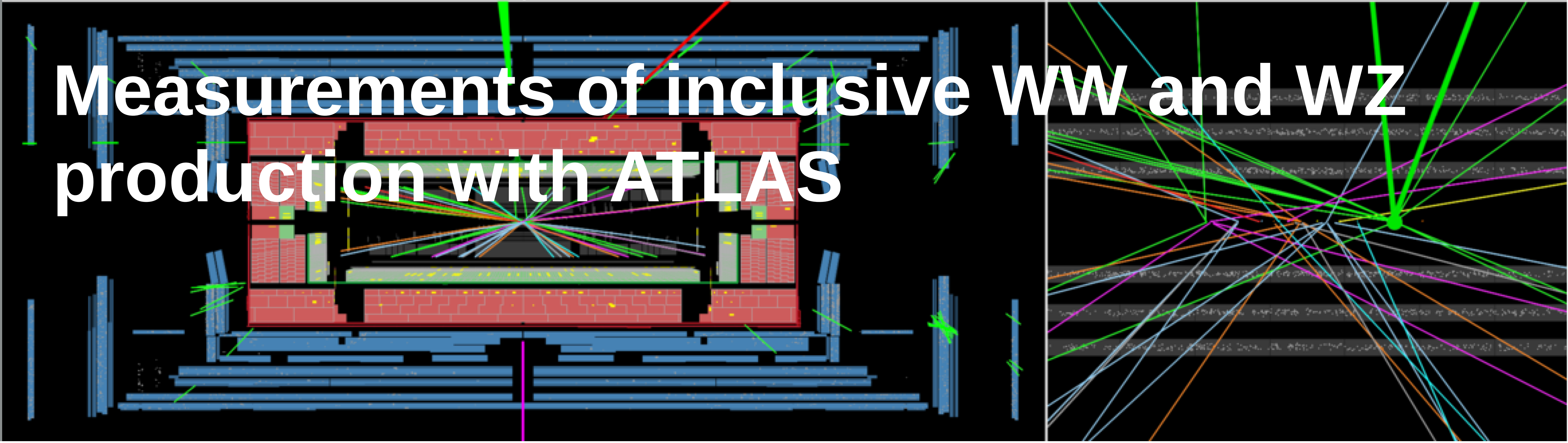
Measurements of inclusive WW and WZ production with ATLAS



Valerie Lang
On behalf of the ATLAS Collaboration

XXVII International Workshop on Deep Inelastic Scattering and Related Subjects

9 April 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

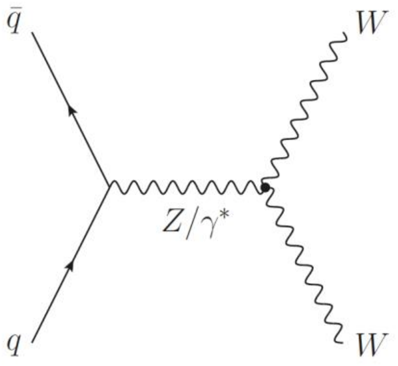
Why look at WW and WZ production?

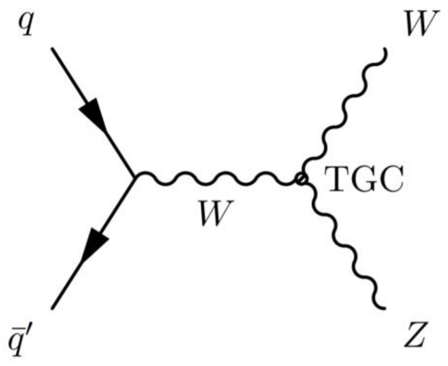
Gauge structure of the electroweak (EW) sector

- Coupling of W and Z bosons to weak isospin
  - W bosons carry weak isospin themselves

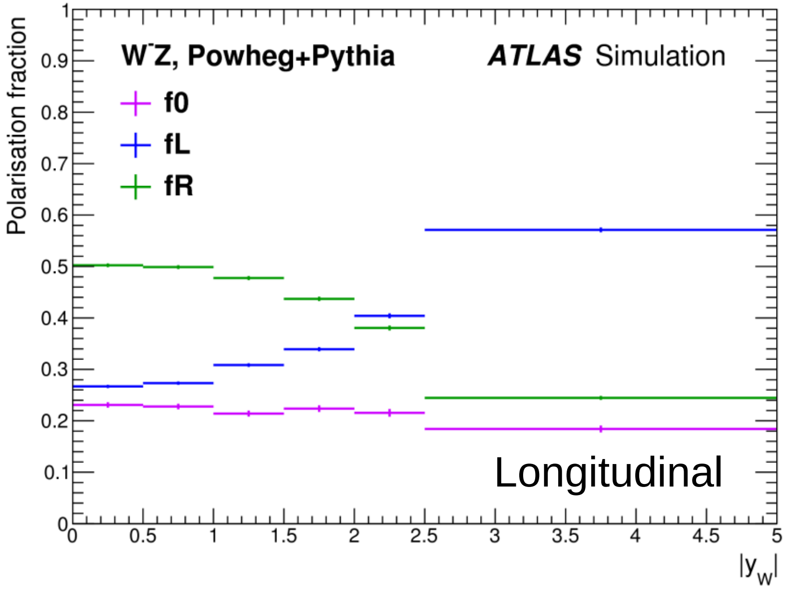
  → Self-coupling of W and Z bosons in SM in certain combinations, e.g. WWZ, WWZZ, WWWW

  → Triple and quartic gauge couplings (TGC, QGC)





- Mass of W and Z bosons → 3 polarisations
  - Longitudinal polarisation from spontaneous symmetry breaking in EW sector
  - Contribution of each polarisation depending on production mechanism
  - Polarisation → angular distribution of decay products

