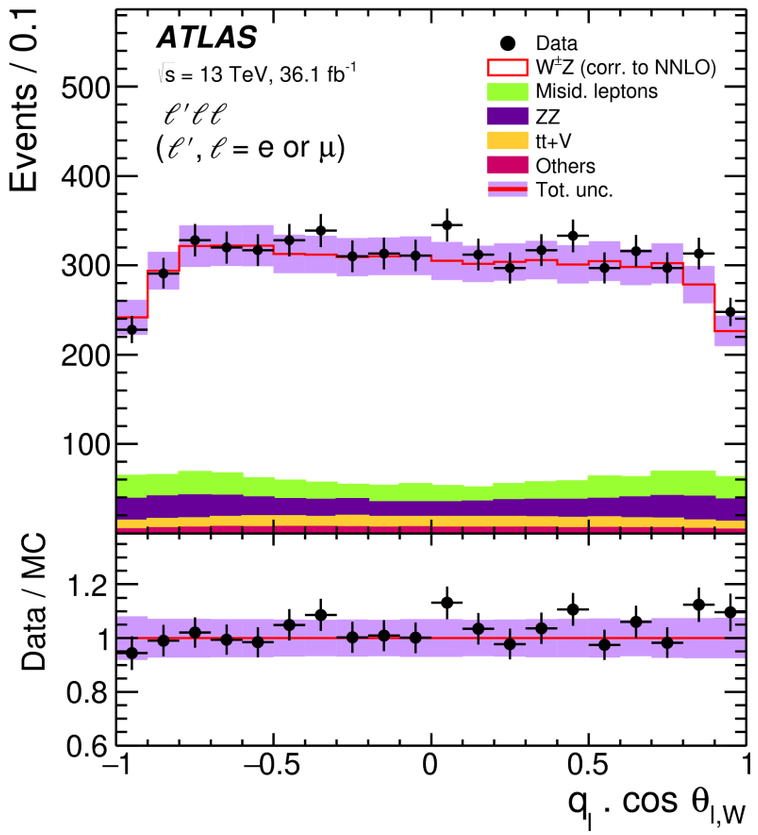


$W^{\pm}/Z$ polarisation

- Measure W/Z polarisation using lepton angular distributions.
- Helicity parameters measured using template fit of $q_\ell \cdot \cos\theta_{\ell,W}$ and $\cos\theta_{\ell,Z}$ distributions.
- m_W constraint to solve for neutrino longitudinal momentum at detector level.

