Diboson production and polarization measurements with the ATLAS Detector

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on behalf of ATLAS Collaboration

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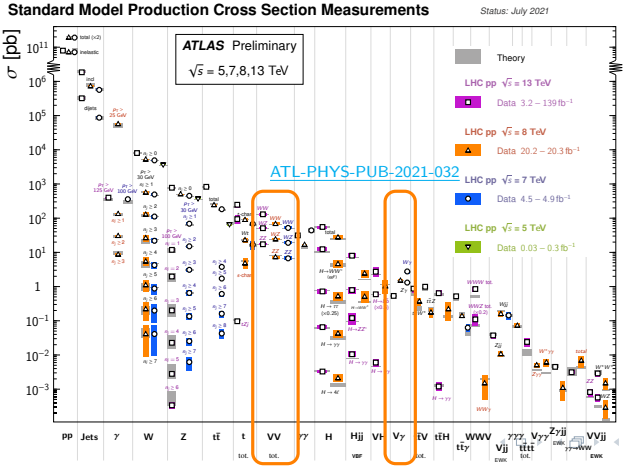
Introduction - Diboson Production

- Important probes of the electroweak gauge structure of the Standard Model.
- Polarization measurement of WZ process tests the particular way the electroweak symmetry is spontaneously broken via the longitudinal helicity state.
- Differential measurements of $Z\gamma$ and WW processes provide inputs for QCD modeling of diboson events and give constraints on anomalous gauge boson couplings.



Outline

1. Measurement of Double-polarization in WZ Production (new!)

2. $Z\gamma$ and WW production in association with jet activity
   - $Z(\to \ell\ell)\gamma + jets$ (new!)
   - Jet-Inclusive $WW(\to e\mu)$ (new!)

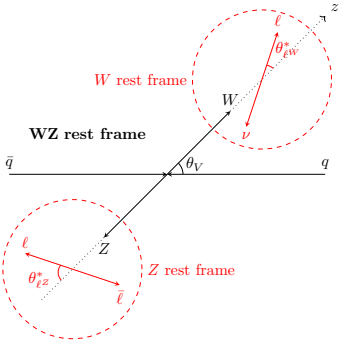
3. Summary

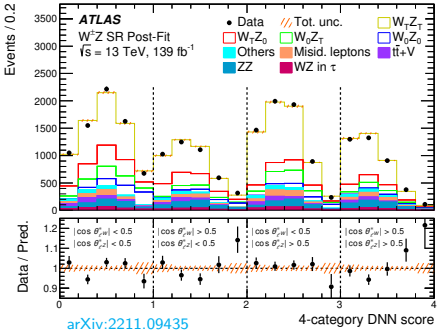
The First Observation of Double-polarization in *WZ*

- The simultaneous pair-production of longitudinally polarised vector bosons is measured for the first time with a significance of 7.1(6.2)σ. STDM-2022-01
- Four linear combinations of the joint spin density matrix $\rho_{\lambda_W \lambda'_W \lambda_Z \lambda'_Z}$ are measured,

$$f_{00} = \rho_{0000},\ f_{0T} = \rho_{00--} + \rho_{00++},\ f_{T0} = \rho_{--00} + \rho_{++00},$$
$$f_{TT} = \rho_{++--} + \rho_{--++} + \rho_{----} + \rho_{++++},\ f_{00} + f_{0T} + f_{T0} + f_{TT} = 1\ (\textit{constraint})$$

- Categorize events depending on the $\cos\theta^*_{\ell W}$ and $\cos\theta^*_{\ell Z}$ observables.



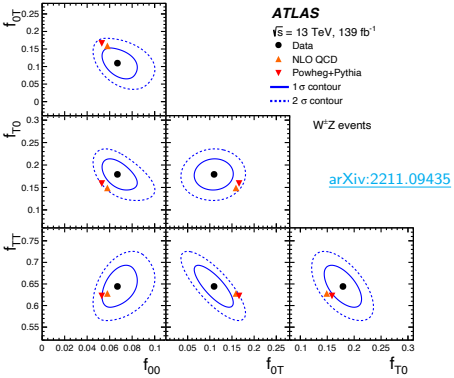


arXiv:2211.09435

The First Observation of Double-polarization in *WZ*

The measurements are compared with predictions from Powheg+Pythia and from NLO QCD fixed-order calculations.