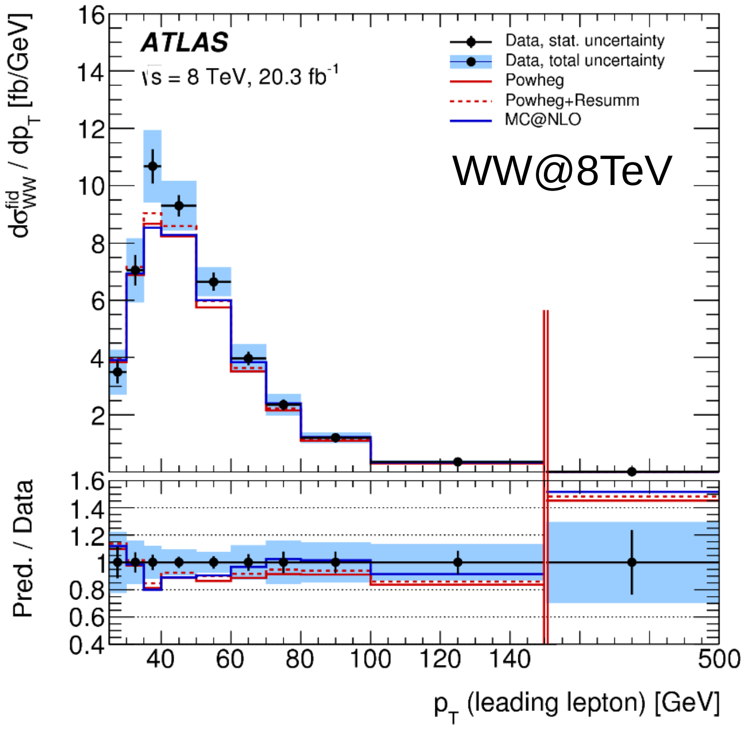


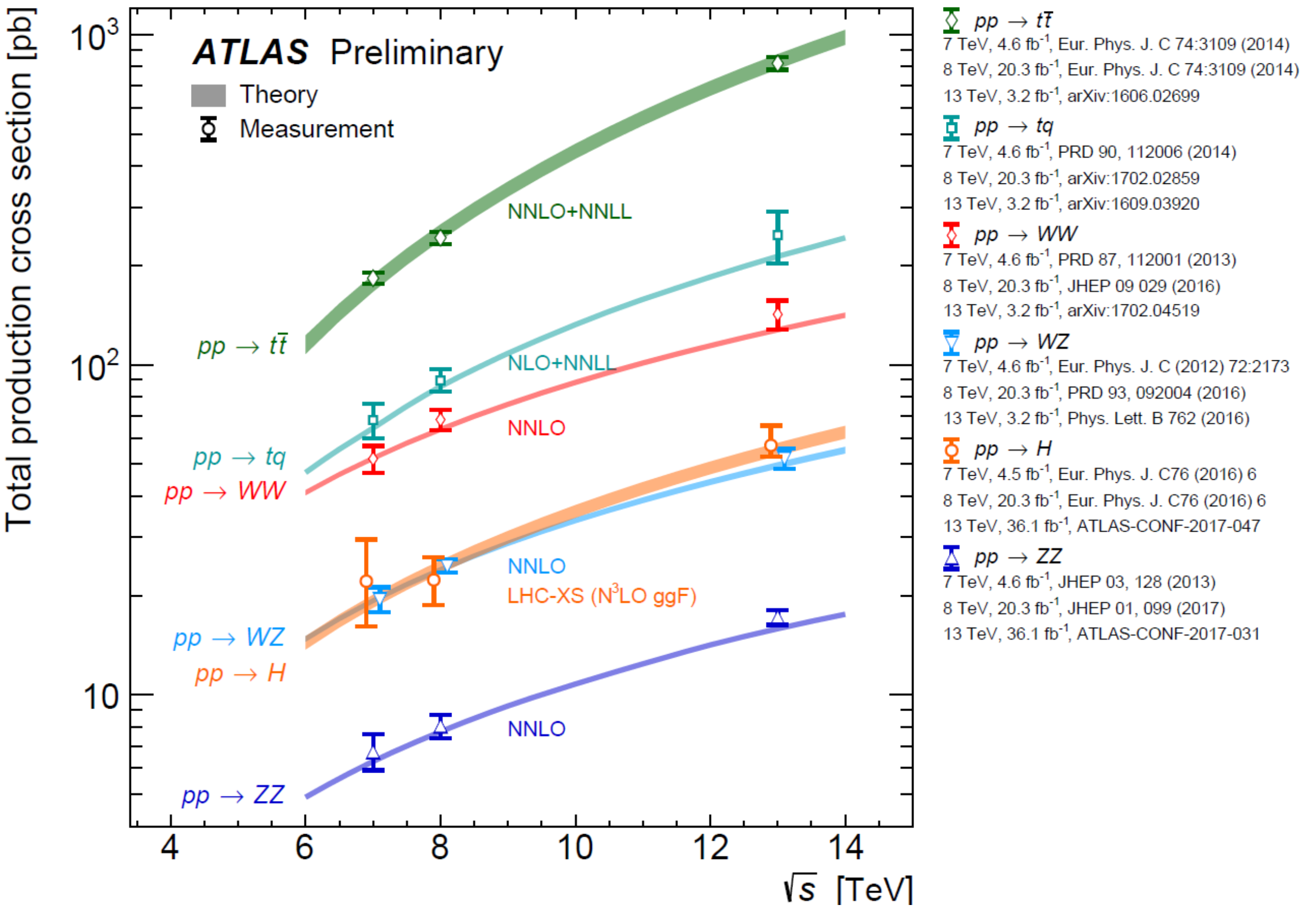
→ Probe validity of the gauge structure of the EW sector in the Standard Model (SM)

WW and WZ production

At the Large Hadron Collider (LHC)

- Large production cross section for WW and WZ
  - Clean signature with leptonic W and Z decays
  - Calculations at next-to-leading order (NLO) in Quantum Chromodynamics (QCD) not sufficient to describe the data





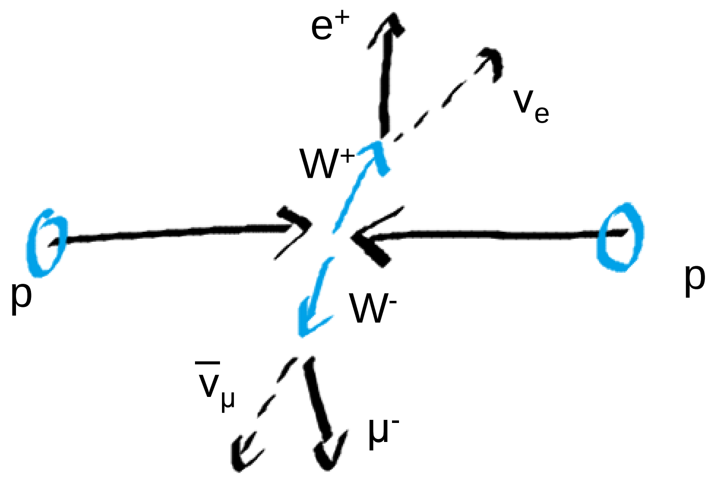
Measurement of WW production

WW @ 13TeV – 36.1fb^{-1}

NEW!

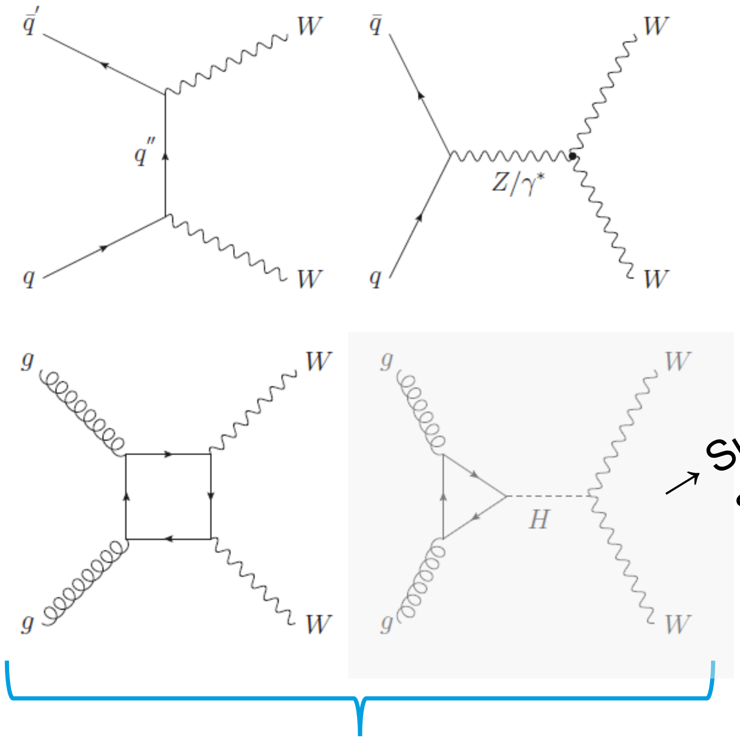
STDM-2017-24

- W pair production @ LHC



- Select $WW \rightarrow e\nu_e\ \mu\nu_\mu$ decay: opposite sign e and μ
  - No b-tagged jets with p_T > 20GeV, |η| < 2.5
  - No jets with p_T > 35GeV, |η| < 4.5
  - No overlapp with H→WW analysis selection (Physics Letters B 789 (2019) 508–529)

→ Contributing signal processes



→ Suppressed by selection

→ Interfere!

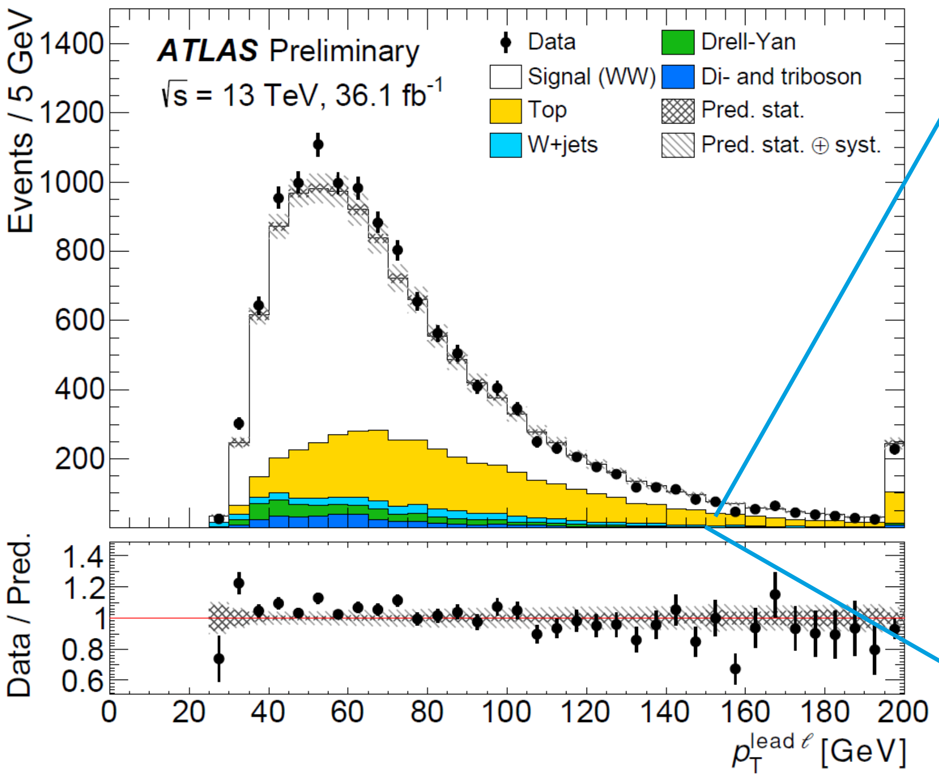
Estimating the backgrounds

WW @ 13TeV – 36.1fb^{-1}

NEW!

