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

Rustem Ospanov
for the ATLAS collaboration

University of Science and Technology of China

July 5, 2018

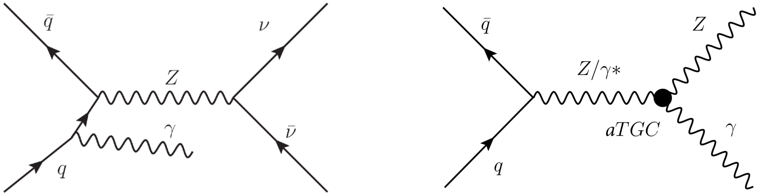
Introduction

- Diboson production processes test gauge structure of Standard Model
- Sensitive to gauge boson self-interactions and longitudinal polarisation
- Precise tests of NNLO in QCD perturbative calculations
- Probe for new phenomena via triple gauge boson coupling measurements

3 new ATLAS results using 36.1 fb^{-1} data at $\sqrt{s} = 13$ TeV in this talk:

- $Z\gamma \rightarrow \nu\nu\gamma$ cross section and anomalous coupling tests
  - ATLAS-CONF-2018-035
- $W^{\pm}Z$ cross section and gauge boson polarisation
  - ATLAS-CONF-2018-034
- Measurement of electroweak production of same-sign WW bosons
  - ATLAS-CONF-2018-030
- Web pages will be public soon after the presentation

$Z\gamma \to \nu\nu\gamma$ cross section and anomalous coupling tests



- Probe for anomalous neutral triple gauge couplings $ZZ\gamma$ and $Z\gamma\gamma$
- High branching fraction and no final state radiation

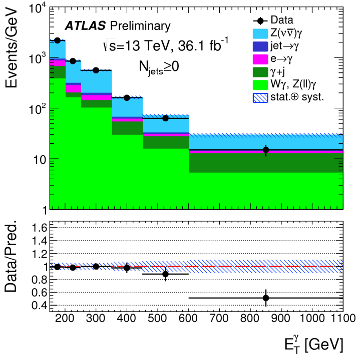
$Z\gamma \to \nu\nu\gamma$

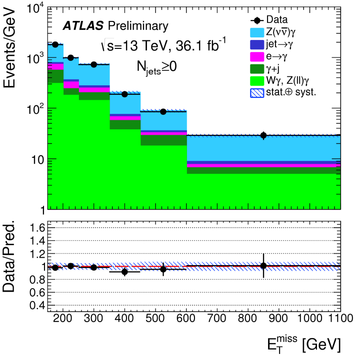
Photon + neutrinos fiducial region:

- Photon with $p_T^\gamma > 150$ GeV and $|\eta| < 2.37$
- Neutrinos with $p_T^{\nu\nu} > 150$ GeV
- Anti-kt 0.4 jets with $p_T > 50$ GeV and $|\eta| < 4.5$

Signal modelling and theory predictions:

- Model $Z\gamma \to \nu\nu\gamma$ with SHERPA 2.2.2 with NNPDF3.0NNLO PDF
- Compare with NNLO in QCD predictions from MCFM and MATRIX
  - Apply particle-to-parton level corrections





$Z\gamma \to \nu\nu\gamma$ experimental summary

Experimental selection:

- Well reconstructed isolated photon with $p_T^{\gamma} > 150$ GeV
- Missing transverse energy $E_T^{miss} > 150$ GeV
- Veto leptons to suppress $W\gamma$ background

Backgrounds and experimental uncertainty:

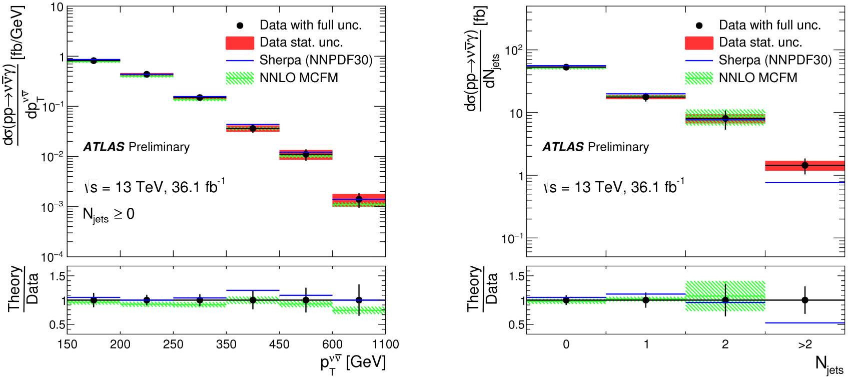
- $W\gamma$ and γ+jet backgrounds are estimated from control regions
- $e \to \gamma$ background is estimated from $Z \to ee$ events
- jet$\to \gamma$ background is estimated from sidebands
- Dominant uncertainty due to mismodelling of photon efficiency and energy scale

