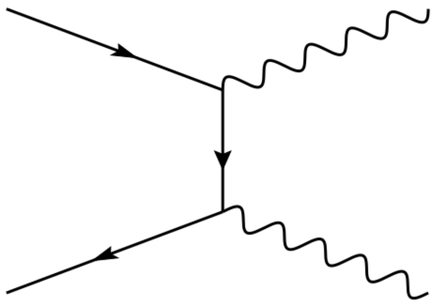
MEASUREMENTS OF DIBOSON PRODUCTION AND PRECISION EFT CONSTRAINTS

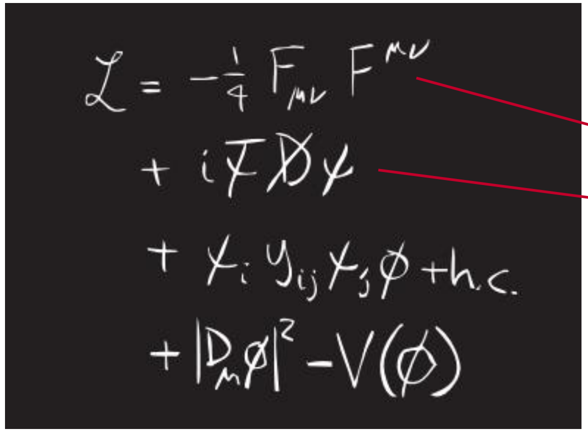
EPS HEP 2025 | 10 July, Marseille

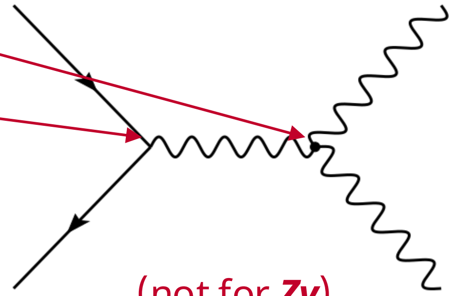
Hannes Mildner on behalf of the ATLAS collaboration

DIBOSON PRODUCTION



- Will discuss three new diboson measurements by the ATLAS collaboration
  - **W^+W^-**: arXiv:2505.11310
  - **$W^\pm Z$**: arXiv:2507.03500
  - **$Z\gamma$**: ATLAS-CONF-2025-001
  - Based on **full 13 TeV dataset of 140 fb^{-1}**
  - **Precision** measurement with leptonic boson decays





(not for $Z\gamma$)

- Probing the SM **electroweak gauge structure**
  - Triple gauge couplings (TGCs) due to non-Abelian gauge symmetry
  - No neutral triple gauge coupling (nTGC) (e.g. $ZZ\gamma$ or $Z\gamma\gamma$)
- Deviations from SM modelled as additional operators in **SMEFT framework**
  - Anomalous TGCs at dimension six
  - nTGCs at dimension eight
  - Diboson sensitive: effects of multiple operators increases with invariant mass

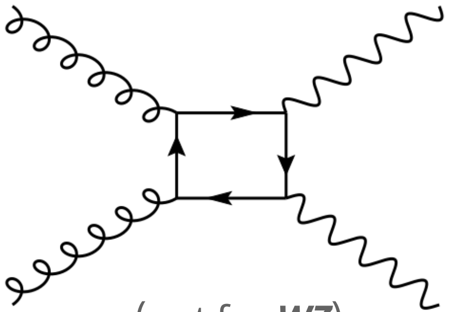
Wilson coefficient (coupling strength)

Higher-dimensional Operator (new/altered interaction)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

SM Lagrangian (dimension four)

Mass scale of new physics



(not for WZ)

WW, WZ, AND ZY: EVENT SELECTION

- ***WW***
  - Electron and muon
  - 0 b-jets (reduce top background)
  - $m_{\ell\ell}$> 85 GeV (reduce DY)
- ***WZ***
  - Three charged leptons
  - $|M_{\ell\ell} - M_Z|$ < 10 GeV
  - $M_T(W)$ > 30 GeV
- ***Zγ***
  - Two charged leptons and a photon
  - $|M_{\ell\ell} - M_Z|$ < 10 GeV
  - $M_{\ell\ell} + M_{\ell\ell\gamma}$ > 182 GeV (reduce FSR)
  - Photon p_T > 200 GeV

Category	Event yield	
Data	144221	
Total SM	139500 ± 2400	
WW	56900 ± 1100	41%
Total background	82600 ± 2100	59%
Top	66500 ± 1900	48%
Drell–Yan	6500 ± 400	5%
Fakes	5000 ± 1300	4%
$WZ, ZZ, V\gamma$	4500 ± 600	3%

Channel	eee	μee	$e\mu\mu$	$\mu\mu\mu$	All
Data	3955	4600	5895	7486	21936
Total expected	4000 ± 500	4900 ± 500	5900 ± 700	7600 ± 900	22400 ± 2500
WZ	78%	83%	79%	82%	81%
ZZ	8%	7%	8%	7%	7%
Misid. leptons	7%	4%	6%	5%	5%
$t\bar{t}+V$	4%	4%	4%	4%	4%
tZj	2%	2%	2%	1%	2%
$WZjj$–EW	1%	1%	1%	1%	1%
VVV	< 1%	< 1%	< 1%	< 1%	< 1%

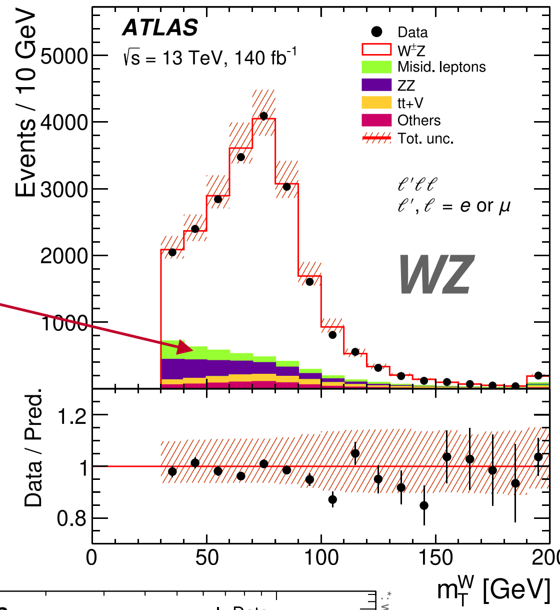
Source	$ee + \mu\mu$
$Z\gamma$ signal	271.0 ± 2.4 (stat.) ± 44.3 (syst.)
Z+jets	82 ± 71 (stat.) ± 98 (syst.)
multiboson	33.5 ± 4.6 (stat.) ± 10.0 (syst.)
pile-up	1.01 ± 0.11 (stat.) ± 0.20 (syst.)
$t\bar{t}\gamma$	0.31 ± 0.18 (stat.) ± 0.05 (syst.)
$tW\gamma$	0.13 ± 0.02 (stat.) ± 0.04 (syst.)
Total prediction	388 ± 71 (stat.) ± 108 (syst.)
Data	344

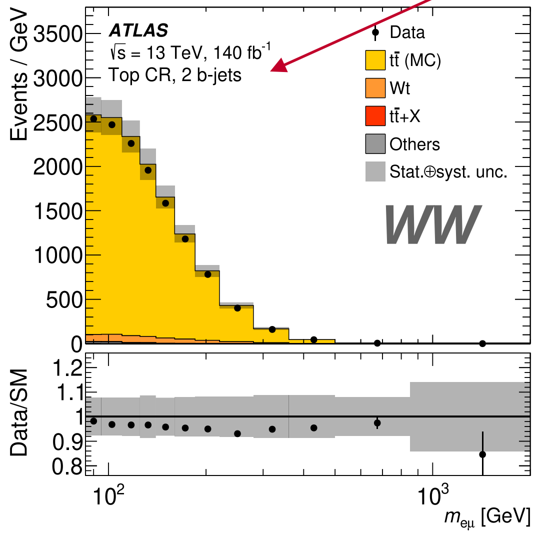
- 3x more ***WW*** events (57k) than ***WZ*** (18k) but 3x larger background fraction
- ***Zγ***: small yield due to photon p_T requirement – focus on nTGC limits
- Will discuss ***WW*** and ***WZ*** first, highlighting similarities and differences