STDM-2017-24

- Selected events and their origin
  - Signal purity ~64%
  - Largest background: top-quark ($t\bar{t}$, Wt) production



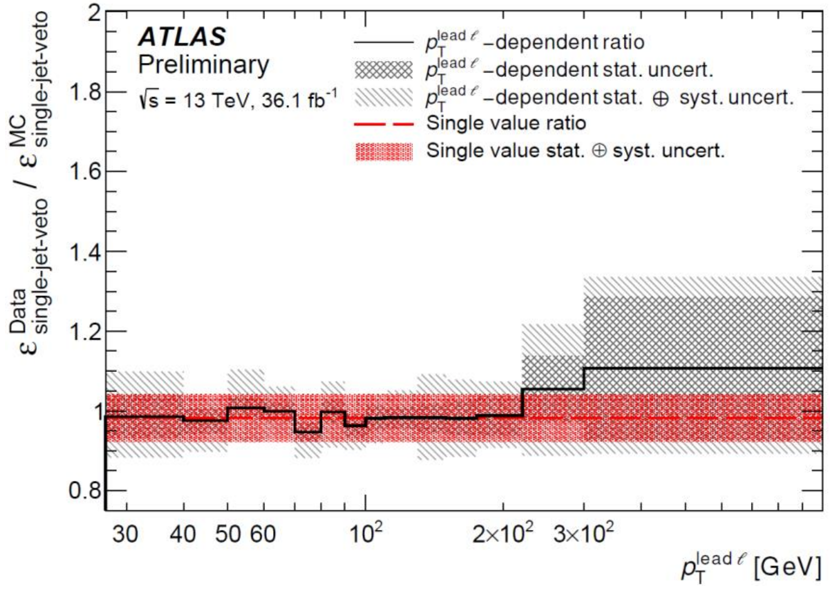
→ Estimated with partly data-driven method

$$N_{top}^{SR} = N_{CR}^{top} \cdot \epsilon_{jet-veto}$$

Allow jets and b-jets

Estimate from simulation, but correct with data

$$\epsilon_{jet-veto} = \epsilon_{jet-veto}^{MC} \cdot \left(\frac{\epsilon_{single-jet-veto}^{Data}}{\epsilon_{single-jet-veto}^{MC}} \right)^{\langle n_{jets} \rangle}$$



→ Close to 1

→ Good systematics cancellation

Estimating the cross section

WW @ 13TeV – 36.1fb^{-1}

NEW!

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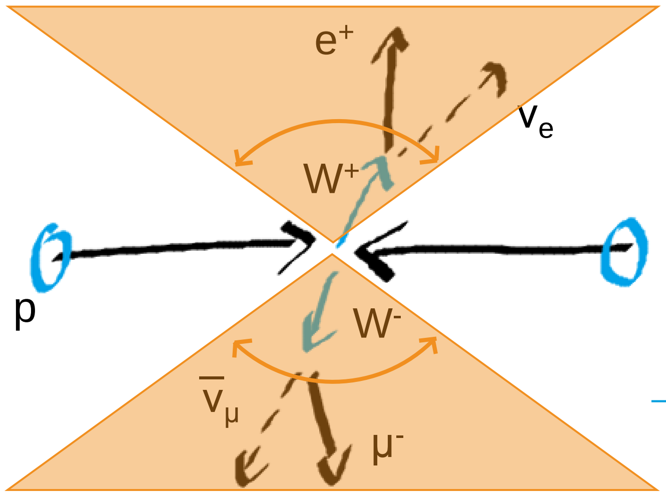
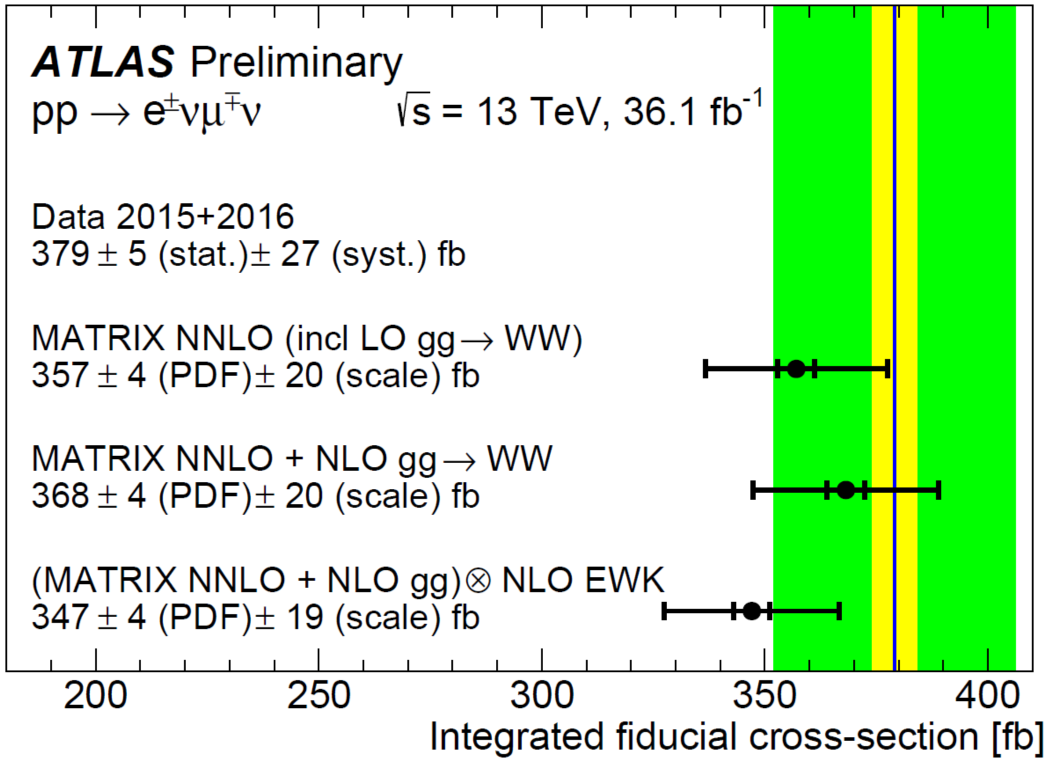
- Cross section

$$\sigma = \frac{N_{data} - N_{bkg}}{L_{int}\, C_{WW}}$$

  - C_{WW} → extrapolate for acceptance, detector efficiency, resolution effects & τ-lepton decays
  - Only measure phase space similar to detector acceptance → small acceptance correction



