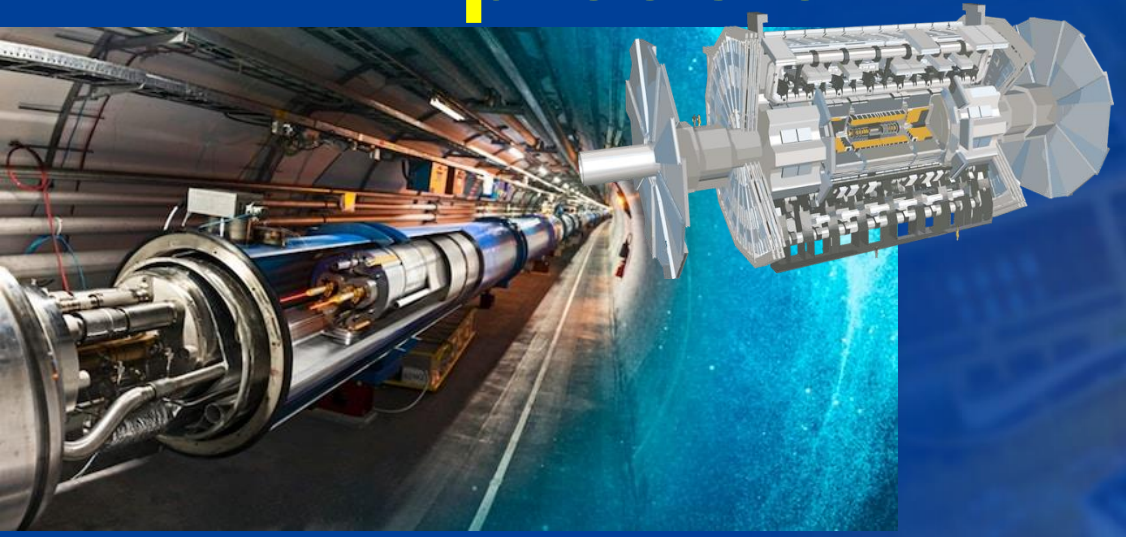
Measurements of Di-Boson productions and precision EFT constraints in ATLAS



Shu Li on behalf of ATLAS Collaboration

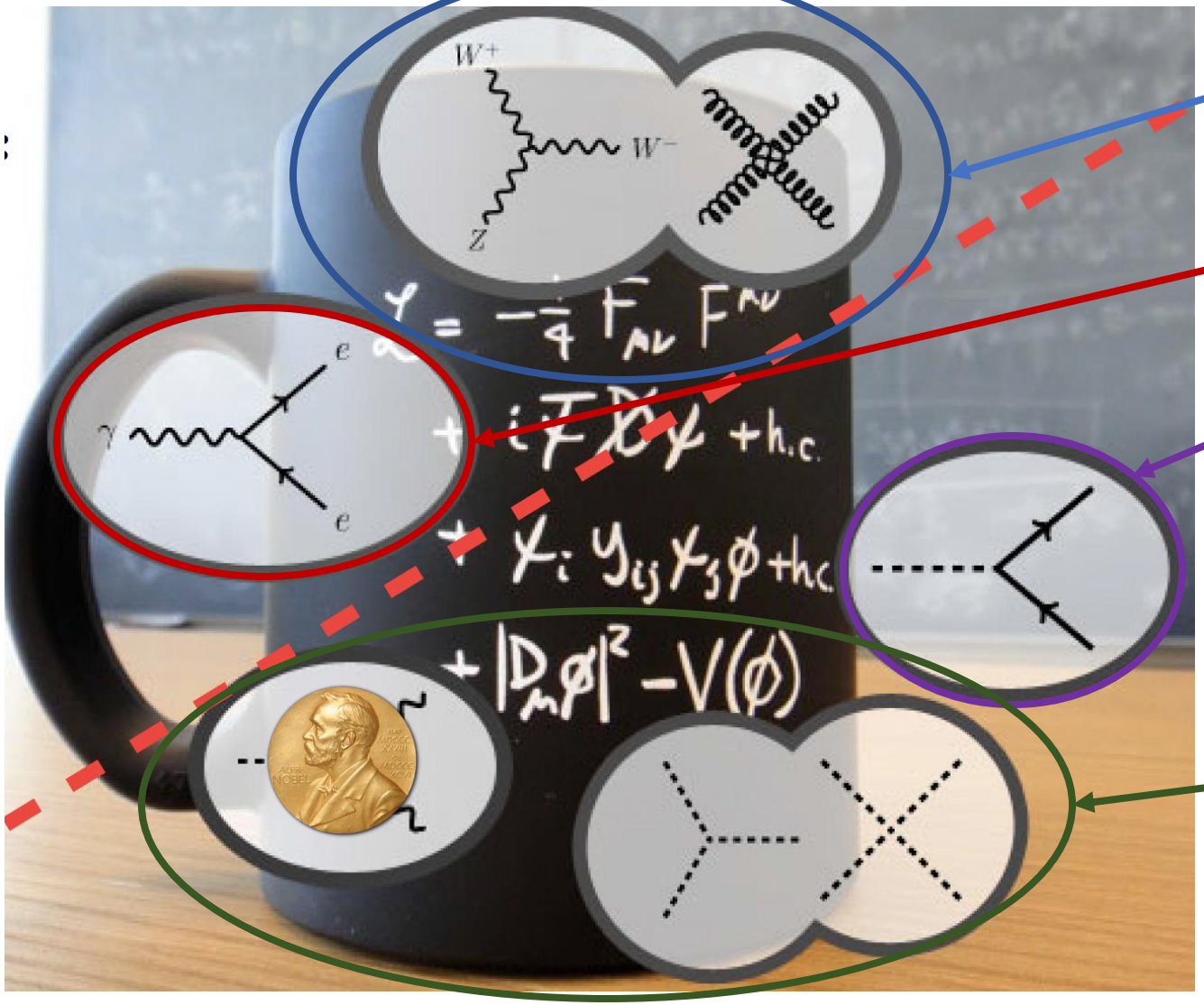
(shuli@cern.ch)

Tsung-Dao Lee Institute, Shanghai Jiao Tong University

Lepton Photon 2025 @ Madison, USA

2025.08.26

Electroweak Bosons:
Keys to deepen the understanding of Standard Model

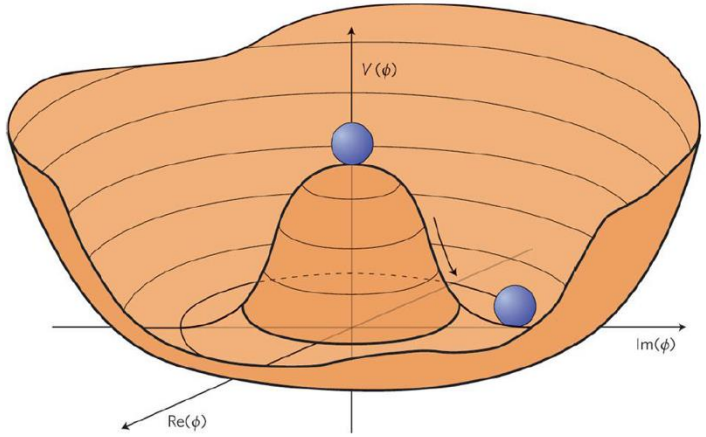


Electromagentic/Weak/Strong (Gauge Boson Self-Interactions)

How Gauge Bosons Interact with Fermions (Leptons & Quarks)

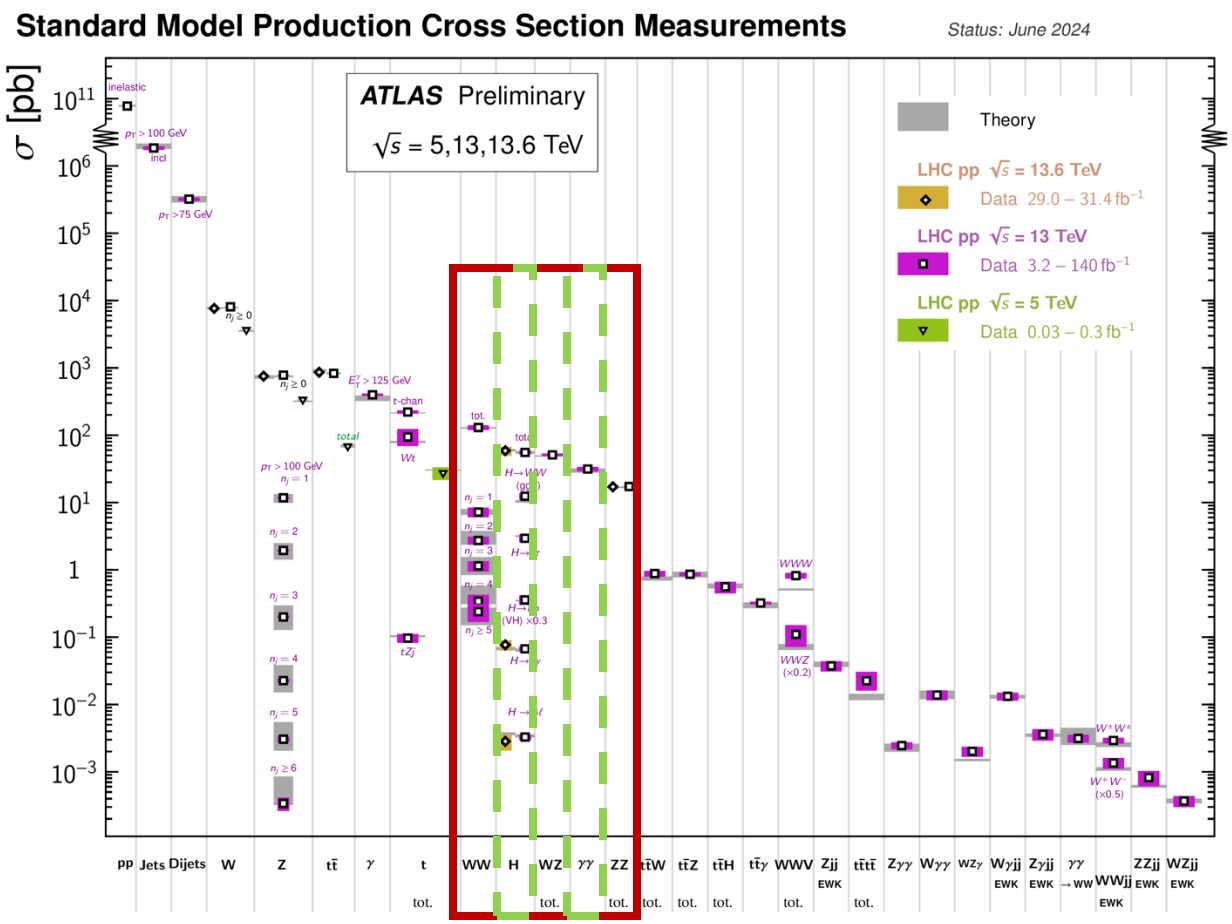
Higgs Yukawa Couplings (Origin of Masses for Leptons and Quarks)