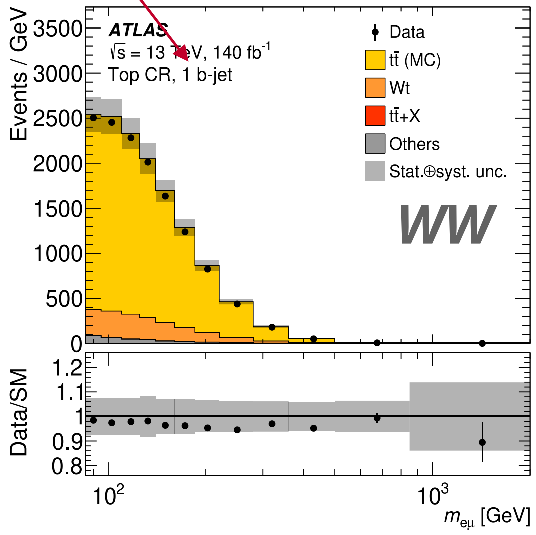
WW AND **WZ**: BACKGROUND ESTIMATION

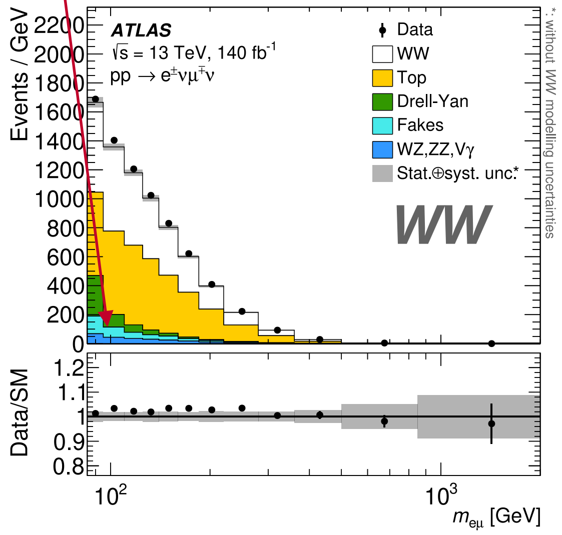
- Fake lepton background
  - Due to non-prompt leptons or objects misidentified as leptons
  - Estimated in regions with loosened lepton identification criteria
- Top quark pair production background (relevant for ***WW*** only)
  - Estimated differentially from 1 and 2 b-jets CRs (SR has 0), simultaneously determining b-tag efficiency ε and top background yield
- Remaining backgrounds
  - Estimated using MC simulation
  - Validated and corrected in data

"fakes"





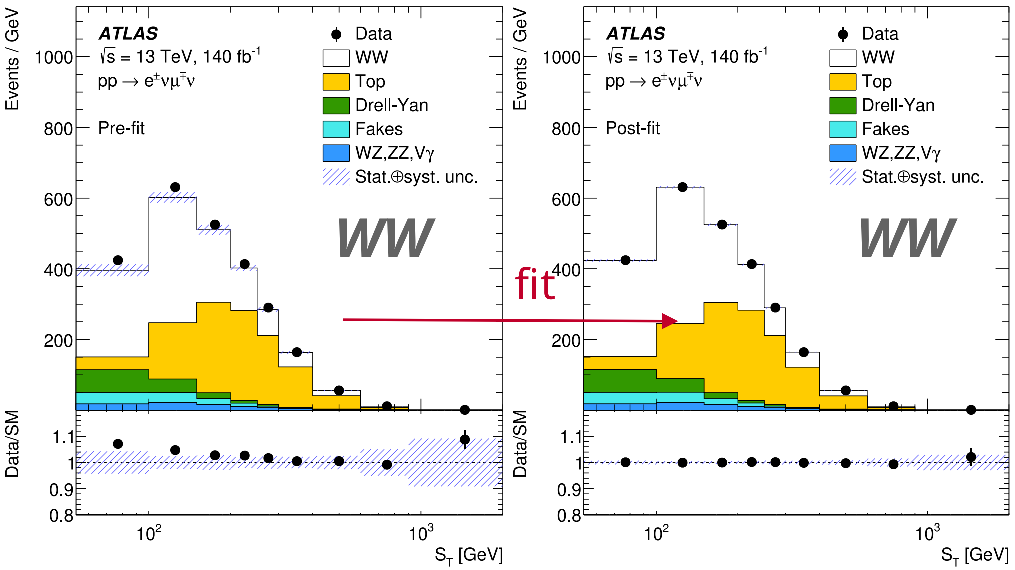




2 b-jets CR: ~ε^2 1 b-jet CR : ~$2\varepsilon(1-\varepsilon)$ 0 b-jet SR: ~$(1-\varepsilon)^2$

WW AND **WZ**: SIGNAL EXTRACTION, UNCERTAINTIES

- ***WZ***: combination of four different three-lepton channels
- ***WW***: Signal extraction in maximum-likelihood fit
  - Further reduce uncertainties of data-driven backgrounds
  - Benefits from state-of-the art MiNNLO$_{PS}$ NNLO+PS model



WZ

	eee	μee	$e\mu\mu$	$\mu\mu\mu$	Combined
	Relative uncertainties [%]				
e energy scale	0.3	< 0.1	0.2	< 0.1	0.1
e efficiency	1.7	1.1	0.6	< 0.1	0.6
μ momentum scale	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
μ efficiency	< 0.1	1.4	0.5	1.7	0.9
E_T^{miss} and jets	0.4	0.4	0.5	0.5	0.4
Trigger	< 0.1	< 0.1	< 0.1	0.2	0.1
Pile-up	1.0	0.9	0.6	0.4	0.6
Misid. leptons background	2.3	1.1	1.5	1.4	1.4
ZZ background	0.9	0.8	0.9	0.8	0.8
Other backgrounds	0.9	0.9	0.9	0.9	0.9
Uncorrelated	0.4	0.3	0.3	0.3	0.2
Total experimental uncertainty	3.4	2.6	2.3	2.6	2.3
Luminosity	0.9	0.9	0.9	0.9	0.9
Theoretical modelling	3.0	3.0	3.0	3.0	3.0
Data statistics	2.0	1.8	1.6	1.4	0.8
Total	5.0	4.5	4.2	4.3	4.0

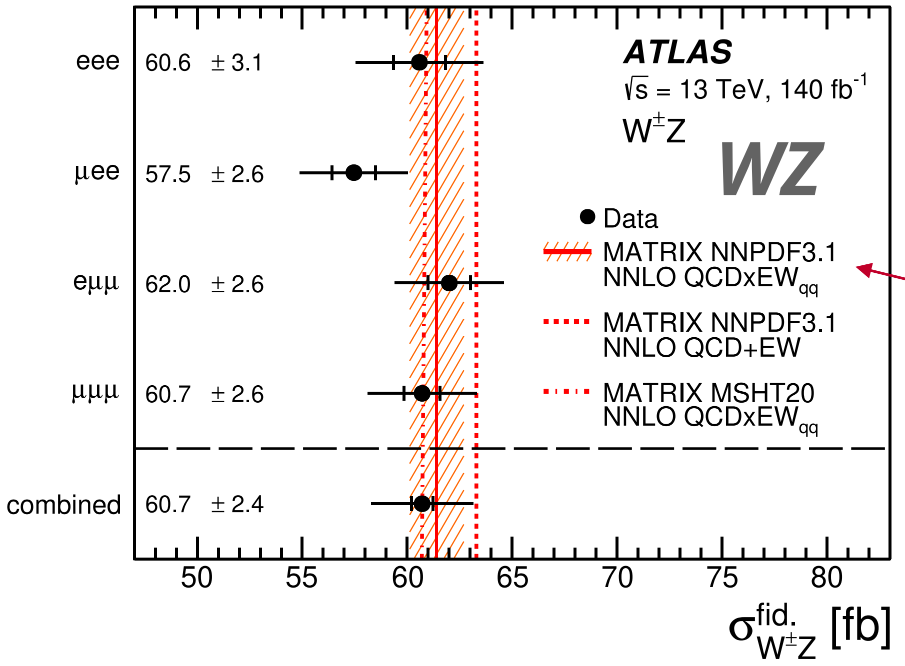
- 3 % (***WW***) and 4% (***WZ***) precision!
- Background uncertainties most important experimental sources
- ***WZ***: large theory uncertainty due to differences in Sherpa and Pythia lepton isolation
  WW: based on MiNNLO$_{PS}$ + Pythia variations (well understood setup)