	Data	POWHEG+PYTHIA	NLO QCD
	$W^{\pm}Z$		
f_{00}	0.067 ± 0.010	0.0590 ± 0.0009	0.058 ± 0.002
f_{0T}	0.110 ± 0.029	0.1515 ± 0.0017	0.159 ± 0.003
f_{T0}	0.179 ± 0.023	0.1465 ± 0.0017	0.149 ± 0.003
f_{TT}	0.644 ± 0.032	0.6431 ± 0.0021	0.628 ± 0.004
	$W^{+}Z$		
f_{00}	0.072 ± 0.016	0.0583 ± 0.0012	0.057 ± 0.002
f_{0T}	0.119 ± 0.034	0.1484 ± 0.0022	0.155 ± 0.003
f_{T0}	0.152 ± 0.033	0.1461 ± 0.0022	0.147 ± 0.003
f_{TT}	0.66 ± 0.04	0.6472 ± 0.0026	0.635 ± 0.004
	$W^{-}Z$		
f_{00}	0.063 ± 0.016	0.0600 ± 0.0014	0.059 ± 0.002
f_{0T}	0.11 ± 0.04	0.1560 ± 0.0027	0.166 ± 0.003
f_{T0}	0.21 ± 0.04	0.1470 ± 0.0027	0.152 ± 0.003
f_{TT}	0.62 ± 0.05	0.6370 ± 0.0033	0.618 ± 0.004



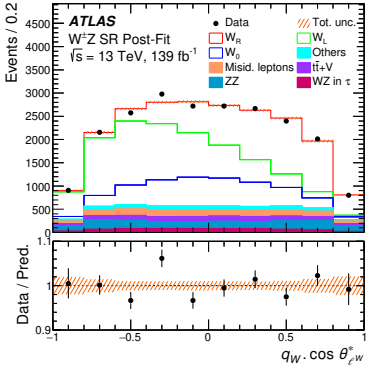
arXiv:2211.09435

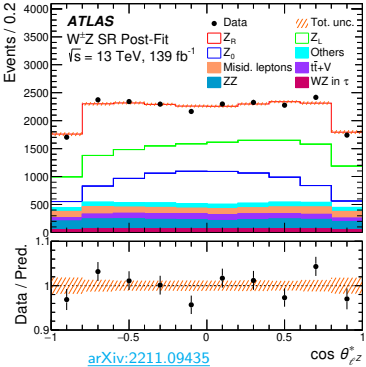
Individual Boson Polarization Measurements in *WZ*

- For individual W and Z boson polarization states, the helicity parameters f_0 and $f_L - f_R$ are measured.

$$\frac{3}{8} f_L[(1 - q_W \cdot \cos\theta^*_{\ell W})^2] + \frac{3}{8} f_R[(1 + q_W \cdot \cos\theta^*_{\ell W})^2] + \frac{3}{4} f_0 \sin^2\theta^*_{\ell W} \quad (1)$$

$$\frac{3}{8} f_L(1 + 2\alpha\cos\theta^*_{\ell Z} + \cos^2\theta^*_{\ell Z}) + \frac{3}{8} f_R(1 - 2\alpha\cos\theta^*_{\ell Z} + \cos^2\theta^*_{\ell Z}) + \frac{3}{4} f_0 \sin^2\theta^*_{\ell Z} \quad (2)$$