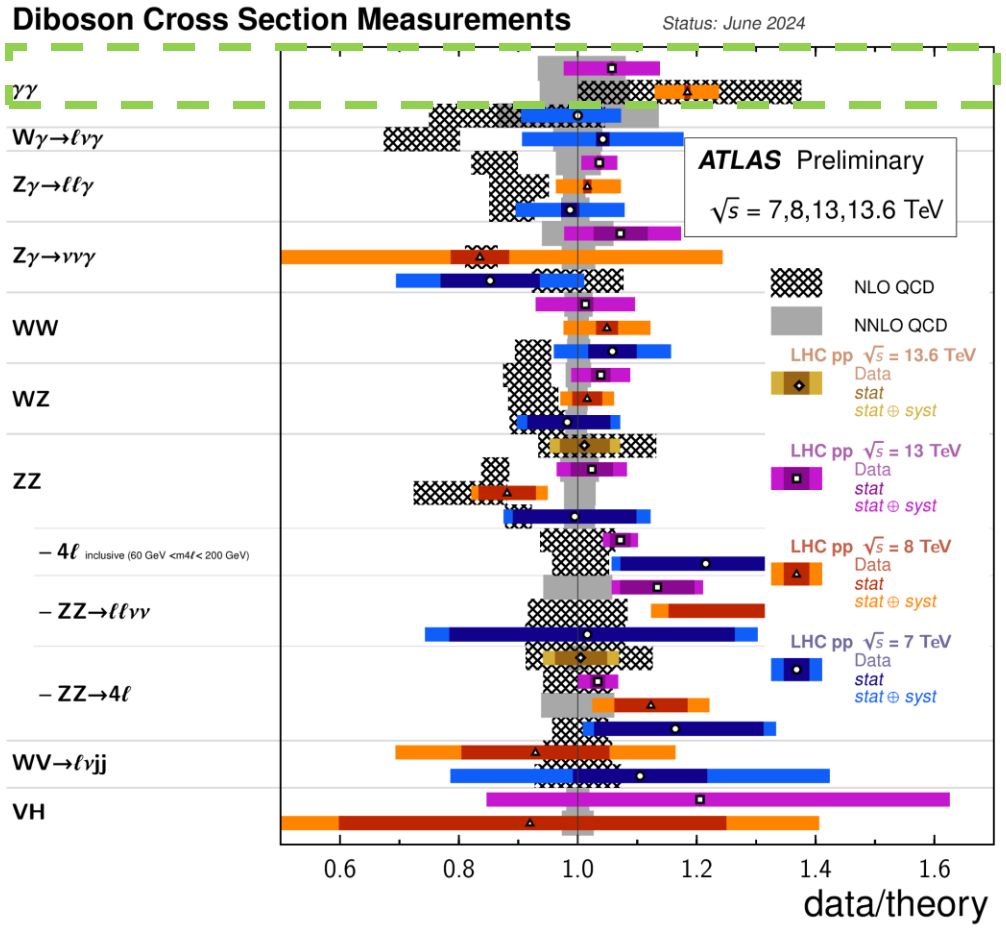
EWSB (Origin of Weak Boson Mass), Higgs Potential (Higgs Self-Interactions)



ATL-PHYS-PUB-2024-011

Summary of ATLAS Diboson measurements

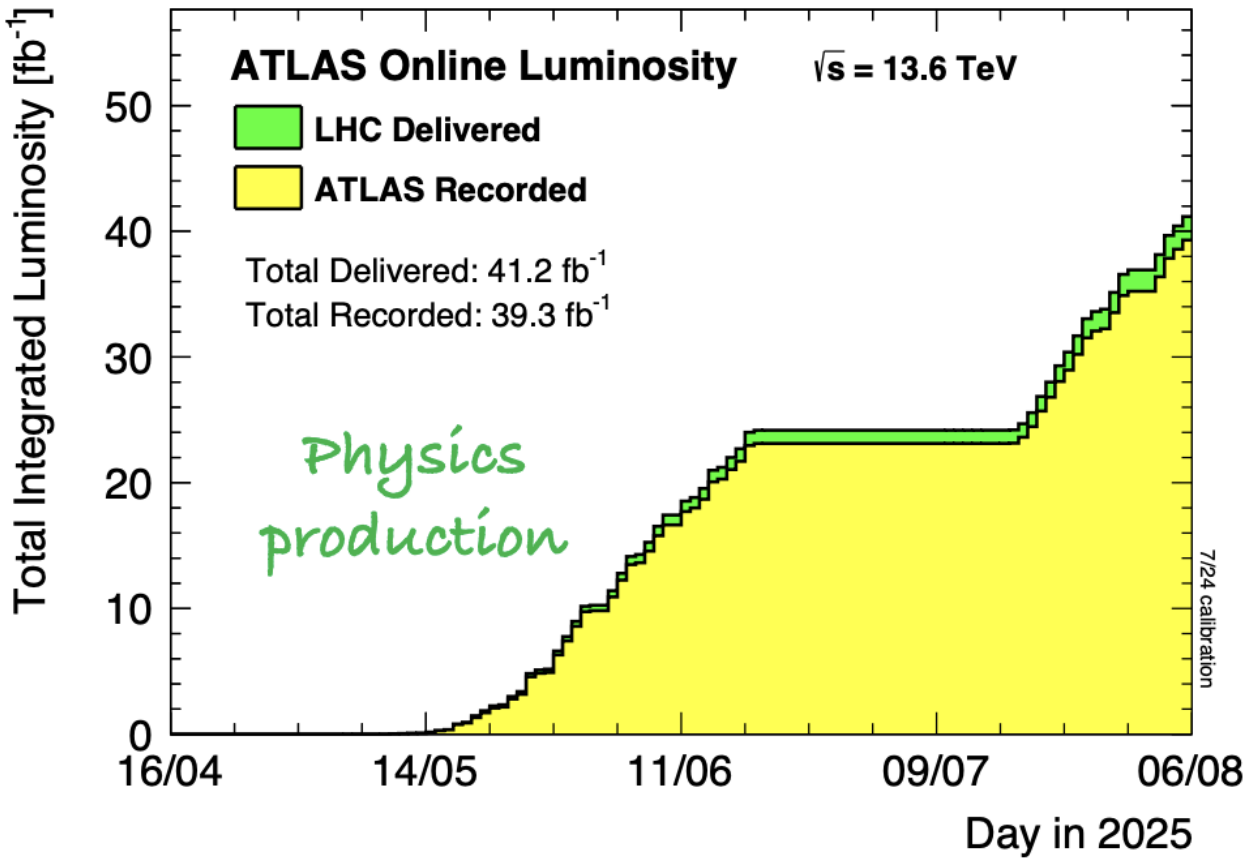


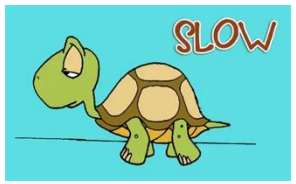


Diboson Physics at ATLAS:

Test of SM EWK Sector w/ high precision and as solid foundation for VBS and triboson measurements; examine perturbative QCD and EW high order effects; irreducible backgrounds for Higgs to diboson decay and other realted BSM searches; sensitive to anomalous Triple Gauge Couplings (aTGCs) with SMEFT; …

ATLAS Run-3 data-taking in-action!

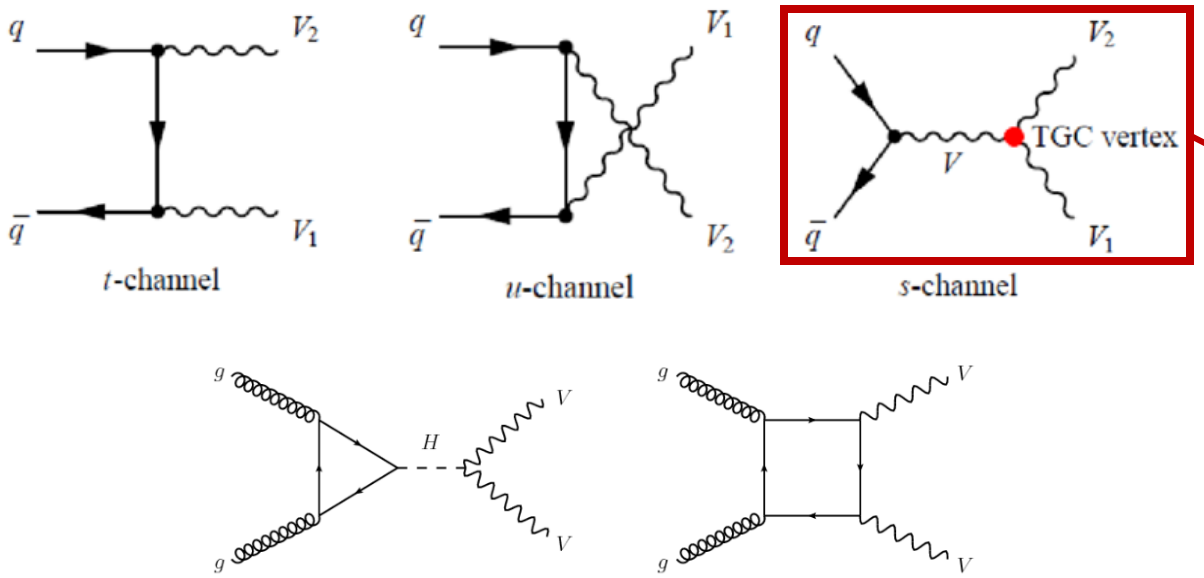




Standard Model Measurements are slow but precise!
Stay tuned ☺
(check out 1st Run3 ZZ results by ATLAS: *Phys. Lett. B 855 (2024) 138764*)

Today's main course

- **$W^+W^-\to\ell\nu\ell\nu$ @13TeV (Full Run2): arXiv:2505.11310**
- **$W^\pm Z\to 3\ell 1\nu$ @13TeV (Full Run2): arXiv:2507.03500**
- **$Z(\ell\ell)\gamma$ differential and nTGC @13TeV (Full Run2): ATLAS-CONF-2025-001**



Wilson coefficient (coupling strength)

Higher-dimensional Operator (new/altered interaction)

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

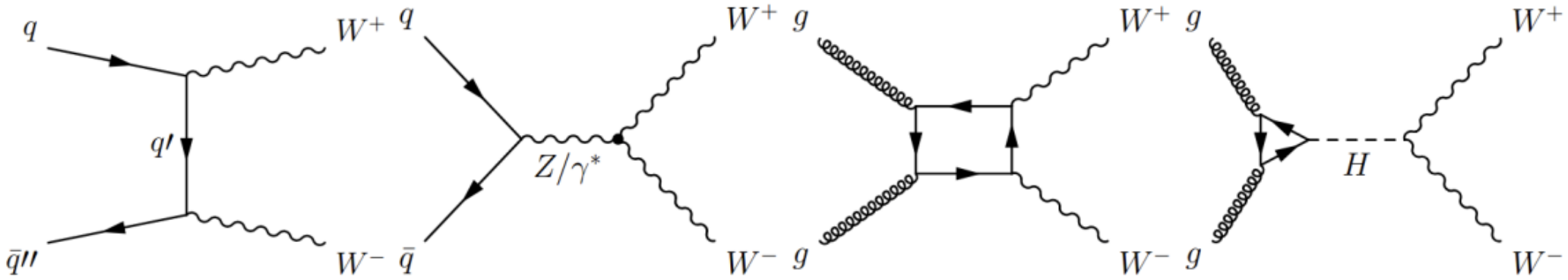
SM Lagrangian (dimension four)