Predicted and observed event yields

	$N_{\mathrm{jets}} \geq 0$ (stat.+syst.)	$N_{\mathrm{jets}} = 0$ (stat.+syst.)
$N^{W\gamma}$	$650 \pm 40 \pm 60$	$360 \pm 20 \pm 30$
$N^{\gamma+jet}$	$409 \pm 18 \pm 108$	$219 \pm 10 \pm 58$
$N^{e\to\gamma}$	$320 \pm 15 \pm 45$	$254 \pm 12 \pm 35$
$N^{jet\to\gamma}$	$170 \pm 30 \pm 50$	$140 \pm 20 \pm 40$
$N^{Z(ll)\gamma}$	$40 \pm 3 \pm 3$	$26 \pm 3 \pm 2$
N^{bkg}_{total}	$1580 \pm 50 \pm 140$	$1000 \pm 40 \pm 90$
$N^{sig}(exp)$	$2328 \pm 4 \pm 135$	$1710 \pm 4 \pm 91$
$N^{sig+bkg}_{total}$	$3910 \pm 50 \pm 190$	$2710 \pm 40 \pm 130$
$N^{data}(obs)$	3812	2599

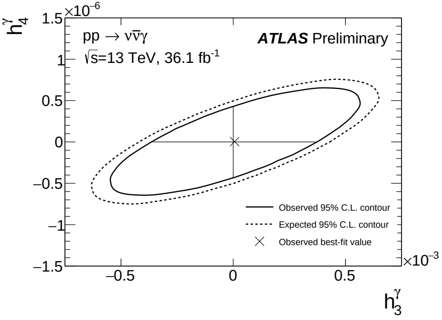
$Z\gamma \to \nu\nu\gamma$ cross section

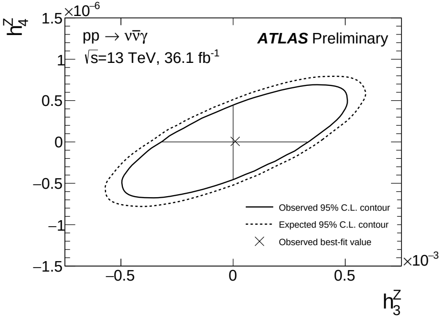
- Measured fiducial σ for $N_{jet} \geq 0$: $\sigma^{\text{ext.fid.}}_{Data} = 83.7^{+3.6}_{-3.5}$ (stat.)$^{+6.9}_{-6.2}$ (syst.)$^{+1.7}_{-2.0}$ (lumi.) fb
- NNLO MCFM prediction for $N_{jet} \geq 0$: $\sigma^{\text{ext.fid.}}_{MCFM} = 78.1 \pm 0.2 \pm 4.4$ fb
- Also measured fiducial and differential cross sections for $N_{jet} = 0$



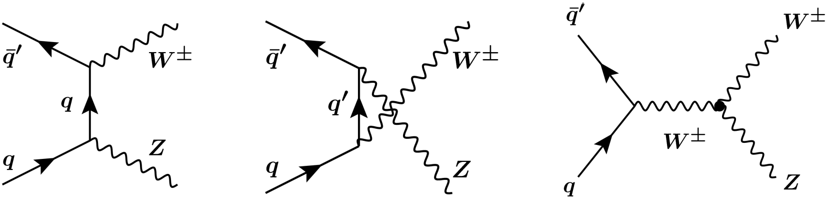
$Z\gamma \to \nu\nu\gamma$ - limits on anomalous couplings

- Select events with $p_T^\gamma > 600$ GeV and zero jets - optimised for best sensitivity
- Predictions modified with MCFM by including $ZZ\gamma$ ($h^Z_{3,4}$) and $Z\gamma\gamma$ ($h^\gamma_{3,4}$) vertices
- h_3 (h_4) corresponds to electric (magnetic) dipole moment CP-conserving parameters
- Set limits in individual parameters and parameter pairs
- Factor of 3-7 improvements over the previous $Z\gamma$ results