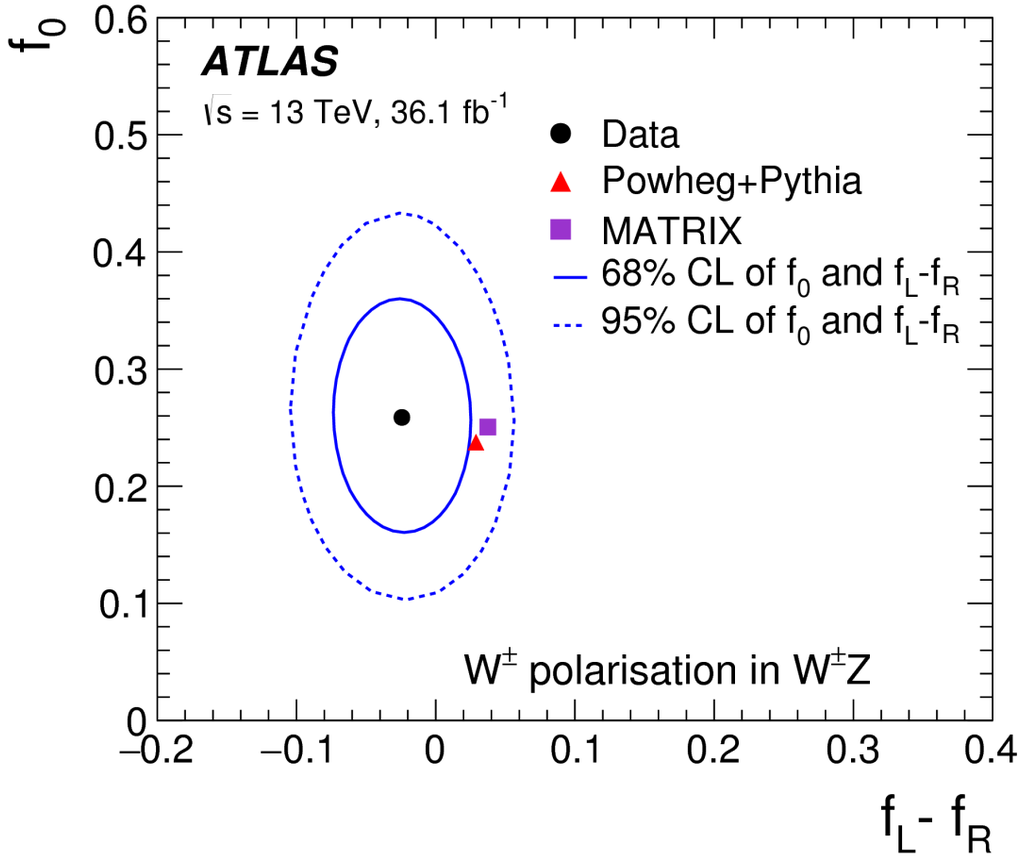


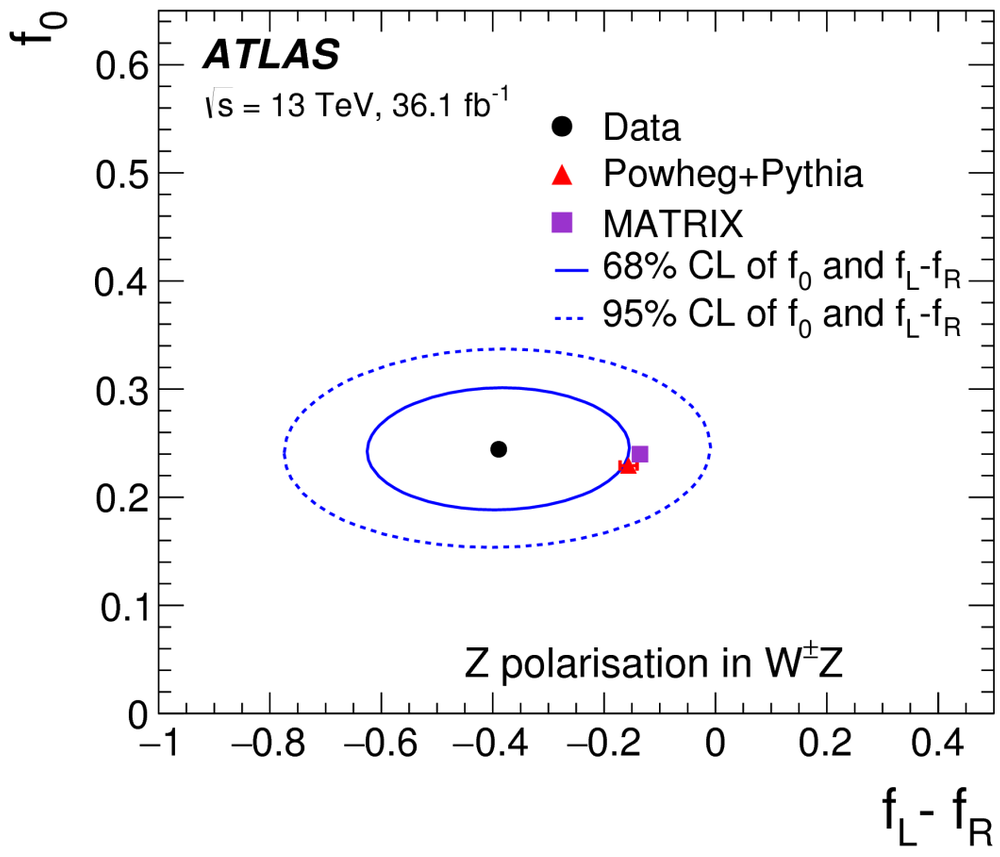




$W^{\pm}/Z$ polarisation

- Obs. (exp.) significance of 4.2σ (3.8σ) for longitudinally polarised W bosons.
- f_0, f_L, f_R: longitudinal, transverse left-handed, transverse right-handed helicity fractions. $f_0 + f_L + f_R = 1$.
- Both MATRIX and Powheg is LO in EW coupling.