Mass scale of new physics

WW with ATLAS Full Run-2 13TeV

arXiv:2505.11310

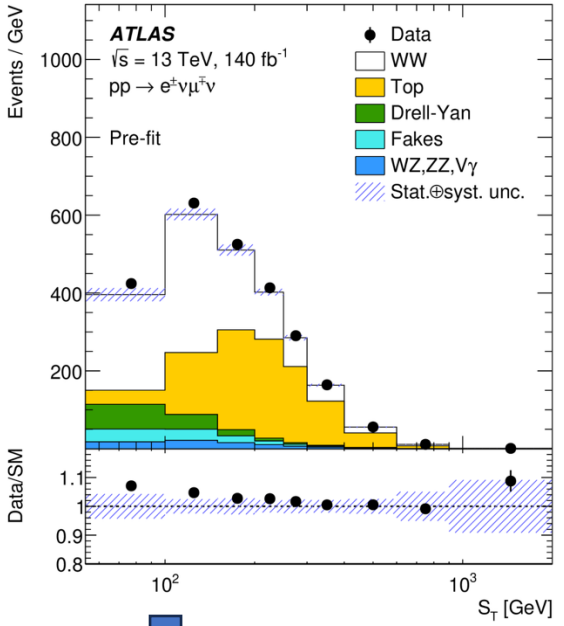
- WW total, fiducial and differential cross section measurements w/ ATLAS Full Run2 DATA (140 fb^{-1}) in fully leptonic final states (diff. flavor & oppo. charge to suppress Drell-Yan backgrounds)
- **Highlights:**
  - Twelve measured observables: $p_T^{\text{lead lep.}}$, $p_T^{\text{sub-lead lep.}}$, $p_T^{e\mu}$, $y_T^{e\mu}$, $m_{e\mu}$, $\Delta\varphi_{e\mu}$, $\cos\theta^* = |\tanh(\Delta\eta(e,\mu)/2)|$, E_T^{miss}, $m_{T,e\mu}$, $H_T^{\text{lep.+MET}}$, S_T, N_{jet}
  - Jet incl. phase space measured w/ high precision (~3.1% unc.)
  - **Evidence of central-forward charge asymmetry**
  - Comparison w/ State-of-Art theory predictions w/ NNLO QCD and NLO EWK (along w/ NLO-QCD gg and γ-induced corrections) and new PDF



WW with ATLAS Full Run-2 13TeV

arXiv:2505.11310

	Requirement	Criteria
Electron	p_{T}	> 27 GeV
	$\lvert\eta\rvert$	$\in [0, 1.37) \cup (1.52, 2.47)$
	Identification	`TightLH` working point
	Isolation	`Gradient`
	Impact parameters	$\lvert d_0/\sigma_{d_0}\rvert < 5$; $\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm
Muon	p_{T}	> 27 GeV
	$\lvert\eta\rvert$	< 2.5
	Identification	`Medium` working point
	Isolation	`Tight_FixedRad`
	Impact parameters	$\lvert d_0/\sigma_{d_0}\rvert < 3$; $\lvert z_0 \cdot \sin\theta\rvert < 0.5$ mm
b-jets	p_{T}	> 20 GeV
	$\lvert\eta\rvert$	< 2.5
	Pile-up suppression	jet-vertex tagger for $p_{\mathrm{T}} < 60$ GeV and $\lvert\eta\rvert < 2.4$
	b-tagging	DL1r, 85% efficiency working point
Jets	p_{T}	> 30 GeV
	$\lvert\eta\rvert$	< 4.5
	Pile-up suppression	jet-vertex tagger for $p_{\mathrm{T}} < 60$ GeV and $\lvert\eta\rvert < 2.4$
Event	Leptons	1 electron and 1 muon of opposite electric charge; no additional lepton with $p_{\mathrm{T}} > 10$ GeV, `Loose` isolation, and `LooseLH` (electron) / `Loose` (muon) identification
	Number of b-jets	0
	$m_{e\mu}$	> 85 GeV

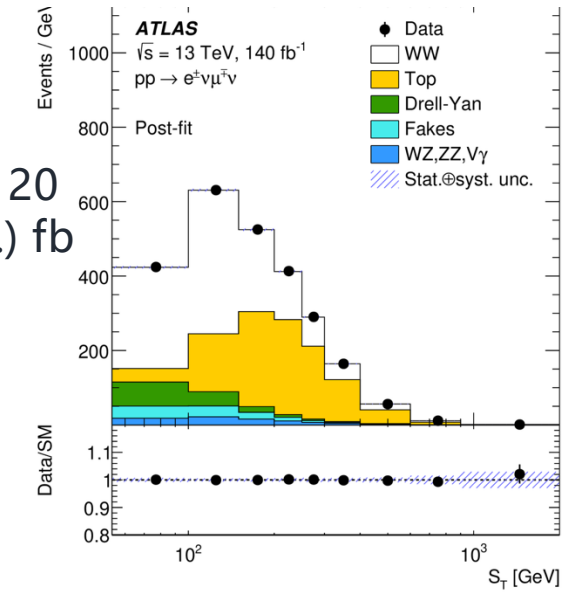


- Int. fid. cross-section determined using profile likelihood fit of S_{T} distribution
- Fid. Phase space:

Object	Requirement	Criteria
Prompt lepton	p_{T}	> 27 GeV
	$\lvert\eta\rvert$	< 2.5
Loose lepton	p_{T}	> 10 GeV
	$\lvert\eta\rvert$	< 2.5
b-jets	p_{T}	> 20 GeV
	$\lvert\eta\rvert$	< 2.5
Jets	p_{T}	> 30 GeV
	$\lvert\eta\rvert$	< 4.5
Event	Leptons	1 prompt electron and 1 prompt muon of opposite electric charge. No additional loose leptons
	Number of b-jets	0
	$m_{e\mu}$	> 85 GeV