→ Fiducial cross section



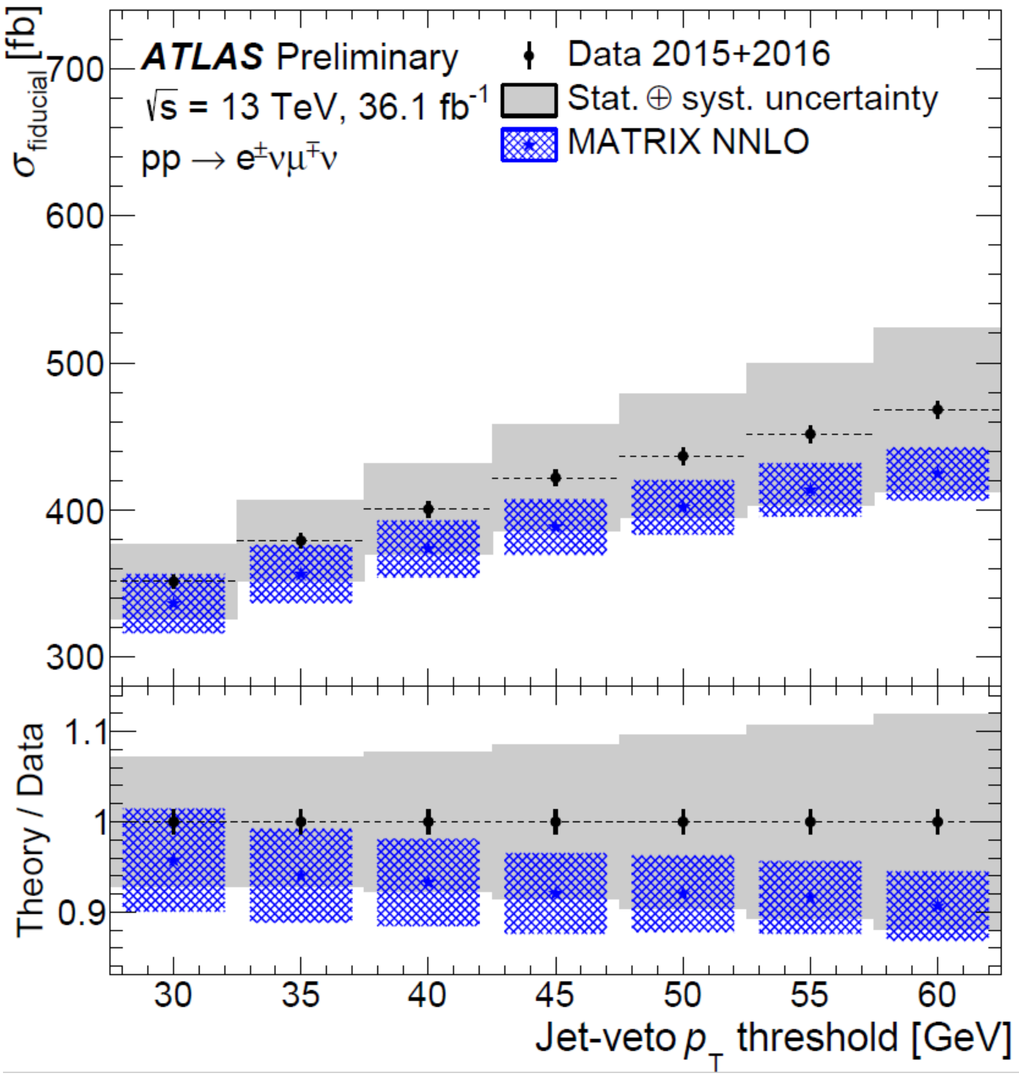
→ Good agreement with NNLO MATRIX prediction
→ At the lower part of the uncertainty band

Jet kinematics in the absence of jets

WW @ 13TeV – 36.1fb^{-1}

STDM-2017-24

- Veto of jets → for suppression of top background
  - Measure of jet kinematics?
    → Fiducial cross section as function of jet-veto p_T threshold
    - Scan from 30GeV to 60GeV
    - Higher threshold → More jets below the threshold
      → Larger possible phase space



→ Good agreement of NNLO MATRIX with data
→ Again at lower boundary

→ Larger difference between prediction and data with more jets
→ Also larger uncertainties

Differential cross section

WW @ 13TeV – $36.1 fb^{-1}$

NEW!

STDM-2017-24

- Differential cross section
  - Unfolded with iterative Bayesian method
- Most sensitive to EW gauge structure and triple gauge couplings → Leading lepton p_T

