MEASUREMENTS OF INCLUSIVE WW AND WZ PRODUCTION

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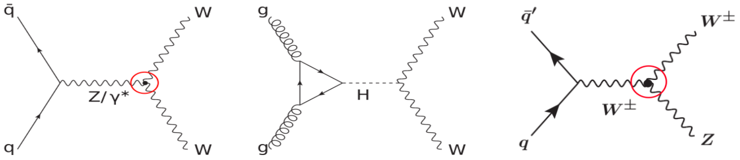
Introduction

- WW (s-channel and H-induced) and WZ (s-channel) pair productions:



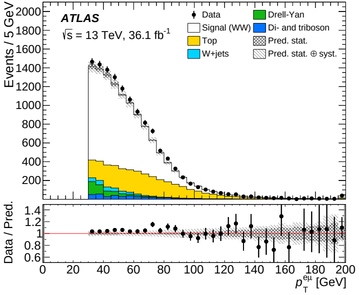
- Motivations for precise measurement of WW and WZ productions:
  - Important backgrouds to searches for new physics and to $H \to WW$ production
  - Probe Standard Model (SM) electroweak gauge symmetry structure, and investigate signal of new physics in a model-independant way

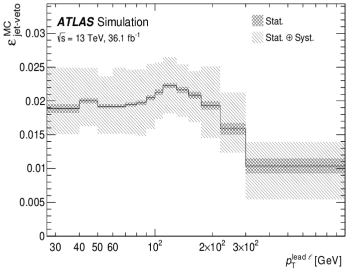
    $\rightarrow$ WW and WZ s-channels include WWZ triple gauge boson coupling (TGC), plus WWγ coupling for WW
  - Angular distributions of decay products could potentially exhibit vector boson (V) polarization behaviours differing from SM predictions

    $\rightarrow$ WZ production is sensitive to W$^{\pm}$ and Z polarizations

Measurement of WW production – Signal region and background modelling

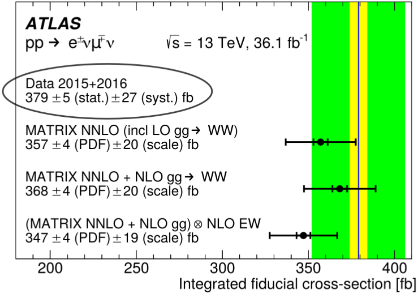
- Submitted to EPJC [$\sqrt{s} = 13\,\text{TeV}$, $36.1\,\text{fb}^{-1}$]
- Analysis of opposite-sign (OS) $e\mu$ channel
- WW signal region (SR):
  - 1 $e\mu$ pair of isolated central leptons
  - No additional leptons (suppress VV)
  - No jet with $p_T > 35\,\text{GeV}$ & no central b-jets (reduce top)
  - $\not{p}_T^{track} > 20\,\text{GeV}$ & $p_T^{e\mu} > 30\,\text{GeV}$ (cut DY)
  - $m_{e\mu} > 55\,\text{GeV}$ (orthogonal to HWW analysis)
- Backgrounds (% of SR):
  - $t\bar{t}$ and Wt ($\sim 26\%$): from top-enriched Data CR w/o jet veto, reweighted with $\epsilon_{jet\,veto}$ (procedure detailed in backup slide)
  - Non-prompt leptons, mostly W+jets ($\sim 3\%$): estimate relies on fake rate from Data
  - DY ($\sim 4\%$), Multi-bosons ($\sim 3\%$): simulated

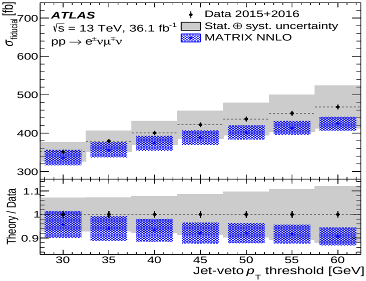




Measurement of WW production – Fiducial cross section

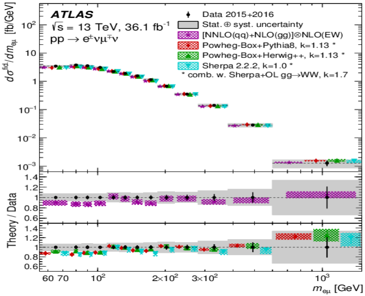
- Measured σ_{WW}^{fid} compared to:
  - NNLO prediction from MATRIX (up to NLO for gg initial states)
  - NLO+PS predictions: SHERPA-v2.2.2 (LO+PS $gg \rightarrow WW$ via OPENLOOPS), and POWHEG+(PYTHIA8 or HERWIG++)
  - NLO+PS and LO+PS predictions scaled to NNLO and NLO, respectively
- σ_{WW}^{fid} computed for different lower thresholds for the p_T of the jets vetoed
- Systematic uncertainty on measured σ_{WW}^{fid} of 6.7% (excl. luminosity):
  - Largest experimental: jet calibration (3%) and b-tagging (3.4%)
  - Largest background modelling: W+jets (3.1%), Top (2.6%)