WW

Uncertainty source	Effect
Total uncertainty	3.1%
Statistical uncertainty	1.1%
Top modelling	1.6%
Fake-lepton background	1.5%
Flavour tagging	0.7%
Other background	0.9%
Signal modelling	1.0%
Jet calibration	0.6%
Luminosity	0.8%
Other systematic uncertainties	0.9%

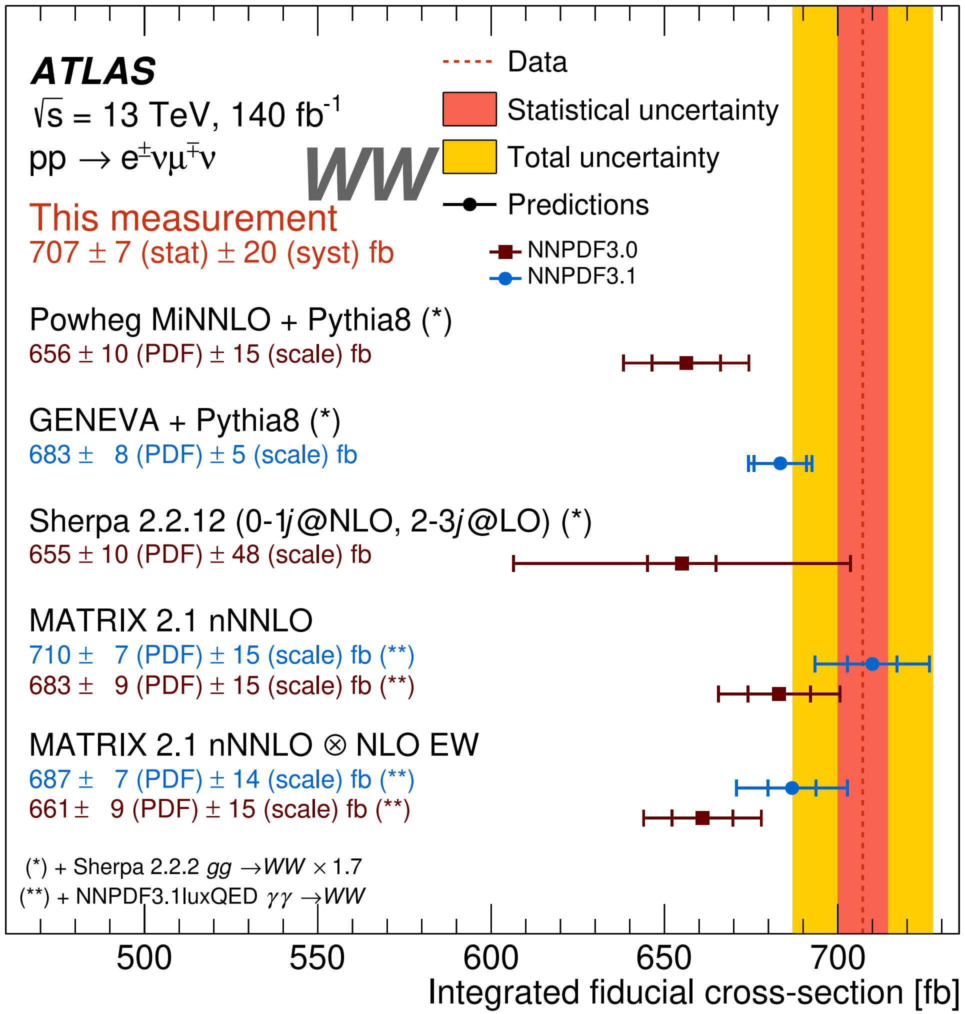
WW AND **WZ**: CROSS-SECTION

- Excellent agreement with precise (n)NNLO QCD x NLO EW fixed-order prediction from MATRIX (incl. NLO corrections to photon and gluon induced)
- Choice of PDF matters, NNPDF3.0 (old ATLAS default) yields too small cross-sections