$W^{\pm}Z$ cross section and gauge boson polarisation



- Probe gauge structure of Standard Model
- Sensitive to anomalous triple gauge boson couplings
- Precise measurements of differential and total cross sections
- Polarisation of W and Z bosons

$W^\pm Z$ production

Trilepton fiducial region:

- Select $Z \rightarrow e^\pm e^\mp / \mu^\pm \mu^\mp$ decays
  - $p_T^{e,\mu} > 15$ GeV and $|\eta^{e,\mu}| < 2.5$
  - $|m_{ll} - m_Z| < 10$ GeV
- Select $W^\pm \rightarrow e^\pm \nu_e / \mu^\pm \nu_\mu$ decays
  - $p_T^{e,\mu} > 15$ GeV and $|\eta^{e,\mu}| < 2.5$
  - Transverse mass $m_T^W > 30$ GeV
- Anti-kt 0.4 jets with $p_T > 25$ GeV and $|\eta| < 4.5$

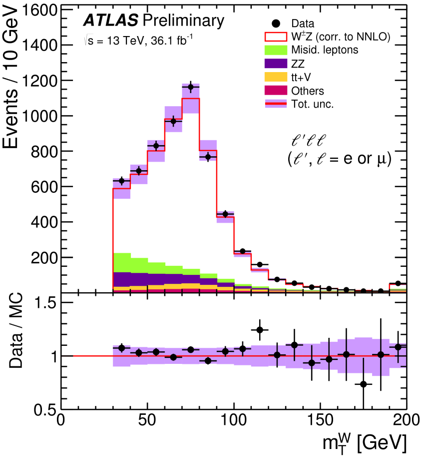
Signal modelling:

- Model $W^\pm Z$ with PowhegBox at NLO in QCD
- Shower with Pythia 8.210 and CTEQ6L1PDF
- Shower with Herwig to estimate uncertainty

Theory predictions:

- NNLO QCD $W^\pm Z$ cross sections with MATRIX
  - Apply particle-to-parton level corrections

Require $m_T^W > 30$ GeV



$W^{\pm}Z$ experimental summary

Experimental selections:

- 3 isolated well reconstructed e and μ, veto fourth lepton to suppress ZZ
- Separate and combined measurements for 4 lepton flavour channels

Backgrounds and experimental uncertainty:

- Fake lepton background measured from data with 30-40% uncertainty
  - 1.9% uncertainty on cross section measurement
- ZZ background normalised from data with 12% uncertainty
- Uncertainties for $t\bar{t}V$, tZ and VVV backgrounds vary 15% to 30%
- e/μ efficiency mismodelling - up to 1.5% uncertainty on cross section measurement
- Integrated luminosity - 2.4% uncertainty on cross section measurement

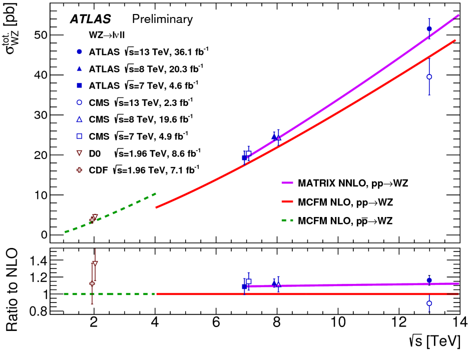
Event yields per channel with only statistical uncertainty

Channel	eee	μee	$e\mu\mu$	$\mu\mu\mu$	All
Data	1279	1281	1671	1929	6160
Total Expected	1221 ± 7	1281 ± 6	1653 ± 8	1830 ± 7	5986 ± 14
WZ	922 ± 5	1077 ± 6	1256 ± 6	1523 ± 7	4778 ± 12
Misid. leptons	138 ± 5	34 ± 2	193 ± 5	71 ± 2	436 ± 8
ZZ	86 ± 1	89 ± 1	117 ± 1	135 ± 1	426 ± 3
$t\bar{t}$+V	50.0 ± 0.7	54 ± 0.7	56.1 ± 0.7	63.8 ± 0.8	225 ± 1
tZ	23.1 ± 0.4	24.8 ± 0.4	28.8 ± 0.4	33.5 ± 0.5	110 ± 1
VVV	2.5 ± 0.1	2.8 ± 0.1	3.2 ± 0.1	3.6 ± 0.1	12.0 ± 0.2