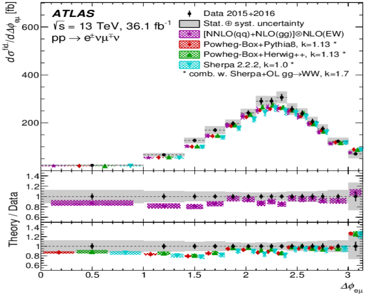




Measurement of WW production – Unfolded differential σ

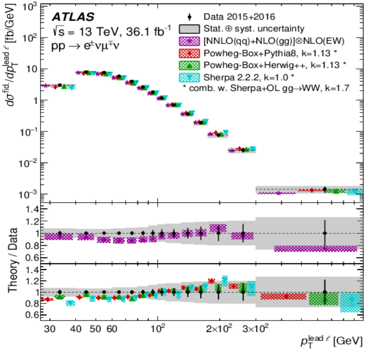
- Unfolding of signal performed via Bayesian iterative technique (1 to 2 iterations) using POWHEG+PYTHIA8
- 6 observables unfolded:
  - $m_{e\mu}$, $p_T^{e\mu}$, and $p_T^{lead\,\ell}$ characterize energy of the process, the latter being sensitive to anomalous TGC (aTGC)
  - $|y_{e\mu}|$, $\Delta\phi_{e\mu}$, and $|\cos\theta^*| = |\tanh(\frac{\Delta\eta_{e\mu}}{2})|$ probe angular correlations and spin state of WW system
- Overall fair description of Data, except in a few regions. Examples:
  - Good description of $m_{e\mu}$ from $\sim 100\,\mathrm{GeV}$
  - Underprediction of Data for $\Delta\phi_{e\mu} < 1.8$, for all MC generators. Similar behaviour already seen in $8\,\mathrm{TeV}$ analyses.





Measurement of WW production – Anomalous couplings

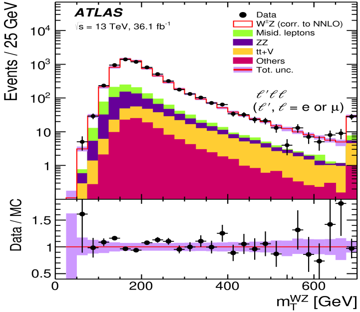
- New physics with aTGC at high energy scale Λ can be probed via WWZ and WWγ vertices
- Considering Effective Field Theory with five dimension-6 operators associated to the couplings: c_{WWW}, c_W, c_B, $c_{\tilde{W}WW}$, $c_{\tilde{W}}$
- Unfolded $p_T^{lead\,\ell}$ distribution exhibits high-q^2 regime, which is sensitive to anomalous couplings (especially last bin), and was used to constrain strength of aTGC
- Signal including aTGC generated with MADGRAPH5_aMC@NLO+PYTHIA8
- Competitive 95% CL intervals for aTGC are derived via a profile likelihood ratio test statistic, thanks to high center-of-mass energy



Parameter	Observed 95% CL [TeV^{-2}]	Expected 95% CL [TeV^{-2}]
c_{WWW}/Λ^2	[−3.4 , 3.3]	[−3.0 , 3.0]
c_W/Λ^2	[−7.4 , 4.1]	[−6.4 , 5.1]
c_B/Λ^2	[−21 , 18]	[−18 , 17]
$c_{\tilde{W}WW}/\Lambda^2$	[−1.6 , 1.6]	[−1.5 , 1.5]
$c_{\tilde{W}}/\Lambda^2$	[−76 , 76]	[−91 , 91]