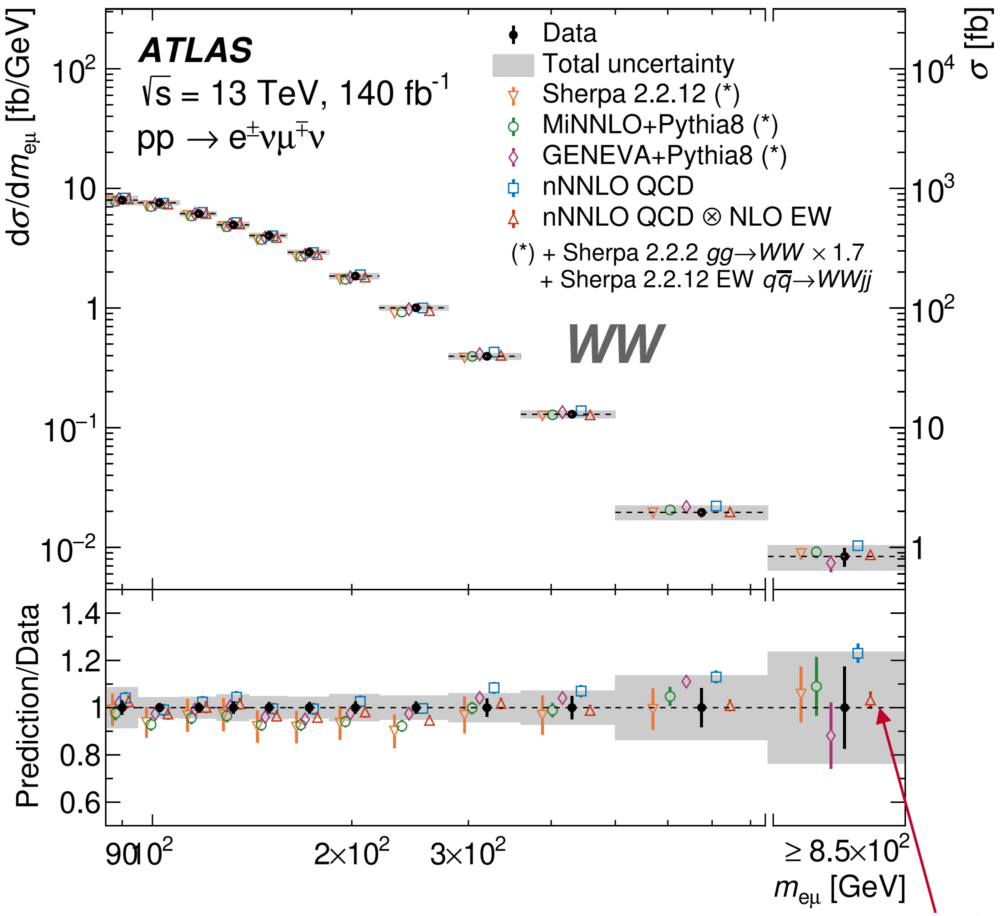
(N)NLO + parton shower models

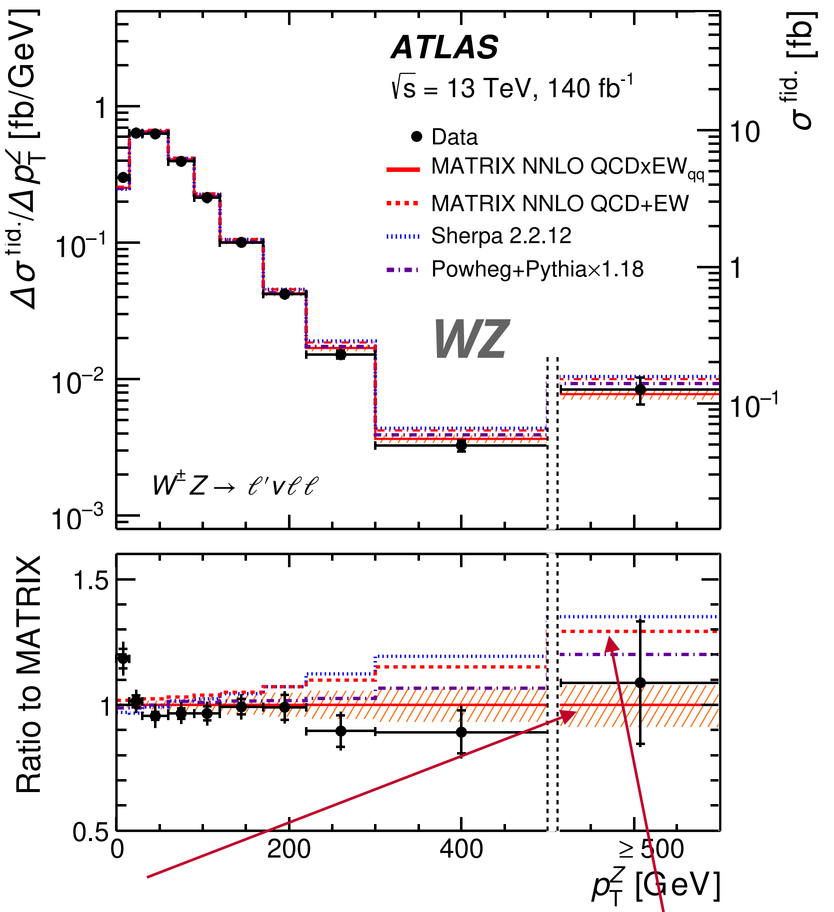
Most precise prediction, (n)NNLO QCD x NLO EW, using NNPDF 3.1 luxQED, in agreement with data



WW AND WZ: DIFFERENTIAL CROSS-SECTION

- Fiducial differential cross-section extracted using iterative Bayesian unfolding
- Reaching O(10%) precision across wide kinematic range
- Best description typically by (n)NNLO QCD and *multiplicative* NLO EW correction
- (N)NLO+PS give good description of data, too

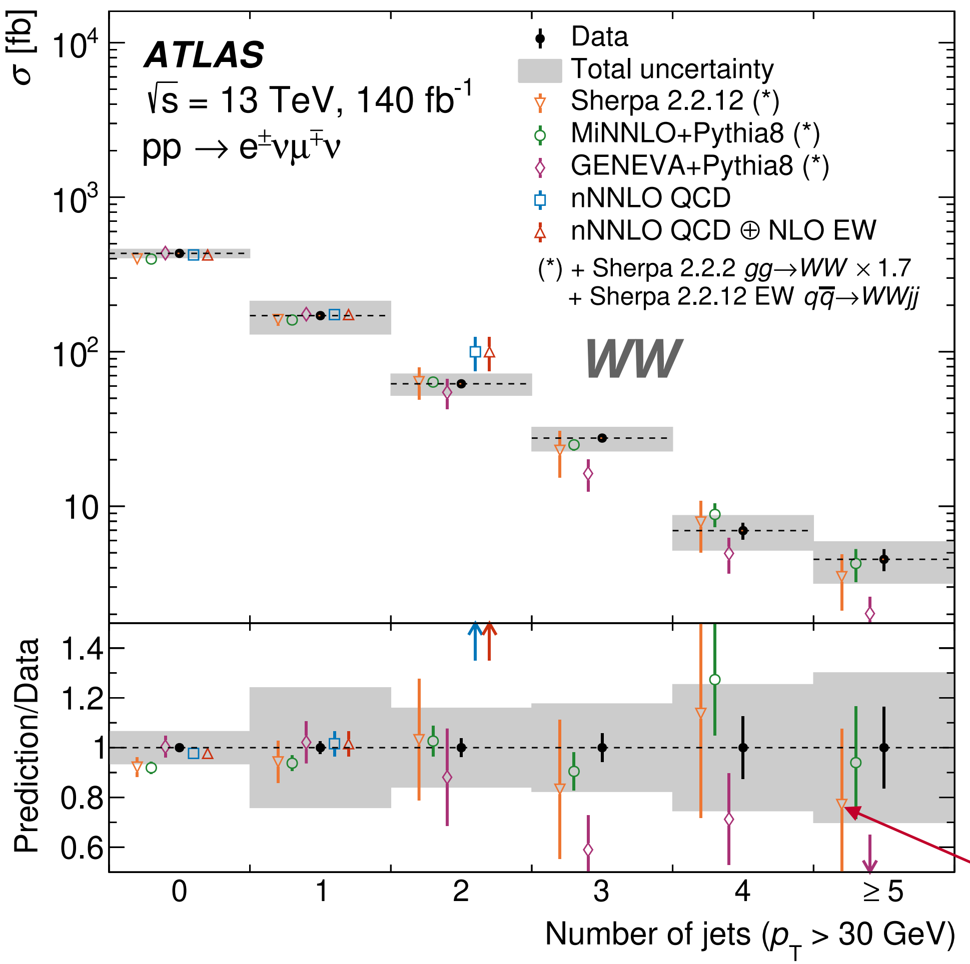


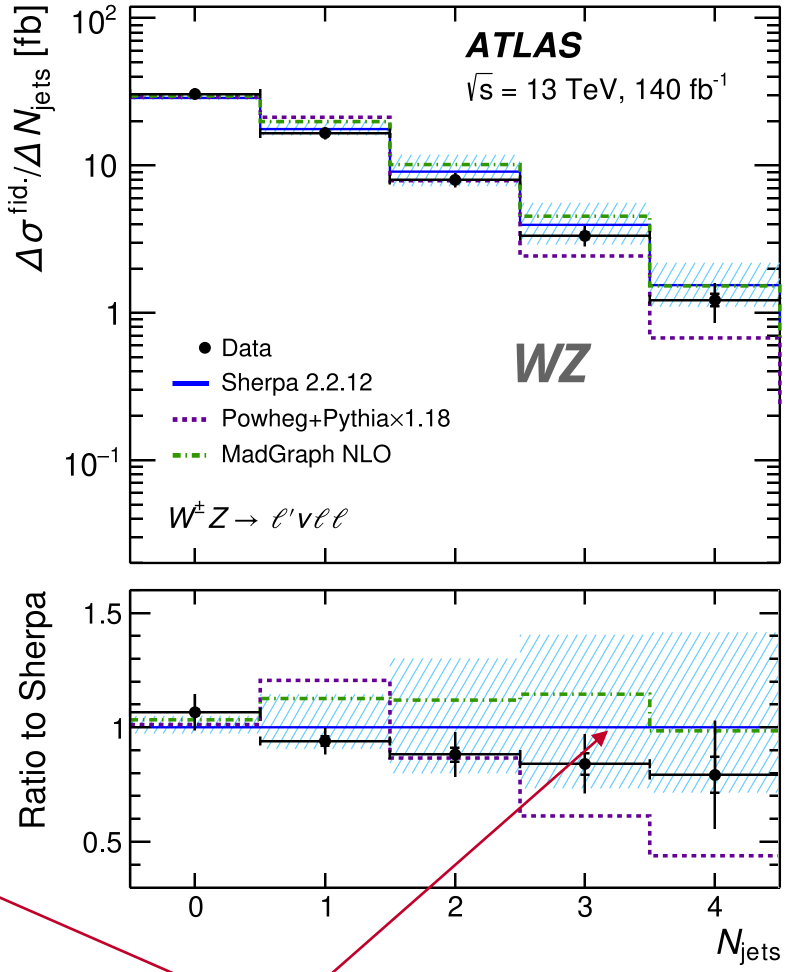


(n)NNLO x NLO EW preferred over (n)NNLO QCD **+** NLO EW

WW AND WZ: DIFFERENTIAL CROSS-SECTION

- Jet multiplicity measured with remarkable precision
- Described within uncertainties by Sherpa multi-jet merged sample (ATLAS main NLO+PS work horse)
- Good description also by MiNNLO$_{PS}$+Pythia model