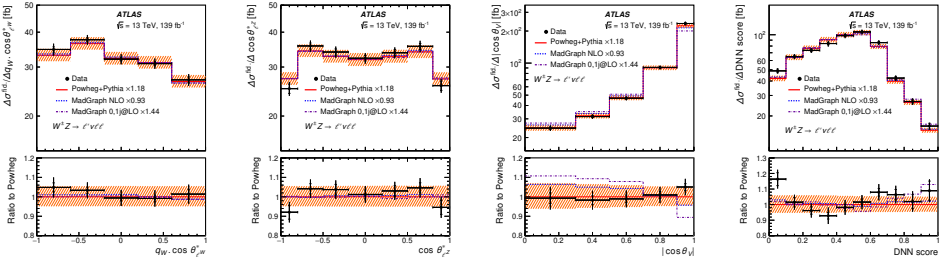




arXiv:2211.09435

Differential WZ Cross-section Measurements

- The inclusive XS of $W^{\pm}Z$ production in the fiducial region
  - Measured: $64.6 \pm 0.5(stat.) \pm 1.8(syst.) \pm 1.1(lumi.)$ fb
  - Prediction (MATRIX NNLO QCD): $64.0^{+1.5}_{-1.3}$ fb
- The measurements are compared with the NLO prediction from Powheg+Pythia (solid line). The dashed band shows sum of QCD scale and PDF uncertainties.
- All predictions have been scaled to the NNLO QCD integrated cross-section predicted by MATRIX.

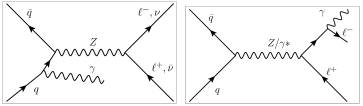


arXiv:2211.09435

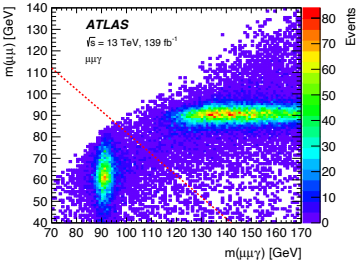
Measurement of $Z(\to \ell\ell)\gamma + jets$ Production

- $Z\gamma + jets$ can be used to test pQCD and constrain the MC models.
  - The measurement covers several observables using the hard and resolution variables, which is very useful to investigate QCD modeling in diboson processes.
- Distributions are measured using events in which the Z goes to two leptons and the photon is usually radiated from ISR.
- Require at least one jet in addition to $Z\gamma$ pair.
- $m_{\ell\ell} > 40$ GeV and $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV reduce contribution from FSR.
- $Z + jets$ is estimated by a 2D sideband method.
- Pile-up background is estimated by using a data-driven method.

The paper has been accepted by JHEP!



arXiv:2212.07184



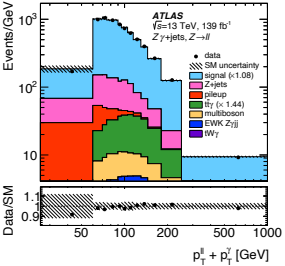
from previous analysis JHEP 03 (2020) 054

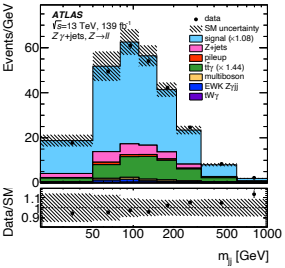
Measurement of $Z(\to \ell\ell)\gamma + jets$ Production

- The fiducial XS for $Z\gamma$ production
  - Measured:
    $533.7 \pm 2.1(stat) \pm 12.3(syst) \pm 9.1(lumi)$ *fb*
  - SHERPA2.2.11+MEPS@LO:
    $479.5 \pm 0.3(stat)$ *fb*
  - MiNNLO$_{PS}$: $493.0 \pm 3.0(stat)$ *fb*

Source	$ee + \mu\mu$
$Z\gamma$+jets signal	73 500 ± 50 (stat.) ± 2 600 (syst.)
$Z+$jets	9 800 ± 460 (stat.) ± 2 100 (syst.)
$t\bar{t}\gamma$	3 600 ± 10 (stat.) ± 540 (syst.)
Pile-up	2 500 ± 70 (stat.) ± 700 (syst.)
Multiboson	950 ± 5 (stat.) ± 280 (syst.)
$tW\gamma$	150 ± 1 (stat.) ± 45 (syst.)
Total prediction	90 500 ± 500 (stat.) ± 3 500 (syst.)
Data	96 410