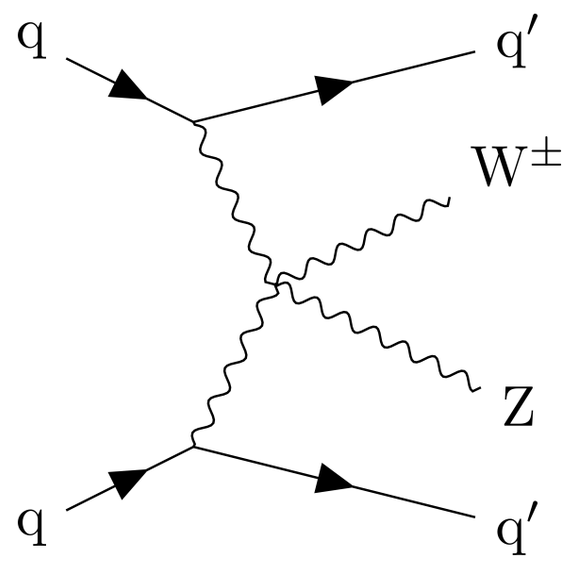




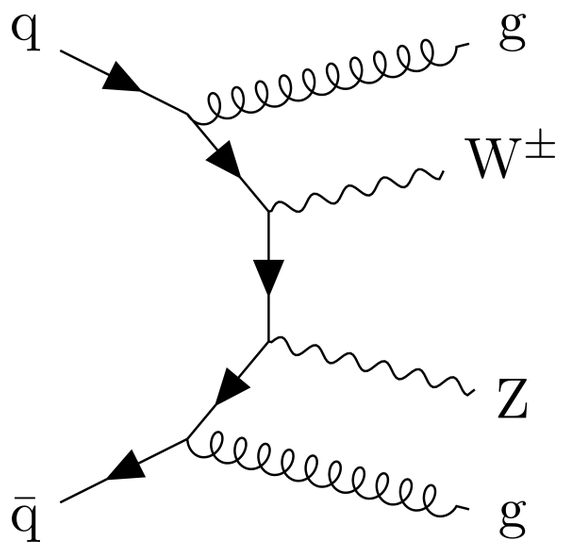
Vector boson scattering

- VBS process is an important test of the electroweak sector.
  - Higgs boson restores unitarity in scattering amplitude.
  - Sensitive to quartic gauge couplings.
- All EW-induced processes (only EW interaction vertices) treated as signal, QCD-induced (at least one strong interaction vertex) as background.
- QCD-induced background dominant (except in same-sign WW).
- VVjj EW and QCD-induced processes interfere.

EW production $\mathcal{O}(\alpha^4)$



QCD-induced production $\mathcal{O}(\alpha^2\alpha_S^2)$



Vector boson scattering

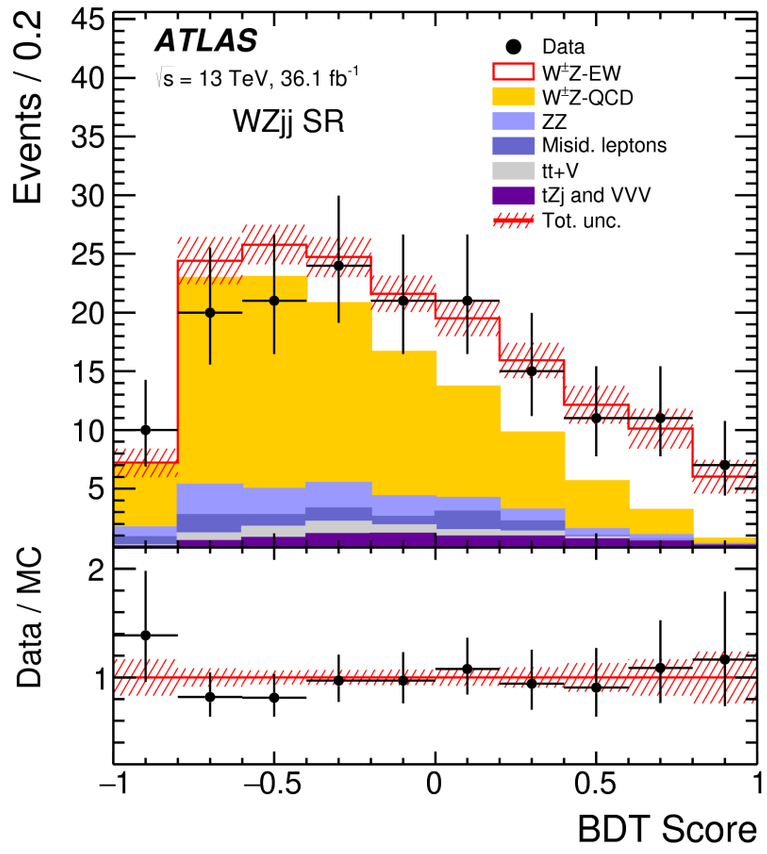
- Typical topology:
  - 2 high energy jets with wide rapidity separation and large m_{jj}.
  - Hadronic activity suppressed between the two jets.
  - Boson pair more central than in non-EWK processes.