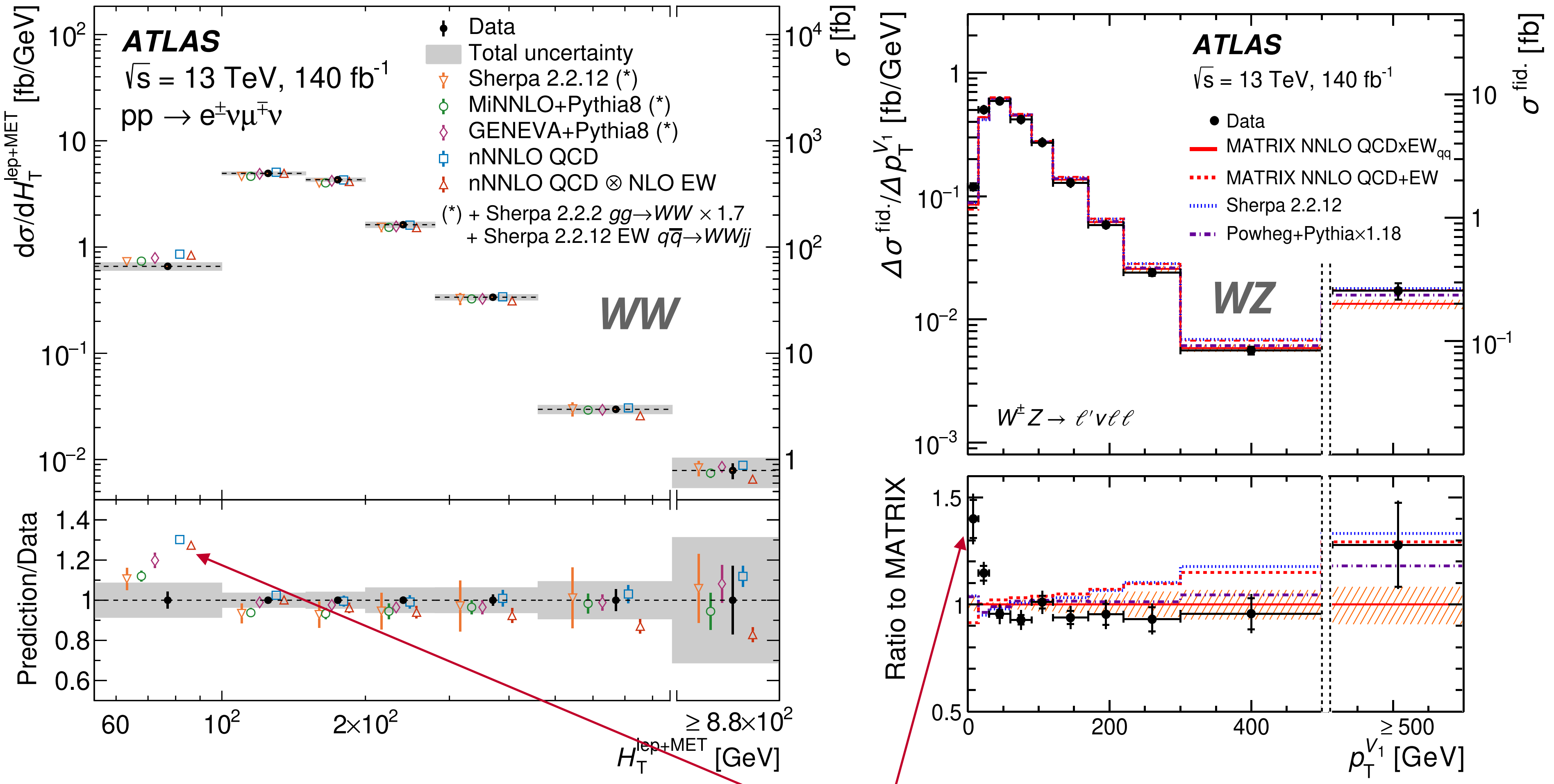




Sherpa NLO+PS

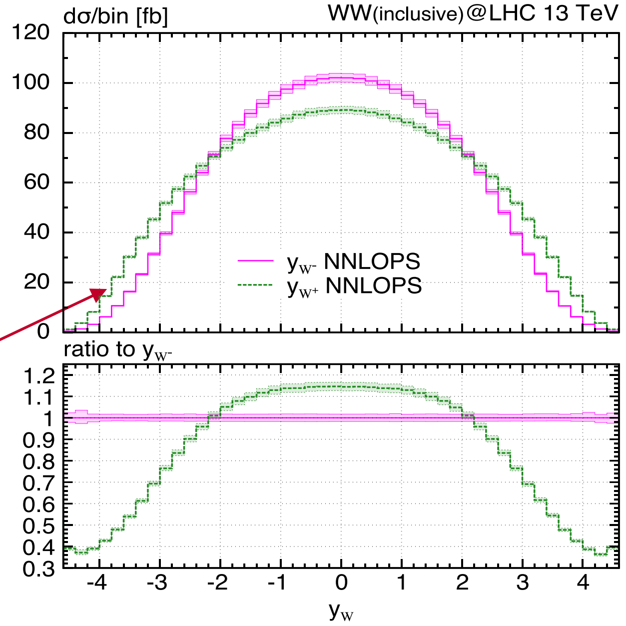
WW AND WZ: DIFFERENTIAL CROSS-SECTION

- Measurements at very low p_T not well described
- Expected to be explained by large logarithms in p_T/m_{VV}
- Resummed predictions in principle available
- Many more observables measured (2D distributions, angular correlations, ….)