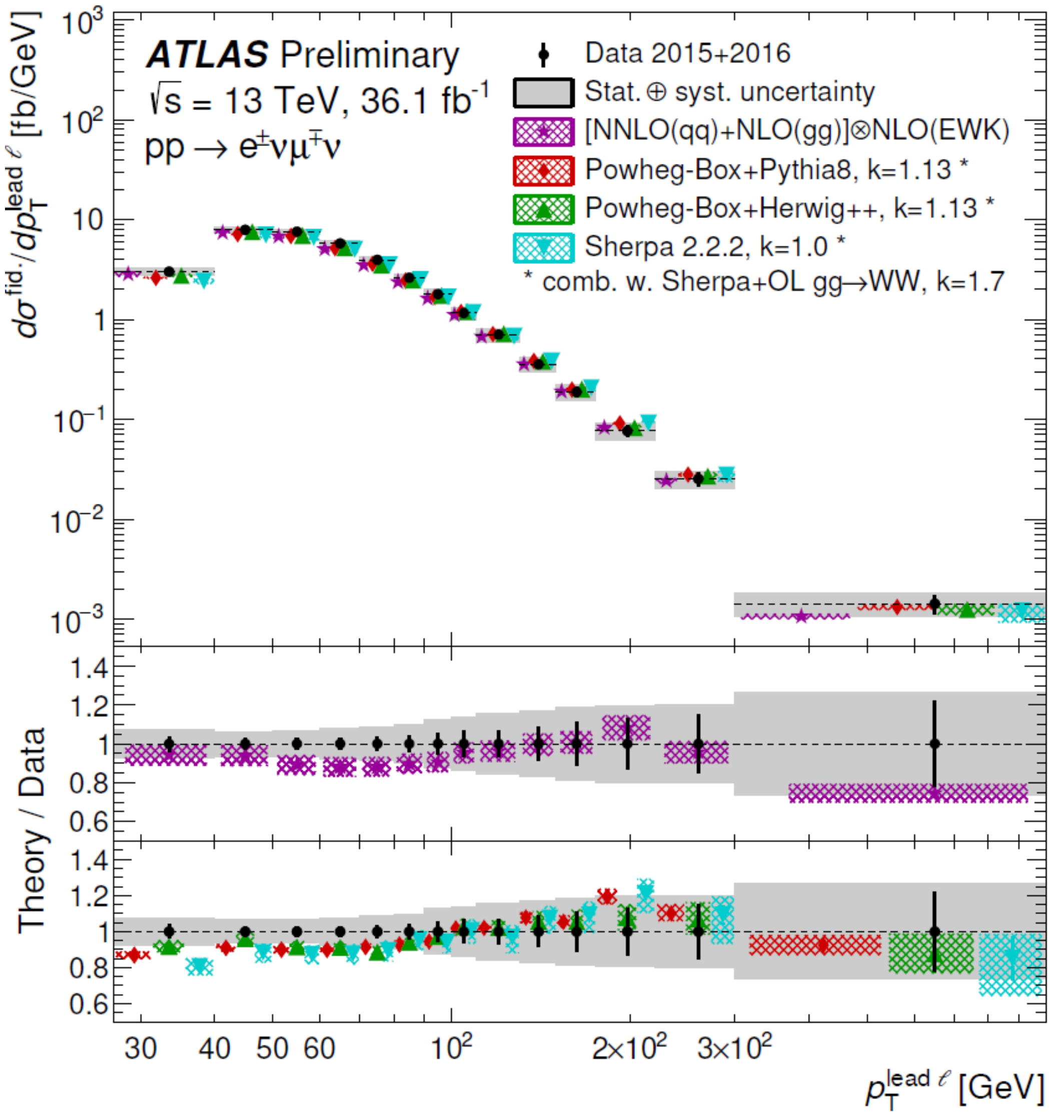
W polarisation

↓

Lepton decay angle
in W rest frame

↓

Lepton p_T in
lab frame



Differential cross section

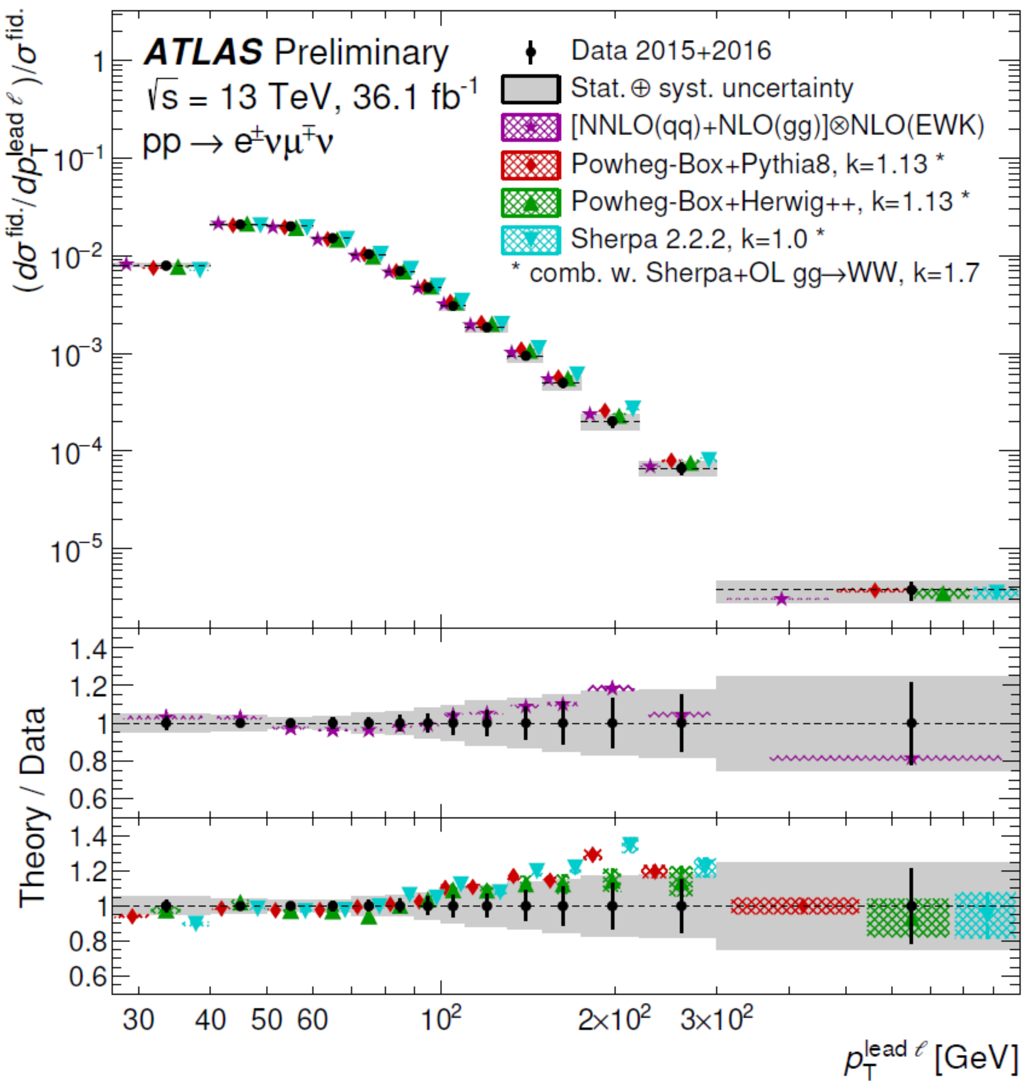
WW @ 13TeV – 36.1fb^{-1}

NEW!

STDM-2017-24

- Differential cross section
  - Unfolded with iterative Bayesian method
- Most sensitive to EW gauge structure and triple gauge couplings → Leading lepton p_T

→ Cross check trends in normalized cross section



→ Good agreement of NNLO MATRIX and 3 NLO+PS predictions with data
→ Tendency to overprediction at large $p_T^{lead\ l}$
→ mostly within uncertainties

What limits our knowledge?

WW @ 13TeV – 36.1fb^{-1}

NEW!

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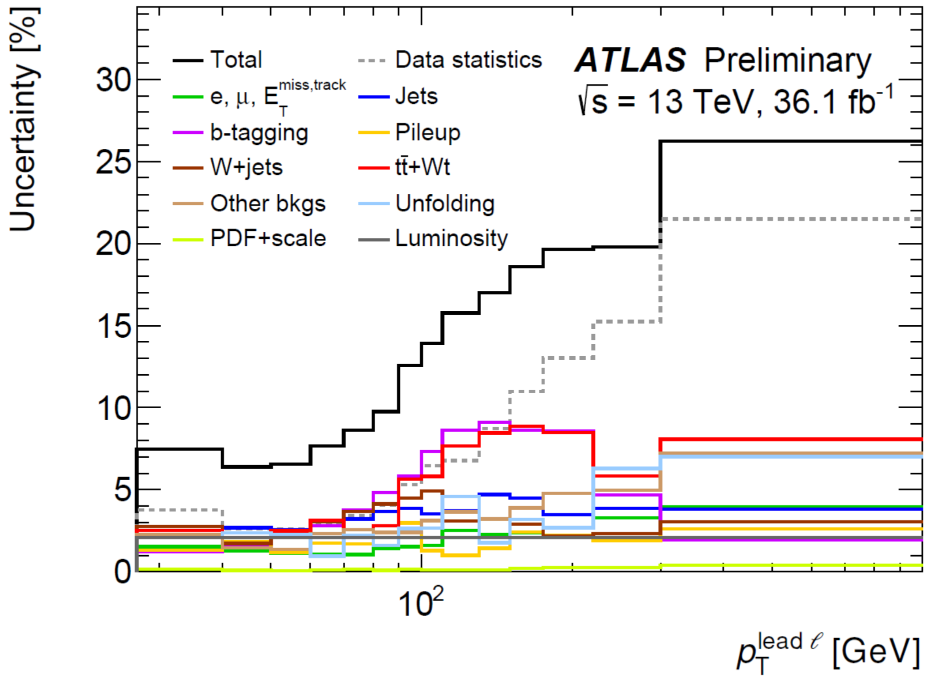
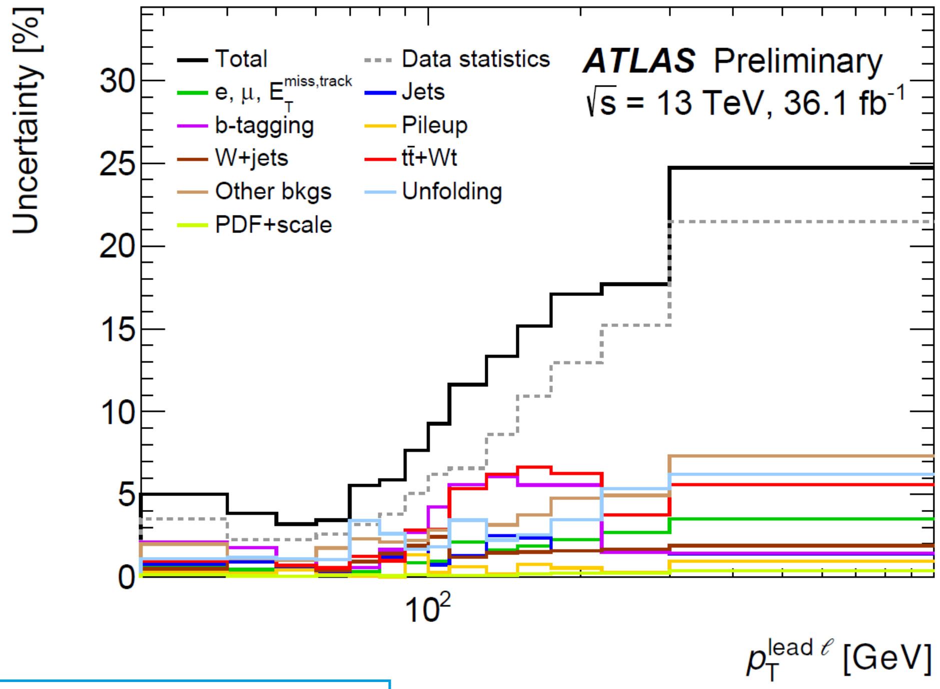
- Largest sensitivity to TGC → Highest $p_T^{lead\ l}$ bins
  - Also sensitive to anomalous TGCs from physics beyond the SM

→ Differential cross section



→ Normalized differential cross section



→ Limiting factor: Statistical uncertainty!

→ Solution: Full Run 2 data: 139fb^{-1} ☺

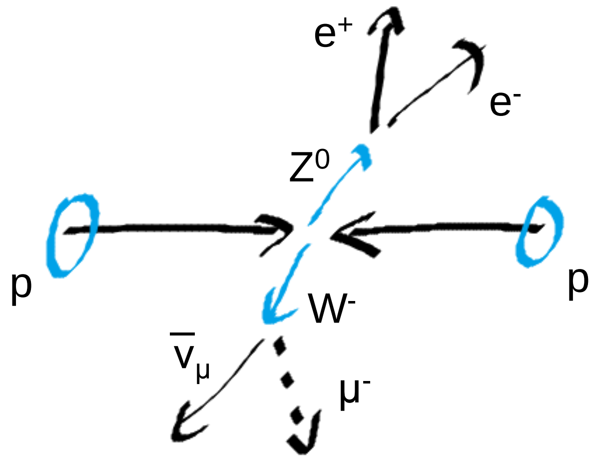
→ Will be very interesting!