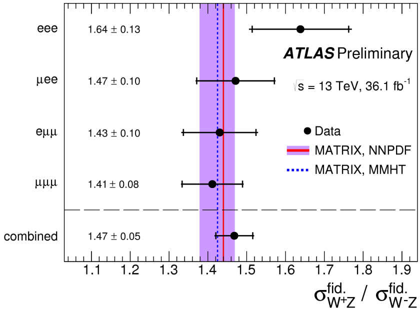
$W^{\pm}Z$ cross section

- Measured: $\sigma^{\text{fid.}}_{W^{\pm}Z\rightarrow\ell'\nu\ell\ell} = 63.7 \pm 1.0\,(\text{stat.}) \pm 2.3\,(\text{sys.}) \pm 0.3\,(\text{modelling}) \pm 1.5\,(\text{lumi.})$ fb.
- MATRIX: $\sigma^{\text{fid.}}_{W^{\pm}Z\rightarrow\ell'\nu\ell\ell} = 61.5^{+1.4}_{-1.3}\,\text{fb}$
- Measured charge ratio: $\sigma^{\text{fid.}}_{W^{+}Z\rightarrow\ell'\nu\ell\ell}/\sigma^{\text{fid.}}_{W^{-}Z\rightarrow\ell'\nu\ell\ell} = 1.47 \pm 0.05\,(\text{stat.}) \pm 0.02\,(\text{sys.})$.

Precise tests of NNLO QCD calculations



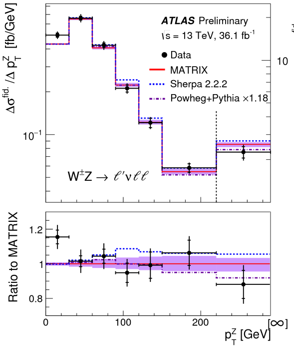
$W^{+}Z/W^{-}Z$



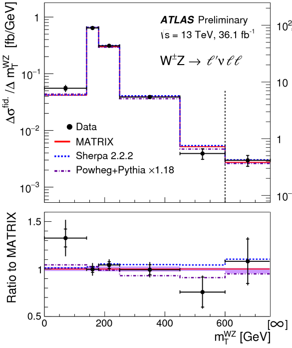
$W^{\pm}Z$ single differential cross sections

- Unfolded single differential cross sections for p_T^Z, M_T^{WZ}, N_{jets} (below) and other variables
- Response matrix obtained with POWHEGBOX+PYTHIA

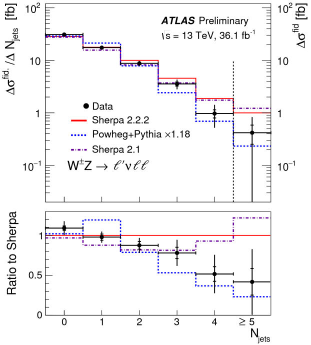
p_T^Z



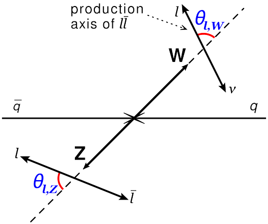
M_T^{WZ}



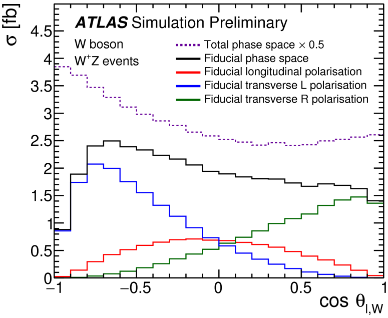
N_{jets}

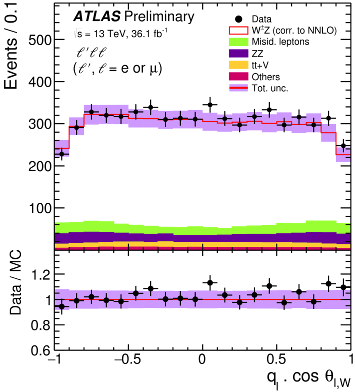


W and Z polarisation measurement



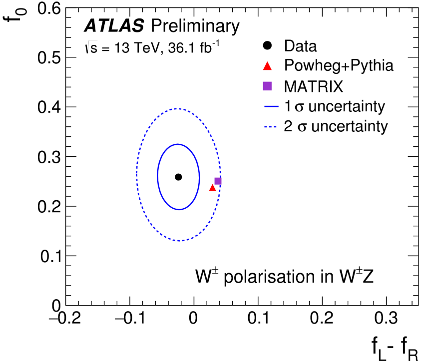
- Measure W/Z polarisation using lepton angular distributions
- f_0, f_L and f_R define the longitudinal, transverse-left handed and transverse-right handed helicity fractions at Born level
- Template fit of $q_\ell \cdot \cos\theta_{\ell,W}$ and of $\cos\theta_{\ell,Z}$ distributions
  - m_W constraint to solve for missing p_Z^ν at detector level