$\sigma_{\mathrm{fid.}}$ = 707 ± 7 (stat.) ± 20 (syst.) ± 6 (lumi.) fb

Post-fit

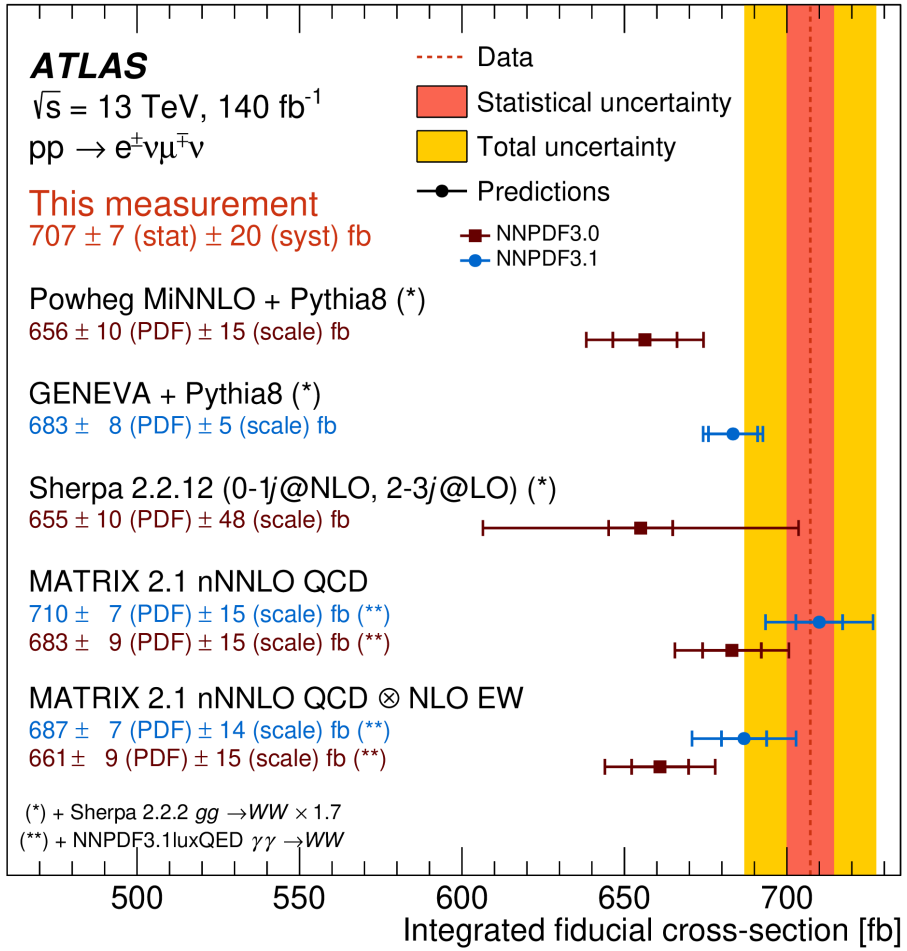


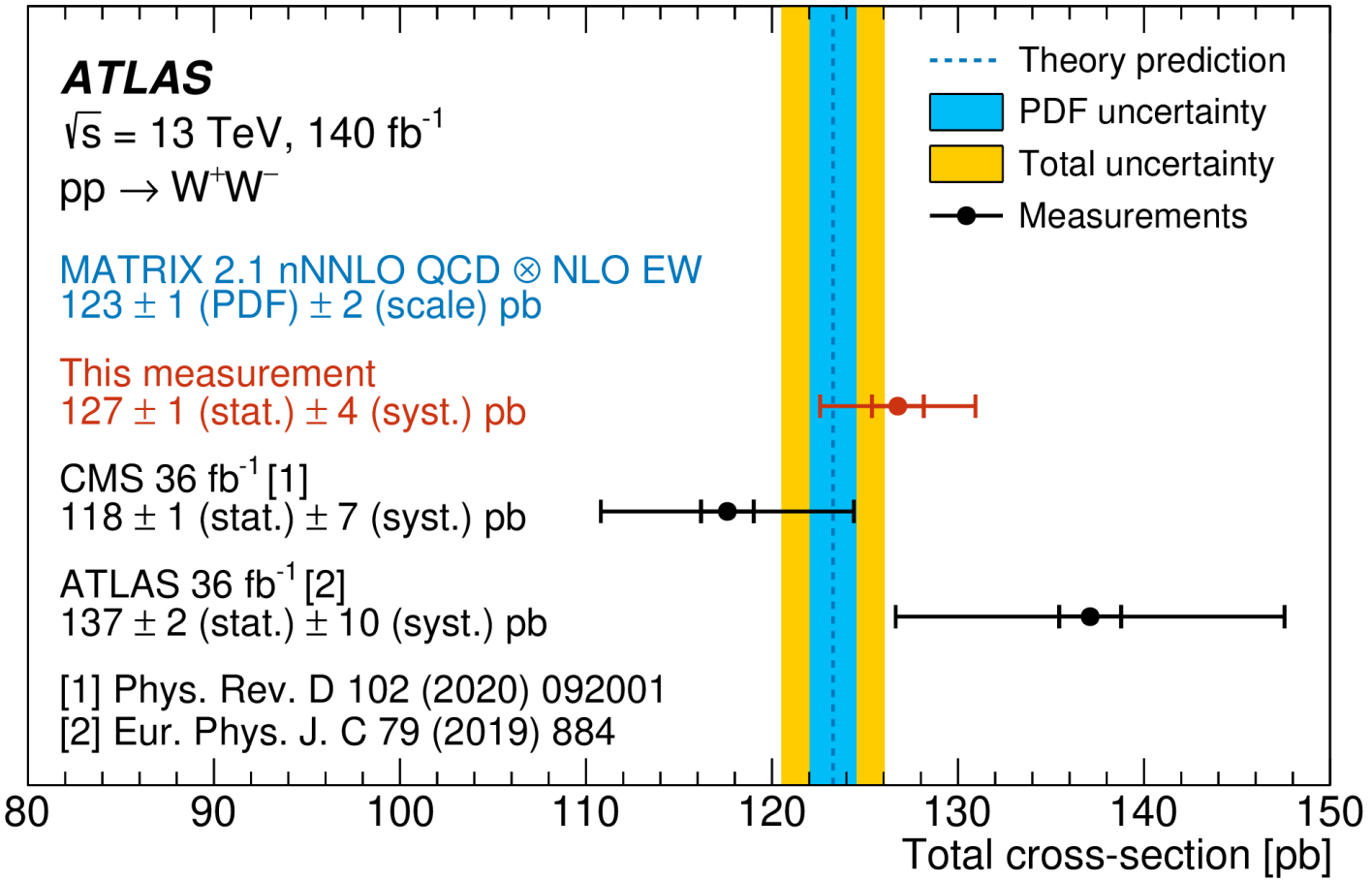
Major phase space cuts, veto b-jet but no further jet veto

arXiv:2505.11310

WW with ATLAS Full Run-2 13TeV

- Measured fid./tot. cross sections consistent w/ MOST precise theo. predictions: nNNLO QCD ⊗ NLO EW using NNPDF3.1 luxQED (better agreement compared w/ NNPDF3.0 PDF)





WW with ATLAS Full Run-2 13TeV

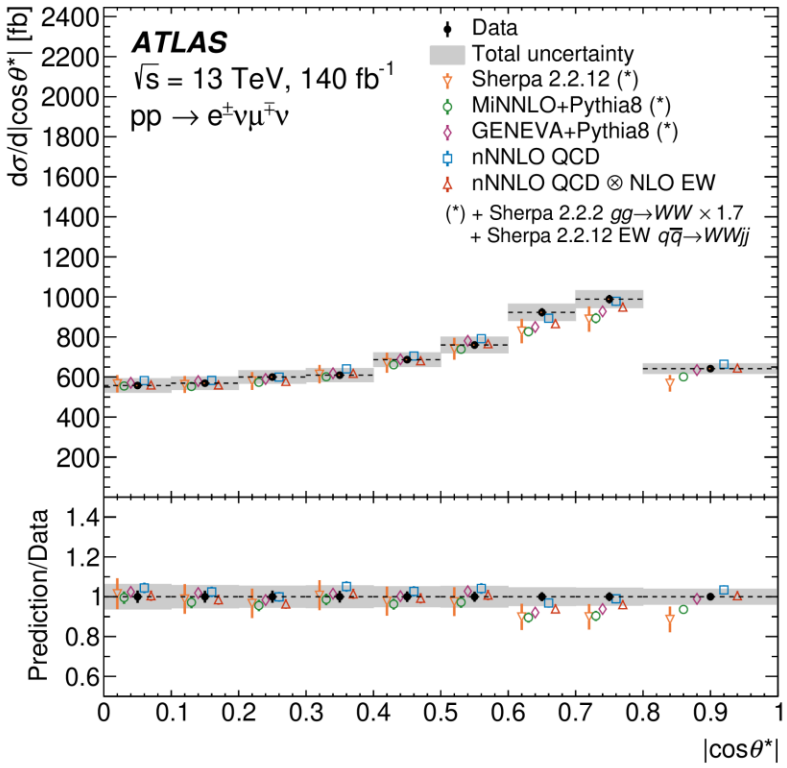
arXiv:2505.11310

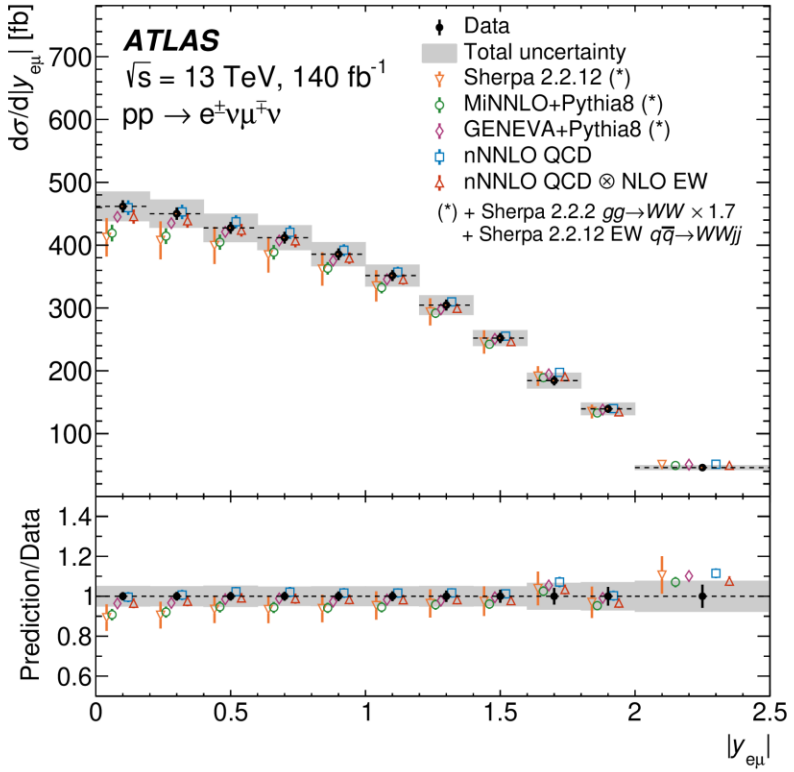
李政道研究所
TSUNG-DAO LEE INSTITUTE

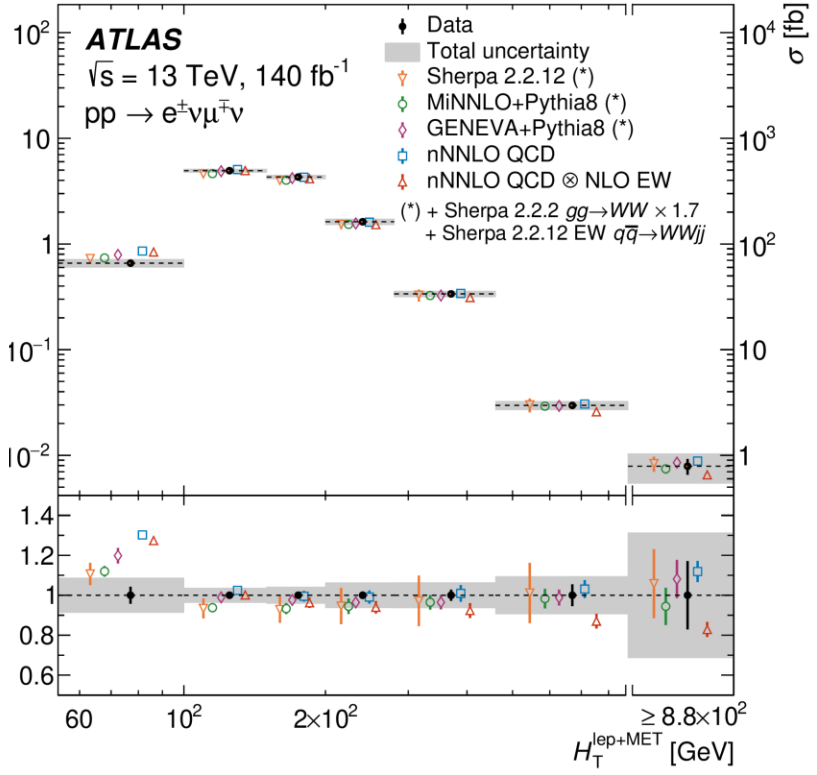
$|\cos\theta^*| = |\tanh(\Delta\eta_{e\mu}/2)|$
Sensitive to WW spin structure

$|y_{e\mu}|$
Absolute rapidity of the dilepton system

$H_T^{\text{lep.+MET}}$
scalar sum of E_T^{miss} and the lepton transverse momenta