Measurement of WZ production

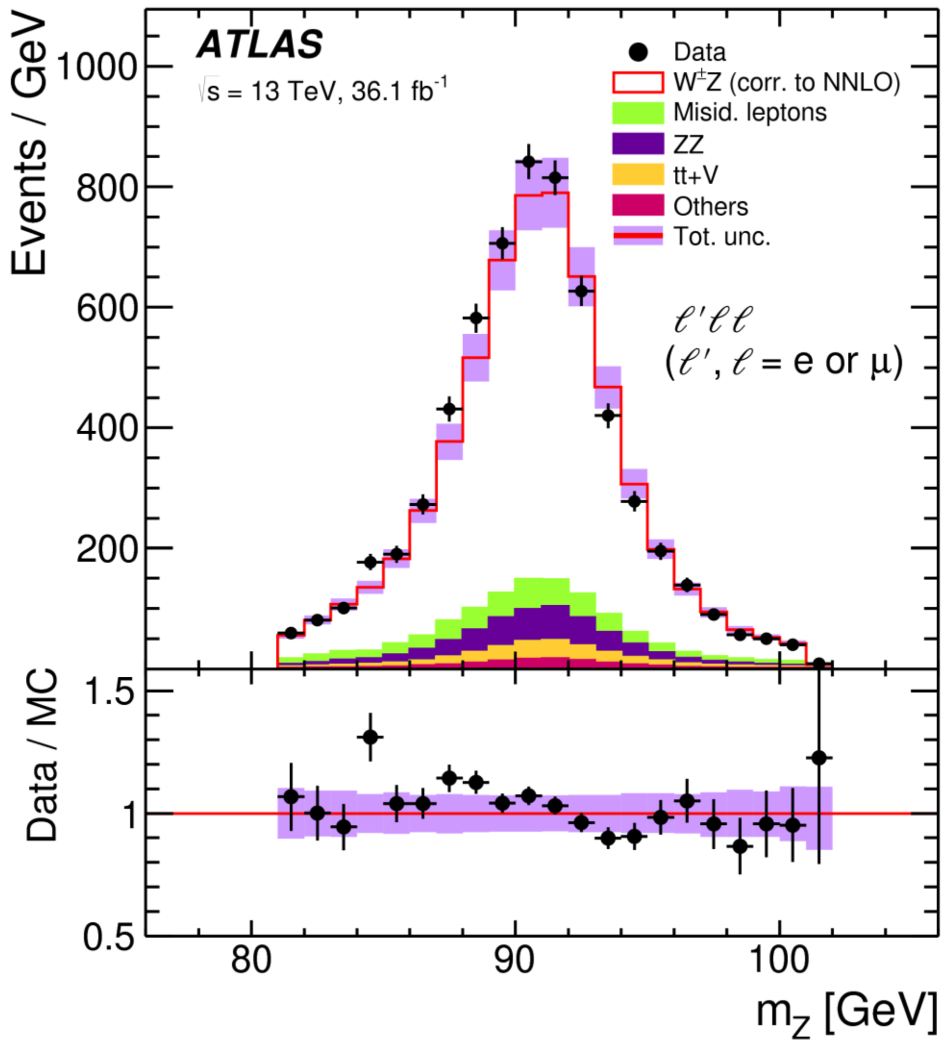
arXiv:1902.05759

WZ @ 13TeV – 36.1fb^{-1}

- WZ production @ LHC



- Select $W^{\pm}Z \rightarrow e^{\pm}(e^{+}e^{-}/\mu^{+}\mu^{-})$ or $W^{\pm}Z \rightarrow \mu^{\pm}(e^{+}e^{-}/\mu^{+}\mu^{-})$
- Assign leptons to W and Z decays according to
  - Resonant shape algorithm (truth level)
  - Closest invariant mass of same flavour, opposite sign lepton pair to Z boson mass (detector level)
- Presence of jets with p_T > 25GeV, $|\eta|$ < 4.5 allowed



Cross section determination

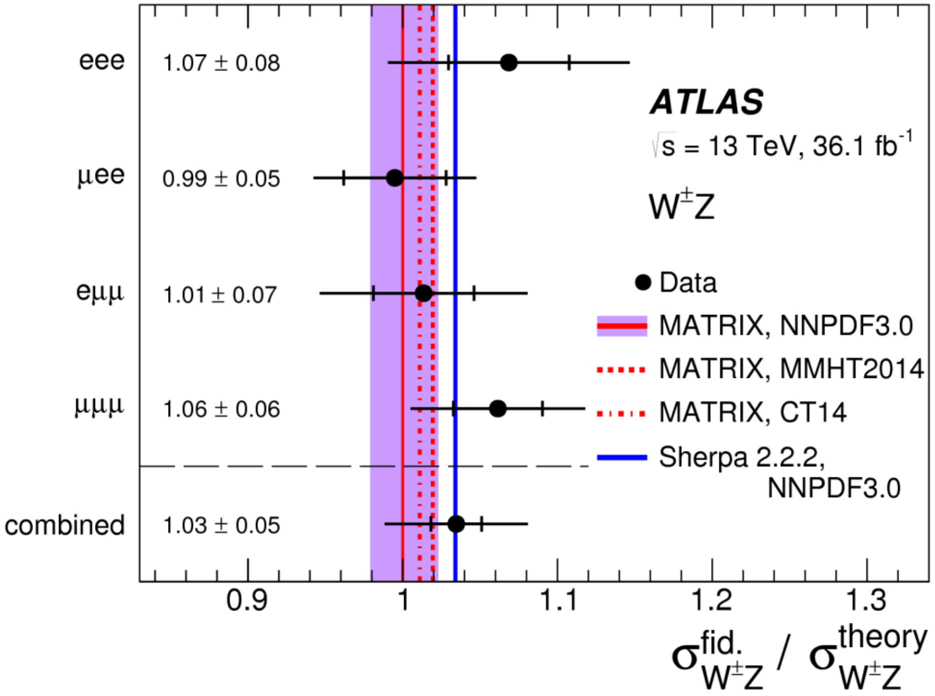
arXiv:1902.05759

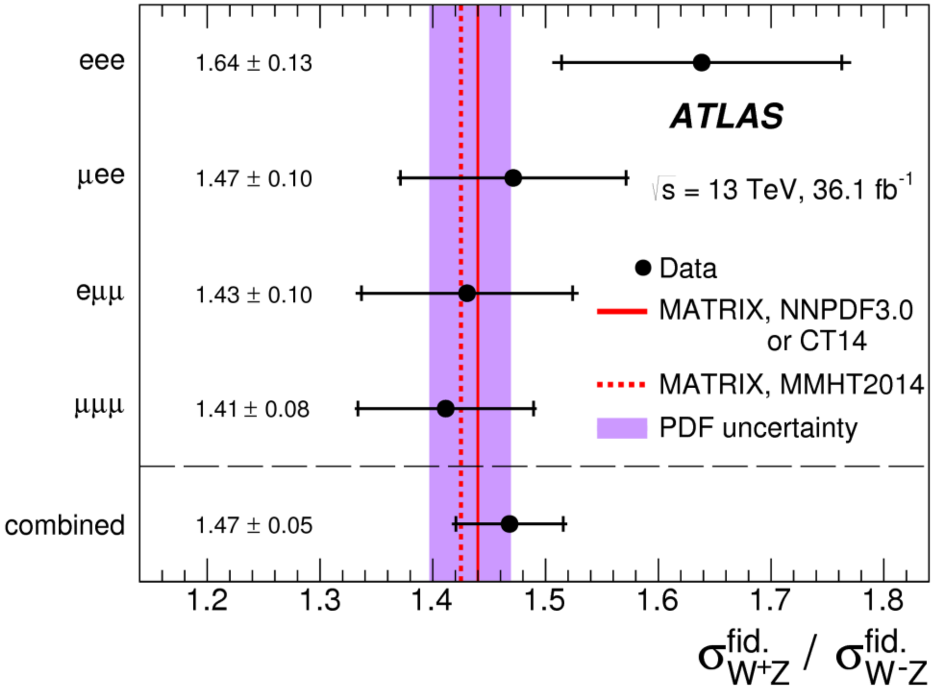
WZ @ 13TeV – 36.1fb^{-1}

- Fiducial cross section

$$\sigma^{\text{fid.}}_{W^\pm Z\to\ell'\nu\ell\ell} = \frac{N_{\text{data}} - N_{\text{bkg}}}{\mathcal{L}\cdot C_{WZ}} \times \left(1 - \frac{N_\tau}{N_{\text{all}}}\right)$$