- ATLAS VBS measurements:

Process	Remarks	√s	L	Reference
$W^{\pm}W^{\pm}$	**this talk**	13 TeV	36.1 fb^{-1}	ATLAS-CONF-2018-030
$W^{\pm}Z$	**this talk**	13 TeV	36.1 fb^{-1}	arXiv:1812.09740 [hep-ex]
$Z\gamma$	2 σ significance, cross-sections, aQGC limits	8 TeV	20.2 fb^{-1}	JHEP07(2017)107
Semi leptonic WW/WZ	aQGC limits	8 TeV	20.2 fb^{-1}	Phys. Rev. D 95 (2017) 032001

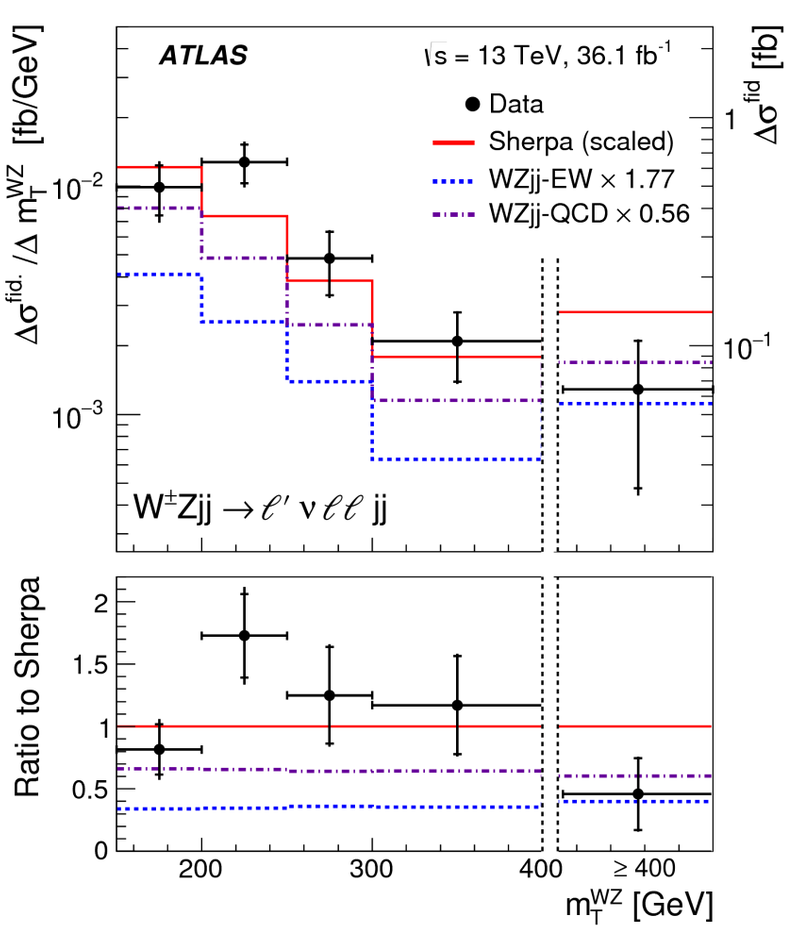
WZ VBS

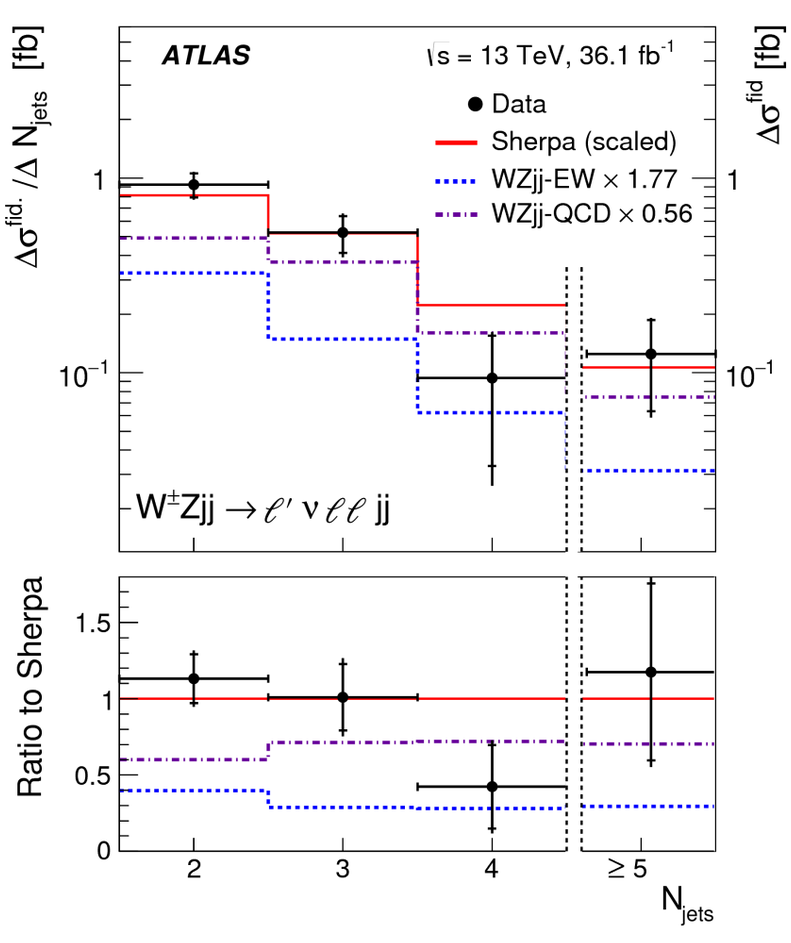
- Fiducial phase-space: similar to the WZ measurement already discussed.
- Additionally, 2 jets with p_T>40 GeV, |η|<4.5, ΔR(j,l)>0.3, m_{jj}>500 GeV, b-jet veto.
- Signal: Sherpa 2.2.2 WZjj
- Background: largest is QCD WZjj (from Sherpa, normalised to data in CR), ZZ, ttV and reducible background.
- Signal purity ~13%.
- Boosted decision tree used to separate signal from background. (15 input variables based on jet, vector boson and lepton kinematics)