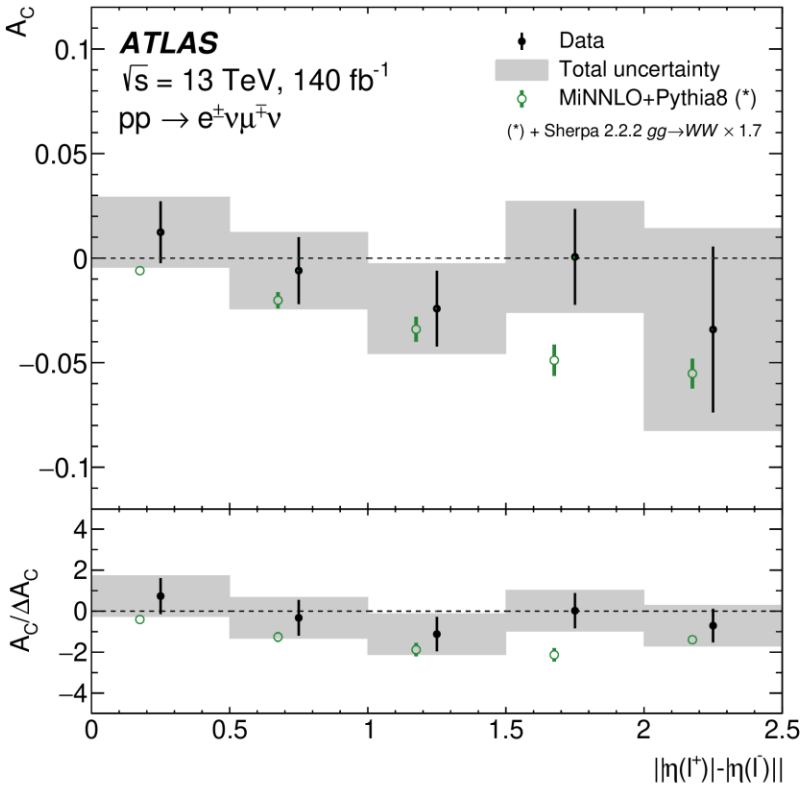


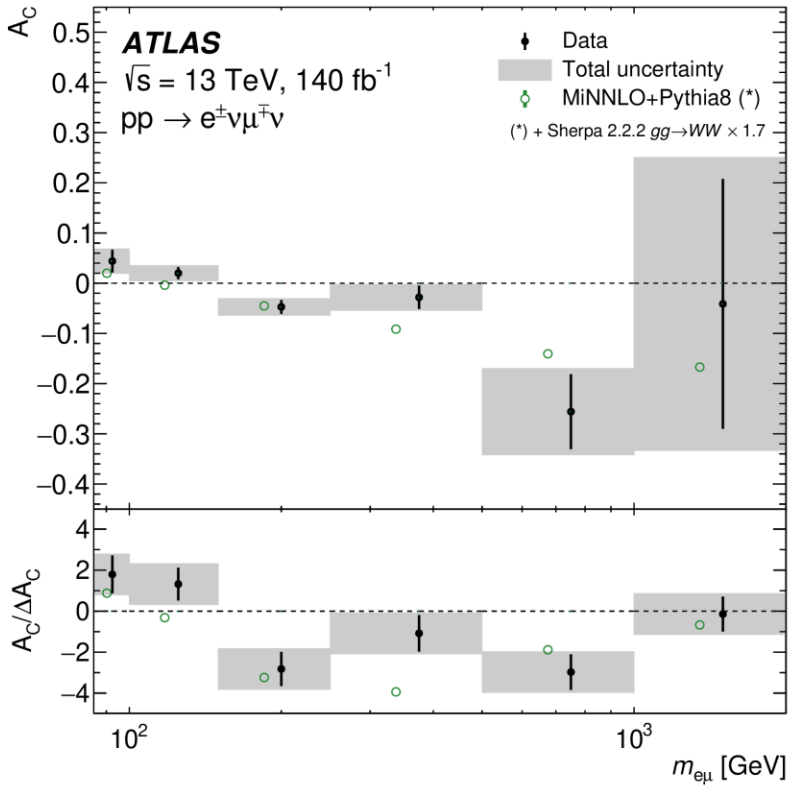


- Differential cross sections measured in general w/ excellent agreement at fixed-order, compared w/ MATRIX prediction jet-inclusively
- Most notable discrepancy is a local 3σ difference in the lowest bin of the H_T distribution

WW with ATLAS Full Run-2 13TeV

arXiv:2505.11310





$$A = \frac{\sigma_{\text{fid}}^{x>0} - \sigma_{\text{fid}}^{x<0}}{\sigma_{\text{fid}}}$$

$$A_C = -0.004 \pm 0.008\ (\text{stat.}) \pm 0.006\ (\text{syst.})$$

A_C: non-zero due to charge asymmetry of the partonic initial state

$$A_{CP} = 0.014 \pm 0.008\ (\text{stat.}) \pm 0.008\ (\text{syst.})$$

A_{CP}: asymmetry in CP-odd observable

$$O_z = \left((\vec{p}_{\ell^-} \times \vec{p}_{\ell^+})_z \,\text{sign}\left(p_{\ell^-,z} - p_{\ell^+,z}\right)\right)$$

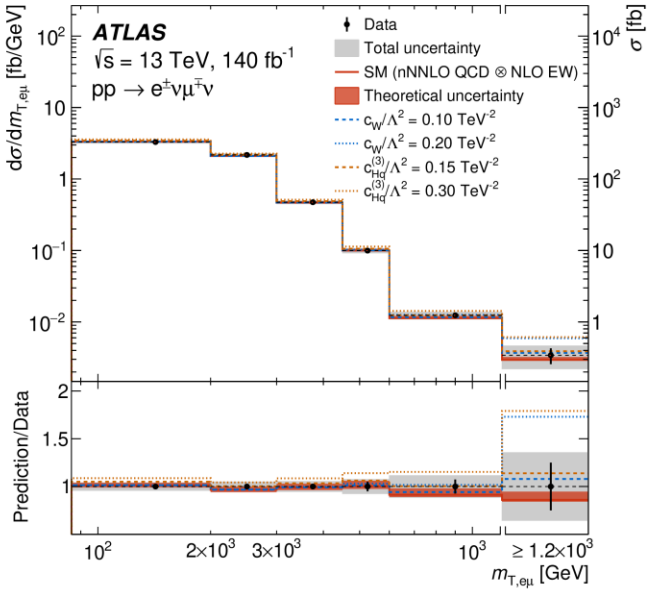
consistent w/ SM prediction (zero) within ~1σ

- Charge asymmetry A_C measured as a function of absolute difference of leptons absolute rapidities $||\eta_{\ell+}| - |\eta_{\ell-}||$, and invariant mass of the dilepton system
- Compared w/ the NNLO+PS predictions from Powheg MiNNLO+Pythia8
- **Significant asymmetry seen for 1st time!** (due to 2:1 ratio of up:down valence quarks)

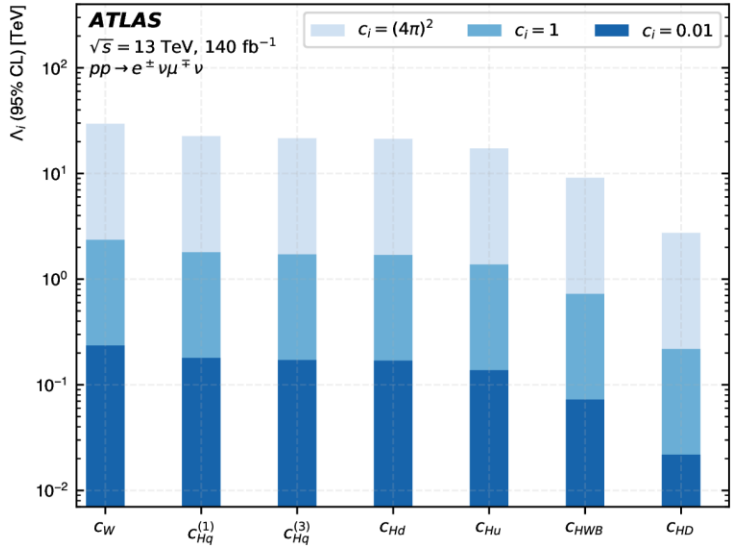
arXiv:2505.11310

WW with ATLAS Full Run-2 13TeV

- $m_{T,e\mu}$ differential distribution is used for aTGCs parameterized with seven SMEFT Wilson coefficients (Warsaw basis)
- Differential cross section also compared with MATRIX nNNLO QCD ⊗ NLO EW prediction using NNPDF3.1 luxQED
- Borders of the 95% confidence intervals as a function of upper mass cut-off is scanned and presented
- Lower limit on the new-physics scale Λ for fixed values are obtained (w/ the remaining six Wilson coefficients profiled)



	$O(\Lambda^{-2})$, individual		$O(\Lambda^{-4})$, individual		$O(\Lambda^{-4})$, profiled	
	Expected	Observed	Expected	Observed	Expected	Observed
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}	$[-8.4, 9.2]$	$[-10, 8]$	$[-1.5, 1.7]$	$[-1.7, 1.9]$	$[-1.7, 1.7]$	$[-1.8, 1.9]$
$c_{Hq}^{(1)}$	$[-2.5, 2.4]$	$[-2.2, 2.8]$	$[-0.27, 0.24]$	$[-0.29, 0.27]$	$[-0.29, 0.29]$	$[-0.31, 0.31]$
$c_{Hq}^{(3)}$	$[-0.69, 0.66]$	$[-0.7, 0.68]$	$[-0.28, 0.22]$	$[-0.31, 0.24]$	$[-0.3, 0.27]$	$[-0.34, 0.29]$
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 with ATLAS Full Run-2 13TeV

- Follow up previous partial Run-2 WZ measurements (*Eur. Phys. J. C 79 (2019) 535*) and Full Run-2 WZ joint polarization (*Phys. Lett. B 843 (2023) 137895*) & high PT polarization measurements (*Phys. Rev. Lett. 133 (2024) 101802*)
- More precise measurements of incl. and differential cross sections w/ ATLAS Full Run-2 dataset (140 fb^{-1}), in comparison w/ NNLO QCD and NLO EWK state-of-art SM predictions
- Probing CP-conserving and CP-violating dimension-6 operators with m_T^{WZ} (low/high categorized)

Variable	Fiducial inclusive
Lepton $\|\eta\|$	< 2.5
p_{T} of ℓ_Z, p_{T} of ℓ_W [GeV]	$> 15, > 20$
m_Z range [GeV]	$\|m_Z - m_Z^{\mathrm{PDG}}\| < 10$
m_{T}^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	$> 0.2, > 0.3$

Inclusive event selection	
ZZ veto	Less than 4 loose leptons
N leptons	Exactly three leptons passing the medium lepton selection
Leading lepton p_{T}	$p_{\mathrm{T}}^{\mathrm{lead}} > 25$ GeV (in 2015) or $p_{\mathrm{T}}^{\mathrm{lead}} > 27$ GeV (2016–2018)
Z leptons	Two same flavor oppositely charged leptons passing the medium lepton selection
Mass window	$\|M_{\ell\ell} - M_Z\| < 10$ GeV
W lepton	Remaining lepton passes the tight lepton selection
W transverse mass	$m_{\mathrm{T}}^W > 30$ GeV

arXiv:2507.03500

WZ with ATLAS Full Run-2 13TeV

New variables added for diff. measurements w.r.t. former results

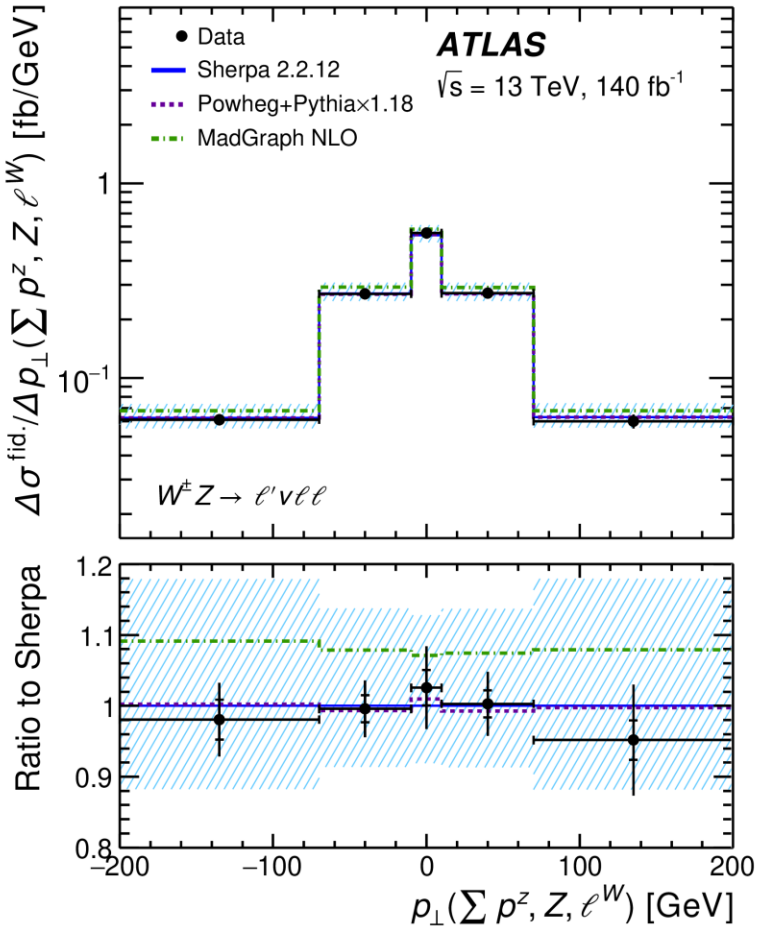
- p_{T}^{Z}
- p_{T}^{W}
- m_{T}^{WZ} → thinner binning
- p_{T}^{ν}
- $|y_Z - y_{\ell,W}|$
- $\Delta\phi(W,Z)$
- $\Delta\phi(\ell^W, Z)$
- p_{T}^{V1}
- p_{T}^{V2}
- ϕ_W^*
- ϕ_Z^*
- $p_\perp(\sum \hat{p}^z, Z, \ell^W)$
- $p_\perp(\ell^{+,z}, \ell^-, \ell^W)$
- N_{jets}
- m_{jj}