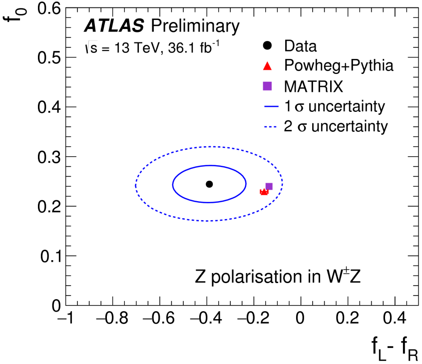




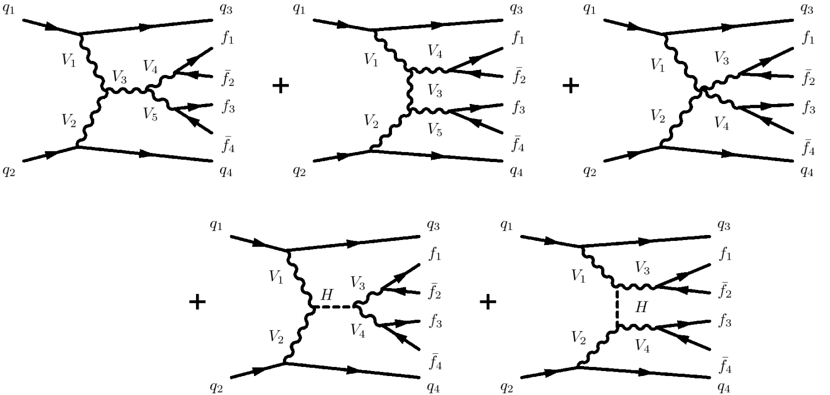
W and Z polarisation measurement

- Observed (expected) significance of 4.2σ (3.8σ) for longitudinally polarised W bosons
- Sensitive to new broad resonances not seen by direct searches





Electroweak production of same-sign WW bosons: $W^{\pm}W^{\pm}jj$



- Measure self-interactions of heavy gauge bosons
- Unitarity at high energies requires presence of the SM Higgs boson

$W^\pm W^\pm jj$ electroweak production

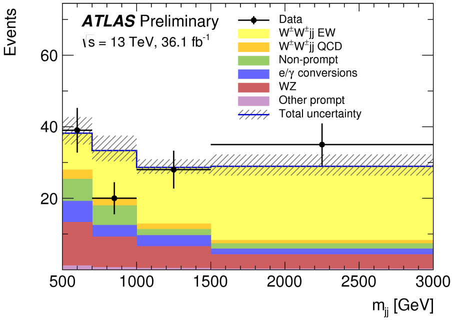
Same-sign dilepton fiducial region:

- Same-sign dilepton events with $m_{ll} > 20$ GeV
  - e or μ with $p_T > 27$ GeV and $|\eta| < 2.5$
- Neutrinos with $p_T^{\nu\nu} > 30$ GeV
- Anti-kit 0.4 jets with $|\eta| < 4.5$
- Optimised VBS jet selections:
  - Two leading jets with $p_T > 65, 35$ GeV
  - Dijet invariant mass $m_{jj} > 500$ GeV
  - Rapidity gap $|\Delta y_{jj}| > 2$

Signal modelling:

- Model $W^\pm W^\pm jj$ electroweak and strong production with SHERPA 2.2.2
- Alternative NLO in QCD sample with with POWHEGBOX +PYTHIA8 for electroweak signal
- $W^\pm W^\pm jj$ strong production with exactly four EW vertices subtracted as background

Dijet invariant mass for $m_{jj} > 500$ GeV



Likelihood fit:

- 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: $200 < m_{jj} < 500 GeV$

$W^{\pm}W^{\pm}jj$ experimental summary

Experimental selection:

- Isolated well reconstructed same-sign dilepton events (e or μ)
- Veto third lepton to suppress WZ and veto b-jets to suppress $t\bar{t}$
- Require $E_T^{miss} > 30$ GeV and VBS jet selections