- Systematics: jet energy scale dominant, followed by modelling.



WZ VBS

- 5.3 (3.20 σ) observed (exp.) significance.
- Fiducial cross-section for the electroweak production process (inc. interference with QCD process): $0.57\ ^{+0.14}_{-0.13}\ (stat.)\ ^{+0.07}_{-0.06}\ (syst.)$ fb
- Sherpa under-predicts EW WZjj cross-section.
- Differential WZjj cross-section for $\sum p_T^l$, $\Delta\phi(W,Z), m_T^{WZ}, N_{jets}, \Delta y_{jj}, m_{jj}, N_{jets}^{gap}, \Delta\phi_{jj}$





same-sign WW VBS

- Largest ratio of EW to QCD production cross-sections.
- Isolated well reconstructed same-sign dilepton events (e or μ).
- Veto third lepton to suppress WZ and veto b-jets to suppress tt.
- Fiducial region:
  - Same sign dilepton: p_T>27 GeV, |η|<2.5, m_{ll}>20 GeV, ΔR(l,l)>0.3
  - vector sum of p_T of the two final state neutrinos $p_T^{\nu\nu} > 30$ GeV
  - Two anti-k_T 0.4 jets with p_T>65,35 GeV, |η|<4.5, m_{jj}>500 GeV, |Δy_{jj}|>2, ΔR(j,l)>0.3
- Signal: Sherpa 2.2.2 WWjj