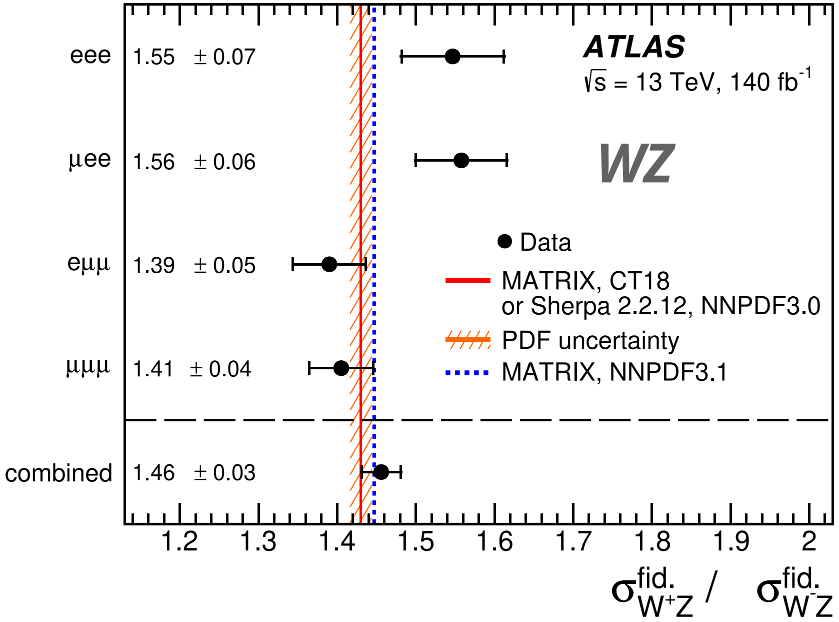


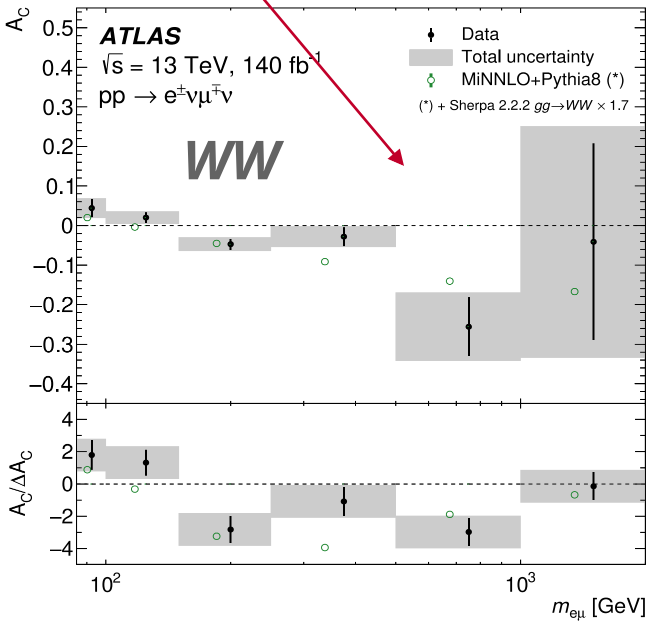
Disagreements at low p_T

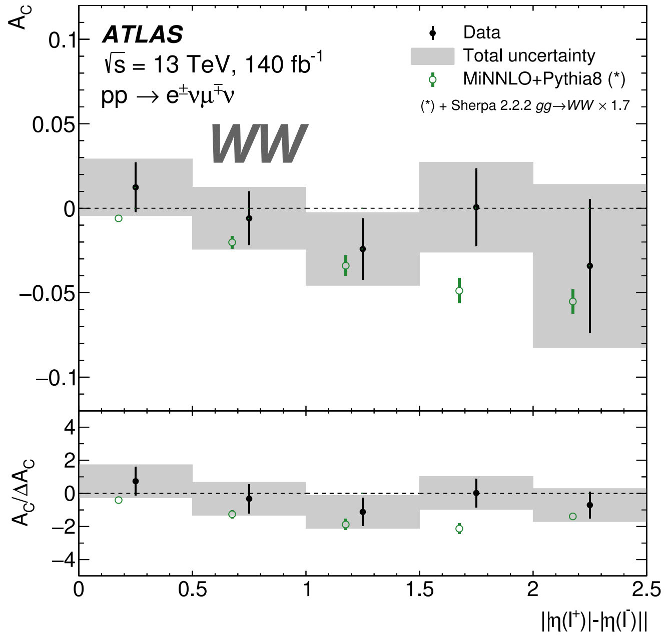
WW AND WZ: CHARGE ASYMMETRIES



- Charge asymmetry due to 2:1 ratio of up:down valence quarks
- ***WZ***: measurement of charge ratio with 2% precision (statistically limited)
- ***WW***: ***W^+*** more boosted, typically following up valence quark direction
  - Less pronounced on lepton level (even inverted due to W decay kinematics)
  - A_C quantifies asymmetry in $|\eta_{\ell+}| > |\eta_{\ell-}|$ vs $|\eta_{\ell+}| < |\eta_{\ell-}|$
  - Evidence for increase of asymmetry with dilepton invariant mass

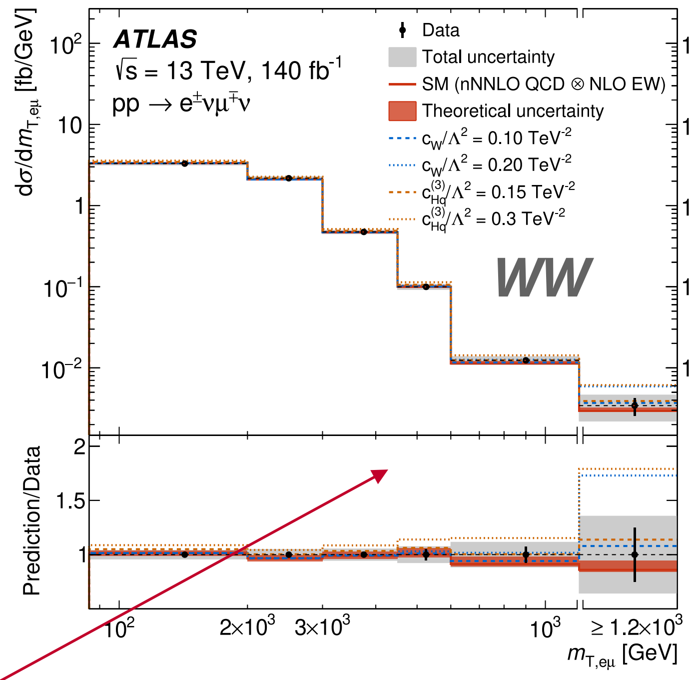


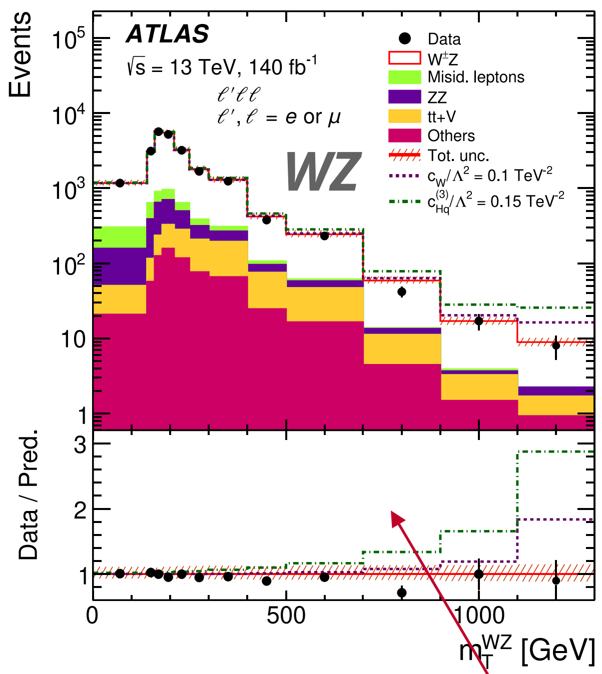




WW AND WZ: SMEFT INTERPRETATION (CP EVEN)

- Limits on SMEFT Wilson coefficients from m_T distribution
- Competitive limits on anomalous TGC and quark-boson couplings (spoiling cancellations in SM)
- Quadratic contribution dominant, interference (linear in c_i/Λ^{-2}) helicity suppressed
- Probing multi-TeV scale
- ***WZ*** better, ***WW*** broader sensitivity