Backgrounds and experimental uncertainty:

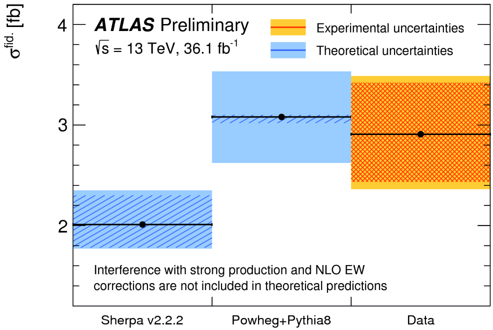
- WZ background is normalised from trilepton control region with 8% uncertainty
- Fake lepton background measured from control regions with 50-90% uncertainty
  - Dominant experimental uncertainty
- Electron charge misidentification and $\gamma \to e$ backgrounds are measured from data
- Other irreducible backgrounds are from Monte-Carlo simulation

Event yields before the 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

$W^\pm W^\pm jj$ electroweak production cross section

- Observed (expected with SHERPA) significance is 6.9σ (4.6σ)
- Measured fiducial cross section: $\sigma^{\rm fid}_{\rm Data} = 2.95 \pm 0.49\ (\rm stat.) \pm 0.23\ (\rm sys.)\ fb$
  - $\sigma^{\rm fid}_{\rm Data}$ includes $W^\pm W^\pm jj$ electroweak plus interference with $W^\pm W^\pm jj$ strong
  - $W^\pm W^\pm jj$ strong production with exactly four EW vertices subtracted as background



Predicted fiducial cross sections:

- POWHEGBOX:
  $\sigma^{\rm fid}_{\rm EWK} = 3.08^{+0.45}_{-0.46}\ (\rm syst.+stat.)$ fb
- SHERPA:
  $\sigma^{\rm fid}_{\rm EWK} = 2.01^{+0.33}_{-0.23}\ (\rm sys.+stat.)$ fb
- NLO electroweak corrections (-16% for SHERPA) and interference ($+6\%$) are not included

Summary and conclusions

- Presented 3 new ATLAS results using 36.1 fb^{-1} of data at $\sqrt{s} = 13$ TeV
  - $Z\gamma \to \nu\nu\gamma$ cross section measurement and anomalous coupling tests
  - $W^{\pm}Z$ cross section and gauge boson polarisation measurements
  - Observed longitudinally polarised W bosons with 4.2σ significance
  - 6.9σ observation of electroweak production of same-sign WW
- So far, measurements agree with SM predictions at NNLO or NLO
- More measurements in pipeline targeting other diboson final states
- These and other measurements will be improved with full Run 2 dataset
- Thank you and stay tuned for more results!

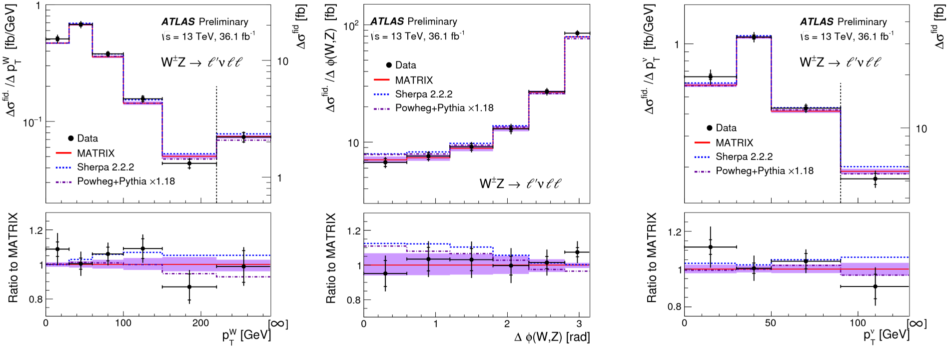
BACKUP

$Z\gamma \to \nu\nu\gamma$ experimental setup

- Backgrounds and experimental uncertainty:
  - $W\gamma$ CR: invert lepton veto, 77% pure, $\sigma_{QCD} = 5.8\%$, $\sigma_{exp.} = 3.8\%$
  - γ+jet CR: invert E_T^{miss} significance, 55% pure, $\sigma_{QCD} = 19\%$
  - $e \to \gamma$ CR: require e instead of γ, $\sigma_{exp.} \approx 14\%$
  - jet$\to \gamma$ background is estimated from sidebands
  - Dominated by mismodelling of photon efficiency and photon energy scale