same-sign WW VBS

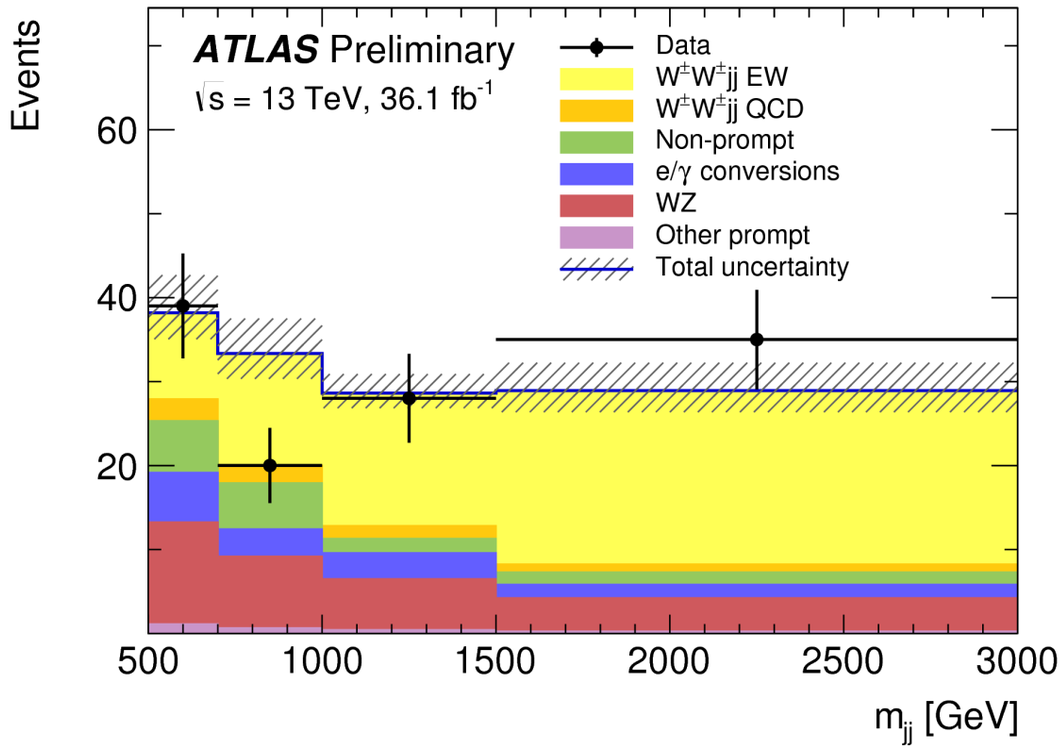
- Background: non-prompt lepton, charge mis-ID, Vγ, ZZ, ttV, VVV, WZ.
  - Non-prompt lepton background measured from control regions with 40-90% uncertainty (Dominant experimental uncertainty)
- Likelihood fit:
  - Categorised into 6 channels: $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, $\mu^{\pm}\mu^{\pm}$.
  - Signal region: 4 m_{jj} bins for $m_{jj} > 500$GeV. Control region: $200 < m_{jj} < 500$GeV.