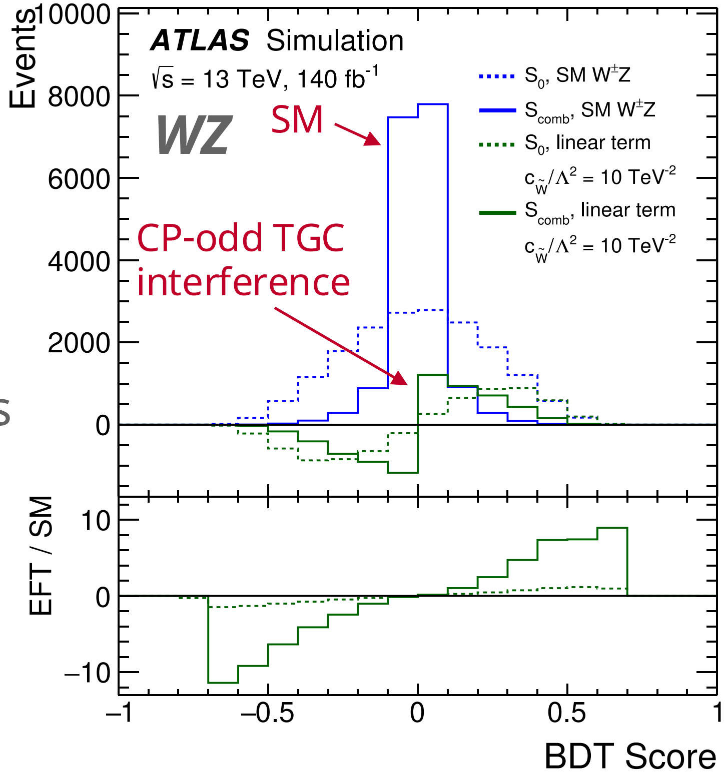
Λ = 1 TeV **assumed, limits scale ~*Λ²***

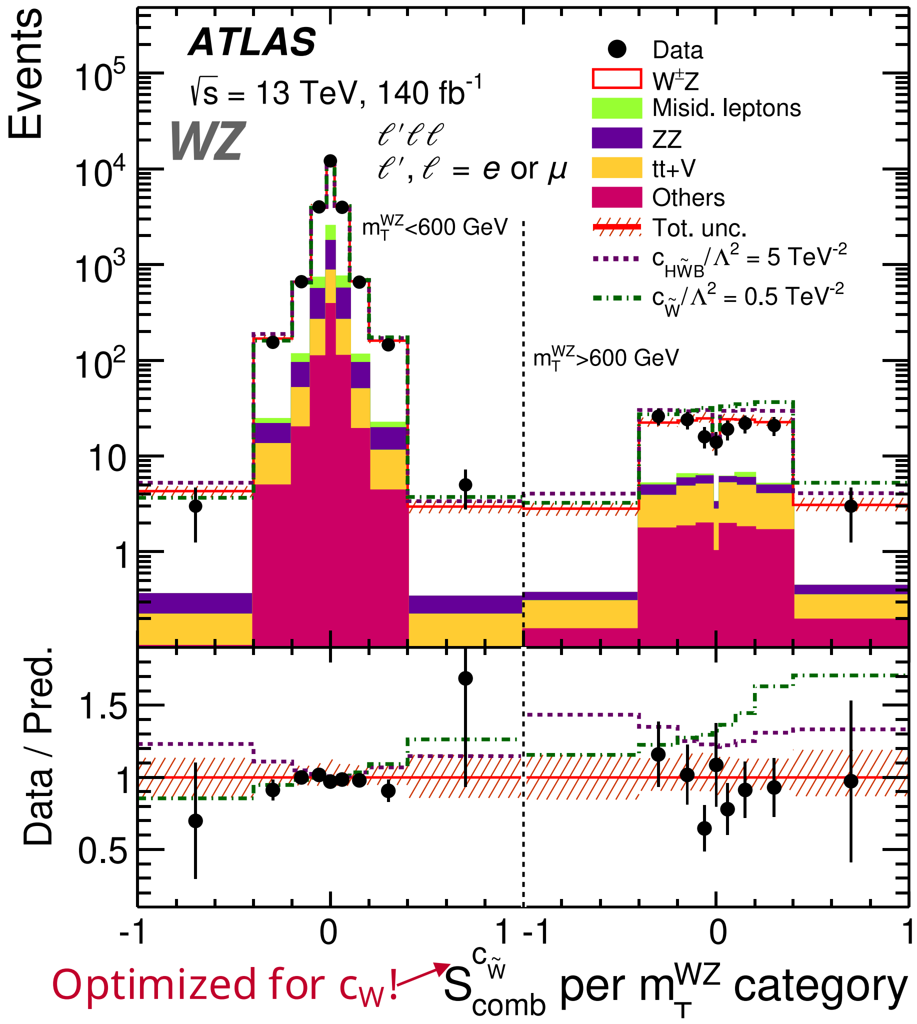
	WW	$O(\Lambda^{-2})$, individual		$O(\Lambda^{-4})$, individual		$O(\Lambda^{-4})$, profiled	
		Expected	Observed	Expected	Observed	Expected	Observed
TGC	c_W	$[-3.5, 3.2]$	$[-3.5, 3.4]$	$[-0.16, 0.16]$	$[-0.18, 0.18]$	$[-0.17, 0.16]$	$[-0.18, 0.18]$
	c_{HD}	$[-8.9, 9.8]$	$[-11, 8]$	$[-7, 21]$	$[-8, 21]$	$[-7, 21]$	$[-8, 21]$
	c_{HWB}	$[-8.4, 9.2]$	$[-10, 8]$	$[-1.5, 1.7]$	$[-1.7, 1.9]$	$[-1.7, 1.7]$	$[-1.8, 1.9]$
Quark-boson only	$c_{Hq}^{(1)}$	$[-2.5, 2.4]$	$[-2.2, 2.8]$	$[-0.27, 0.24]$	$[-0.29, 0.27]$	$[-0.29, 0.29]$	$[-0.31, 0.31]$
	$c_{Hq}^{(3)}$	$[-0.69, 0.66]$	$[-0.7, 0.68]$	$[-0.28, 0.22]$	$[-0.31, 0.24]$	$[-0.3, 0.27]$	$[-0.34, 0.29]$
	c_{Hu}	$[-3.2, 3.0]$	$[-3.0, 3.4]$	$[-0.31, 0.29]$	$[-0.35, 0.32]$	$[-0.32, 0.31]$	$[-0.35, 0.33]$
	c_{Hd}	$[-11, 11]$	$[-11, 11]$	$[-0.45, 0.46]$	$[-0.5, 0.51]$	$[-0.49, 0.49]$	$[-0.52, 0.53]$

WZ	Expected [TeV $^{-2}$]		Observed [TeV $^{-2}$]	
	95% CL (lin.)	95% CL (lin.+quad.)	95% CL (lin.)	95% CL (lin.+quad.)
c_W/Λ^2	[-0.668, 0.733]	[-0.103, 0.095]	[-1.150, 0.181]	[-0.093, 0.079]
c_{HWB}/Λ^2	[-0.326, 0.412]	[-0.326, 0.413]	[-0.470, 1.440]	[-0.458, 1.520]
c_{HD}/Λ^2	[-8.107, 9.096]	[-4.494, 3.976]	[-18.0, 1.7]	[-5.840, 1.680]
$c_{Hq}^{(1)}/\Lambda^2$	[-1.994, 2.122]	[-2.923, 1.615]	[-0.367, 3.980]	[-0.503, 2.550]
$c_{Hq}^{(3)}/\Lambda^2$	[-0.097, 0.106]	[-0.145, 0.074]	[-0.146, 0.0275]	[-0.165, 0.015]

WZ ONLY: CP-ODD SMEFT INTERPRETATION

- CP-odd observable S_{comb}
  - Combines BDTs trained to reduce SM contribution *and* maximize interference
  - Large $|S_{comb}|$ reduces backgr.
  - Strongest positive (negative) interf. for large S_{comb} ($-S_{comb}$)
- Separation in two m_T categories enhances sensitivity
- Strong limits on CP-odd TGC thanks to optimized sensitivity to interference effect