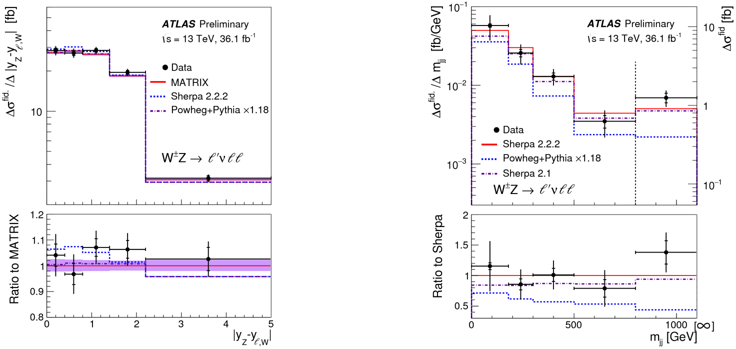
$W^{\pm}Z$ single differential cross sections

- Unfolded single differential cross sections
- Response matrix obtained with POWHEGBOX+PYTHIA model



$W^{\pm}Z$ single differential cross sections

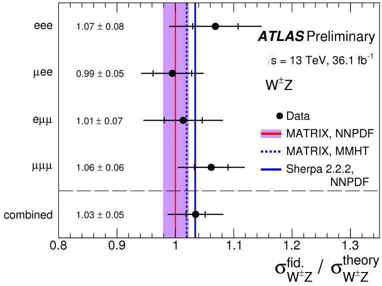
- Unfolded single differential cross sections
- Response matrix obtained with POWHEGBOX+PYTHIA model



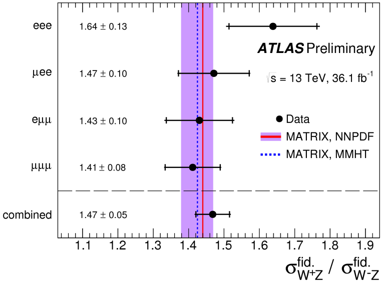
$W^{\pm}Z$ cross section

- Measured: $\sigma^{\mathrm{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 63.7 \pm 1.0\,(\mathrm{stat.}) \pm 2.3\,(\mathrm{sys.}) \pm 0.3\,(\mathrm{mod.}) \pm 1.5\,(\mathrm{lumi.})$ fb.
- MATRIX: $\sigma^{\mathrm{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 61.5^{+1.4}_{-1.3}$ fb
- $\dfrac{\sigma^{\mathrm{fid.}}_{W^{+}Z\to\ell'\nu\ell\ell}}{\sigma^{\mathrm{fid.}}_{W^{-}Z\to\ell'\nu\ell\ell}} = 1.47 \pm 0.05\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{sys.})$.

Measured/Theory

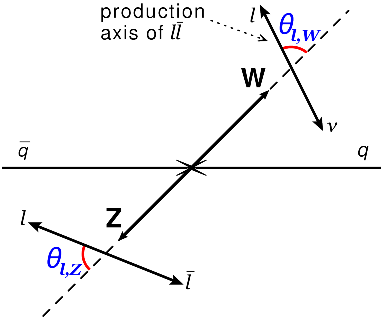


$W^{+}Z/W^{-}Z$



W and Z polarisation measurement

- Measure polarisation of W and Z gauge bosons using lepton angular distributions
- f_0, f_L and f_R define the longitudinal, transverse-left handed and transverse-right handed helicity fractions at Born level



- W polarisation:
$$\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,W}} = \frac{3}{8}f_L(1\mp\cos\theta_{\ell,W})^2 + \frac{3}{8}f_R(1\pm\cos\theta_{\ell,W})^2 + \frac{3}{4}f_0\sin^2\theta_{\ell,W}$$

- Z polarisation:
$$\frac{1}{\sigma_{W^\pm Z}}\frac{d\sigma_{W^\pm Z}}{d\cos\theta_{\ell,Z}} = \frac{3}{8}f_L(1+2\alpha\cos\theta_{\ell,Z}+\cos^2\theta_{\ell,Z}) + \frac{3}{8}f_R(1+\cos^2\theta_{\ell,Z}-2\alpha\cos\theta_{\ell,Z}) + \frac{3}{4}f_0\sin^2\theta_{\ell,Z}$$

Observation of $W^{\pm}W^{\pm}jj$ electroweak production