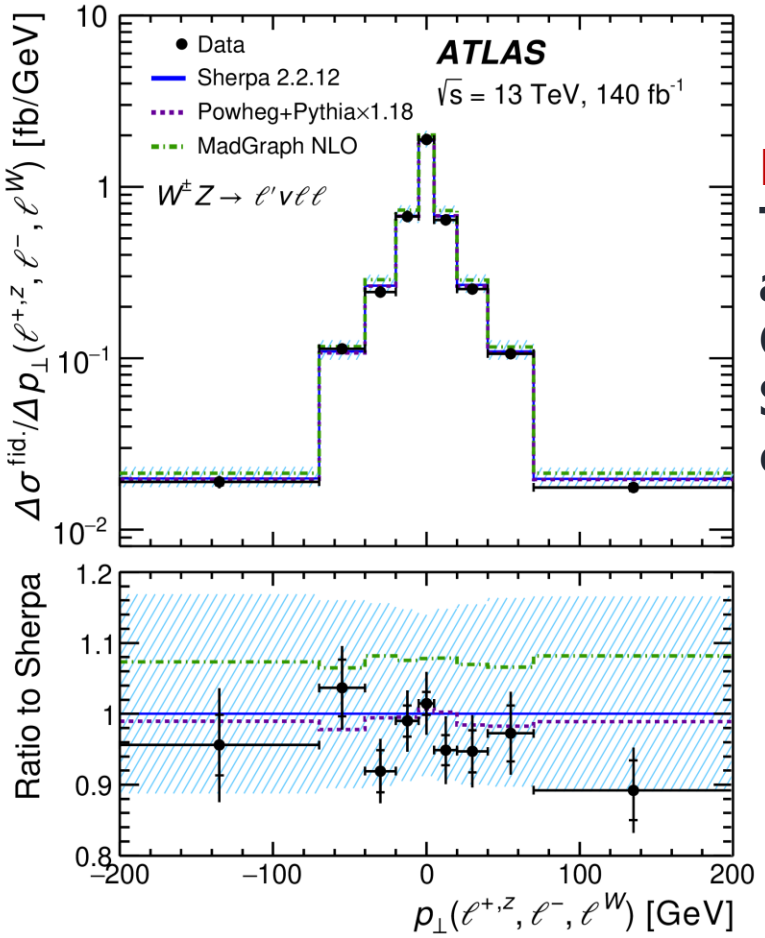
$$p_\perp(A,B,C) = \vec{p}_A \cdot \frac{\vec{p}_B \times \vec{p}_C}{|\vec{p}_B \times \vec{p}_C|}$$

$$\sum \hat{p}^z = \sum_{i \in \ell,\nu} \hat{p}_i^z$$

V_1 (resp. V_2) is the (sub-)leading boson in p_T.

ϕ_W^* (resp. ϕ_Z^*) azimuthal angle of ℓ^W (resp. ℓ^-) in the boson rest frame with respect to the $\vec{p}_W$ (resp. $\vec{p}_Z$) axis.

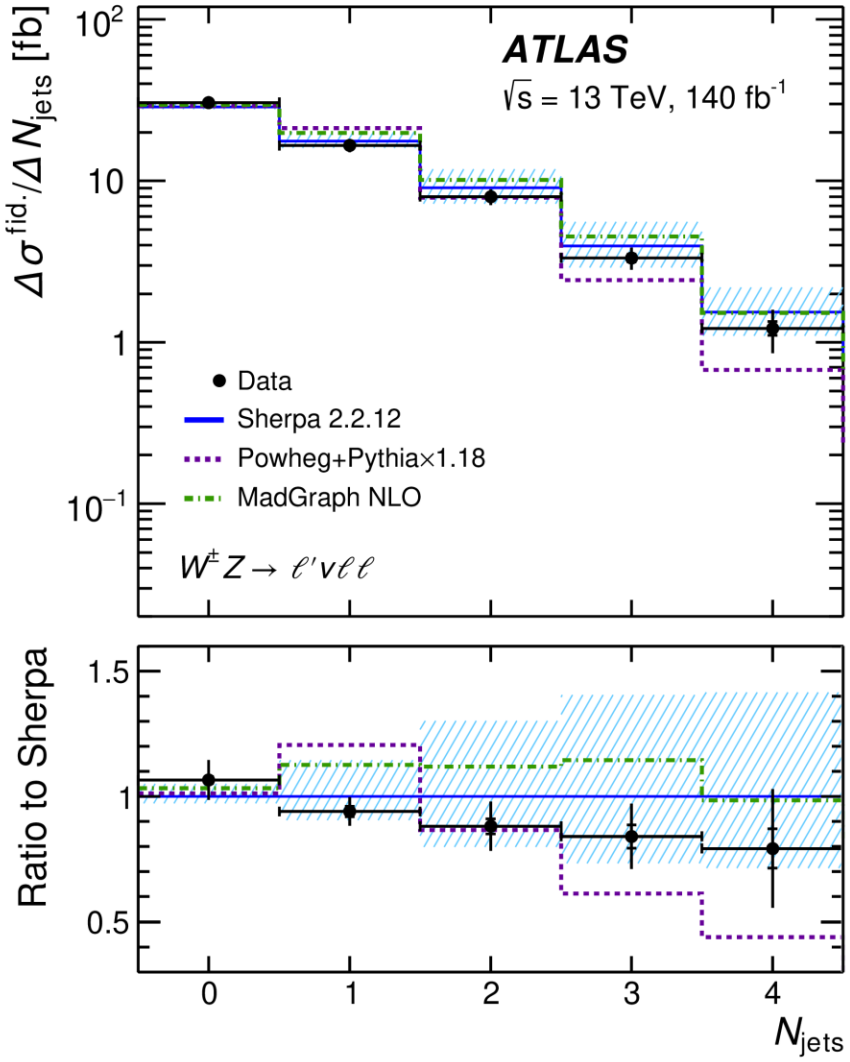


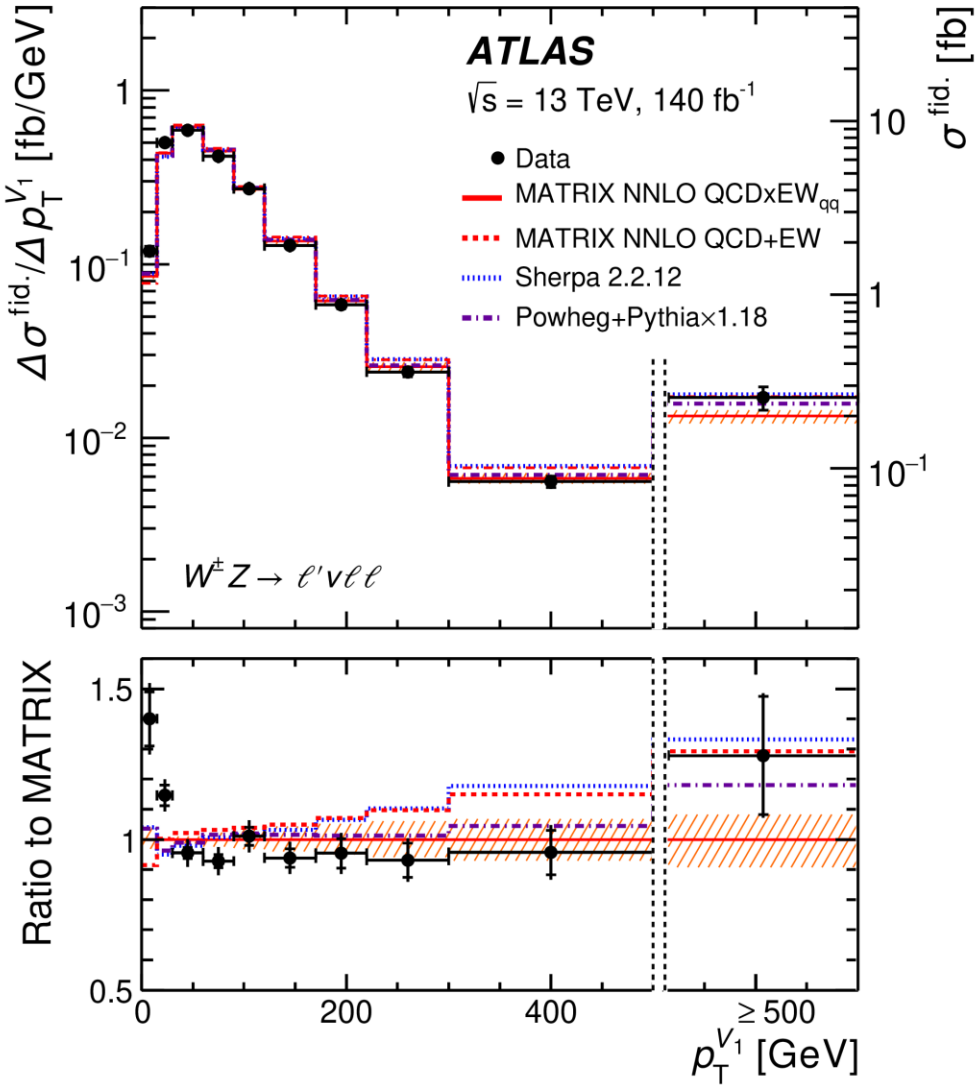


NEW!
Triple products are sensitive to CP-Violating SMEFT operators!