  - Explicit correction for τ-lepton branching fraction
  - Combination of the 4 channels with χ^2-minimization method → taking correlated systematic uncertainties into account





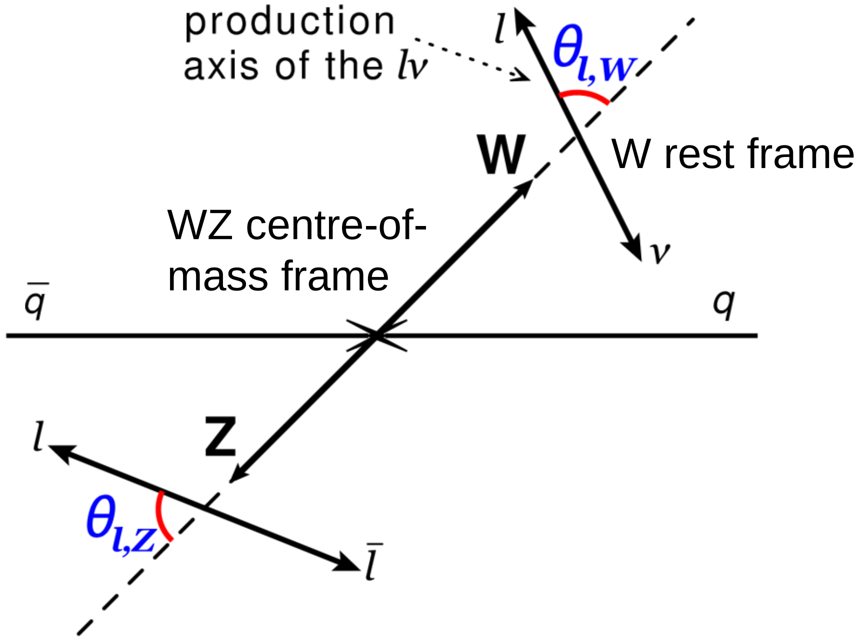
→ Good agreement of NNLO MATRIX and NLO ME+PS prediction with data

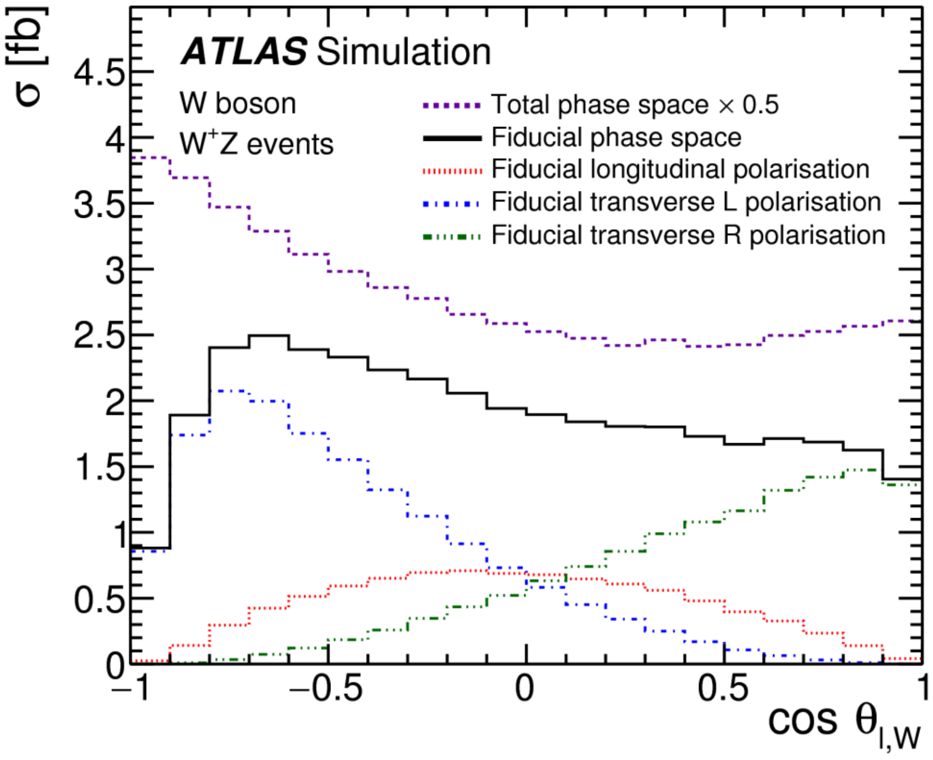
Polarisation of WZ events

arXiv:1902.05759

WZ @ 13TeV – 36.1fb^{-1}

- Transverse left-handed (f_L), transverse right-handed (f_R) and longitudinal helicity (f_0) fractions
  - Related to decay angles





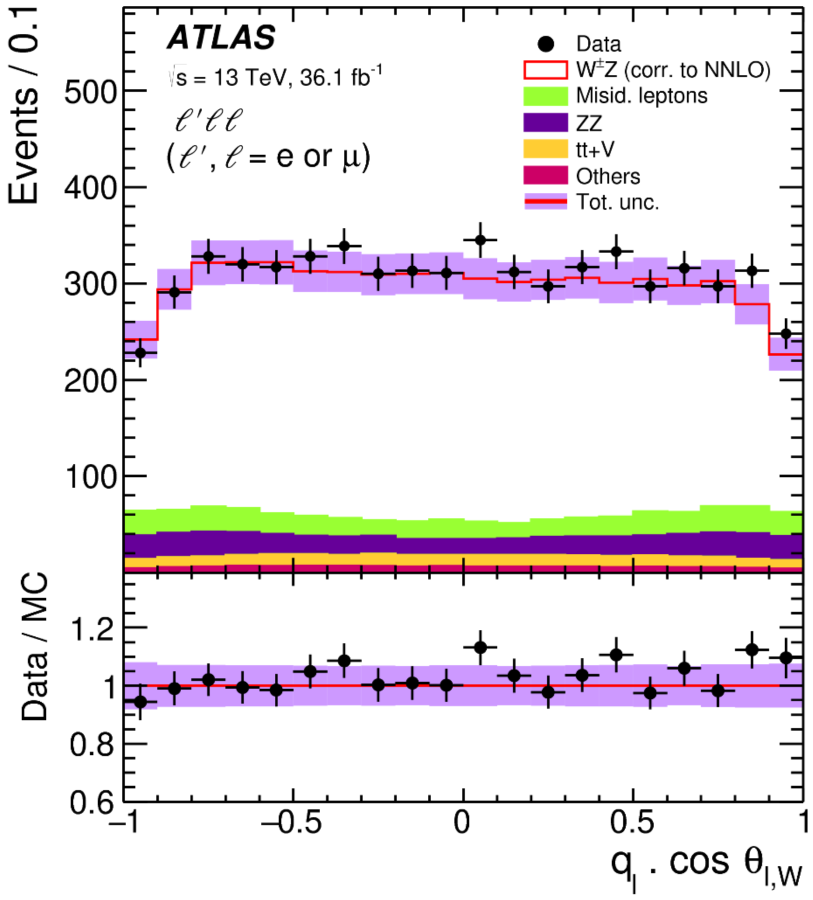
  - Lepton and neutrino p_T and η requirements → suppress $|\cos\theta_{l,W/Z}|$ at ~1 for fiducial compared to the total phase space

Polarisation of WZ events

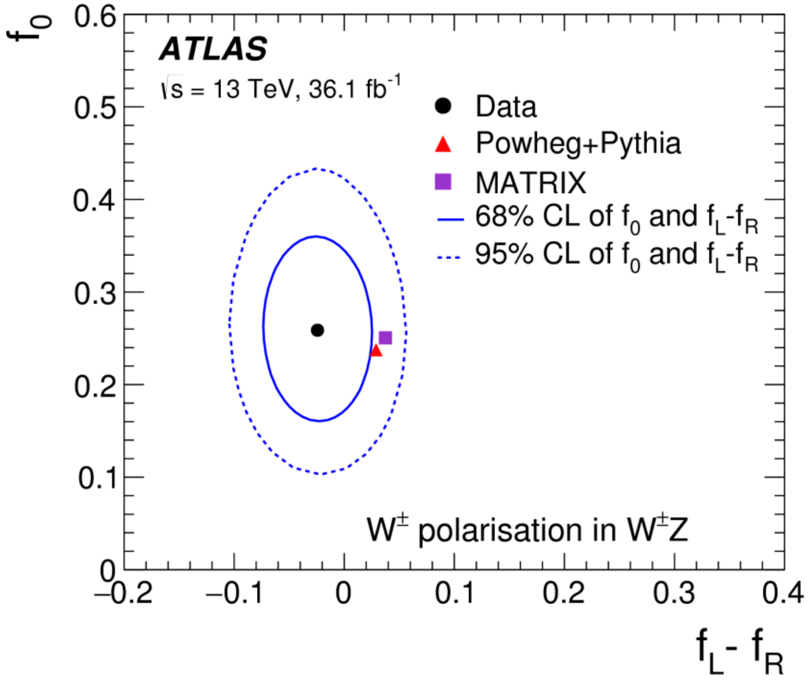
arXiv:1902.05759

WZ @ 13TeV – 36.1fb^{-1}

- Combine the 4 decay channels → Binned profile likelihood fit with templates for the three helicity states
  - Fit q_l*$\cos\theta_{l,W}$ and $\cos\theta_{l,Z}$ → Extract f_0, f_L-f_R and the fiducial cross section for W and Z bosons, respectively



