Recent Electroweak Measurements with ATLAS

Brigitte Vachon
McGill University

On behalf of the ATLAS Collaboration

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The Electroweak Theory

- Rich phenomenology arises from the non-Abelian gauge group structure and spontaneous EW symmetry breaking in the Standard Model

$$SU(2)_{\mathrm{L}} \times U(1)_{\mathrm{Y}} \longrightarrow W^+, W^-, Z^0, \gamma$$

- Mass of electroweak gauge bosons and interactions strength predicted precisely from: g, g', v, λ

$$\rho = \frac{m_W^2}{m_Z^2 cos^2\theta_W}$$

- Or alternatively can use as input parameters, e.g., $\alpha_{\mathrm{QED}}, G_F, m_Z, m_H$

- **LHC offers unique environment to test EW theory!**

Electroweak Tests at LHC

Precision Frontier

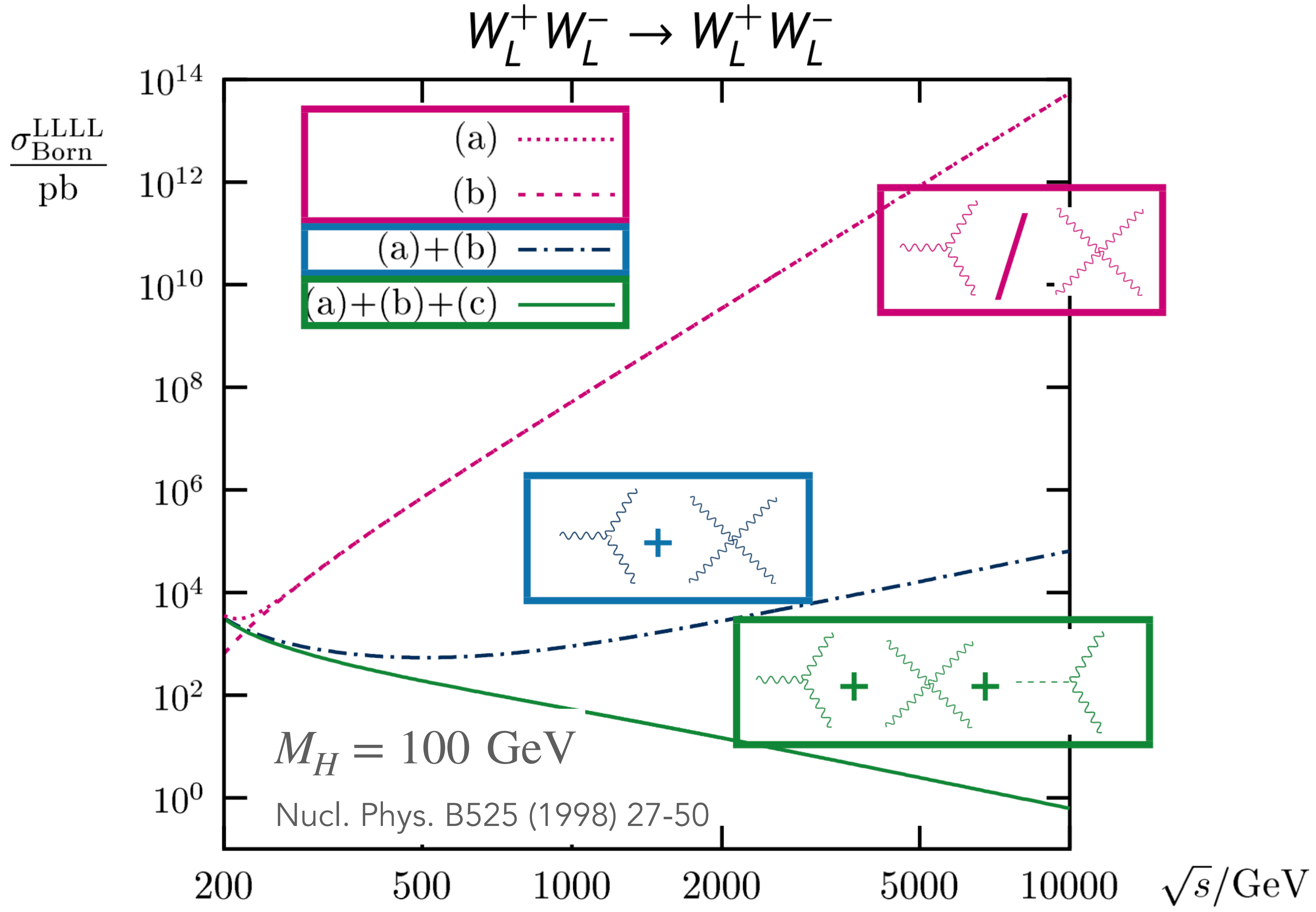
Radiation corrections modify propagators and decay vertices

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

- Sensitivity to a wide range of physics through quantum loops

Measurements of SM parameters

Energy Frontier



- Delicate gauge cancellations at high energy
- Enhanced sensitivity to non-SM contributions

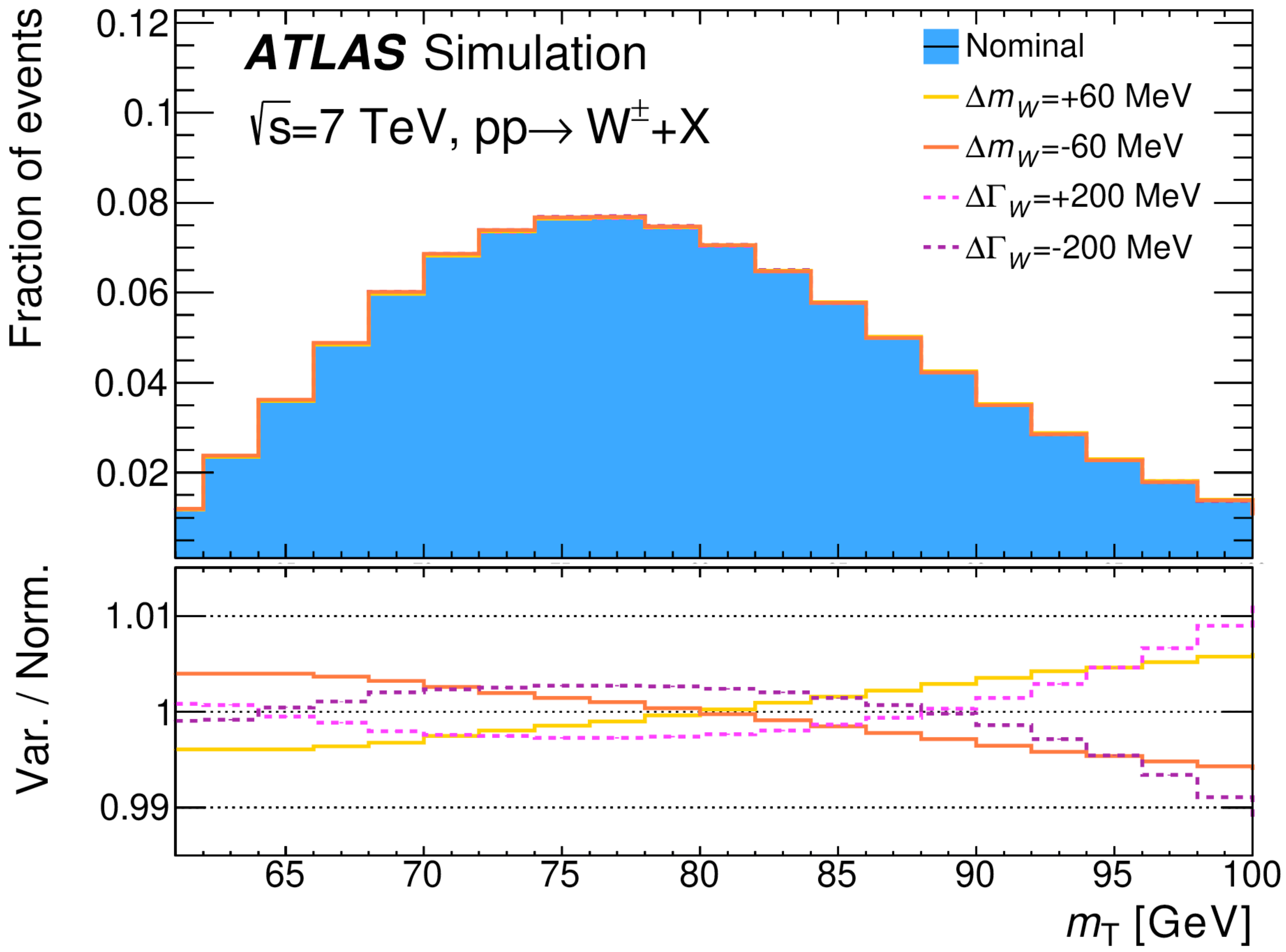
Investigation of EW gauge structure

Measurements of SM parameters

W Boson Mass and Width

Eur. Phys. J. C 84 (2024) 1309, arXiv:2403.15085

- Re-analysis of 2011 data
  - Favourable experimental environment for m_W measurement
  - Consolidate earlier ATLAS results, in the context of CDF latest measurement.
- Fit p_T^ℓ and m_T^W distributions in $W \to \ell\nu$ decays
  - Improved statistic based on the profile likelihood
  - Updated to more modern PDF sets
- Measurement requires excellent precision in lepton energy/momentum calibration ($O(10^{-4})$) and recoil response (~ few %).

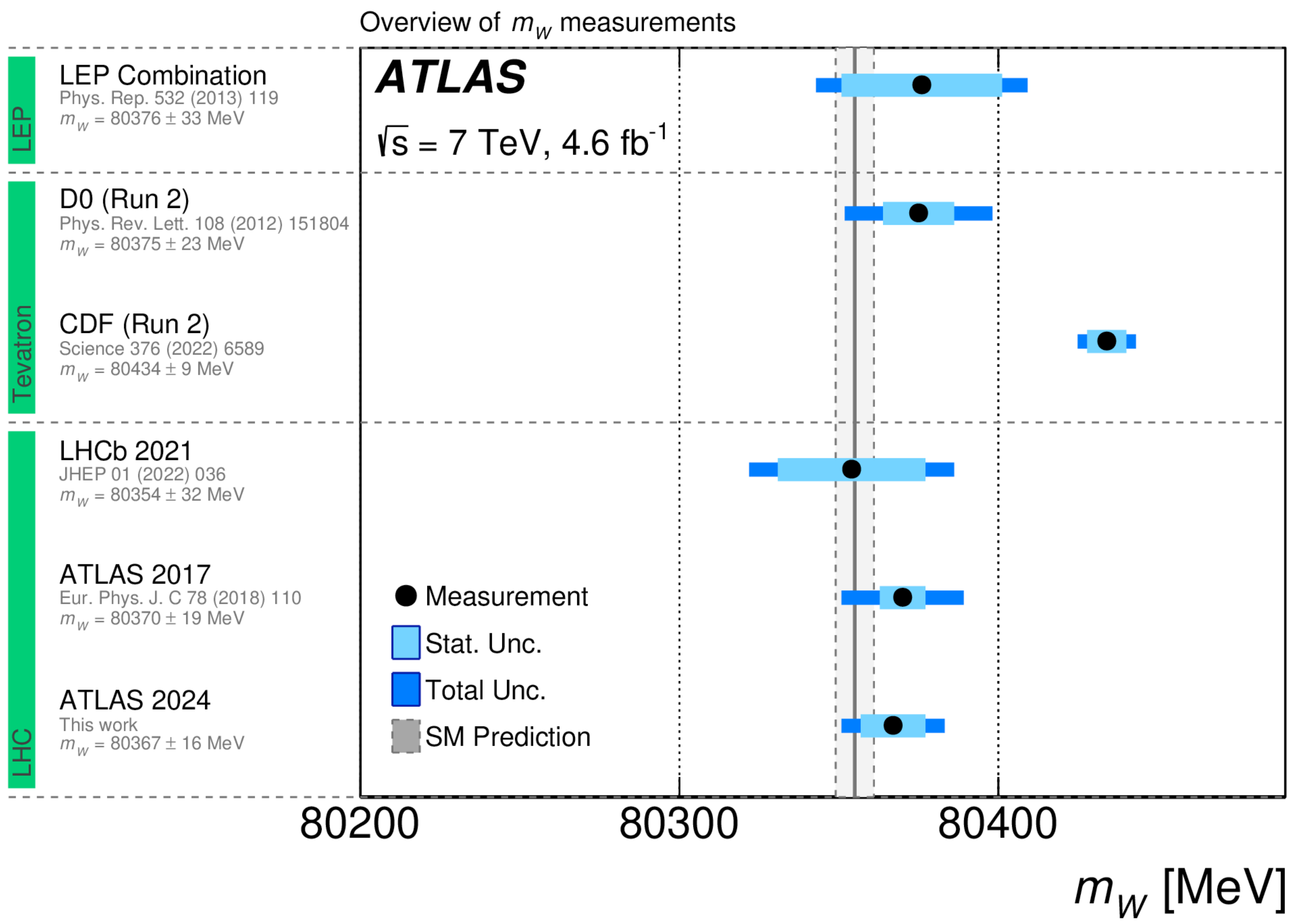


W Boson Mass and Width

Eur. Phys. J. C 84 (2024) 1309, arXiv:2403.15085

W boson mass

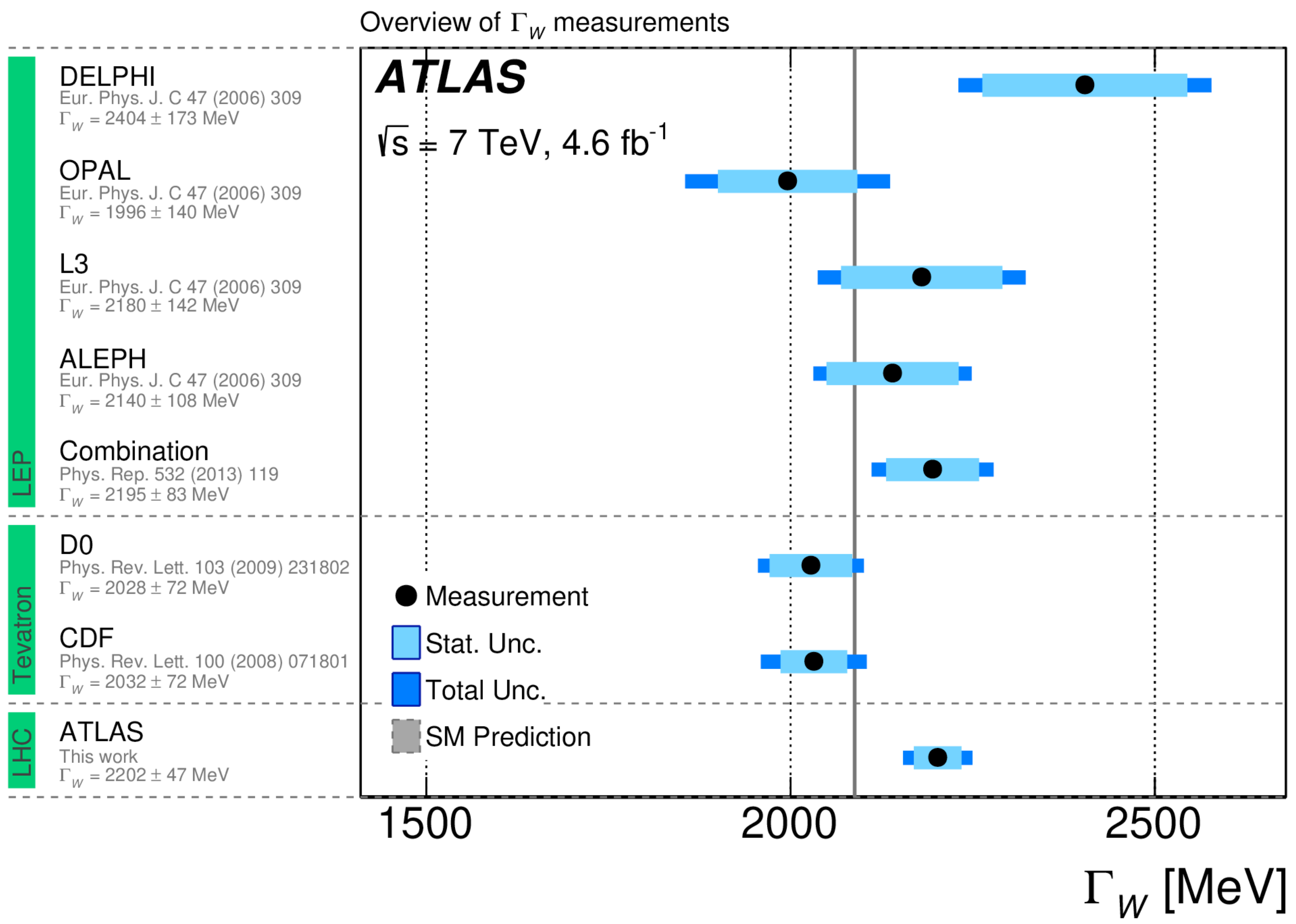
$$m_W = 80{,}366.5 \pm 15.9 \text{ MeV}$$



- Total uncertainty reduced by ~ 15%

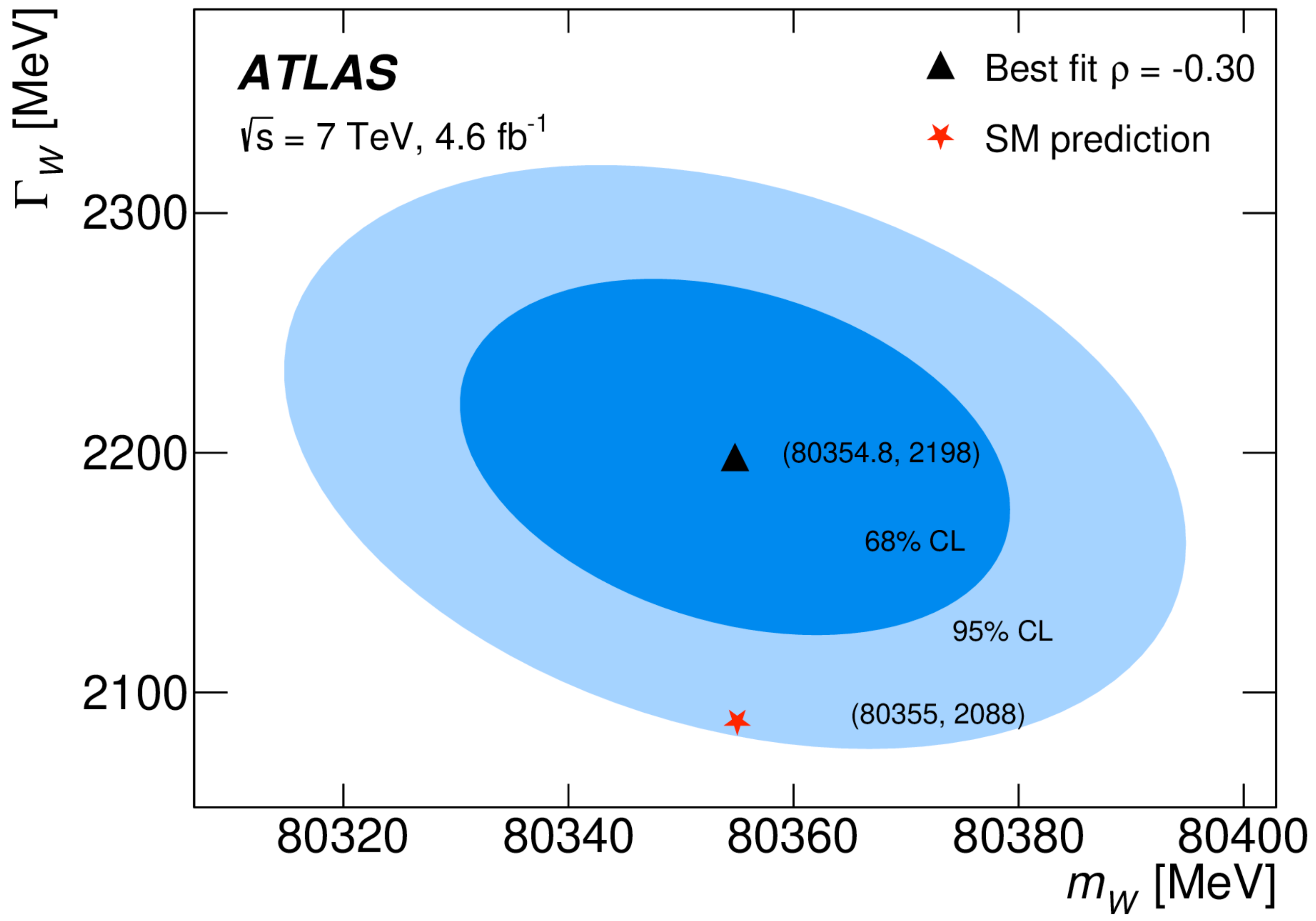
W boson width

$$\Gamma_W = 2202 \pm 47 \text{ MeV}$$



- **First measurement at LHC**
- **Most precise single-experiment measurements.**

Simultaneous extraction of m_W and Γ_W

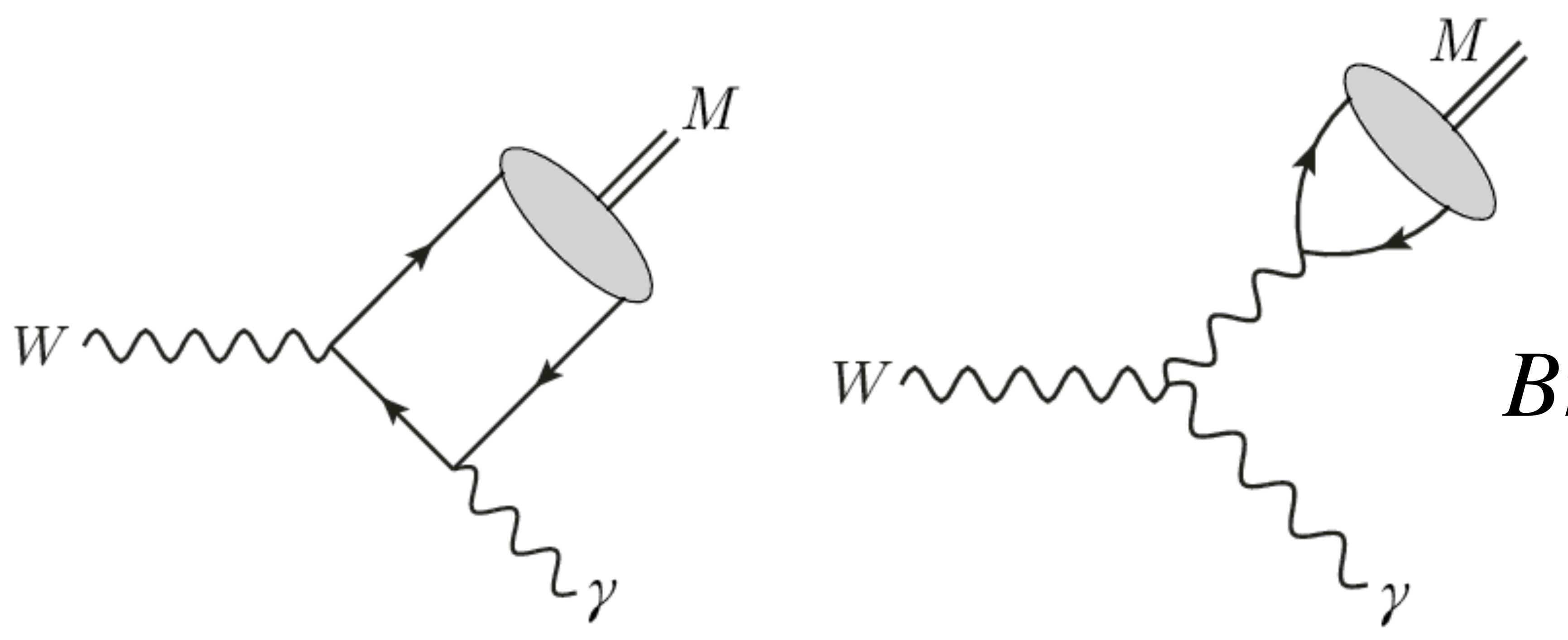


- Correlation of -30%

Exclusive W Boson hadronic decays

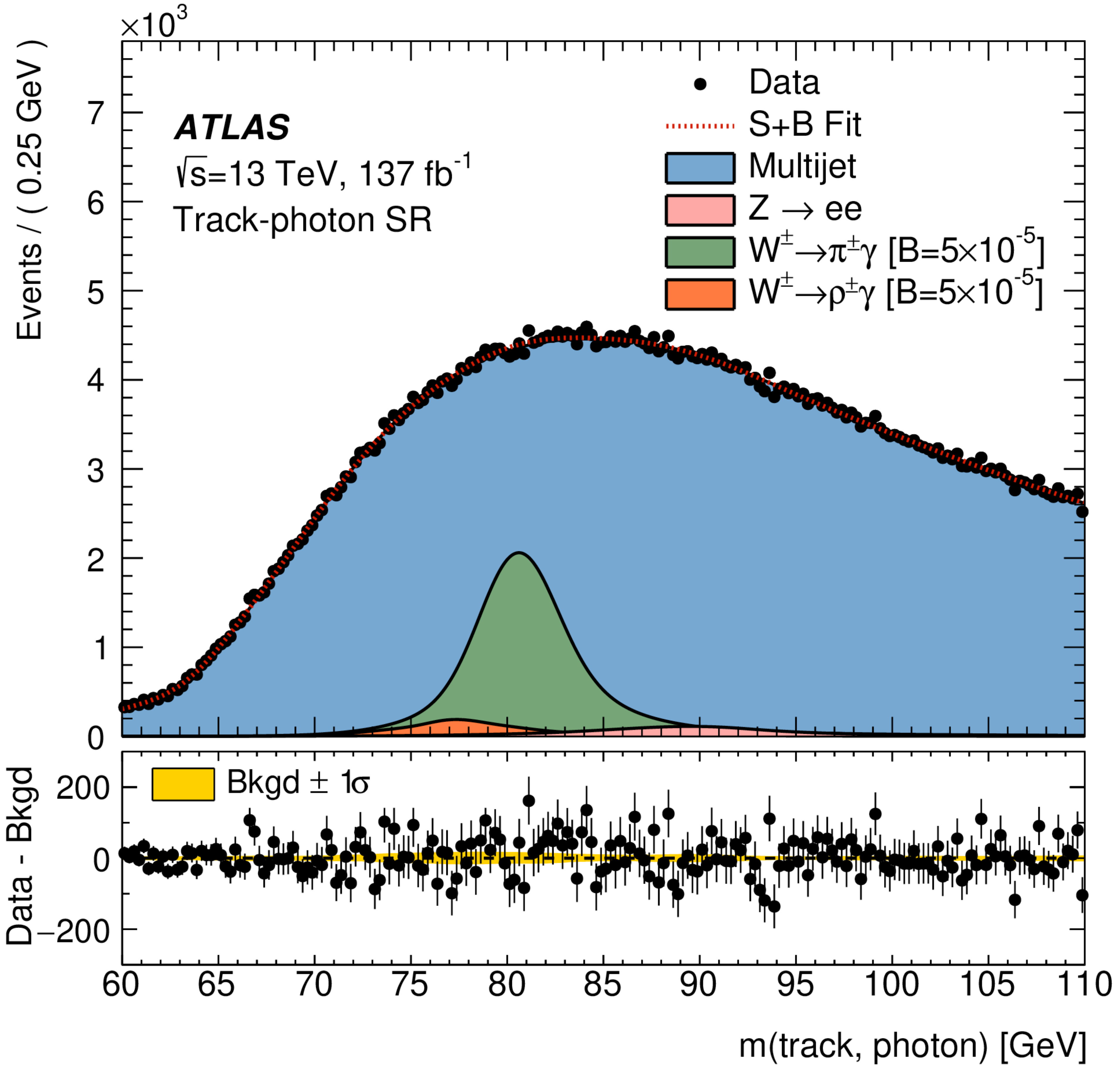
Phys. Rev. Lett. 133 (2024) 161804, arXiv:2309.15887

- Test bench for the QCD factorization framework
- Could enable W boson mass measurement with a fully reconstructed final state at future colliders
- Analysis enabled by special photon + track trigger



$$Br(W^{\pm} \to M^{\pm}\gamma) \sim 10^{-9}$$

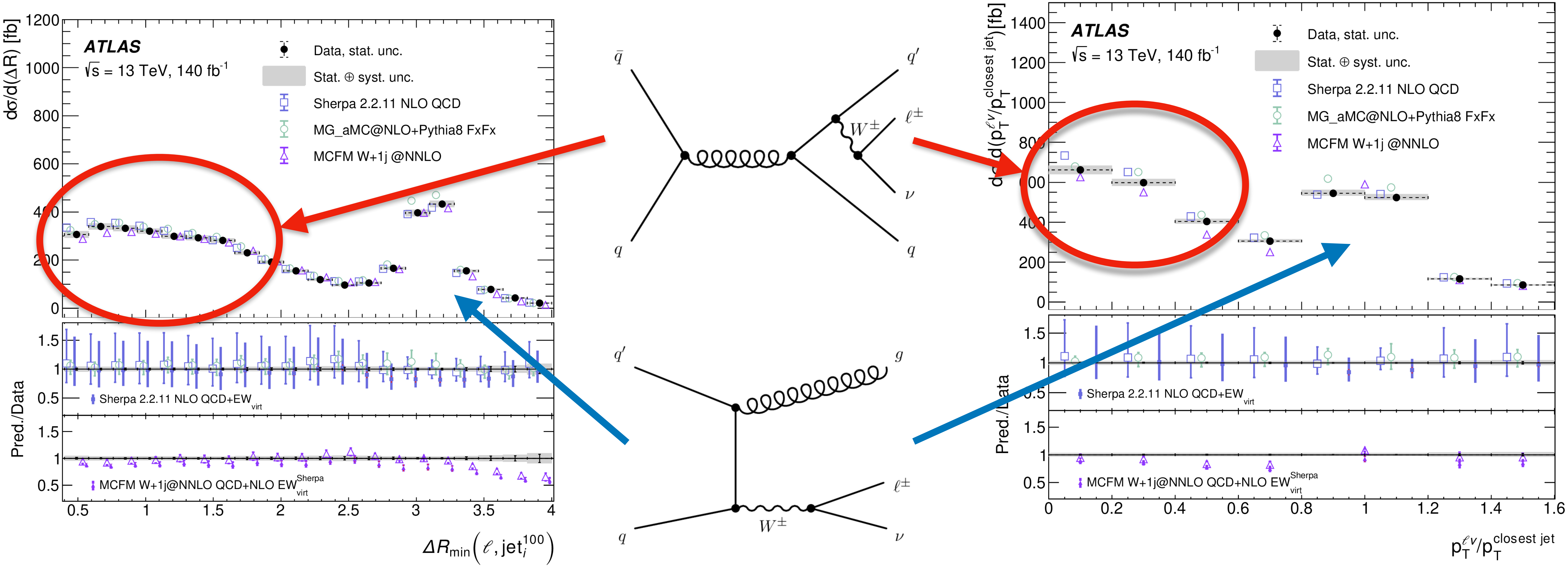
Branching fraction	95% CL upper limits: Expected $\times 10^{-6}$	95% CL upper limits: Observed $\times 10^{-6}$	
$\mathcal{B}(W^{\pm} \to \pi^{\pm}\gamma)$	$1.2^{+0.5}_{-0.3}$	1.9	**x4 improvement**
$\mathcal{B}(W^{\pm} \to K^{\pm}\gamma)$	$1.1^{+0.4}_{-0.3}$	1.7	**First upper limits**
$\mathcal{B}(W^{\pm} \to \rho^{\pm}\gamma)$	$6.0^{+2.3}_{-1.7}$	5.2	



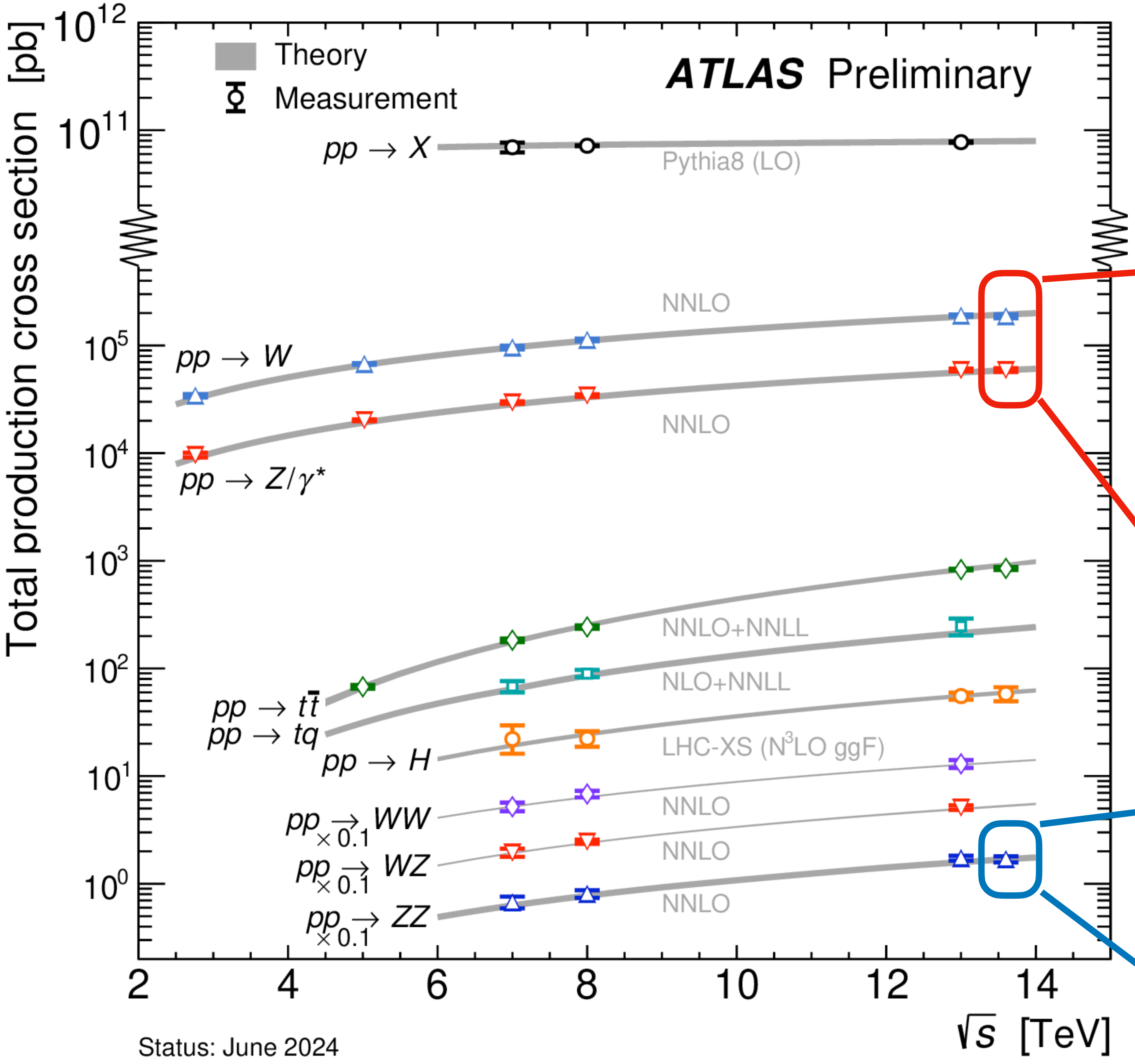
W+jets Production

arXiv:2412.11644

- Inclusive and differential cross-section measurements in the collinear phase space as a function of a variety of observables
- Explore the modelling of kinematic variables in the high momentum phase space



W and Z Boson Production



ATL-PHYS-PUB-2024-011

- First step in the study of gauge bosons at **13.6TeV**
  - Total/fiducial/differential cross-section measurements

$pp \to W$ and *$pp \to Z/\gamma^*$*

PLB 854 (2024) 138725, arXiv:2403.12902

- Uncertainty ~ 2-3% dominated by luminosity uncertainty
- Ratio measurements for increased sensitivity to PDF
- Good agreement with NNLO+NNLL QCD and NLO EW predictions

$pp \to ZZ$

PLB 855 (2024) 138764, arXiv:2311.09715

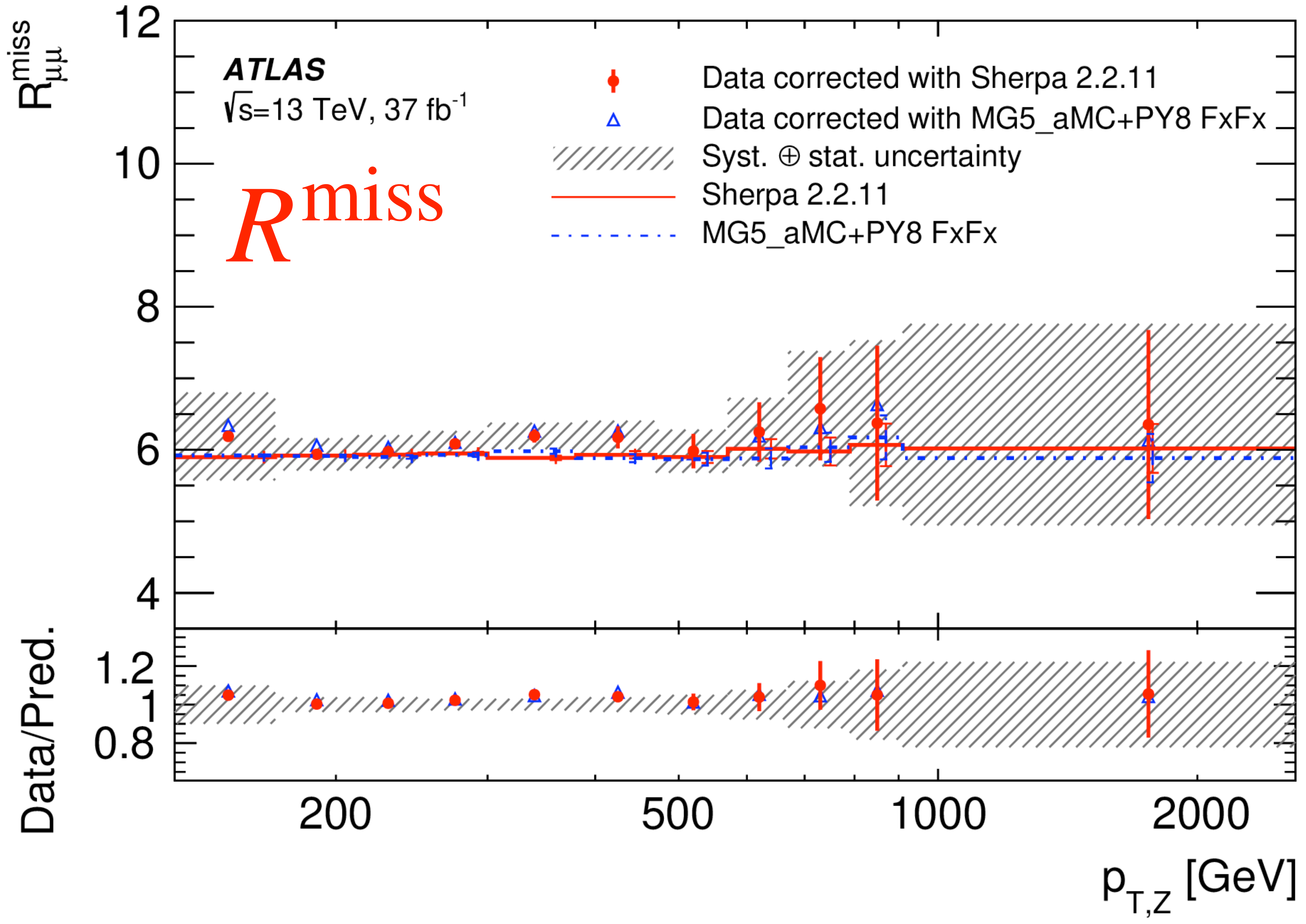
- Uncertainty ~ 6% (with comparable stat./syst. uncertainties)
- Good agreement with NNLO QCD + NLO EW predictions

Z Boson Invisible Width

Phys. Lett. B 854 (2024) 138705, arXiv:2312.02789

- Sensitive to number of light neutrinos coupling to Z boson and potential non-SM contributions
- Measurements via different final states and analysis strategies test the consistency of SM

$$\Gamma(Z \rightarrow \text{inv}) = R^{\text{miss}} \cdot \Gamma(Z \rightarrow \ell\ell)$$



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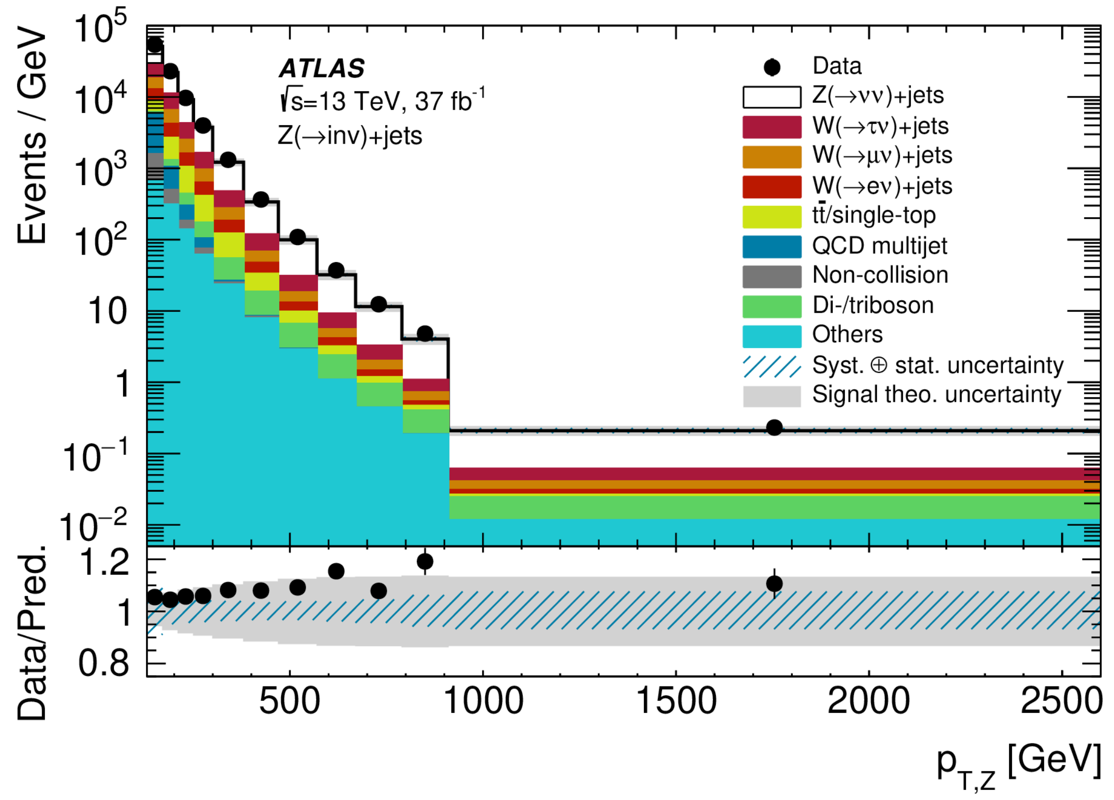
$Z(\rightarrow \text{inv}) + \text{jets}$



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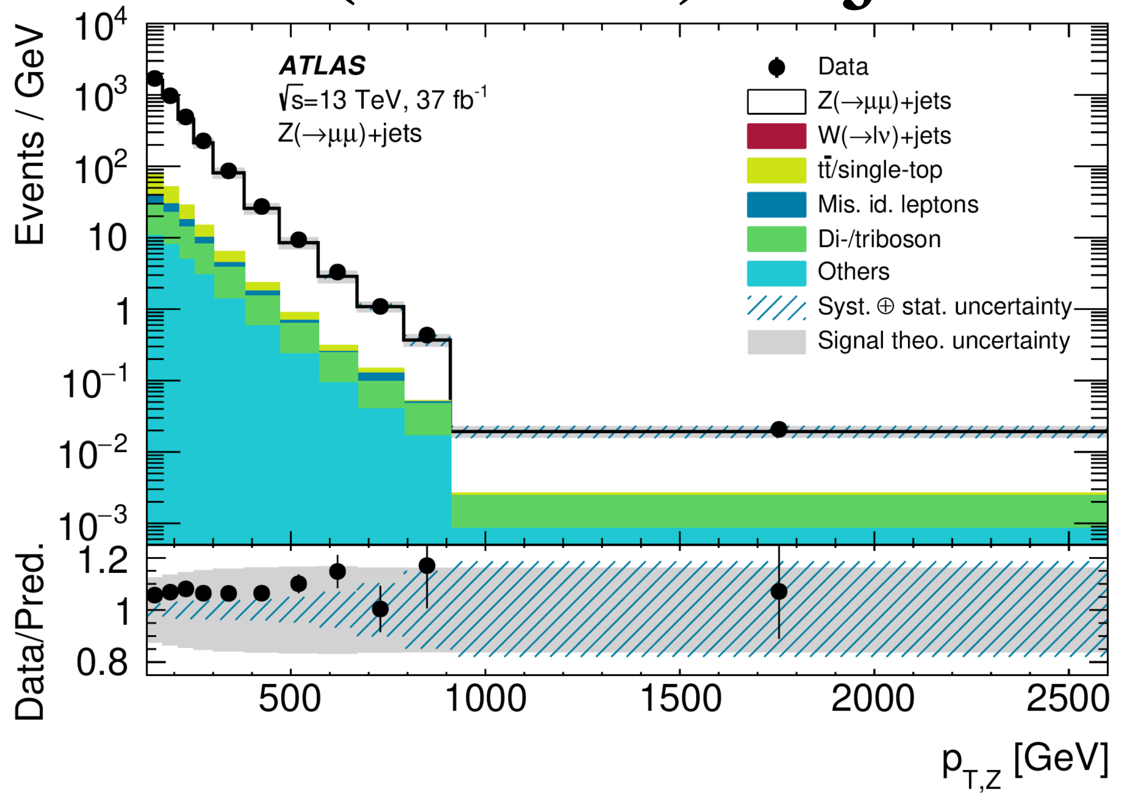
$Z(\rightarrow \ell\ell) + \text{jets}$

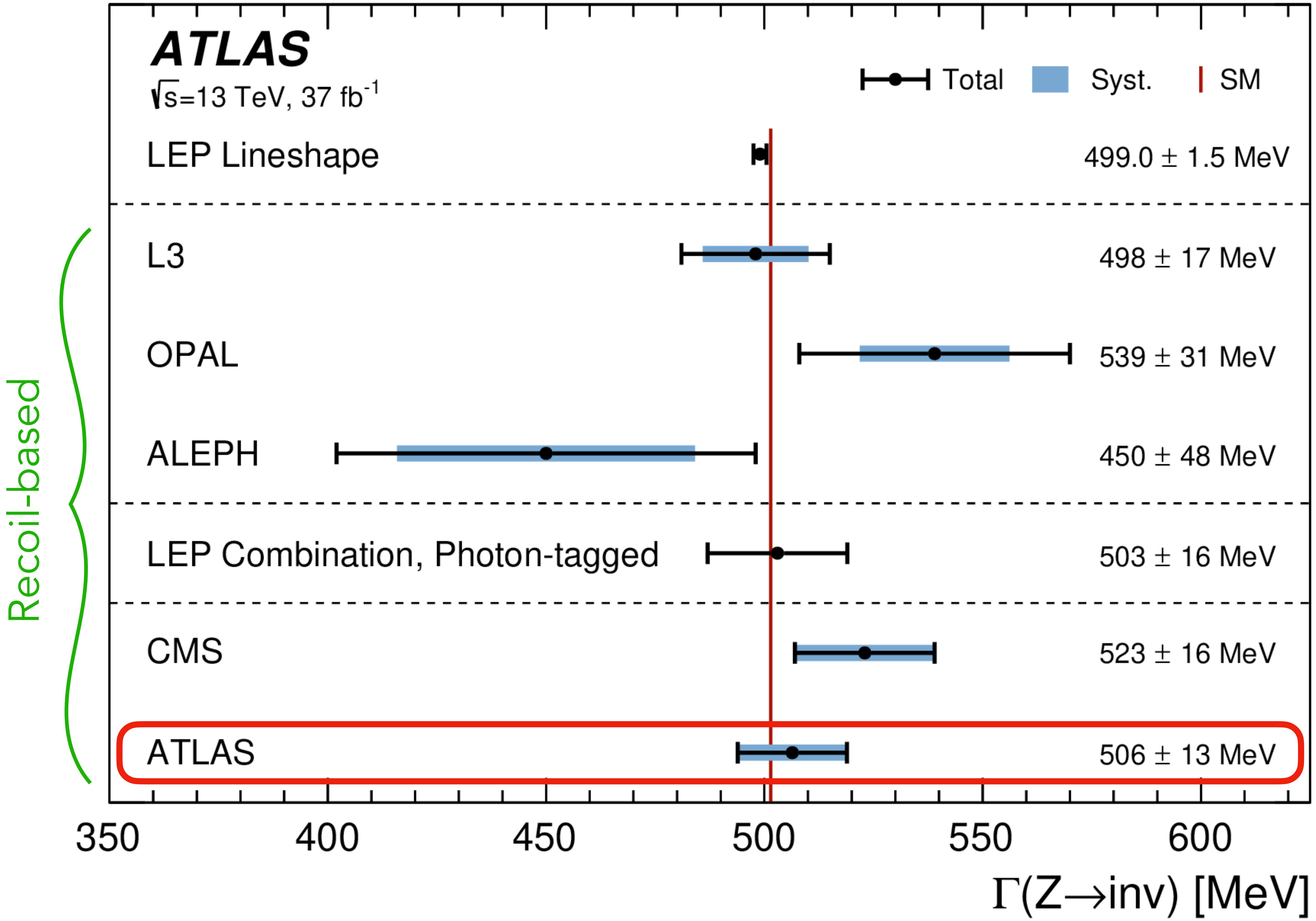


Z Boson Invisible Width

Phys. Lett. B 854 (2024) 138705, arXiv:2312.02789

$$\Gamma(Z \rightarrow \text{inv}) = 506 \pm 2(\text{stat}) \pm 12(\text{stat})$$

- **Single most precise recoil-based measurement** (~ 2.5%)
- Dominated by systematic uncertainties (leptons)
- Result in agreement with LEP combination and SM predictions



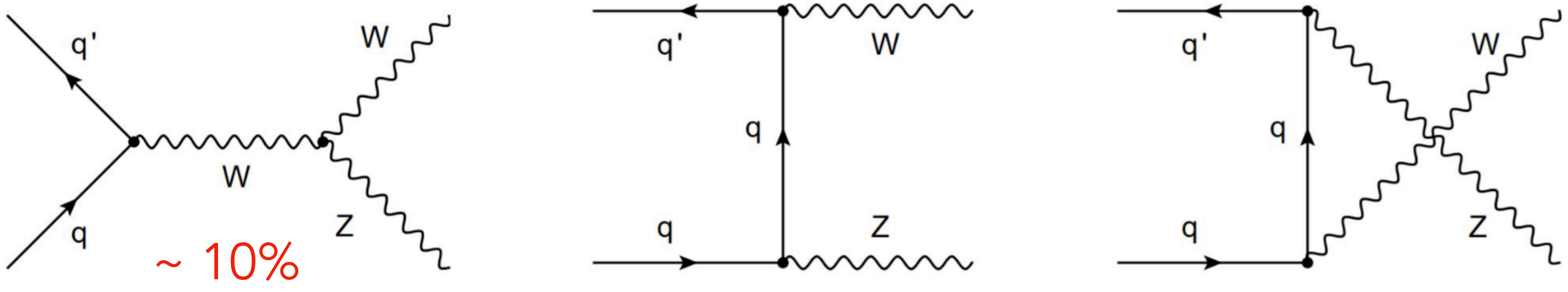
Investigation of EW Gauge Structure

WZ Polarization

Phys. Rev. Lett. 133 (2024) 101802, arXiv:2402.16365

- Study of diboson polarization probes gauge symmetry structure and electroweak symmetry breaking mechanism.
  - Longitudinal polarisation generated by Goldstone bosons in EWSB
  - Unitarity of $V_L V_L$ scattering cross-section at high energies guaranteed by gauge symmetry.

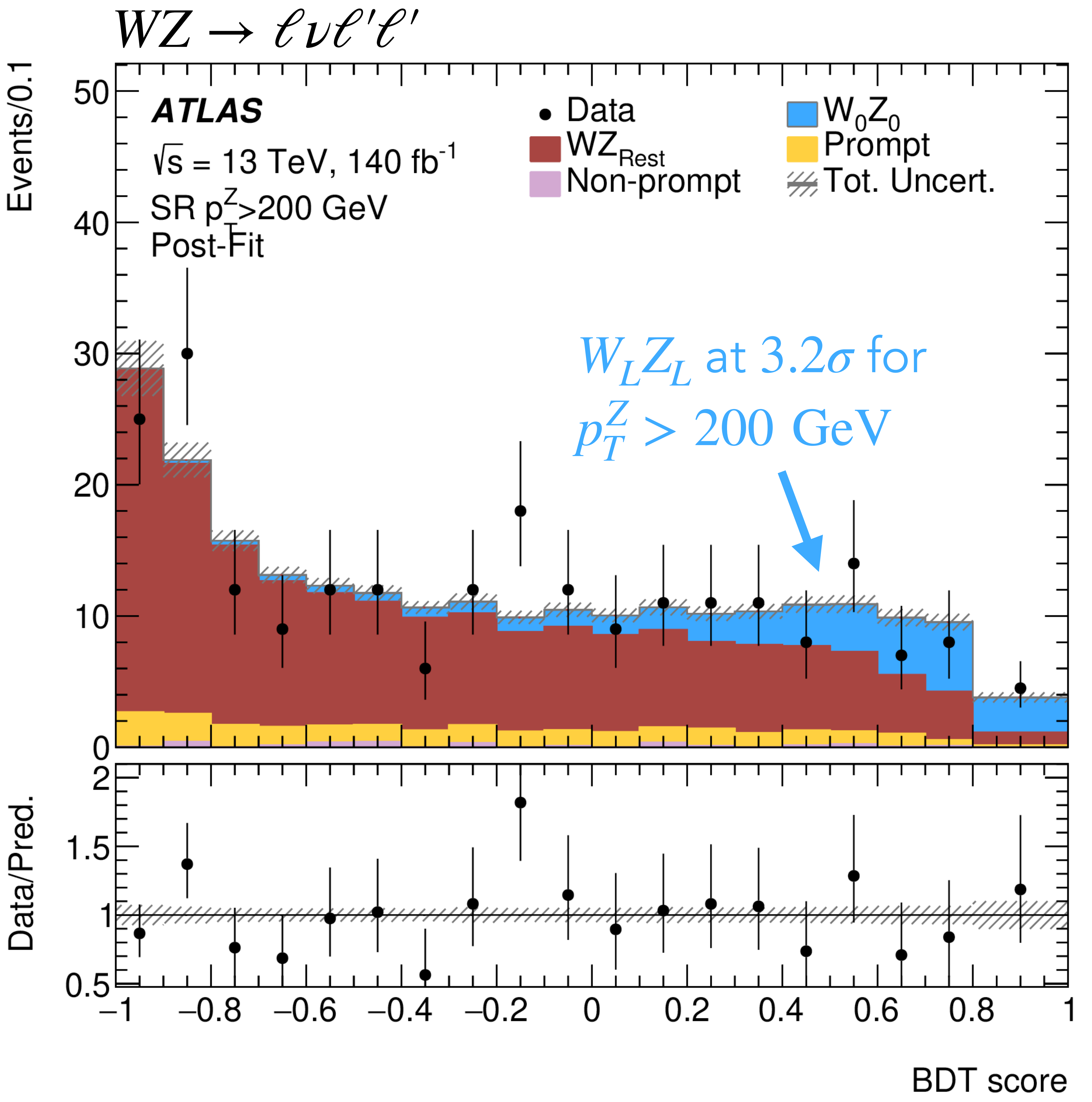
- Experiments gaining sensitivity to $V_L V_L$ production and starting to study energy dependence of cross-section.



WZ Polarization

Phys. Rev. Lett. 133 (2024) 101802, arXiv:2402.16365

- The $W_L Z_L$ final state only makes up ~ 6% of total WZ cross-section.
- Measure polarization fractions in longitudinally-enriched regions.
  - $p_T^{WZ} < 70$ GeV ➔ Reduce jet activity
  - High p_T^Z ➔ Enhance s-channel contributions
- Measurements compatible with SM predictions.

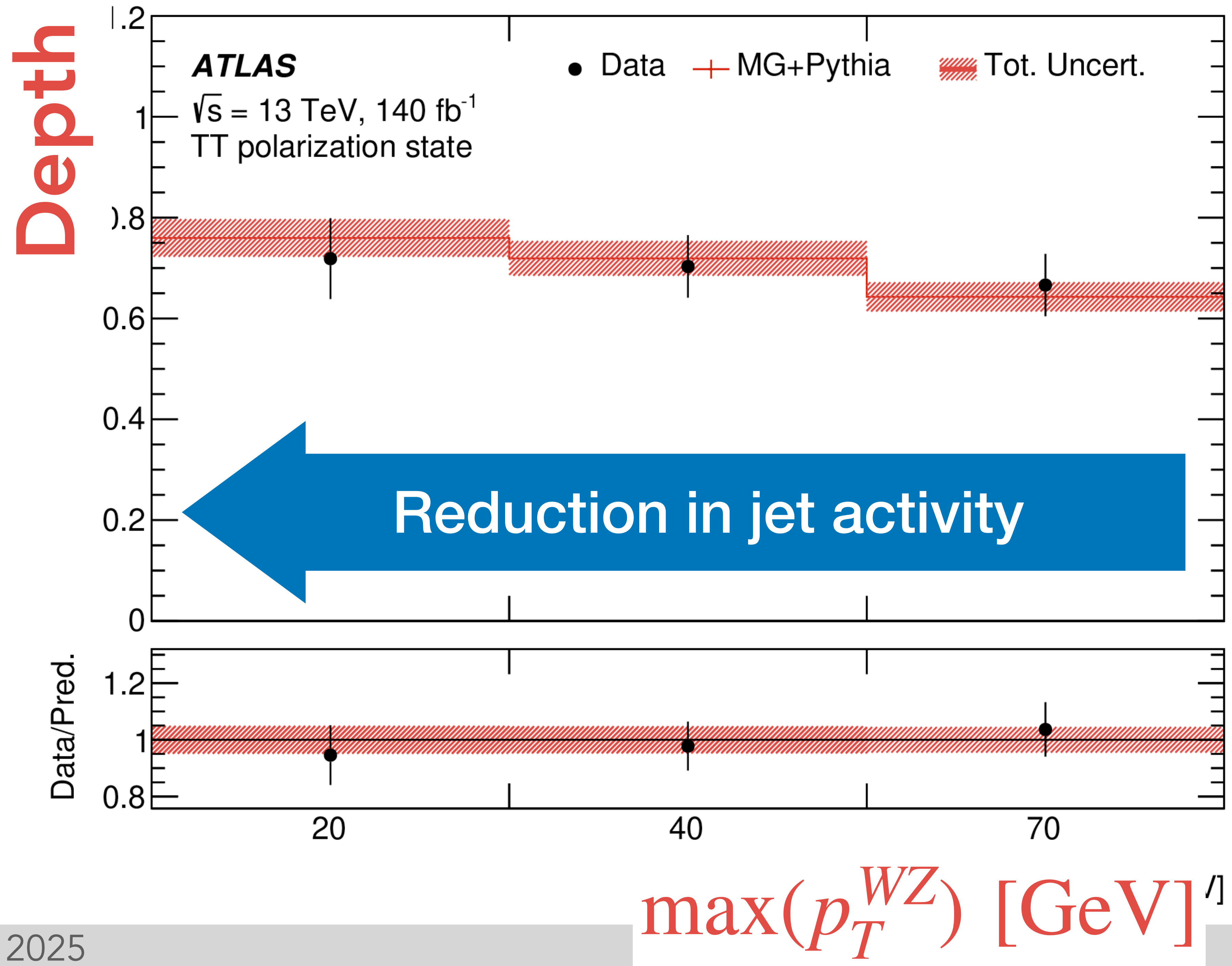


	Measurement $100 < p_T^Z \leq 200$ GeV	Measurement $p_T^Z > 200$ GeV		Prediction $100 < p_T^Z \leq 200$ GeV	Prediction $p_T^Z > 200$ GeV
f_{00}	$0.17 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.01}_{0.02}$ (syst)	$0.16 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.02}_{0.03}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{XX}	$0.83 \pm^{0.02}_{0.02}$ (stat) $\pm^{0.02}_{0.01}$ (syst)	$0.84 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.03}_{0.02}$ (syst)	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{00} obs (exp) sig.	7.7 (6.9) σ	3.2 (4.2) σ	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
			f_{TT}	0.619 ± 0.007	0.646 ± 0.008

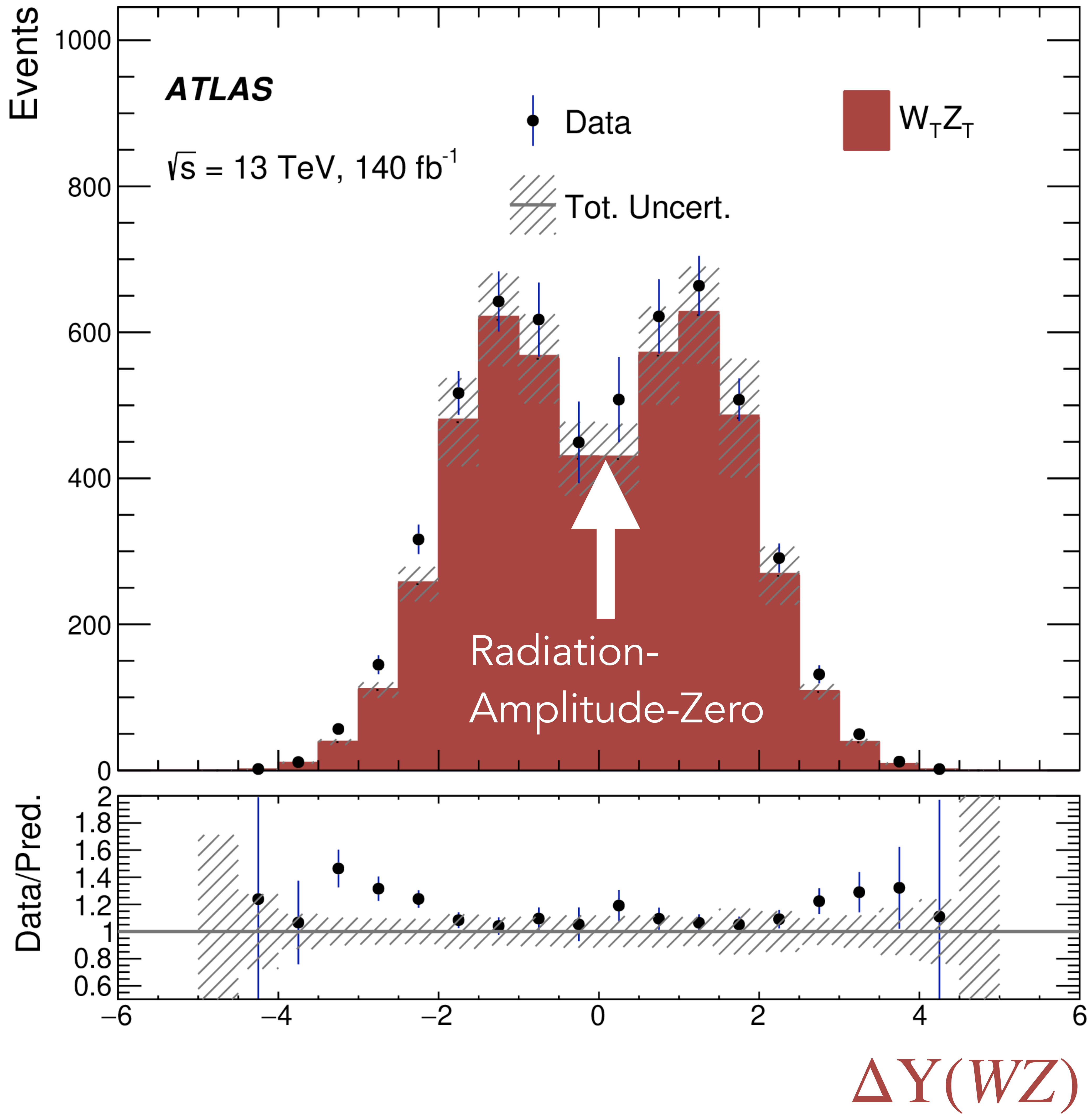
WZ Radiation-Amplitude-Zero (RAZ)

Phys. Rev. Lett. 133 (2024) 101802, arXiv:2402.16365

- At LO, scattering amplitudes predicted to be zero for specific W scattering angle in the WZ rest frame
- Variables sensitive to RAZ effect: $\Delta Y(WZ), \Delta Y(\ell_W Z)$
- RAZ arises primarily from $W_T Z_T$ amplitude
  - Subtract measured $W_L Z_L$ fractions and background
- Unfolded distributions compatible with SM prediction

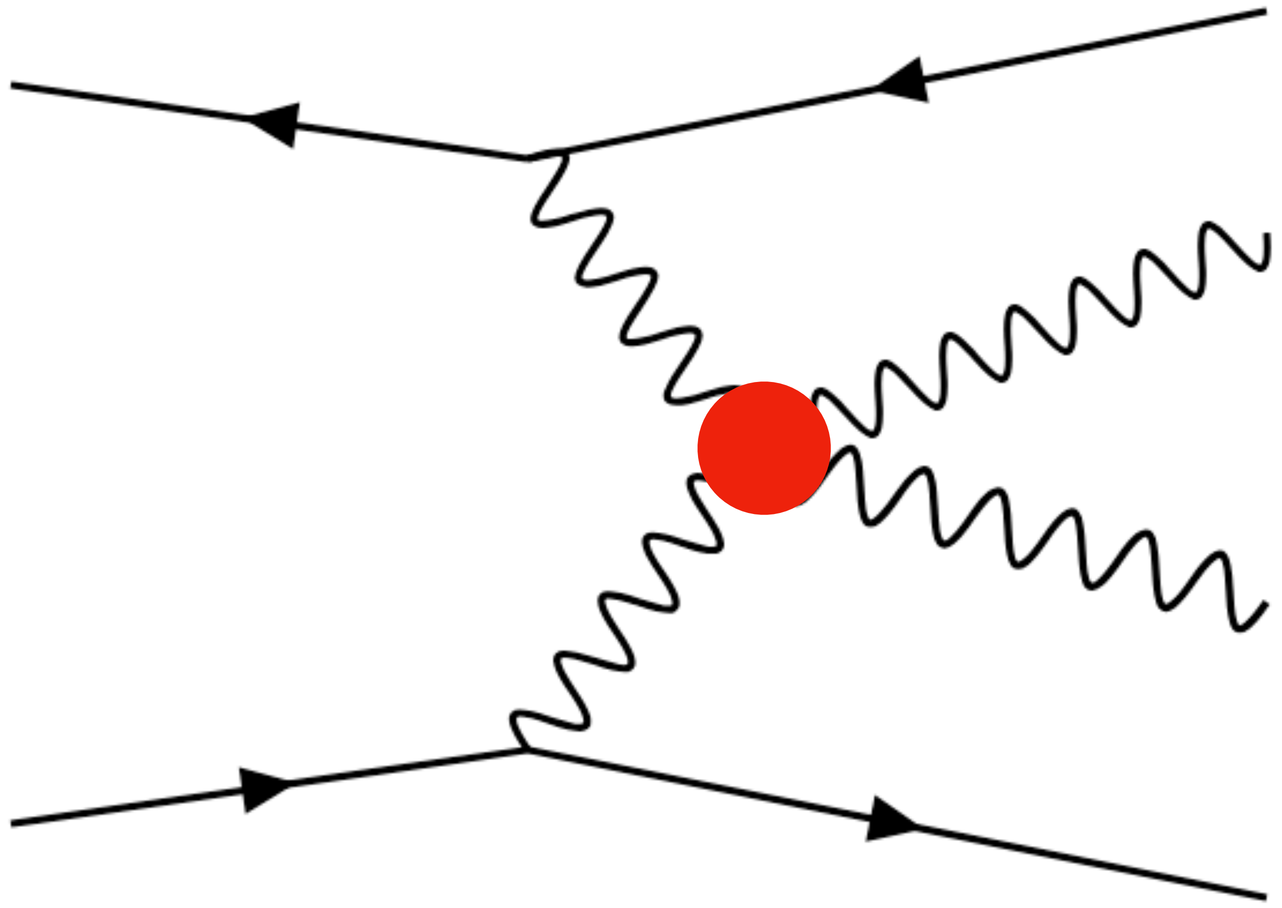


Transversely-polarized $W_T Z_T$



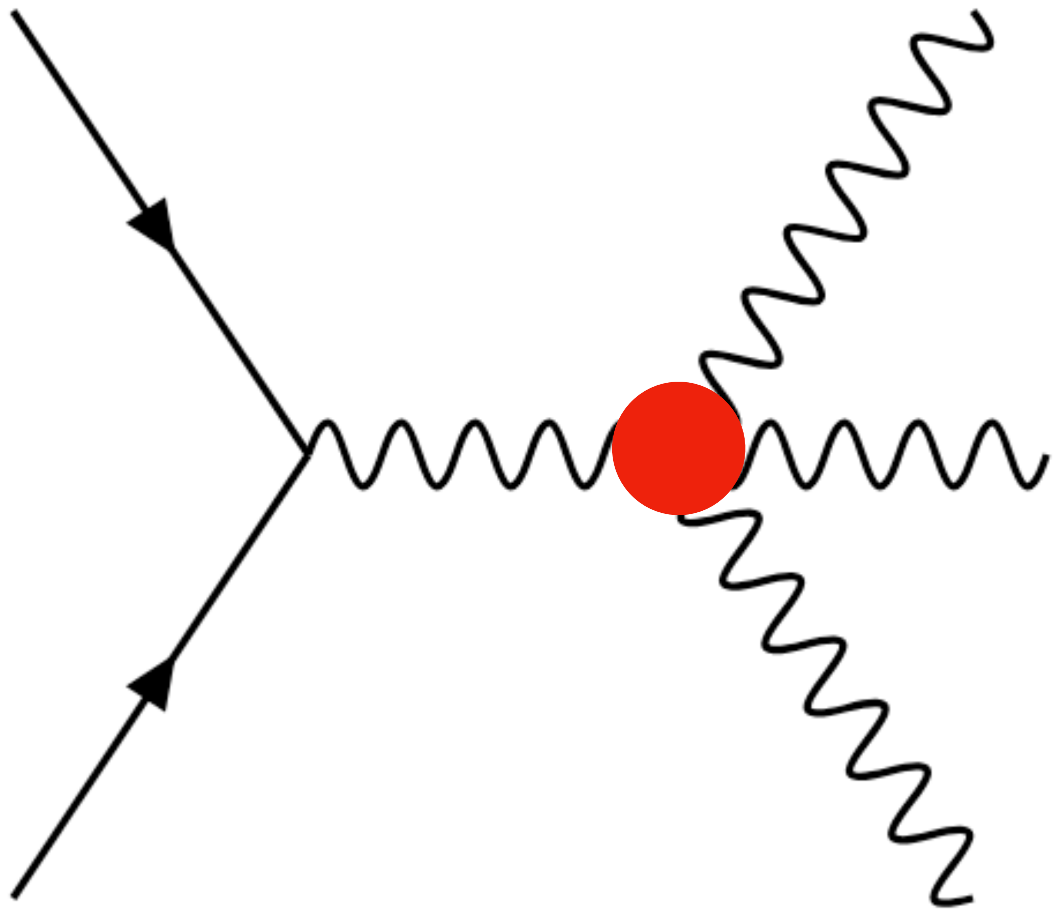
Quartic Electroweak Couplings

- Some of the rarest processes experimentally accessible at LHC
  - Vector-boson scattering observed in most channels
  - Increasing sensitivity to triboson production



Diboson

$W\gamma jj,\ WZjj$



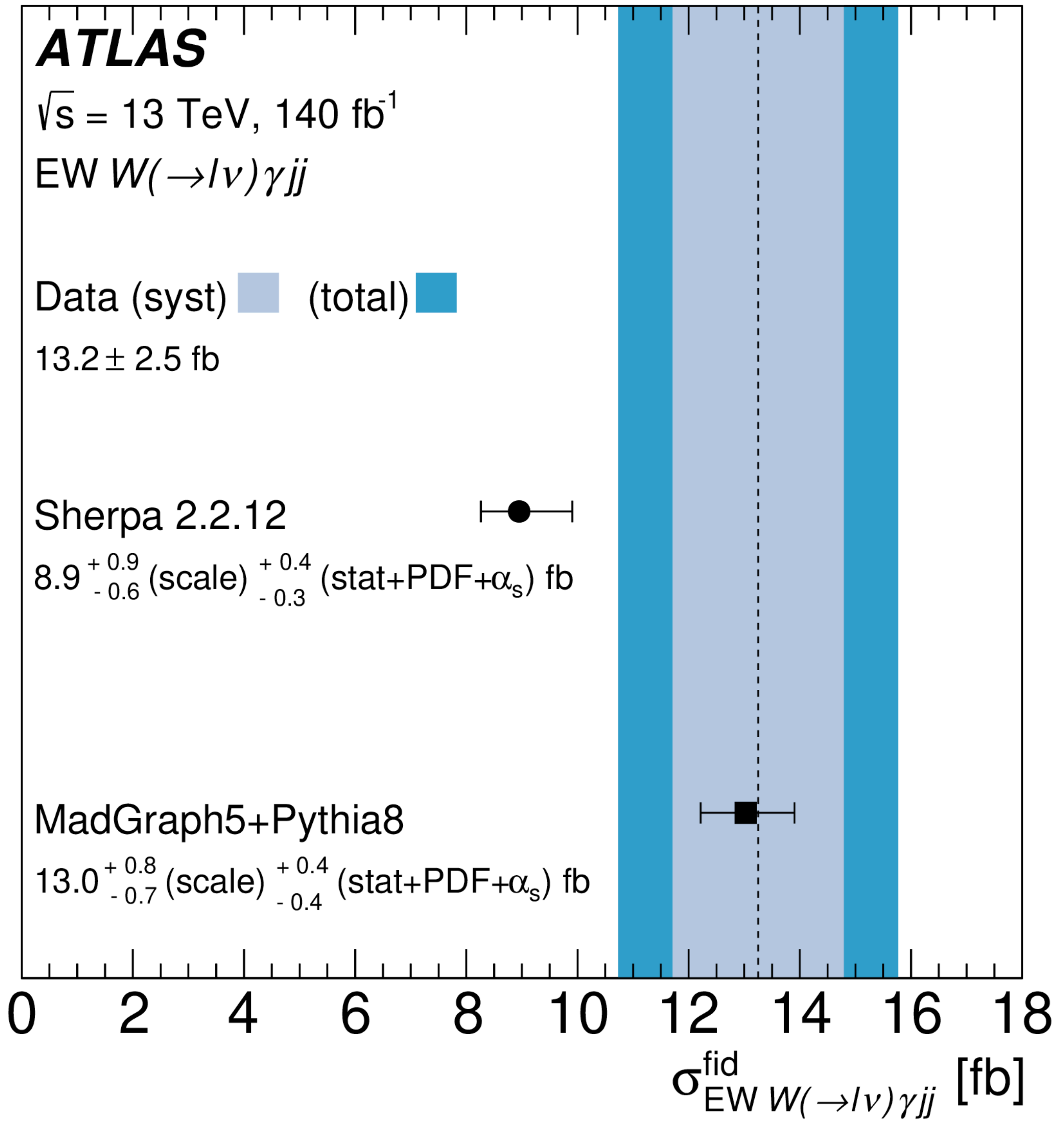
Triboson

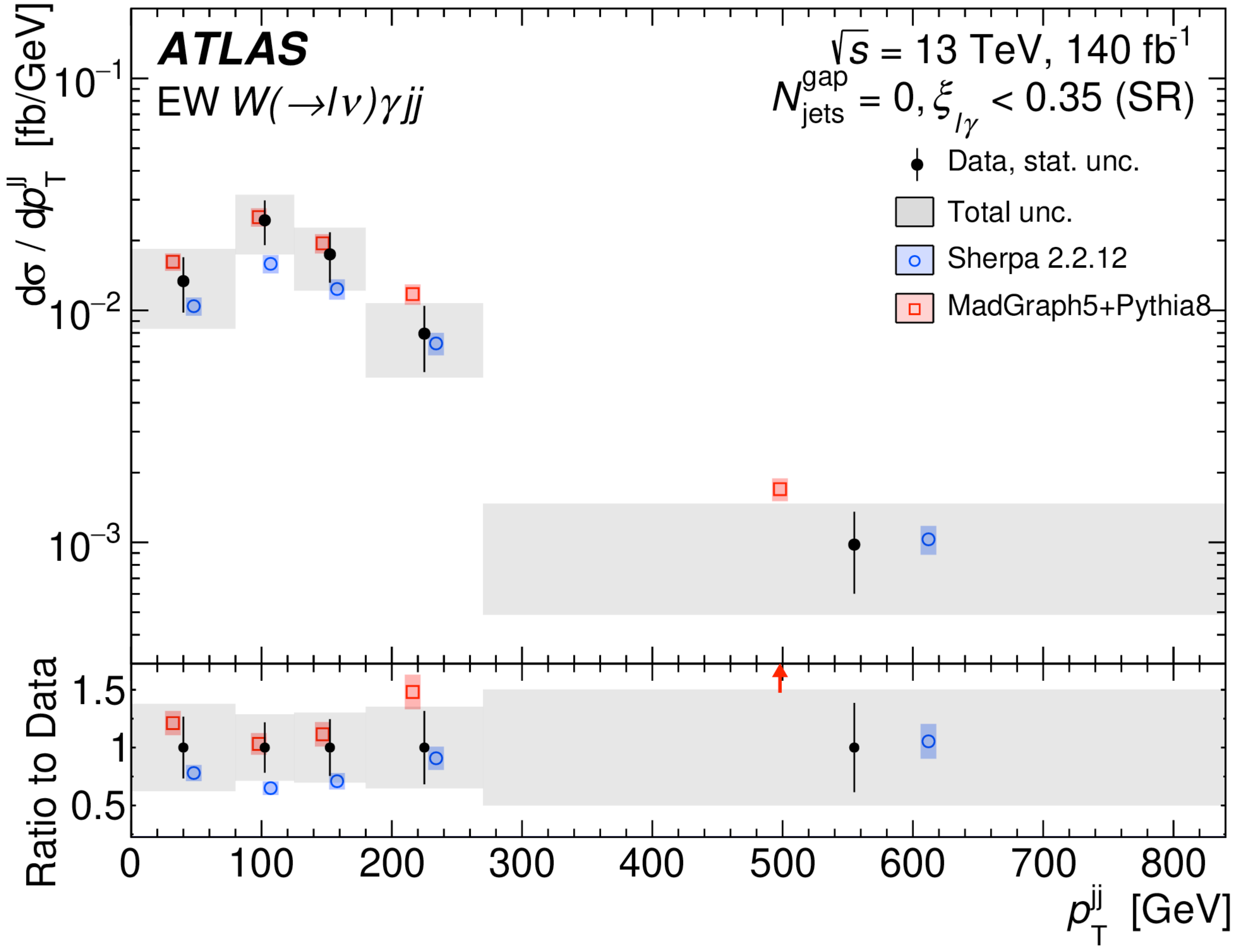
$W\gamma\gamma,\ VVZ$

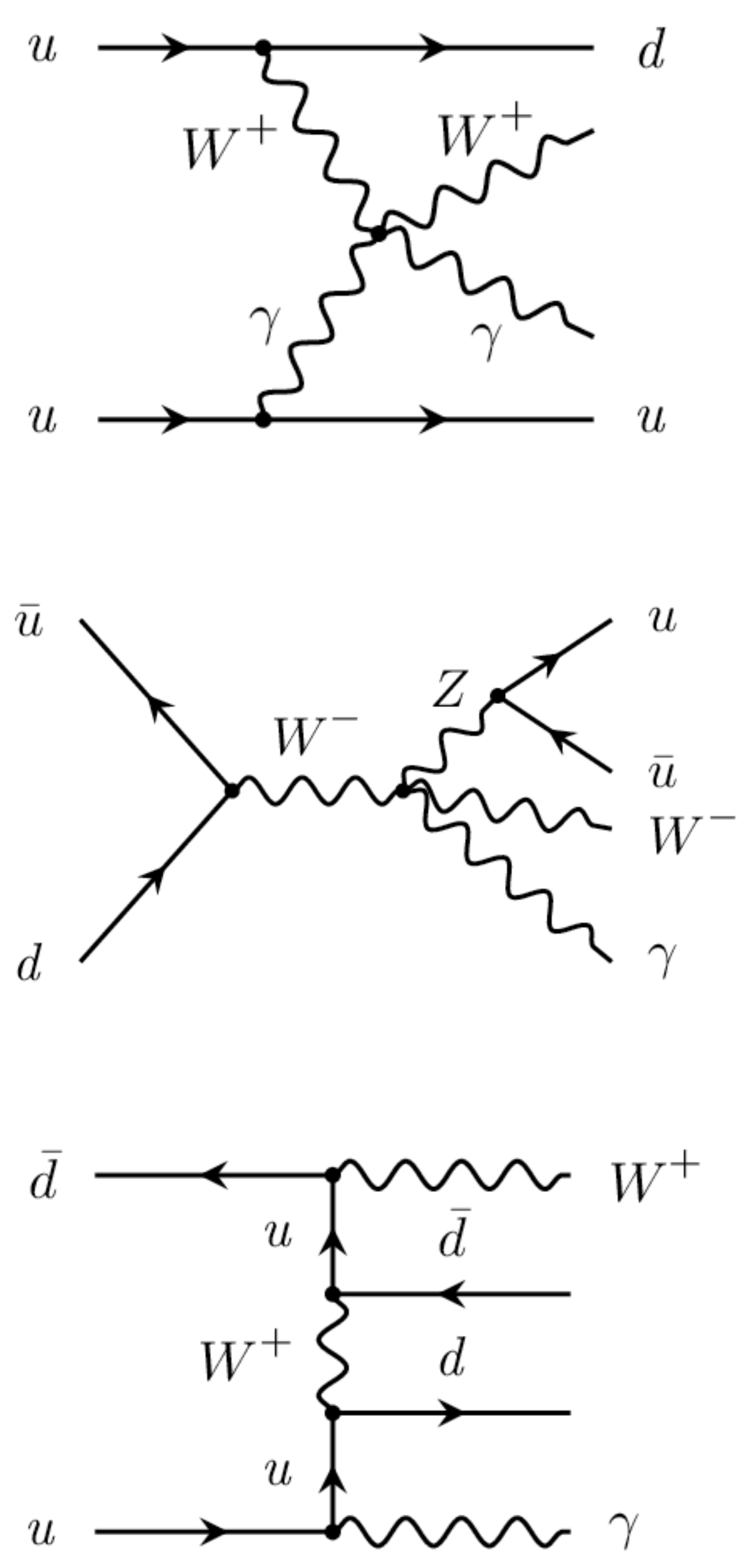
Diboson: $W\gamma jj$

Eur. Phys. J. C 84 (2024) 1064, arXiv:2403.02809

- Observation of EW $W\gamma jj$ with $> 6\sigma$ established using ML techniques
- Study modelling of several key kinematic observables.



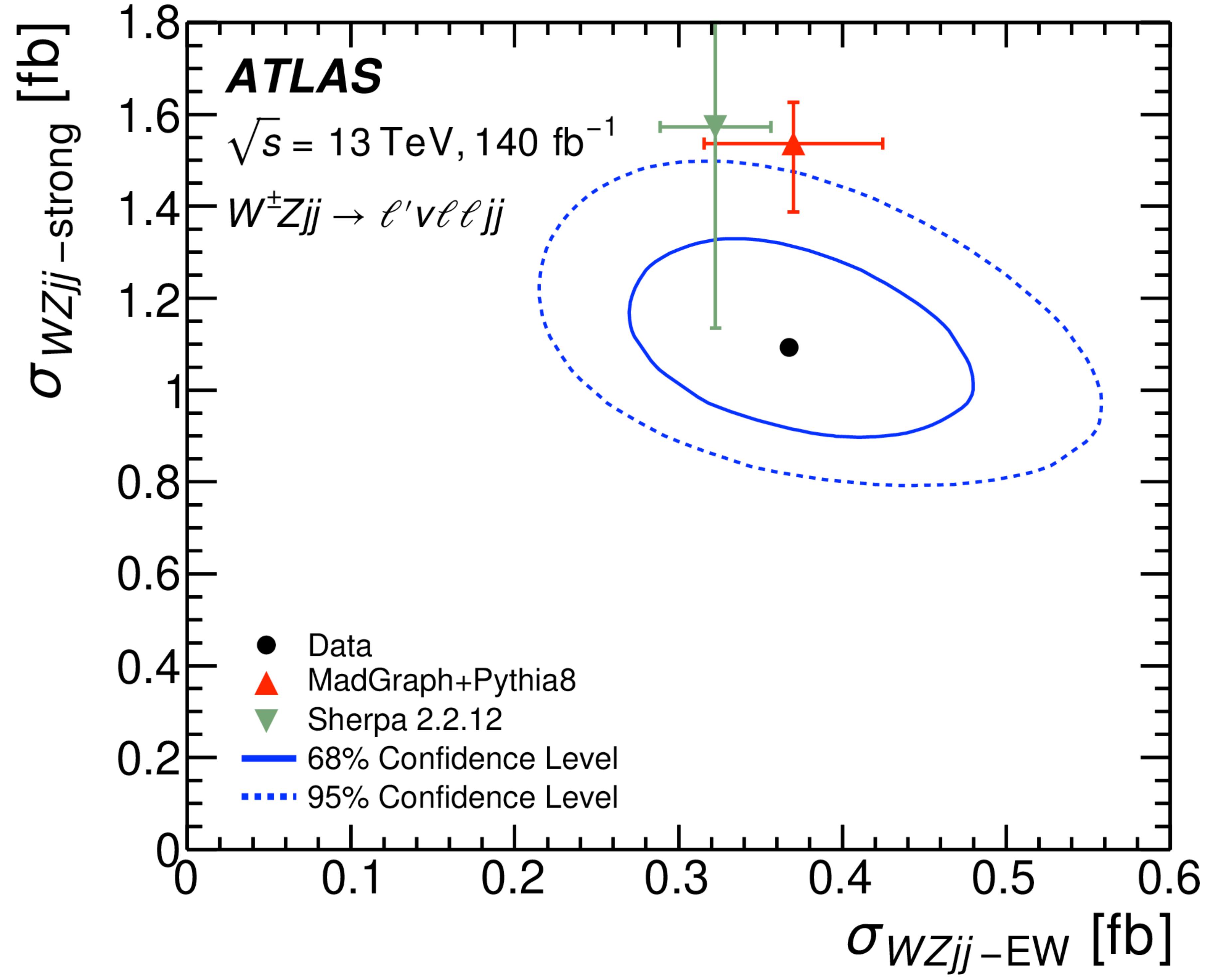


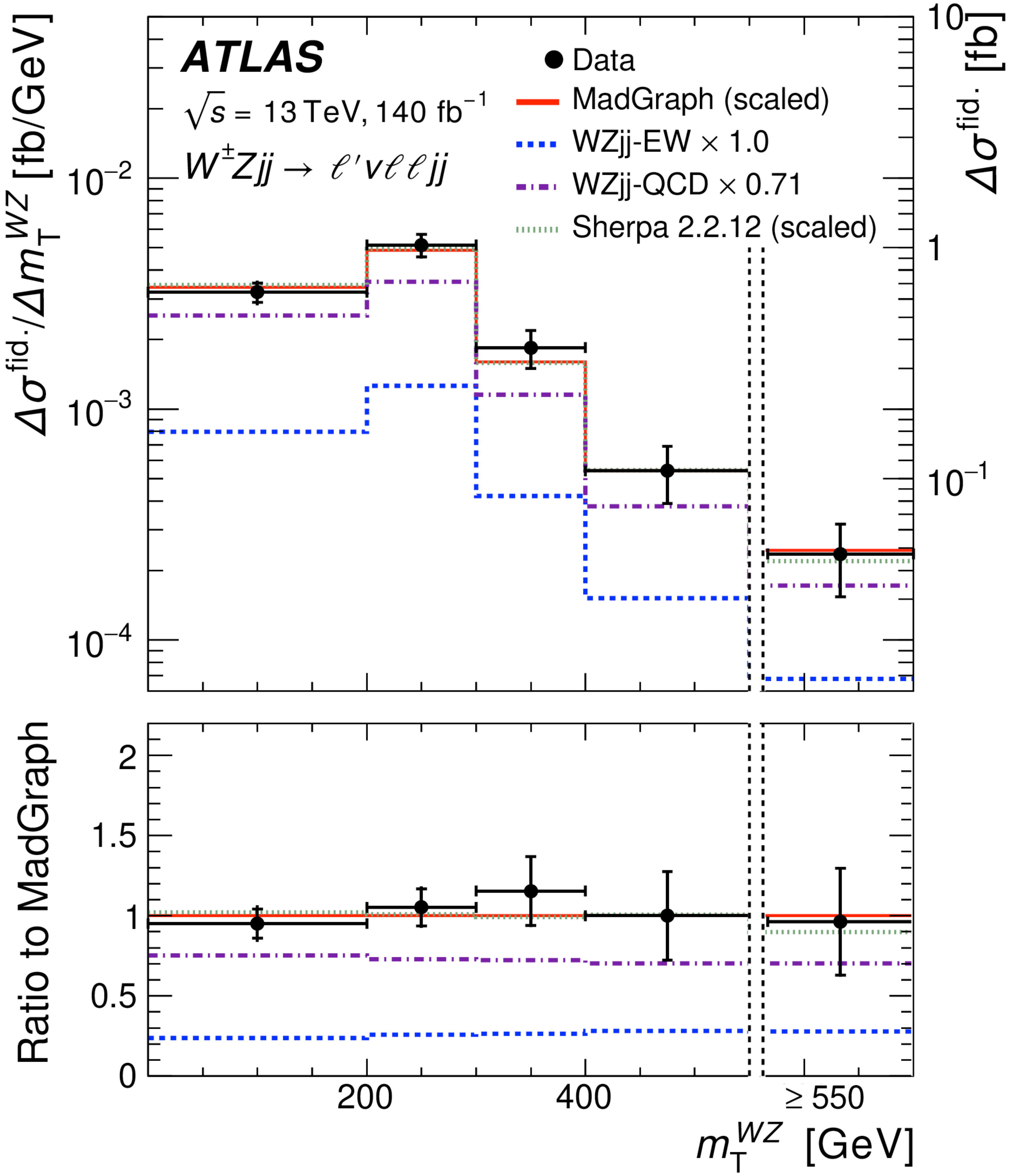


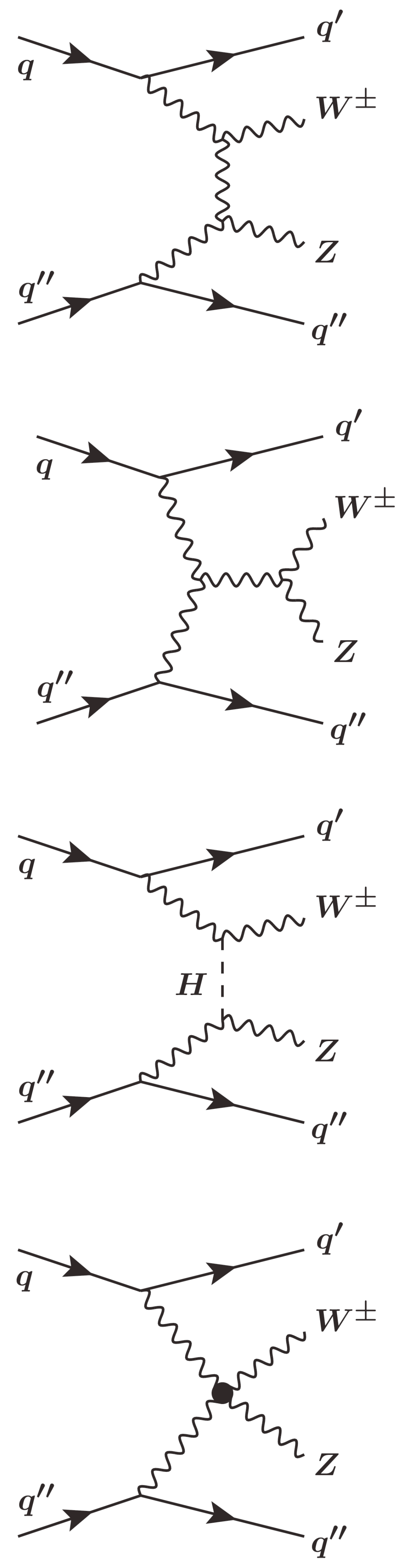
Diboson: *WZjj*

JHEP 06 (2024) 192, arXiv:2403.15296

- Multivariate discriminant used to separate EW and strong production modes
- First study of modelling of several key kinematic observables





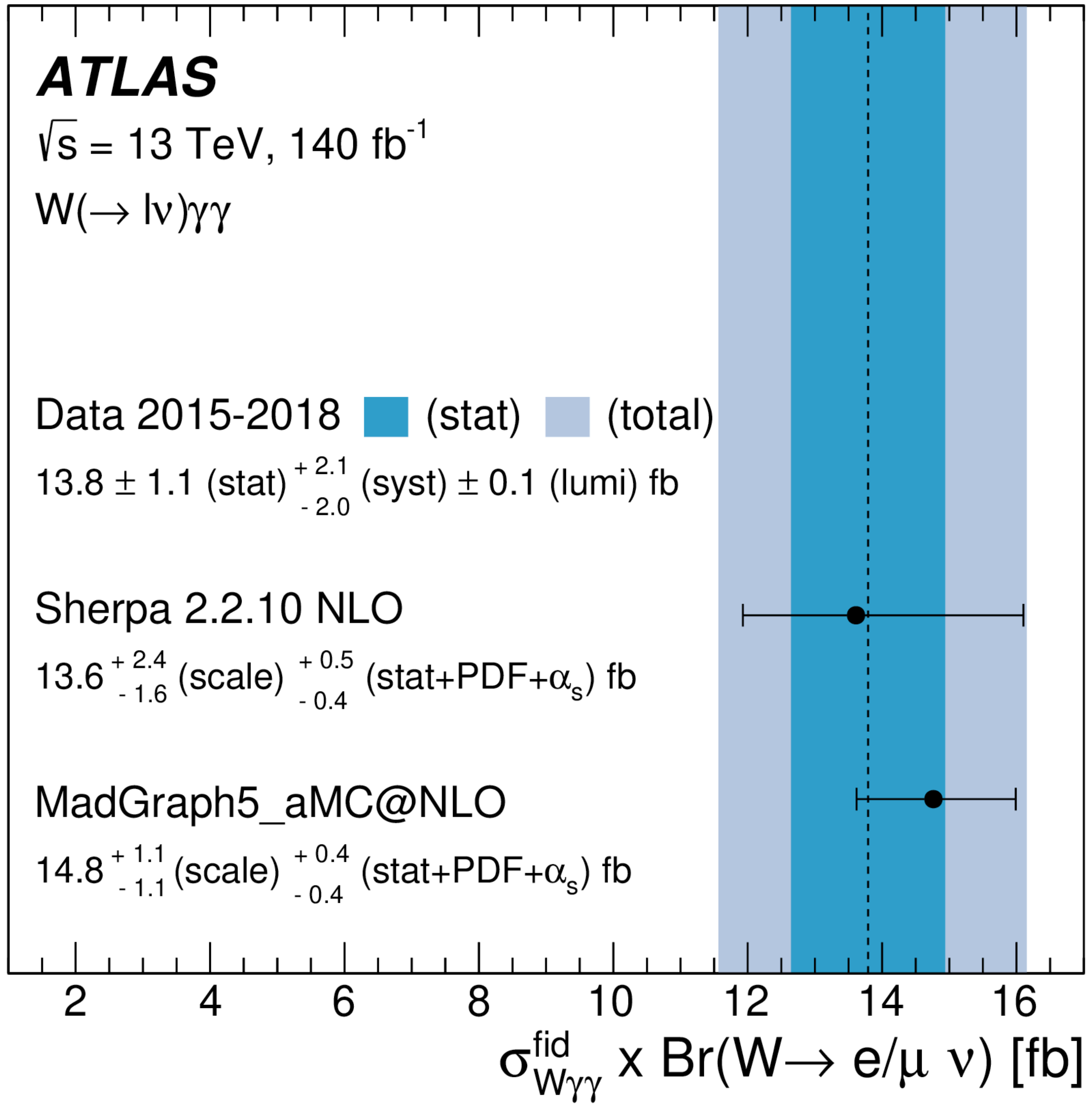


Triboson

$W\gamma\gamma$

Phys. Lett. B 848 (2024) 138400

Observation with 5.6σ significance



VVZ

arXiv:2412.15123

NEW

- BDT discriminants trained in each event category to enhance the separation between signal and background

Observation

Process	Signal strength	Cross section (fb)	Observed (expected) sensitivity
VVZ	$1.43 \pm 0.20(\text{stat.})^{+0.21}_{-0.19}(\text{syst.})$	$660^{+93}_{-90}(\text{stat.})^{+88}_{-81}(\text{syst.})$	6.4 (4.7) σ
WWZ	$1.33 \pm 0.28(\text{stat.})^{+0.21}_{-0.17}(\text{syst.})$	$442 \pm 94(\text{stat.})^{+60}_{-52}(\text{syst.})$	4.4 (3.6) σ
WZZ	$2.13^{+1.18}_{-0.96}(\text{stat.})^{+0.76}_{-0.41}(\text{syst.})$	$200^{+111}_{-91}(\text{stat.})^{+65}_{-37}(\text{syst.})$	2.8 (1.6) σ

Evidence

Anomalous Quartic Gauge Couplings

- Deviations from the SM are quantified in an Effective Field Theory approach

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{f_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_i \frac{f_i^{(8)}}{\Lambda^4} O_i^{(8)} + \dots$$

- Considering only operators affecting QGC at dimension-8
- Limits on Wilson coefficients reported without and with unitarity preservation using clipping technique.

$W\gamma jj$

Eur. Phys. J. C 84 (2024) 1064, arXiv:2403.02809

Coefficients [TeV^{-4}]	Observable	Expected [TeV^{-4}]	Observed [TeV^{-4}]
f_{T0}/Λ^4	p_T^{jj}	[-2.4, 2.4]	[-1.8, 1.8]
f_{T1}/Λ^4	p_T^{jj}	[-1.5, 1.6]	[-1.1, 1.2]
f_{T2}/Λ^4	p_T^{jj}	[-4.4, 4.7]	[-3.1, 3.5]
f_{T3}/Λ^4	p_T^{jj}	[-3.3, 3.5]	[-2.4, 2.6]
f_{T4}/Λ^4	p_T^{jj}	[-3.0, 3.0]	[-2.2, 2.2]
f_{T5}/Λ^4	p_T^{jj}	[-1.7, 1.7]	[-1.2, 1.3]
f_{T6}/Λ^4	p_T^{jj}	[-1.5, 1.5]	[-1.0, 1.1]
f_{T7}/Λ^4	p_T^{jj}	[-3.8, 3.9]	[-2.7, 2.8]
f_{M0}/Λ^4	p_T^{l}	[-28, 28]	[-24, 24]
f_{M1}/Λ^4	p_T^{l}	[-43, 44]	[-37, 38]
f_{M2}/Λ^4	p_T^{l}	[-10, 10]	[-8.6, 8.5]
f_{M3}/Λ^4	p_T^{l}	[-16, 16]	[-13, 14]
f_{M4}/Λ^4	p_T^{l}	[-18, 18]	[-15, 15]
f_{M5}/Λ^4	p_T^{l}	[-17, 14]	[-14, 12]
f_{M7}/Λ^4	p_T^{l}	[-78, 77]	[-66, 65]

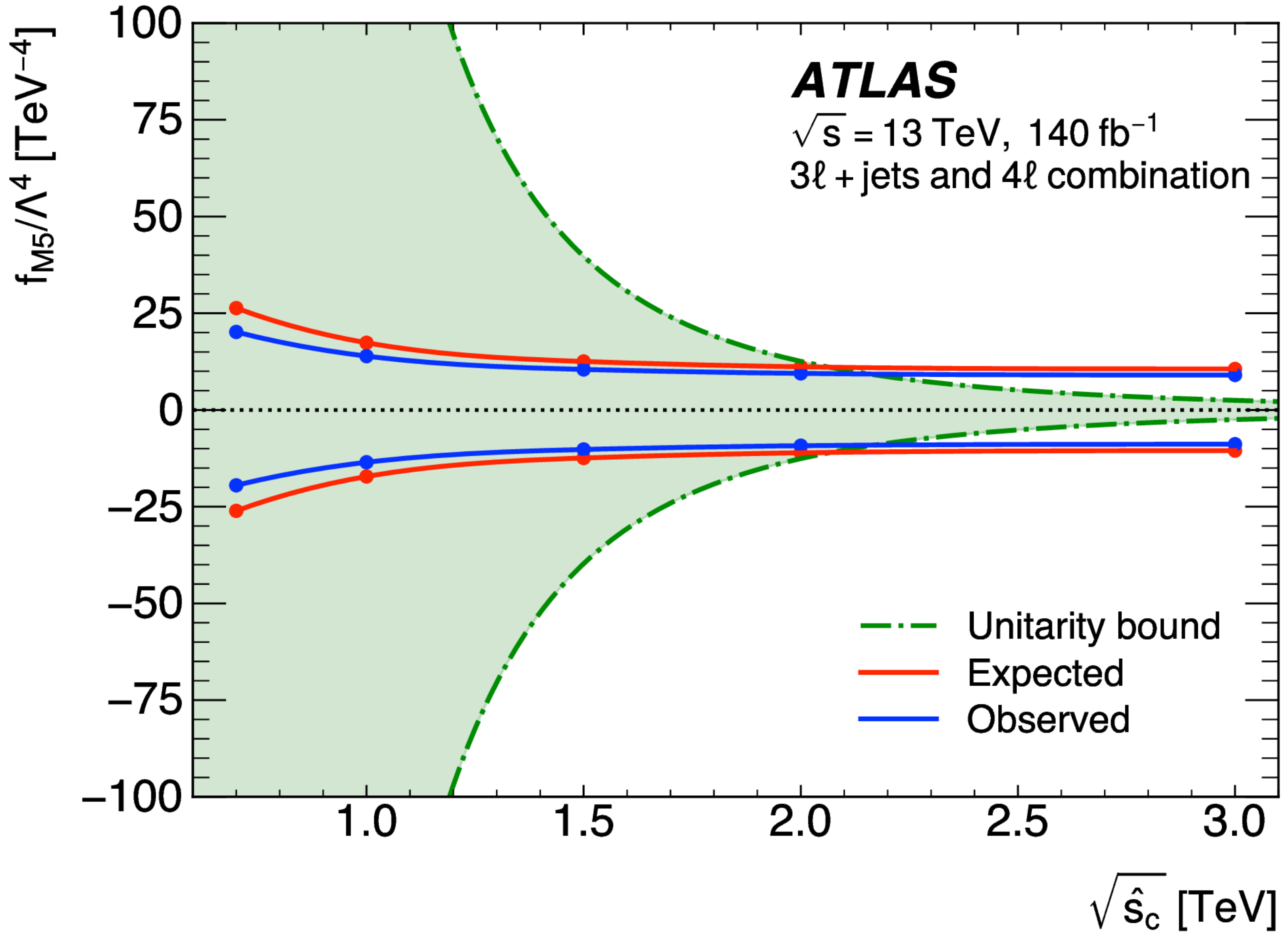
First LHC constraints

VVZ

NEW

arXiv:2412.15123

Most sensitive to $f_{M2}, f_{M3}, f_{M4}, f_{M5}$



Summary

- The LHC and ATLAS are providing a wealth of valuable insights into the electroweak sector.
- ATLAS has made significant strides in **precision measurements**, **studies of the electroweak gauge structure**, and **exploring rare processes**.
- With growing datasets and more refined techniques, the opportunities for discovery are as good as ever.
- New physics might just be around the corner, and the search continues.

All ATLAS results available at
https://twiki.cern.ch/twiki/bin/view/AtlasPublic