Measurement of WZ production – Signal region and background modelling

- Published: EPJC 79 (2019) 535 $[\sqrt{s} = 13\,\mathrm{TeV},\ 36.1\,\mathrm{fb}^{-1}]$
- eee, $e\mu\mu$, $ee\mu$, and $\mu\mu\mu$ channels combined
- WZ candidate selection:
  - ZZ veto: less than 4 "loose" leptons
  - Exactly 3 isolated "tighter" leptons
  - Z selection: same-flavor OS lepton pair, with invariant mass close to m_Z
  - W selection and fake lepton suppression: remaining 3rd lepton to pass more stringent quality criteria and such that $m_T^W > 30\,\mathrm{GeV}$



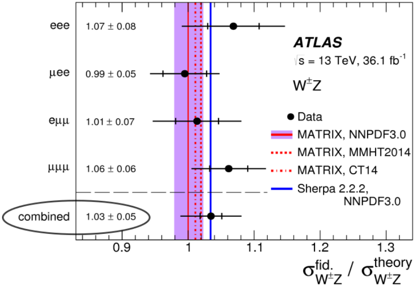
- Main backgrounds (% of SR):
  - Mis-identified leptons (~7%): estimated using fake rate from Data
  - ZZ and $t\bar{t}+V$ (reducible to ~11%): simulated and normalized to Data via 4-leptons & 2-b-jets control regions

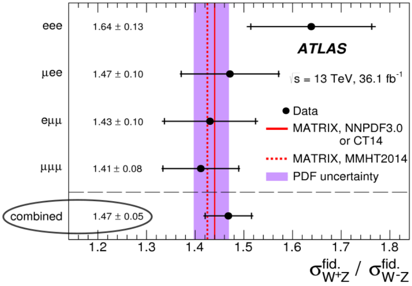
Measurement of WZ production – Fiducial cross sections

- Measured σ^{fid}_{WZ} compared to:
  - NNLO prediction from MATRIX
  - NLO+PS predictions: SHERPA-v2.2.2 + COMIX/OPENLOOPS, POWHEG+PYTHIA8 (scaled to NNLO)
- Combined measurements:

  $\sigma^{fid}_{WZ} = 63.7 \pm 4.5\,\text{fb}$ [MATRIX: $61.5^{+2.3}_{-2.1}$ fb]

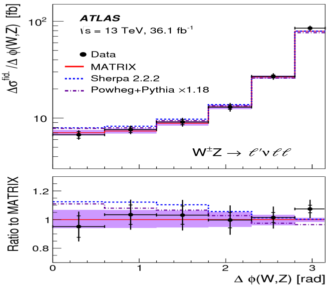
  $\sigma^{tot}_{WZ} = 51.0 \pm 2.4\,\text{pb}$ [MATRIX: $49.1^{+1.1}_{-1.0}$ pb]
- Ratio $\sigma^{fid}_{W^+Z}/\sigma^{fid}_{W^-Z}$ also computed, since sensitive to parton distribution functions
- Systematic uncertainty on measured σ^{fid}_{WZ} of 3.6% (excl. lumi.), with:
  - Background modelling: mis-id. (1.9%), ZZ (1.0%), others (1.4%)
  - Lepton calib. (1.9%) and pile-up (1.3%)

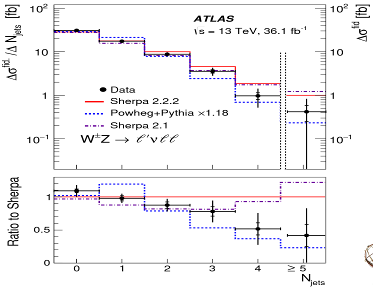




Measurement of WZ production – Unfolded differential σ

- Unfolding of signal performed via Bayesian iterative technique (2 to 4 iterations) using POWHEG+PYTHIA8
- 8 observables unfolded:
  - p_T^Z and m_T^{WZ}, with high energy tails sensitive to aTGC
  - $|\Delta\phi(W,Z)|$ sensitive to QCD higher-order pertubative effects
  - N_{jets}, m_{jj}, p_T^W, p_T^ν, $|y_Z - y_{\ell,W}|$
- Examples:
  - $|\Delta\phi(W,Z)|$ better described at NNLO
  - N_{jets} better described by SHERPA-v2.2.2 (up to one parton NLO) for 0-&1-jet bins, while SHERPA-v2.1 then performs better up to 3-jets bin (up to 3 partons at LO)





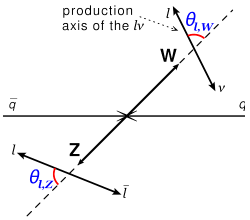
Measurement of WZ production – W and Z polarizations