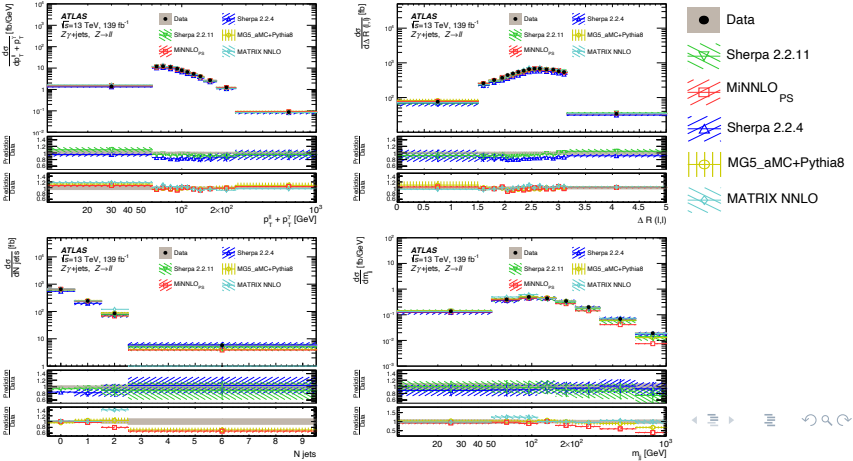
arXiv:2212.07184





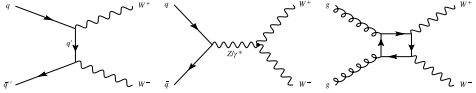
Measurement of $Z(\to \ell\ell)\gamma + jets$ Production

- Jet activity is generally well described but some trends are observed in the different predictions.
- SHERPA describes the data well but underestimates the measured total XS. Others have some deviations from the data at high jet multiplicity. arXiv:2212.07184

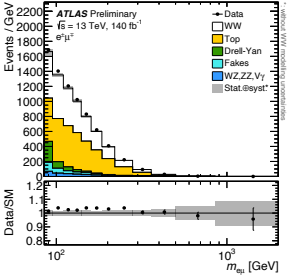


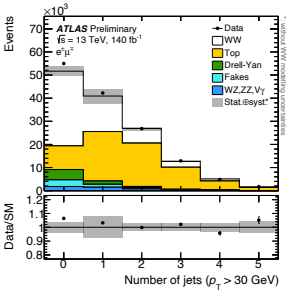
Measurement of Jet-Inclusive $WW(\rightarrow e\mu)$ Production

ATLAS-CONF-2023-012



- Sensitive to the gauge-boson self-couplings.
- Provides a test of the predictions of pQCD.
- The measurements are performed without any requirement on jets other than b-jets.
  - No b-jets are allowed to reduce the top background.
  - This jet-inclusive measurement allows for the comparison with precise. predictions in pQCD.
- $m_{e\mu} > 85$ GeV to reduce Drell-Yan backgrounds.
- Events with more than two prompt leptons are vetoed to reduce WZ and ZZ background.
- Dominant background is from top-related processes
  - $t\bar{t}$ and fake-lepton background are obtained using data-driven techniques.
  - Other backgrounds are estimated using MC.





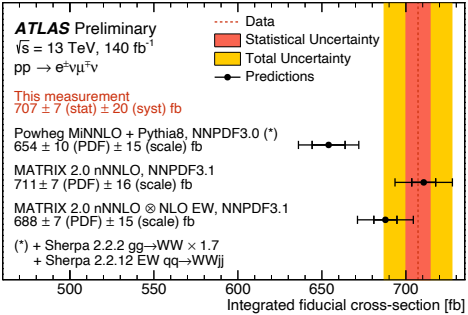
Measurement of Jet-Inclusive $WW(\rightarrow e\mu)$ Production