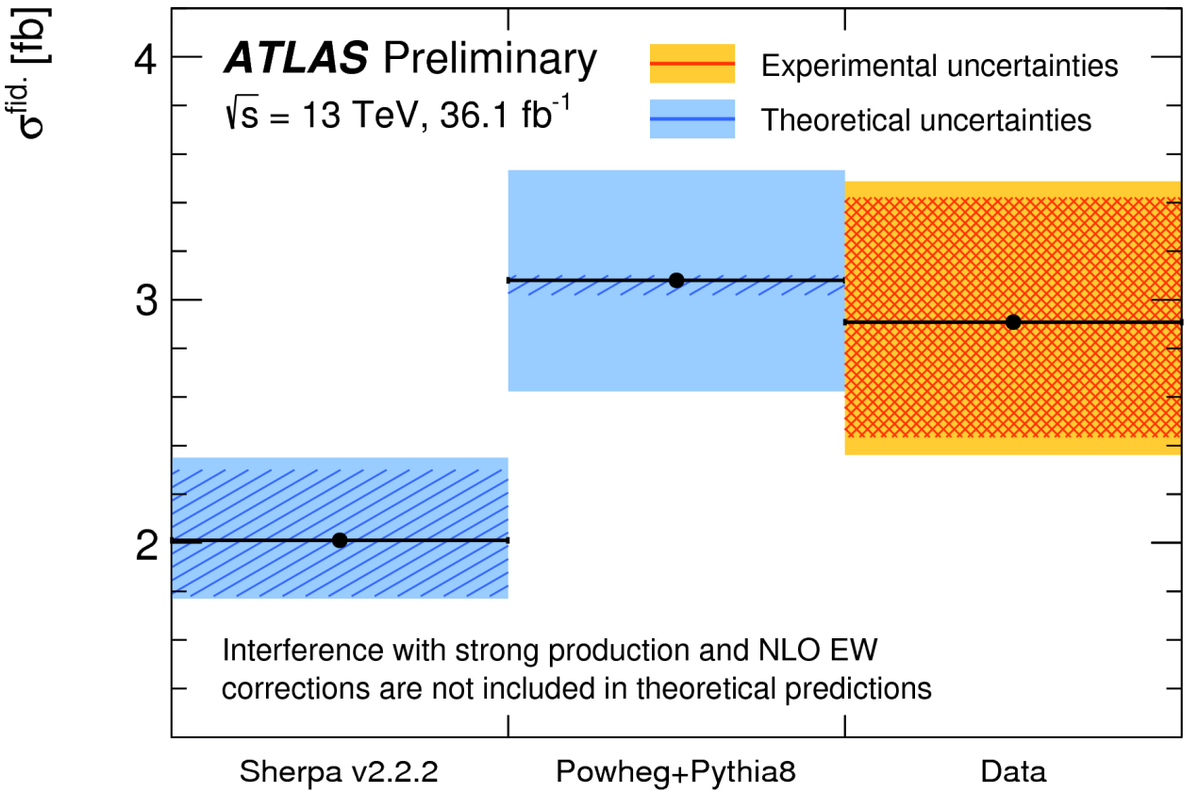
Event yield before fit

	e^+e^+	e^-e^-	$e^+\mu^+$	$e^-\mu^-$	$\mu^+\mu^+$	$\mu^-\mu^-$	combined
WZ	1.7 ± 0.6	1.2 ± 0.4	13 ± 4	8.1 ± 2.5	5.0 ± 1.6	3.3 ± 1.1	32 ± 9
Non-prompt	4.1 ± 2.4	2.3 ± 1.8	9 ± 6	6 ± 4	0.57 ± 0.16	0.67 ± 0.26	23 ± 12
e/γ conversions	1.74 ± 0.31	1.8 ± 0.4	6.1 ± 2.4	3.7 ± 1.0	-	-	13.4 ± 3.5
Other prompt	0.17 ± 0.06	0.14 ± 0.05	0.90 ± 0.24	0.60 ± 0.25	0.36 ± 0.12	0.19 ± 0.07	2.4 ± 0.5
$W^{\pm}W^{\pm}$jj strong	0.38 ± 0.13	0.16 ± 0.06	3.0 ± 1.0	1.2 ± 0.4	1.8 ± 0.6	0.76 ± 0.26	7.3 ± 2.5
Expected background	8.1 ± 2.4	5.6 ± 1.9	32 ± 7	20 ± 5	7.7 ± 1.7	4.9 ± 1.1	78 ± 15
$W^{\pm}W^{\pm}$jj electroweak	3.80 ± 0.30	1.49 ± 0.13	16.5 ± 1.2	6.5 ± 0.5	9.1 ± 0.7	3.50 ± 0.29	40.9 ± 2.9
Data	10	4	44	28	25	11	122

same-sign WW VBS

- Observed (expected) signal significance of 6.9 (4.6) σ.
- Modelling of this process studied in ATL-PHYS-PUB-2019-004.





- Fiducial cross section for the electroweak production process (inc. interference):

$$2.91\ ^{+0.51}_{-0.47}\ (stat.)\ \pm 0.27\ (sys.)\ \text{fb}$$

Summary

- Presented 3 ATLAS results using 36.1 fb^{-1} of data at $\sqrt{s}$ = 13 TeV.
  - WZ production cross sections and polarisation
  - Observation of electroweak $W^{\pm}Zjj$
  - Observation of electroweak same-sign $W^{\pm}W^{\pm}jj$
- Helicity fractions of diboson measured first time in hadron collider.
- Vector boson scattering in WZ and same-sign WW has been observed with 5.3 and 6.9 σ.
- Measurements agree with SM predictions so far.
- More diboson measurements coming soon, stay tuned.

Back-up slides

Resonant shape algorithm

- Dressed leptons, and final-state neutrinos are matched to the W and Z boson decay products using a Monte Carlo generator-independent algorithm, called the “resonant shape” algorithm.

$$P = \left| \frac{1}{m^2_{(\ell^+,\ell^-)} - \left(m_Z^{\mathrm{PDG}}\right)^2 + i\,\Gamma_Z^{\mathrm{PDG}}\,m_Z^{\mathrm{PDG}}} \right|^2 \times \left| \frac{1}{m^2_{(\ell',\nu_{\ell'})} - \left(m_W^{\mathrm{PDG}}\right)^2 + i\,\Gamma_W^{\mathrm{PDG}}\,m_W^{\mathrm{PDG}}} \right|^2$$

- The final choice of which leptons are assigned to the W or Z bosons corresponds to the configuration exhibiting the largest value of the estimator.

Transverse mass

$$m_{\mathrm{T}}^{W} = \sqrt{2 \cdot p_{\mathrm{T}}^{\nu} \cdot p_{\mathrm{T}}^{\ell} \cdot [1 - \cos \Delta\phi(\ell, \nu)]}$$

- p_T^{ν} at detector level computed using E_T^{miss}.