Fit & correct to particle level



→ Presence of longitudinally polarised bosons
- W: 4.2σ observed (3.8σ expected) → Evidence
- Z : 6.5σ observed (6.1σ expected) → Observation!

Summary

(WW & WZ) @ 13TeV

- WW and WZ production at the LHC
  - Sensitive probe to gauge structure of electroweak sector in SM (triple gauge coupling, longitudinal polarisation)

- WW @ 13TeV, 36.1fb^{-1}
  - First differential WW measurement at 13 TeV
  - Fiducial cross section with similar precision to WW@8TeV → Best so far

- WZ @ 13TeV, 36.1fb^{-1}
  - First measurement of polarisation fractions for diboson events in hadronic collisions
    - Observation of longitudinal polarisation of Z bosons in WZ events
    - Evidence for longitudinal polarisation of W bosons in WZ events

Thank you for your attention

Theoretical predictions for WW so far

History of previous publications

- 0-jet case

Analysis	Data set [fb^{-1}]	Highest order prediction	Data	Prediction	Difference in σ_{exp}	Reference
WW@7TeV	4.6	NLO [MC@NLO (qq)+ GG2WW (gg)	51.9 ±2.0 (stat) ±3.9 (syst) ±2.0 (lumi) pb [total cross section]	44.7 $^{+2.1}_{-1.9}$ pb	2.1	Phys. Rev. D 87, 112001 (2013)
WW@8TeV	20.3	NNLO	71.1 ±1.1 (stat) $^{+5.7}_{-5.0}$ (syst) ±1.4 (lumi) pb [total cross section]	63.2 $^{+1.6}_{-1.4}$ (scale) ±1.2 (PDF) pb	1.4	JHEP09 (2016) 029
WW@13TeV	3.16	nNNLO+H [NNLO (qq) + NLO (gg) + NLO (gg→H)	529 ±20 (stat.) ±50 (syst.) ±11 (lumi.) fb [fiducial]	478 ±17 fb	0.9	Phys. Lett. B 773 (2017) 354
WW@13TeV	36.1	[NNLO (qq) + NLO(gg)]xNLO EW	379 ±5 (stat) ±27 (syst,incl lumi) fb [fiducial]	347 ±4 (PDF) ±19 (scale) fb	1.2	STDM-2017-24

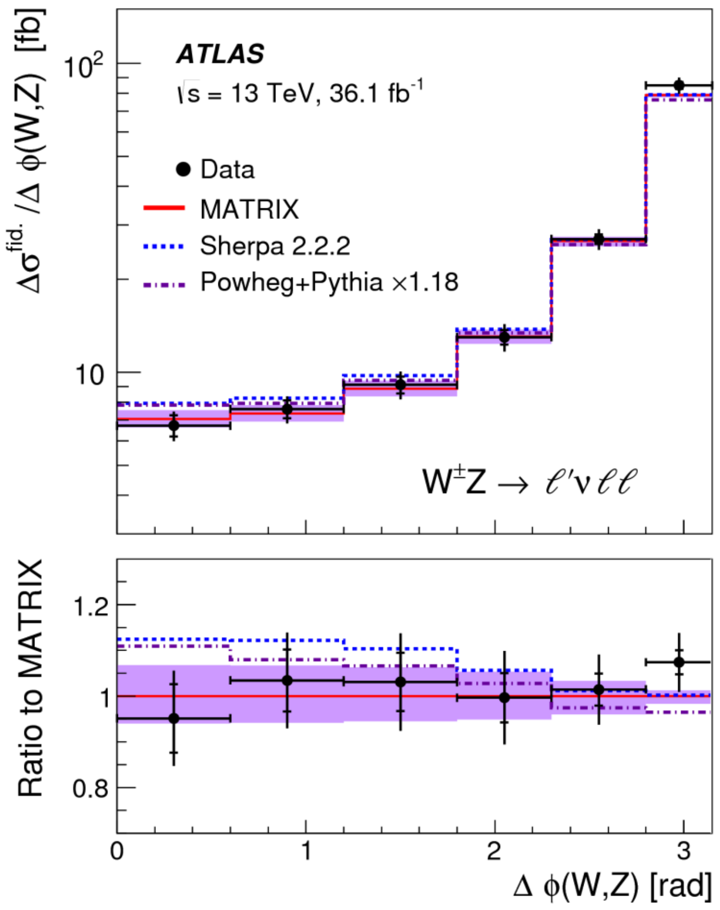
Differential cross sections

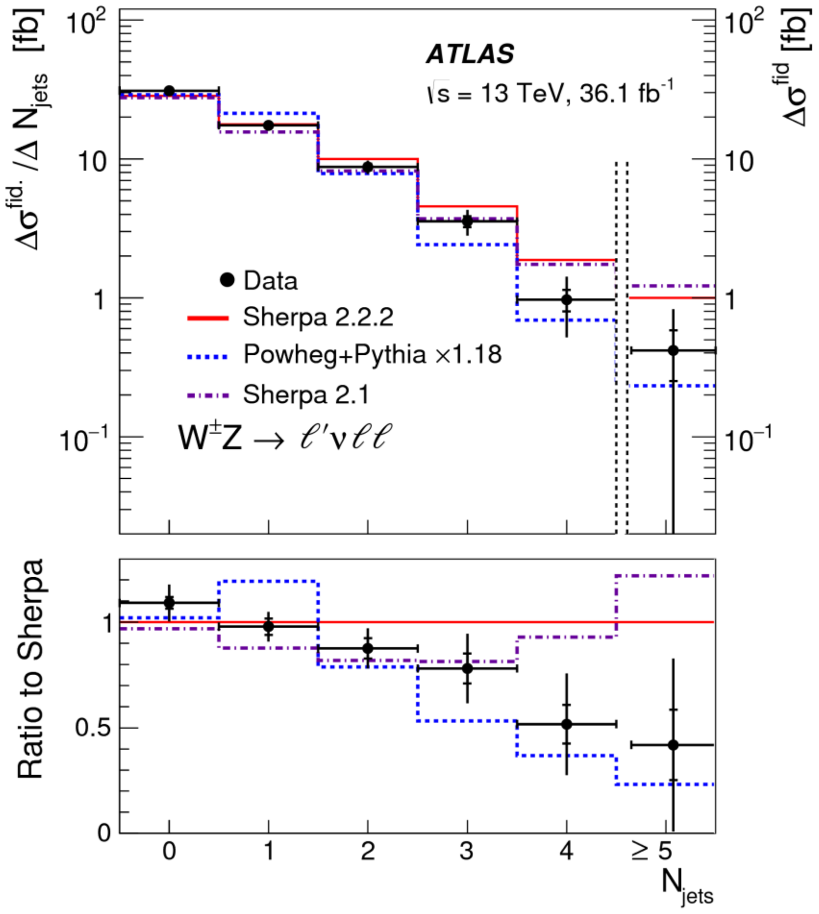
arXiv:1902.05759

WZ @ 13TeV – 36.1fb^{-1}

- Combined unfolding of the 4 decay channels with iterative Bayesian method
  - Kinematics of the WZ system

Kinematics of the associated jets





→ Comparison to NNLO MATRIX, NLO Powheg+Pythia (scaled to NNLO) and NLO Sherpa 2.2.2 (and 2.1)

→ Improved agreement with data for NNLO MATRIX than for NLO predictions

→ Difficulties of predictions to describe jet multiplicity correctly