WZ with ATLAS Full Run-2 13TeV

arXiv:2507.03500



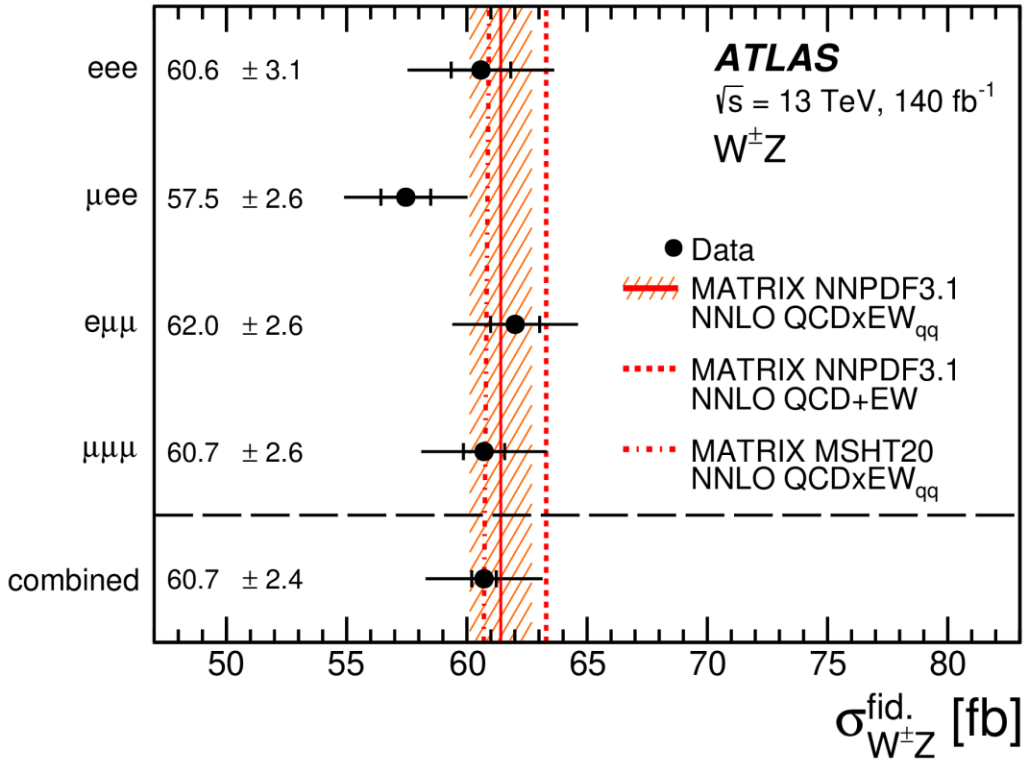


- MATRIX ⊕ vs ⊗ schemes differ at high p_T^{V1}
- Sherpa has a more complete description in high N_{jets} differing from PowHeg+Pythia
- Very low p_T discrepancies possibly explained by large logarithms in p_T /m_{VV}

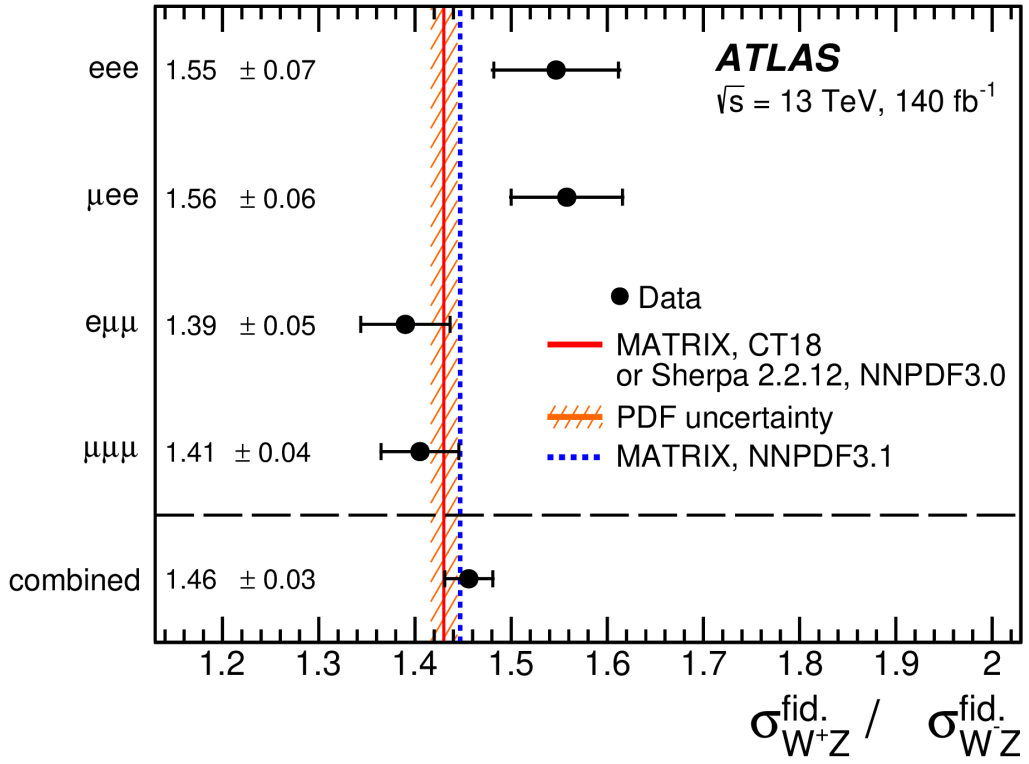
WZ with ATLAS Full Run-2 13TeV

arXiv:2507.03500

$$\sigma^{\text{fid.}}_{W^{\pm}Z\to\ell'\nu\ell\ell} = 60.7 \pm 0.5\,(\text{stat.}) \pm 1.4\,(\text{exp. syst.}) \pm 1.8\,(\text{mod. syst.}) \pm 0.6\,(\text{lumi.})\ \text{fb}$$



$$\frac{\sigma^{\text{fid.}}_{W^{+}Z\to\ell'\nu\ell\ell}}{\sigma^{\text{fid.}}_{W^{-}Z\to\ell'\nu\ell\ell}} = 1.456 \pm 0.025\,(\text{stat.}) \pm 0.010\,(\text{syst.})$$



- Measured WZ fid. cross sections in agreement w/ NNLO QCD⊗EW$_{qq}$ SM prediction from MATRIX using the NNPDF3.1nnlo_as_118_luxqed PDF and MSHT20nnlo PDF
- Measurement of charge ratio w/ ~2% precision (stat. limited)

WZ with ATLAS Full Run-2 13TeV

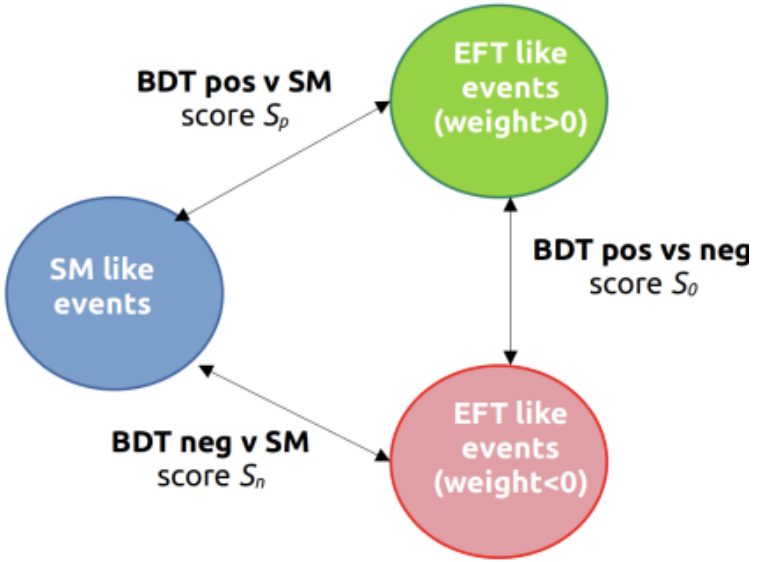
arXiv:2507.03500

CP-conserving EFT limits extracted with m_T^{WZ} distribution

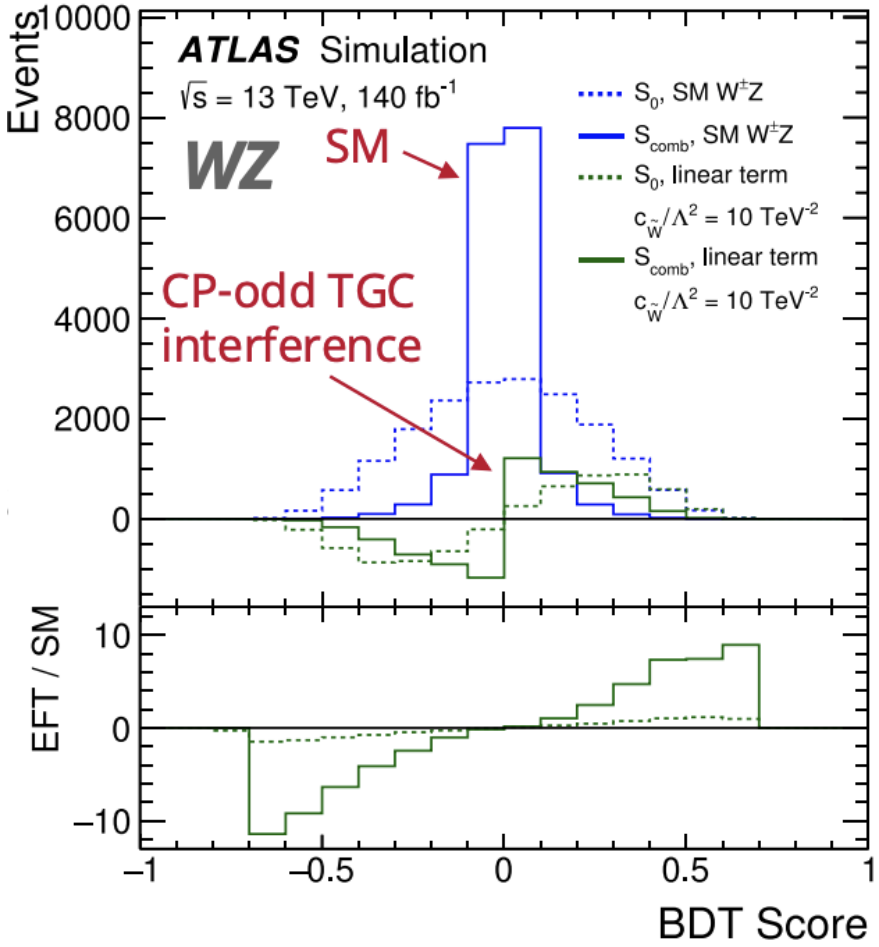
- c_W, c_{HWB}, c_{HD}, $c^{(1)}_{Hq}$, $c^{(3)}_{Hq}$

CP-violating EFT (**Strong!**) limits: BDTs for each operator to enhance sensitivity to CP-violation

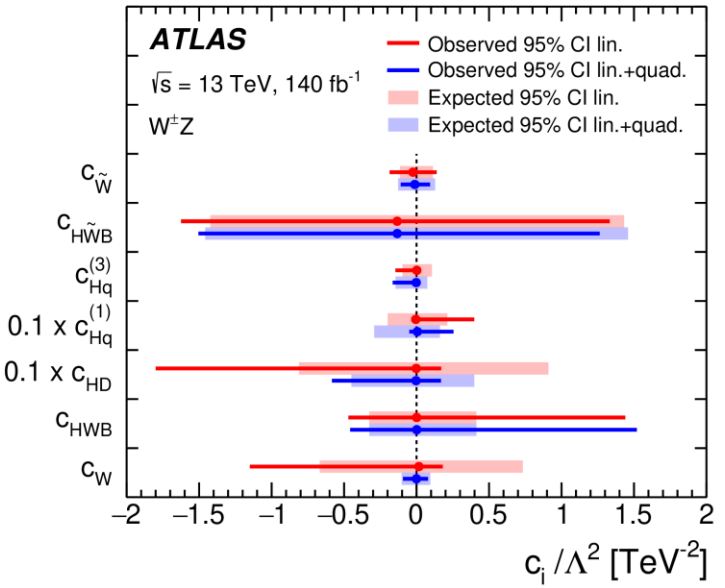
- c_{Wtild}, $c_{HWtildB}$

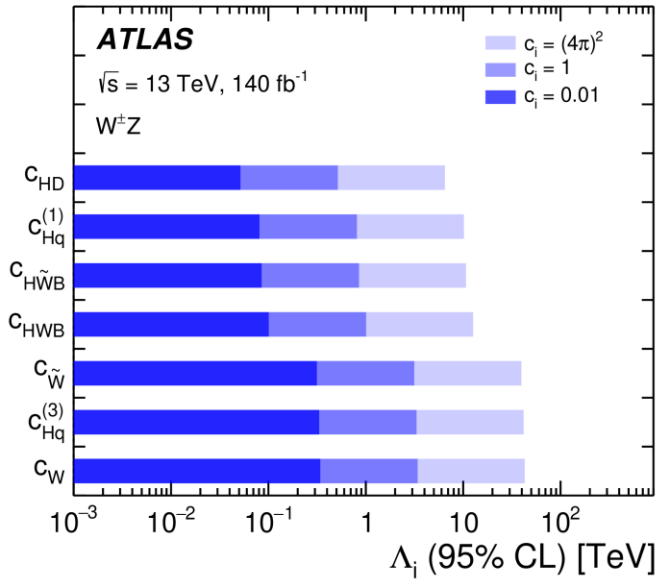


$$S_{comb} = S_0 \times \frac{1+S_p}{2} \times \frac{1+S_n}{2}$$

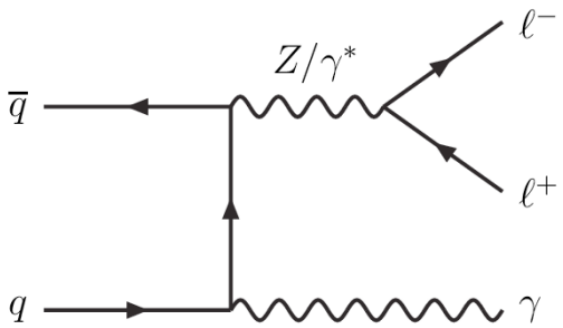


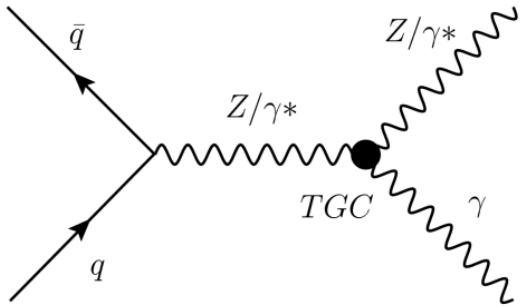
Strongest positive (negative) interf. for large S_{comb} ($-S_{comb}$)





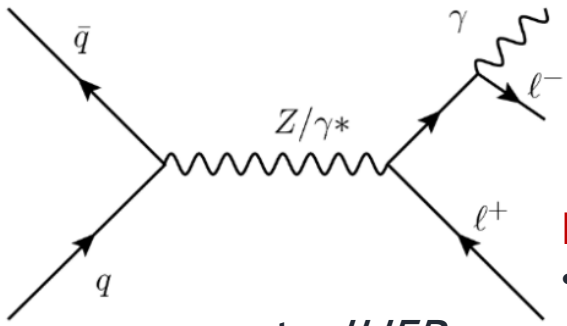
Zγ high p_T differential measurements and NEW nTGC at 13TeV





Suppressed w/ FSR rejection Cut

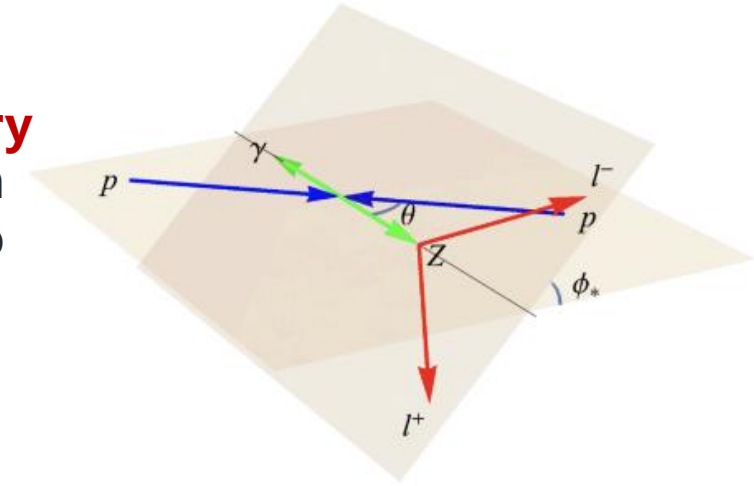
$m_{ll} + m_{lly} > 182$ GeV ~ 2 m_Z



- Analysis designed on top of previous Zγ+jets differential measurements *JHEP 07 (2023) 072*
- Focus on **high $p_T(\gamma)>200$GeV with on-shell Z**: sensitive to neutral aTGCs (nTGCs): prohibited at SM tree level, but 1st arise from dimension-8 SMEFT
- Two approaches adopted to probe nTGCs
  - Dimension-8 operators in SMEFT approach
  - Form Factor (FF) in effective vertex approach
- Incorporating for **1st time $SU(2)_L \otimes U(1)_Y$ fully gauge invariant symmetry** [*PRD 107 (2023) 035005*] and cancelling spurious energy dependent term
- Conventional FF formulation only incorporated $U(1)$ symmetry, leading to limits overestimation by two orders of magnitude (**now corrected** ☺)

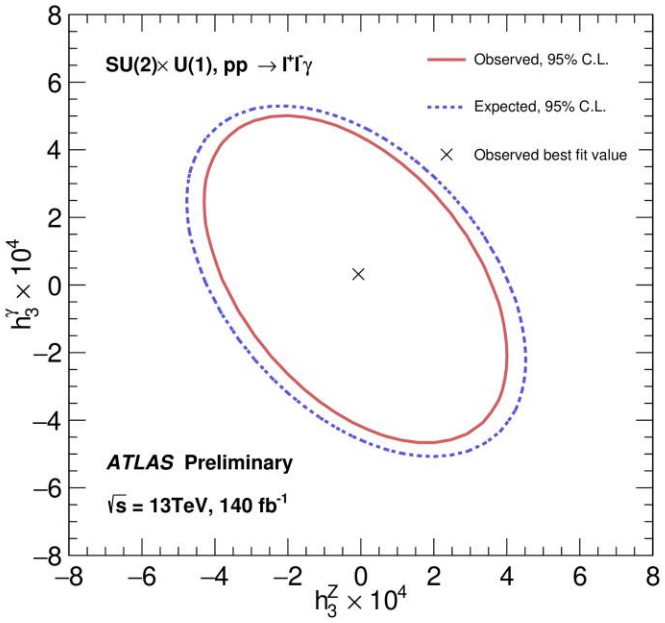
NEW diff. meas. of ϕ^*

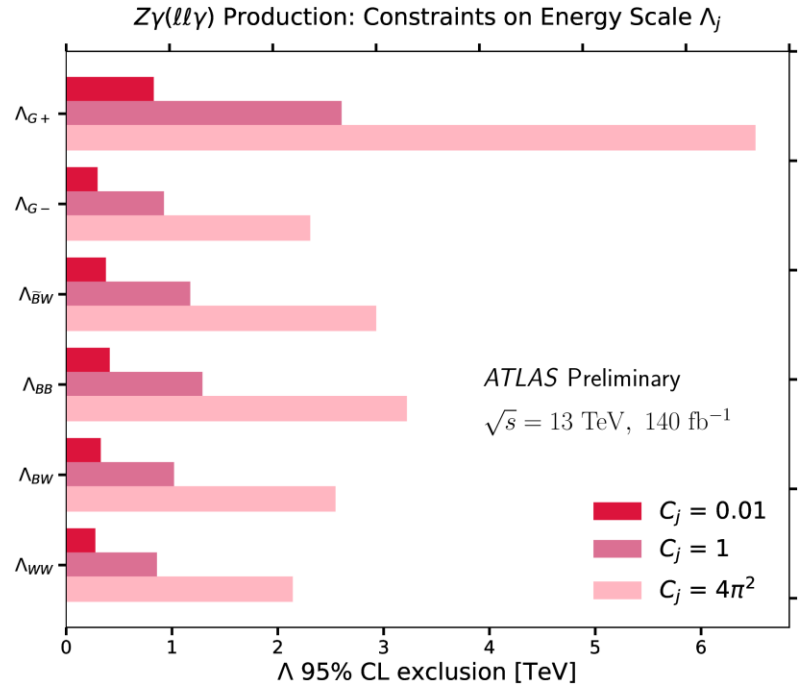
- Angle b/w scattering plane and decay plane of Z in the $\ell^+\ell^-$ frame
- Sensitive to interference b/w SM and pure BSM terms



Zγ high p_T differential measurements and NEW nTGC at 13TeV

- Limits extracted from high $p_T(\gamma)$ region differential cross section
- **NEW**! 1D and 2D limits w/ dimension-8 Wilson coefficients using fully gauge invariant theory treatment (**for 1st time at LHC**) and conversion FF limits
- Significantly relax the previous h_4 limits w/ only U(1) symmetry treatment





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

Summary

- Dibosons from ATLAS Full Run-2 keep voicing out w/ **NEW** higher precision cross section results and stronger constraints on BSM w/ SMEFT
  - WW and WZ reaching unprecedented precision (3%~4%) in measured cross sections
  - WW **charge asymmetry evidence** concluded, and most precise predictions are compared: NNLO QCD+NLO EWK w/ NLO-QCD gg and γ-induced corrections and latest NNPDF3.1nnlo_as_118_luxqed PDF set
  - **CP-violating sensitive observables** are for 1st time measured differentially in WZ, providing strong constraints w/ combined BDT analyses and low/high m_T^{WZ} categorizations
  - **NEW $SU(2)_L \otimes U(1)_Y$ fully gauge invariant formulation** adopted for **1st time at LHC** via Zγ high $p_T(\gamma)$ differential analysis, relaxing former nTGC FF limits by orders of magnitudes
- ATLAS Run-3 keeps delivering high quality and statistically rich proton-proton collision DATA while SM diboson new results yet need patience ☺
  - **check out 1st Run3 ZZ results by ATLAS: *Phys. Lett. B 855 (2024) 138764***