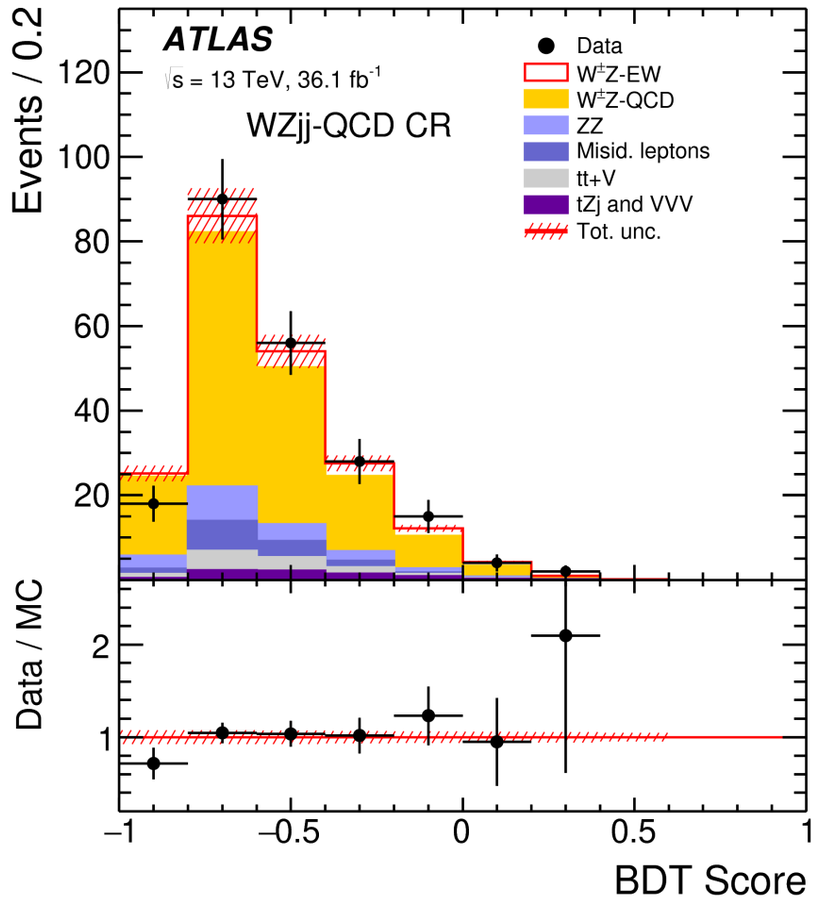
$$m_{\mathrm{T}}^{WZ} = \sqrt{\left(\sum_{\ell=1}^{3} p_{\mathrm{T}}^{\ell} + E_{\mathrm{T}}^{\mathrm{miss}}\right)^2 - \left[\left(\sum_{\ell=1}^{3} p_x^{\ell} + E_x^{\mathrm{miss}}\right)^2 + \left(\sum_{\ell=1}^{3} p_y^{\ell} + E_y^{\mathrm{miss}}\right)^2\right]}$$

Neutrino p_Z from W mass constraint

- $W^{\pm}$ boson mass constraint is used to solve for the z component p_Z^{ν} of the neutrino momentum. This generally leaves a two-fold ambiguity which is resolved by choosing the solution with the smaller $| p_Z^{\nu} |$.
- If the measured transverse mass is larger than the nominal $W^{\pm}$ mass, no real solutions exist for p_Z^{ν}. The most likely cause is that the measured E_T^{miss} is larger than the actual neutrino p_T. In this case, the best estimate is obtained by choosing the real part of the complex solutions with the smaller magnitude.

BDT

- Used to separate W Z j j–EW signal and the W Z j j–QCD and other backgrounds.
- 15 variables:
  - jet-kinematic variables: m_{jj}, p_T^{j1}, p_T^{j2}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, y_{j1}, N_{jets}
  - vector-bosons-kinematics variables: p_T^W, $_{pT}^Z$, η_W, $|y_Z - y_{l,W}|$, m_T^{WZ}
  - variables related to jets and leptons kinematics: $\Delta R(j1, Z)$, event balance R_{pT}^{hard}, centrality of WZ system relative to the tagging jets
- The good modelling by MC simulations of the distribution shapes and the correlations of all input variables to the BDT is verified in the WZjj–QCD CR



- R_{pT}^{hard} : transverse component of the vector sum of the WZ bosons and tagging jets momenta, normalised to their scalar pT sum,