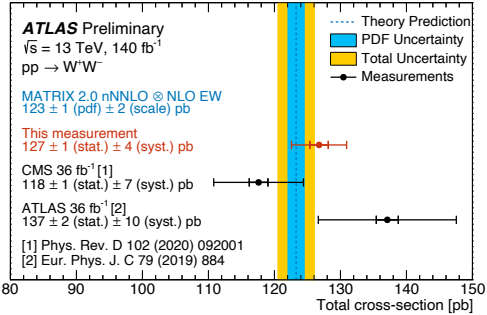
- The measured fiducial XS for WW production with $WW \rightarrow e\mu$ is

$$707 \pm 7(stat.) \pm 20(syst.)\ fb$$

- The measurements is extrapolated to the full phase space of WW production

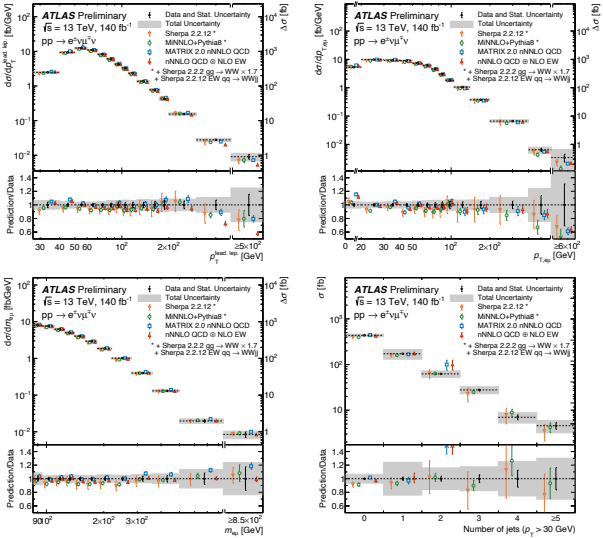
$$127 \pm 1(stat.) \pm 4(syst.)\ pb$$





Differential XS of $WW(\to e\mu)$ Production

Excellent agreement with the fixed-order MATRIX prediction is observed.



Data and Stat. Uncertainty
Total Uncertainty
Sherpa 2.2.12 *
MiNNLO+Pythia8 *
MATRIX 2.0 nNNLO QCD
nNNLO QCD ⊕ NLO EW
* + Sherpa 2.2.2 gg → WW × 1.7
+ Sherpa 2.2.12 EW qq → WWjj

Summary

- All measurements mentioned in this talk are carried out using the full run2 data set from ATLAS with $\sqrt{s} = 13$ TeV, 139 fb^{-1}.
  - The first observation of the longitudinally polarised vector bosons in WZ production with a significance of $7.1(6.2)\sigma$
  - Fiducial cross-section of $Z(\rightarrow \ell\ell)\gamma + jets$ processes measured to be $533.7 \pm 2.1(stat.) \pm 12.3(syst.) \pm 9.1(lumi.)\ fb$
  - Fiducial cross-section of $WW(\rightarrow e\mu)$ processes measured to be $707 \pm 7(stat.) \pm 20(syst.)\ fb$
- Run 3 has already commenced with $\sqrt{s} = 13.6$ TeV and an expected luminosity that is twice that of Run 2. The increased statistics will be advantageous in enabling a more thorough exploration of boson polarization and rare multiboson processes.

Backup

Input Variables of DNN in WZ Measurements

- The transverse momenta of the three leptons and of the neutrino
  - $p_T^{\ell^W}$
  - $p_T^{\ell_1^Z}$
  - $p_T^{\ell_2^Z}$
  - E_T^{miss}
- The angular variables as the absolute difference between the rapidities of the Z boson and the lepton from the decay of the W boson
  - $|y_W - y_{\ell^W}|$
- the azimuthal angle difference between the two leptons of each Z and W-boson decay
  - $\Delta\phi(\ell^W, \nu)$
  - $\Delta\phi(\ell_1^Z, \ell_2^Z)$
- and the transverse momentum of the WZ system
  - p_T^{WZ}