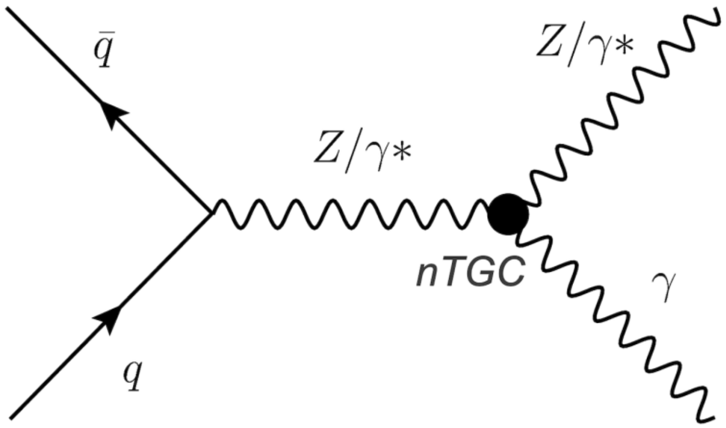


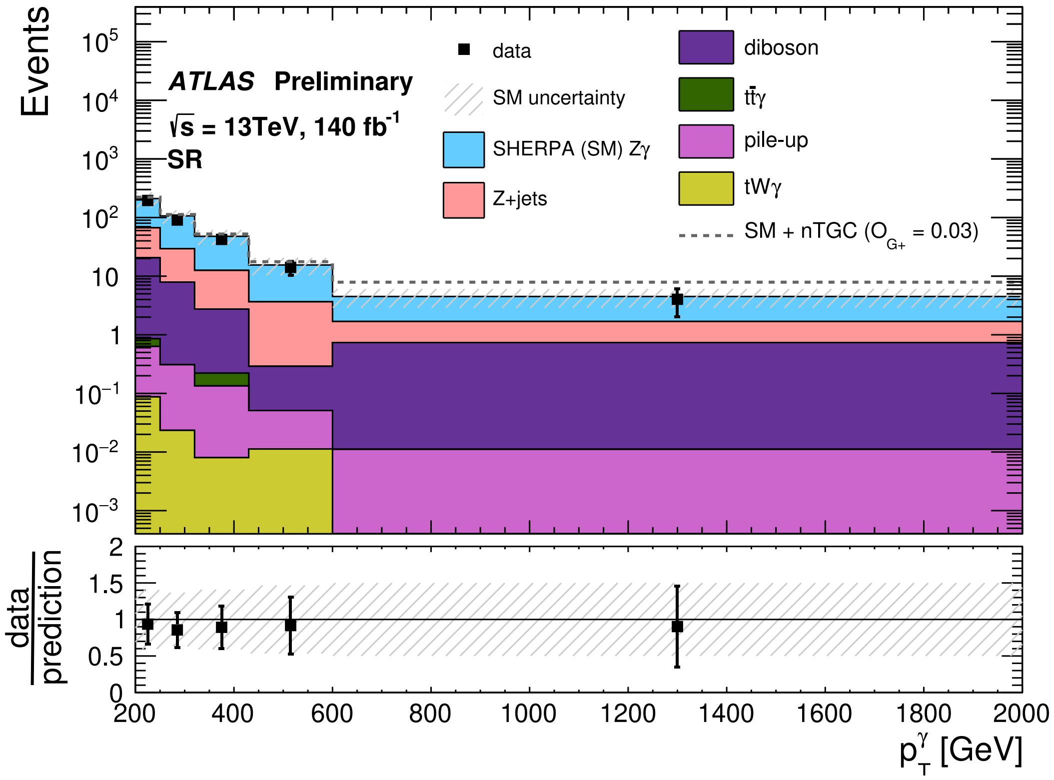


	Expected [TeV $^{-2}$]		Observed [TeV $^{-2}$]	
	95% CL (lin.)	95% CL (lin.+quad.)	95% CL (lin.)	95% CL (lin.+quad.)
$c_{H\tilde{W}B}/\Lambda^2$	[-1.463, 1.456]	[-1.458, 1.459]	[-1.625, 1.332]	[-1.505, 1.263]
$c_{\tilde{W}}/\Lambda^2$	[-0.162, 0.162]	[-0.127, 0.128]	[-0.186, 0.139]	[-0.109, 0.093]

ZY MEASUREMENT

- Previous formulations of nTGC violate SM gauge symmetry
  - Addressed by Ellis et al [e.g *Phys. Rev. D* **107** (2023) 035005]
  - New form factor introduced that cancels spurious energy dependent term
- ATLAS Measurement focused on extracting nTGC limits:
  - high-p_T event selection
  - Jet veto to enhance nTGC effect
  - Limits extracted from photon p_T distribution
  - Statistically limited
  - Z+jets background (photon fakes, estimated from data) source of dominant systematic uncertainty





ZY: NEUTRAL TRIPLE GAUGE COUPLINGS

- Limits on dimension-eight Wilson coefficients using fully gauge invariant model
- Converted to form factor limits
- For h_3 nTGC form factor limits match sensitivity of previous measurements in ***Z(νν)γ*** final state
- For h_4 sensitivity reduced – as expected

Parameters	Limits at 95% C.L.	
	Observed 95% C.L. [TeV^{-4}]	Expected 95 % C.L. [TeV^{-4}]
C_{G+}/Λ^4	[-0.022, 0.020]	[-0.025, 0.023]
C_{G-}/Λ^4	[-1.41, 1.08]	[-1.50, 1.23]
C_{BB}/Λ^4	[-0.37, 0.37]	[-0.44, 0.44]
$C_{\tilde{B}W}/\Lambda^4$	[-0.54, 0.53]	[-0.62, 0.61]
C_{BW}/Λ^4	[-0.87, 0.95]	[-1.05, 1.14]
C_{WW}/Λ^4	[-1.90, 1.78]	[-2.26, 2.13]

This measurement — old ***Z(νν)γ*** measurement

Parameters	Current limits at 95% C.L. (140 fb^{-1}) using new formalism		Limits at 95% C.L. from Reference [61] (36.1 fb^{-1}) using old formalism	
	Observed 95% C.L.	Expected 95 % C.L.	Observed 95% C.L.	Expected 95 % C.L.
h_4^γ	$[-1.3\times10^{-5}, 1.4\times10^{-5}]$	$[-1.5\times10^{-5}, 1.6\times10^{-5}]$	$\cancel{[-4.4\times10^{-7}, 4.3\times10^{-7}]}$	$\cancel{[-5.1\times10^{-7}, 5.0\times10^{-7}]}$
h_4^Z	$[-2.4\times10^{-5}, 2.6\times10^{-5}]$	$[-2.8\times10^{-5}, 3.0\times10^{-5}]$	$\cancel{[-4.5\times10^{-7}, 4.4\times10^{-7}]}$	$\cancel{[-5.3\times10^{-7}, 5.1\times10^{-7}]}$
h_3^γ	$[-3.5\times10^{-4}, 4.6\times10^{-4}]$	$[-4.0\times10^{-4}, 4.9\times10^{-4}]$	$[-3.7\times10^{-4}, 3.7\times10^{-4}]$	$[-4.2\times10^{-4}, 4.3\times10^{-4}]$
h_3^Z	$[-3.2\times10^{-4}, 3.2\times10^{-4}]$	$[-3.7\times10^{-4}, 3.6\times10^{-4}]$	$[-3.2\times10^{-4}, 3.3\times10^{-4}]$	$[-3.8\times10^{-4}, 3.8\times10^{-4}]$

CONCLUSION

- Presented three new diboson measurements by the ATLAS collaboration
  - ***WW***: arXiv:2505.11310
  - ***WZ***: arXiv:2507.03500
  - ***Zγ***: ATLAS-CONF-2025-001
- ***WW*** and ***WZ*** measurements
  - Reach 3% and 4% precision thanks to precise background estimates
  - Measure many differential distributions with high precision up to TeV scale
  - Study of novel observables (*WW* charge asymmetry, powerful CP-odd observable in *WZ*)
  - Testing state-of-the-art SM predictions
  - Constrain new physics at the of multi-TeV scale in SMEFT framework
- ***Zγ***: first constraints on nTGC respecting SM gauge symmetries
- A lot to look forward to:
  - A few Run 2 precision EW measurements still forthcoming
  - Run 3 measurements on their way, too!