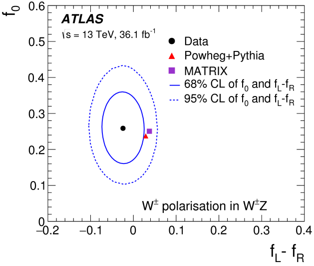
- W and Z polarisations can be derived from angular distribution of decay products

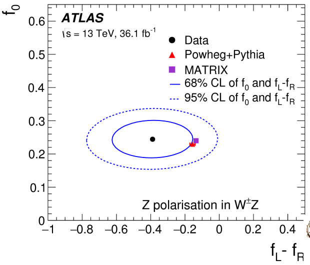
$\rightarrow$ $\frac{d\sigma_{WZ}}{d\cos\theta_{\ell,V}}$ can be expressed as function of longitudinal (f_0), right-handed (f_R), and left-handed (f_L) helicity fractions, involving $\cos\theta_{\ell,V}$ and $\sin\theta_{\ell,V}$

- f_0 and f_L-f_R measured in fiducial region separately for Z and W in W^+Z, W^-Z, and $W^{\pm}Z$ events via profile likelihood fit of $f_{0/L/R}$ templates (POWHEG+PYTHIA8) to observed $q_\ell.\cos\theta_{\ell,W}$ and $\cos\theta_{\ell,Z}$. Results further corrected to particle-level.

- First measurement in VV events from hadronic collisions: f_0 and f_L-f_R values agree within 1σ and 2σ with predictions at (N)NLO in QCD and LO in EW corrections







Conclusion

- WW and WZ production cross sections have been measured at $\sqrt{s} = 13\,\mathrm{TeV}$ using $36.1\,\mathrm{fb}^{-1}$ of Data
- Unfolded differential production cross sections have been estimated for both WW and WZ production cross sections, including observables sensitive to anomalous gauge couplings
- Stringent constraints have been put on triple-gauge-boson anomalous couplings using the WW channel, in the framework of a dimension-6 Effective Field Theory
- Longitudinal and transverse helicity fractions of W and Z have been measured in W^+Z, W^-Z, and $W^\pm Z$ events, and are in agreement with SM predictions

→ For more information:
https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

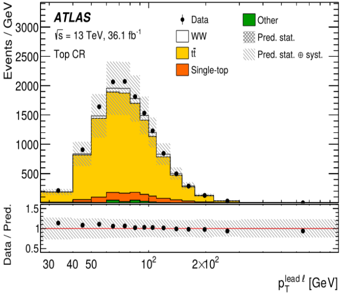
BACKUP

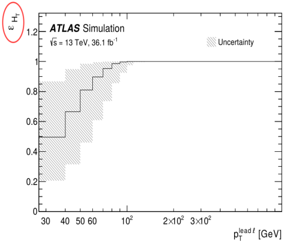
Measurement of WW production – Top background modelling

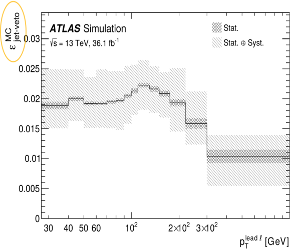
- Top control region enriched in top events, w/o jet veto, and $H_T = \sum_{jets,lepton} p_T > 200\,\mathrm{GeV}$
- After substracting background from CR:

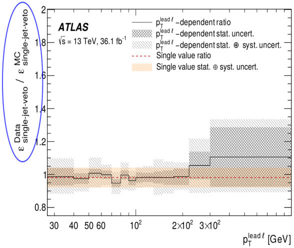
$$N_{SR}^{top} = \frac{N_{CR}^{top}}{\epsilon_{H_T}} \times \epsilon_{jet\,veto}$$ with:

  - $\epsilon_{jet\,veto} = \epsilon_{jet\,veto}^{MC} \times \left(\frac{\epsilon_{single\,jet\,veto}^{Data}}{\epsilon_{single\,jet\,veto}^{MC}}\right)^{<n_{jets}>}$
  - $< n_{jets} > \sim 2.5$ (from top CR)





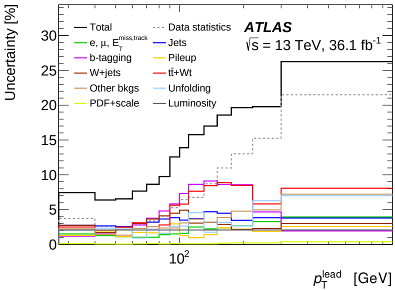




Measurement of WW and WZ production – Systematics

- Systematic uncertainties on differential cross section measurements as function of $p_T^{lead\,\ell}$ and jet multiplicity, for the WW and WZ productions, respectively:

WW production:



WZ production:

N_{jets} (p_T>25 GeV)	0	1	2	3	4	≥ 5
$\Delta\sigma^{\text{fid.}}_{W^+Z}$ [fb]	31.02	17.44	8.75	3.56	0.97	0.42
Relative Uncertainties [%]						
Statistics	2.5	3.9	5.5	9.1	17.6	39.8
All systematics	7.2	5.6	9.0	18.7	42.9	89.1
Luminosity	2.2	2.2	2.3	2.5	2.6	2.5
Total	8.0	7.2	10.8	20.9	46.5	97.7
Uncorrelated	0.2	0.3	0.4	0.6	1.3	3.2
Unfolding	0.1	0.2	0.2	3.5	10.1	2.4
Electrons	1.1	1.3	1.3	1.4	1.7	1.5
Muons	1.6	1.6	1.7	1.7	1.8	2.0
Jets	5.7	2.6	5.8	14.3	22.0	26.5
Red. Background	2.1	3.7	6.0	7.7	13.2	21.2
Irred. Background	1.4	2.2	2.5	8.1	32.6	81.9
Pileup	3.0	0.7	0.2	2.0	3.0	7.2
Born → dressed	0.963	0.960	0.955	0.951	0.956	0.961

Measurement of WZ production – W and Z polarizations

- WZ differential cross section as function of helicity fractions:
  - $\frac{1}{\sigma_{WZ}} \frac{d\sigma_{WZ}}{d\cos\theta_{\ell,W}} = \frac{3}{8} f_L (1 \mp \cos\theta_{\ell,W})^2 + \frac{3}{8} f_R (1 \pm \cos\theta_{\ell,W})^2 + \frac{3}{4} f_0 \sin^2\theta_{\ell,W}$
  - $\frac{1}{\sigma_{WZ}} \frac{d\sigma_{WZ}}{d\cos\theta_{\ell,Z}} = \frac{3}{8} f_L (1 + 2\alpha\cos\theta_{\ell,Z} + \cos^2\theta_{\ell,Z}) + \frac{3}{8} f_R (1 + \cos^2\theta_{\ell,Z} - 2\alpha\cos\theta_{\ell,Z}) + \frac{3}{4} f_0 \sin^2\theta_{\ell,Z}$

  with $\alpha = (2c_\nu c_a)/(c_\nu^2 + c_a^2)$, vector term $c_a = -\frac{1}{2}$,
  axial-vector term $c_\nu = -\frac{1}{2} + 2\sin^2\theta_W^{eff}$ and Weinberg angle $\sin^2\theta_W^{eff} = 0.23152$

- Measured helicity fractions in the fiducial phase space (with Born-level leptons):

	f_0			$f_L - f_R$		
	Data	Powheg+Pythia	MATRIX	Data	Powheg+Pythia	MATRIX
W^+ in W^+Z	0.26 ± 0.08	0.233 ± 0.004	0.2448 ± 0.0010	-0.02 ± 0.04	0.091 ± 0.004	0.0868 ± 0.0014
W^- in W^-Z	0.32 ± 0.09	0.245 ± 0.005	0.2651 ± 0.0015	-0.05 ± 0.05	-0.063 ± 0.006	-0.034 ± 0.004
$W^\pm$ in $W^\pm Z$	0.26 ± 0.06	0.2376 ± 0.0031	0.2506 ± 0.0006	-0.024 ± 0.033	0.0289 ± 0.0022	0.0375 ± 0.0011
Z in W^+Z	0.27 ± 0.05	0.225 ± 0.004	0.2401 ± 0.0014	-0.32 ± 0.21	-0.297 ± 0.021	-0.262 ± 0.009
Z in W^-Z	0.21 ± 0.06	0.235 ± 0.005	0.2389 ± 0.0015	-0.46 ± 0.25	0.052 ± 0.023	0.0468 ± 0.0034
Z in $W^\pm Z$	0.24 ± 0.04	0.2294 ± 0.0033	0.2398 ± 0.0014	-0.39 ± 0.16	-0.156 ± 0.016	-0.135 ± 0.006

Measurement of WZ production – W and Z polarizations

- Measured $q_\ell . \cos\theta_{\ell,W}$ (left) and $\cos\theta_{\ell,Z}$ (right) to which templates of the 3 helicity states ($f_{0/L/R}$) from POWHEG+PYTHIA8 are fitted: