Electroweak Physics with ATLAS, CMS and LHCb

Heather M. Gray on behalf of the ATLAS, CMS and LHCb Collaborations

Introduction

- **Electroweak (EW)** interaction lies at the heart of particle physics and is derived from symmetry principles
  - $SU(2)_L \times U(1)_Y$
- Four **gauge bosons** remain after electroweak symmetry breaking
  - W^+, W^-, Z, γ
- **Mass** and **dynamics** of EW gauge bosons are predicted precisely by EW theory
  - $\rho = \dfrac{m_W^2}{m_Z^2 \cos^2 \theta_W}$
- At the LHC, test EW theory through
  - precision measurements of **W/Z bosons**
  - **multiboson** production at high-energy

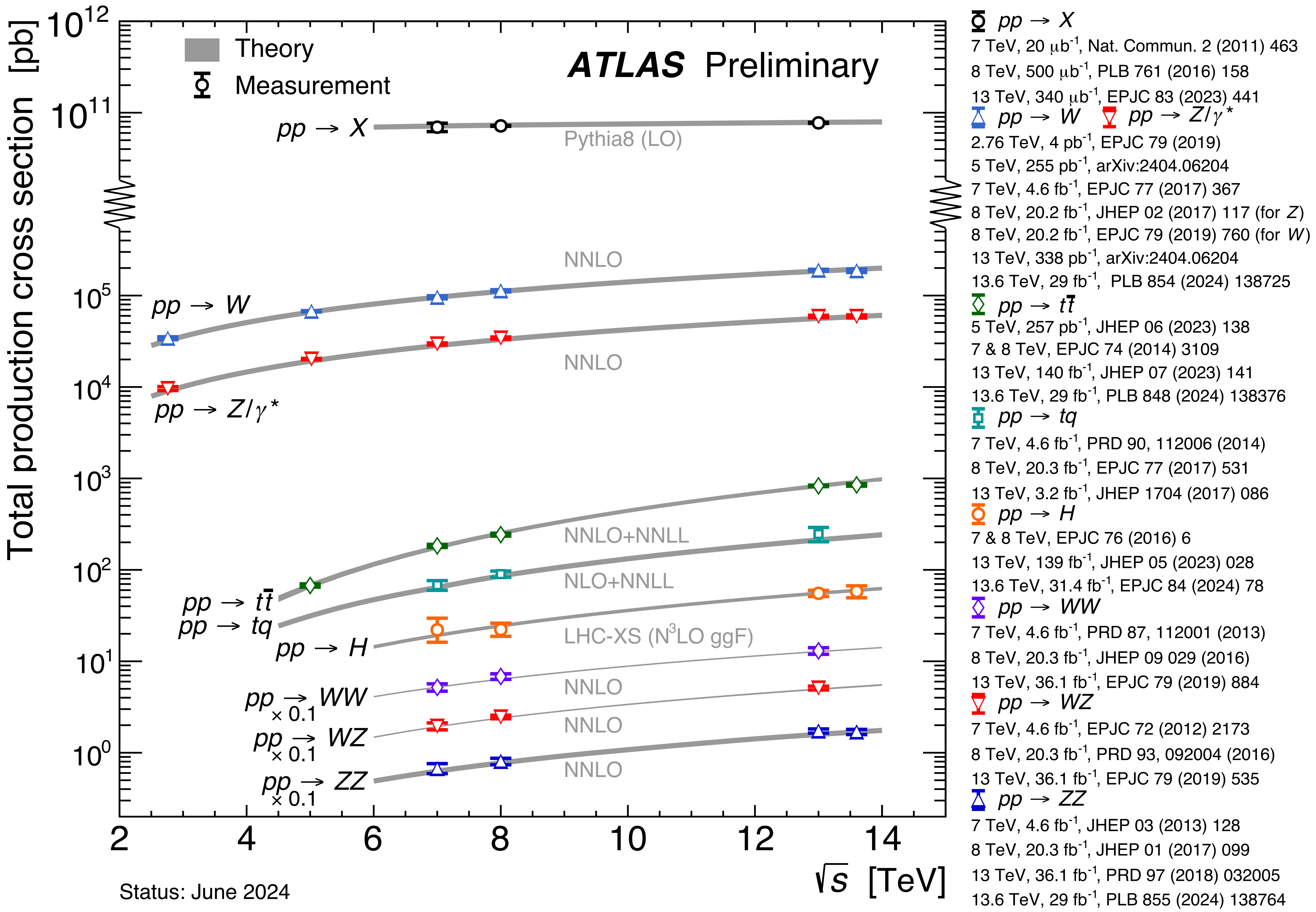
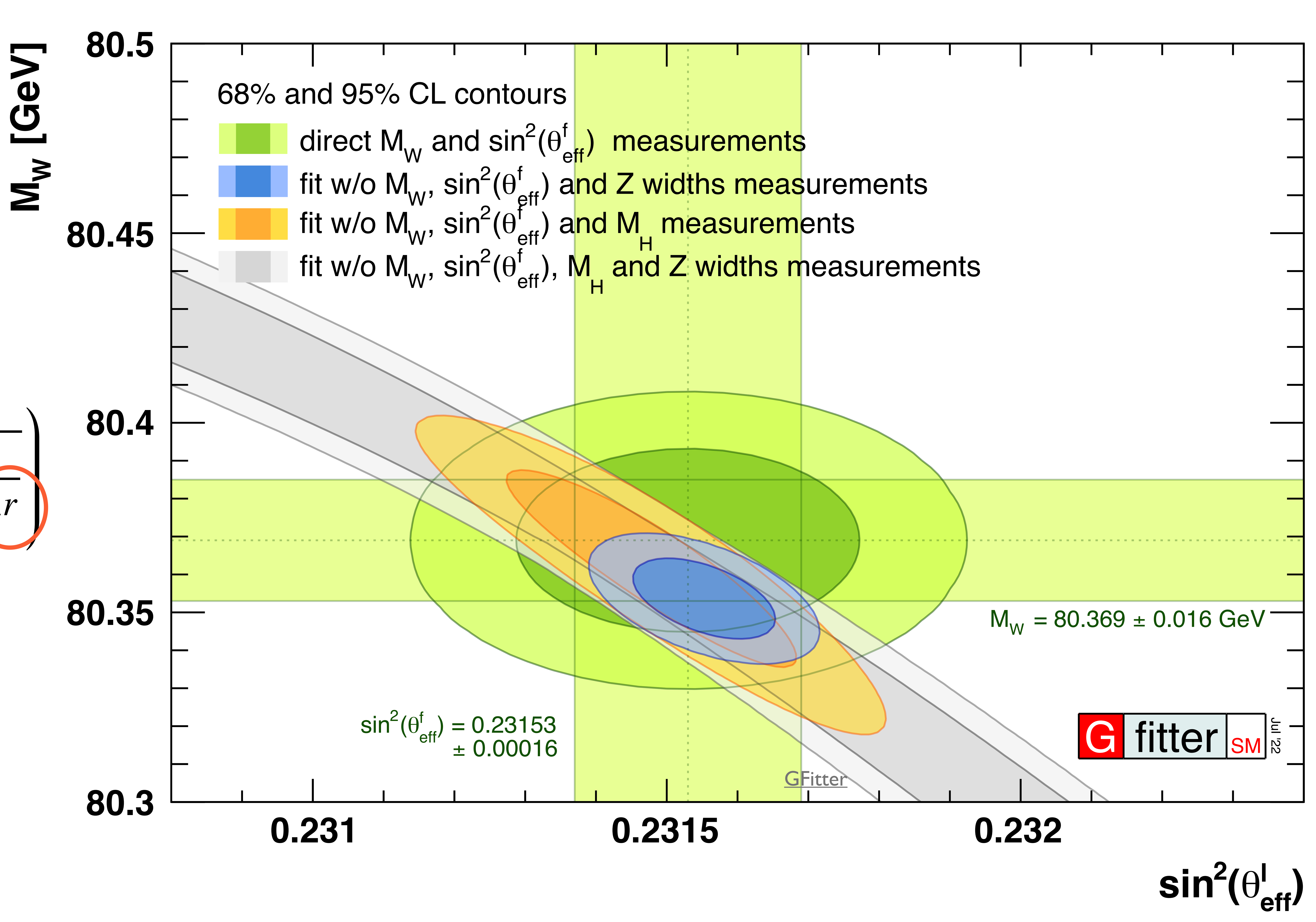


Image Credit

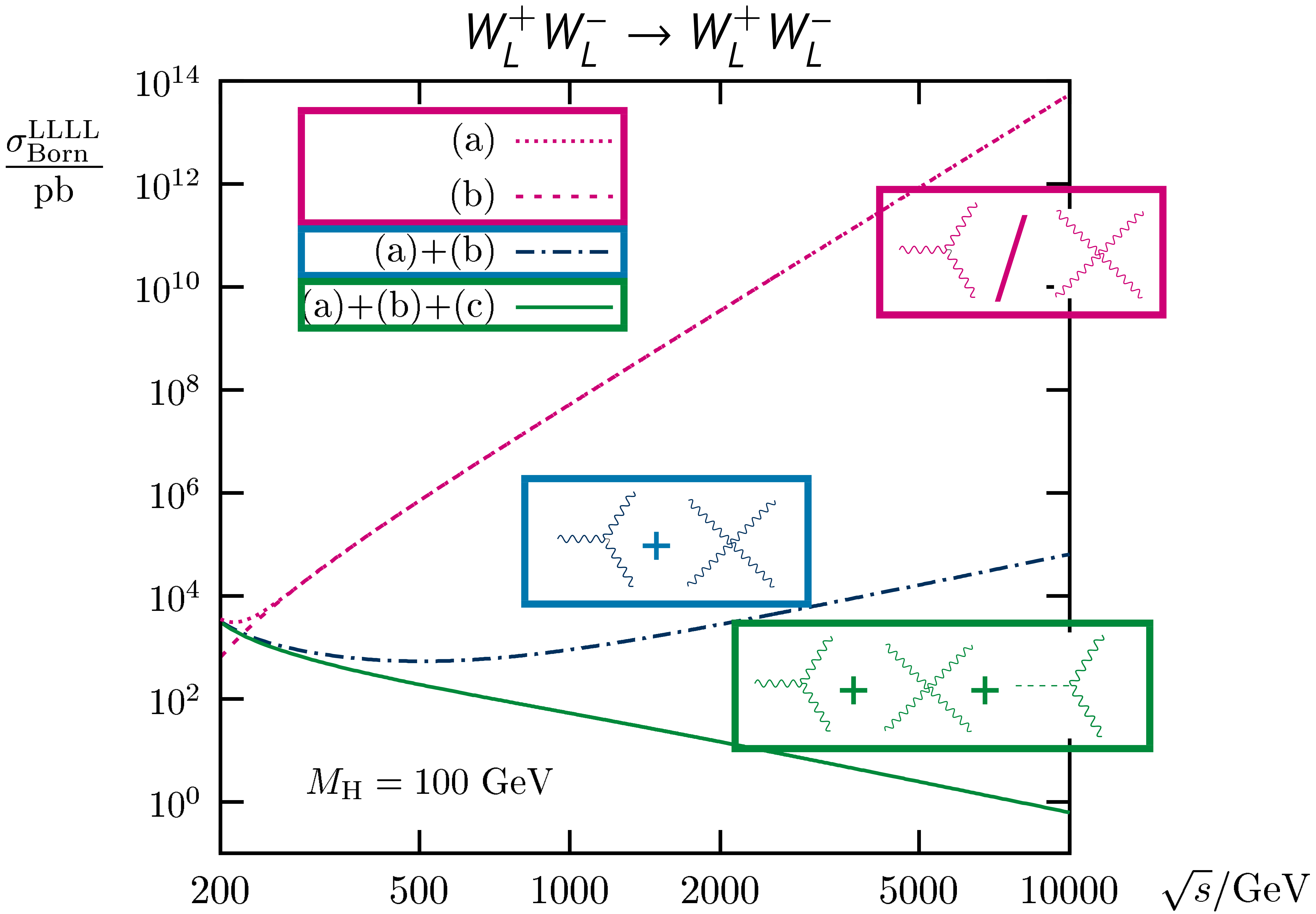
Precision Tests at the LHC

- **High-precision** measurements of SM parameters can probe a wide range of models for physics **beyond the SM**
- Radiative corrections modify propagators and decay vertices
  - $m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-4\frac{\pi\alpha}{\sqrt{2}G_F M_Z^2}\frac{1}{1-\Delta r}}\right)$
  - $\sin^2\theta_W \rightarrow \kappa_F \sin^2\theta_W = \sin^2\theta^f_{eff}$
- Sensitivity to a wide range of physics through **quantum loops**



High-energy tests of EW Physics

- Test electroweak theory by measuring processes sensitive to delicate **gauge cancellations** at high-energy
- Small deviations can lead to potentially **large effects**
- Directly probe the mechanism of **electroweak symmetry** breaking



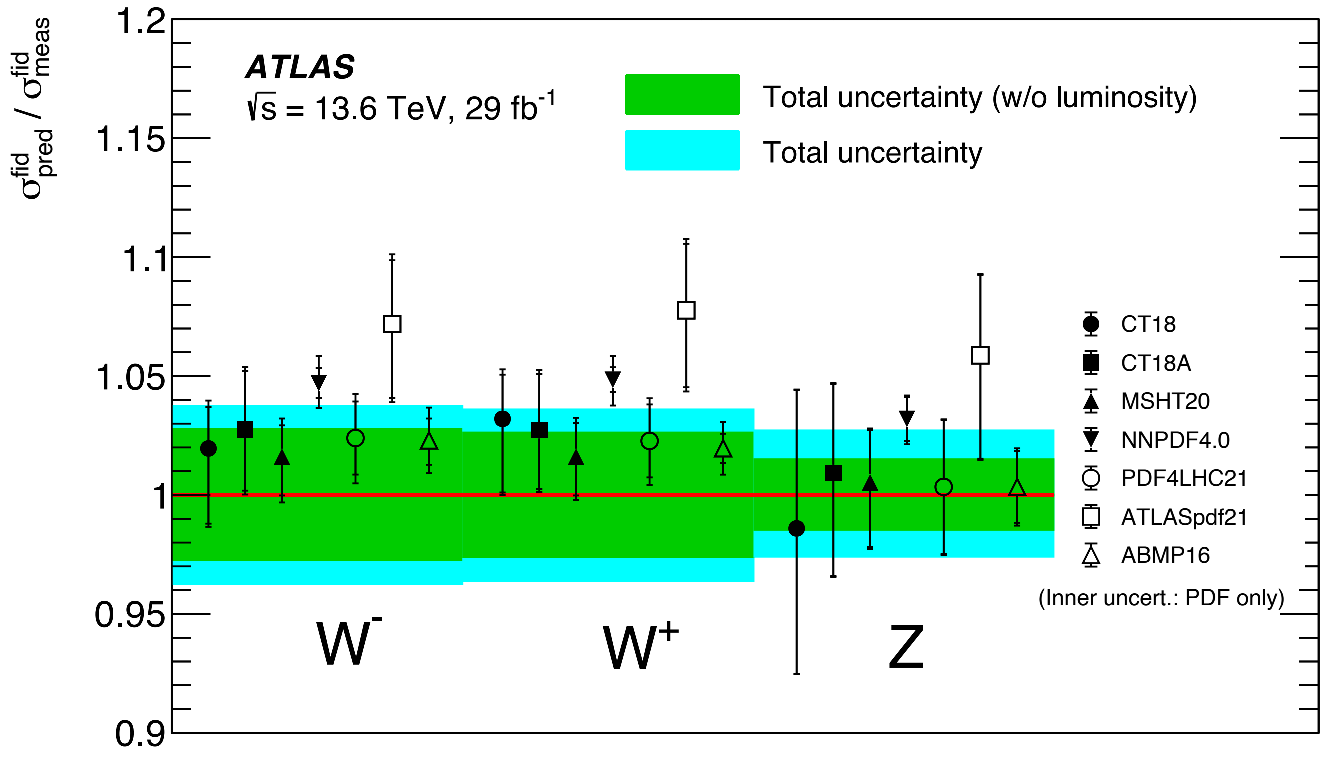
P. Sommer after Nucl. Phys. B525:27-50, 1998

Precision Measurements of W and Z Bosons

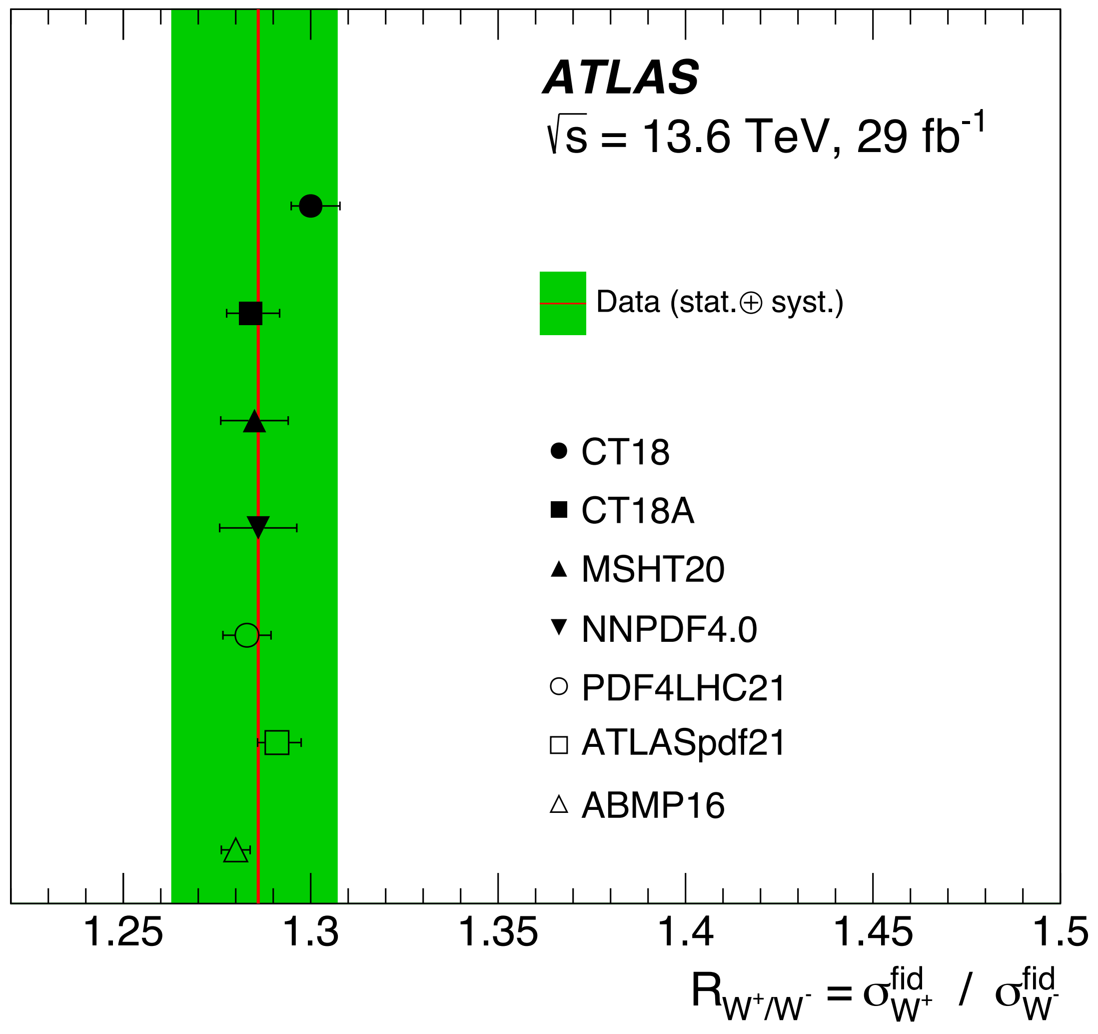
Image Source

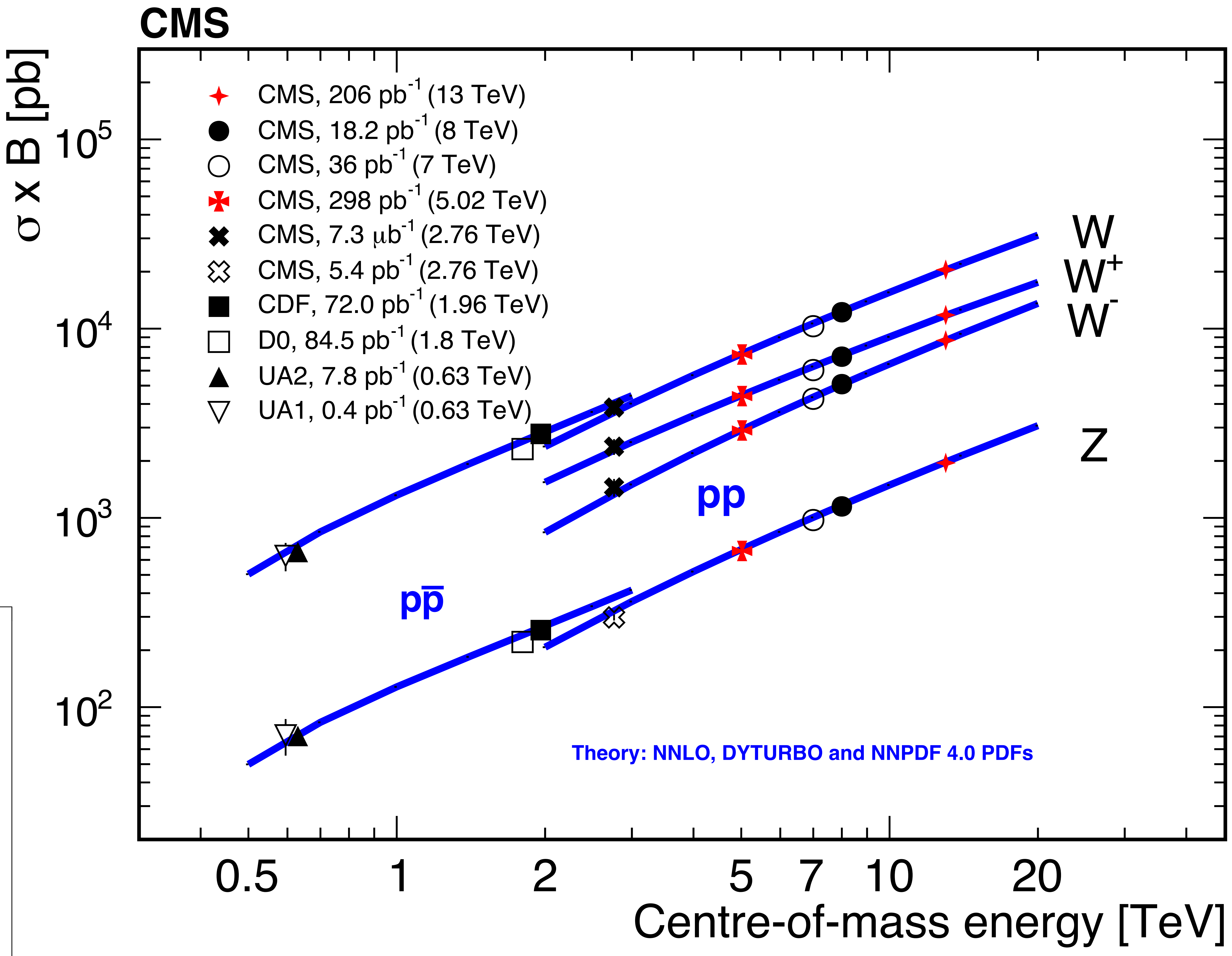
W and Z cross sections

- Fundamental SM measurements with a precision of up to 1.9% (ratios 0.35%)
- LHC measurements for energies ranging from 2.76 - 13.6 TeV
  - **Luminosity** uncertainty dominates for total cross-sections
  - **Lepton efficiencies** for ratios
- Profit from special low-μ datasets at 5 and 13 Te
- Generally, **good agreement** with SM predictions



PLB 854 (2024) 138725

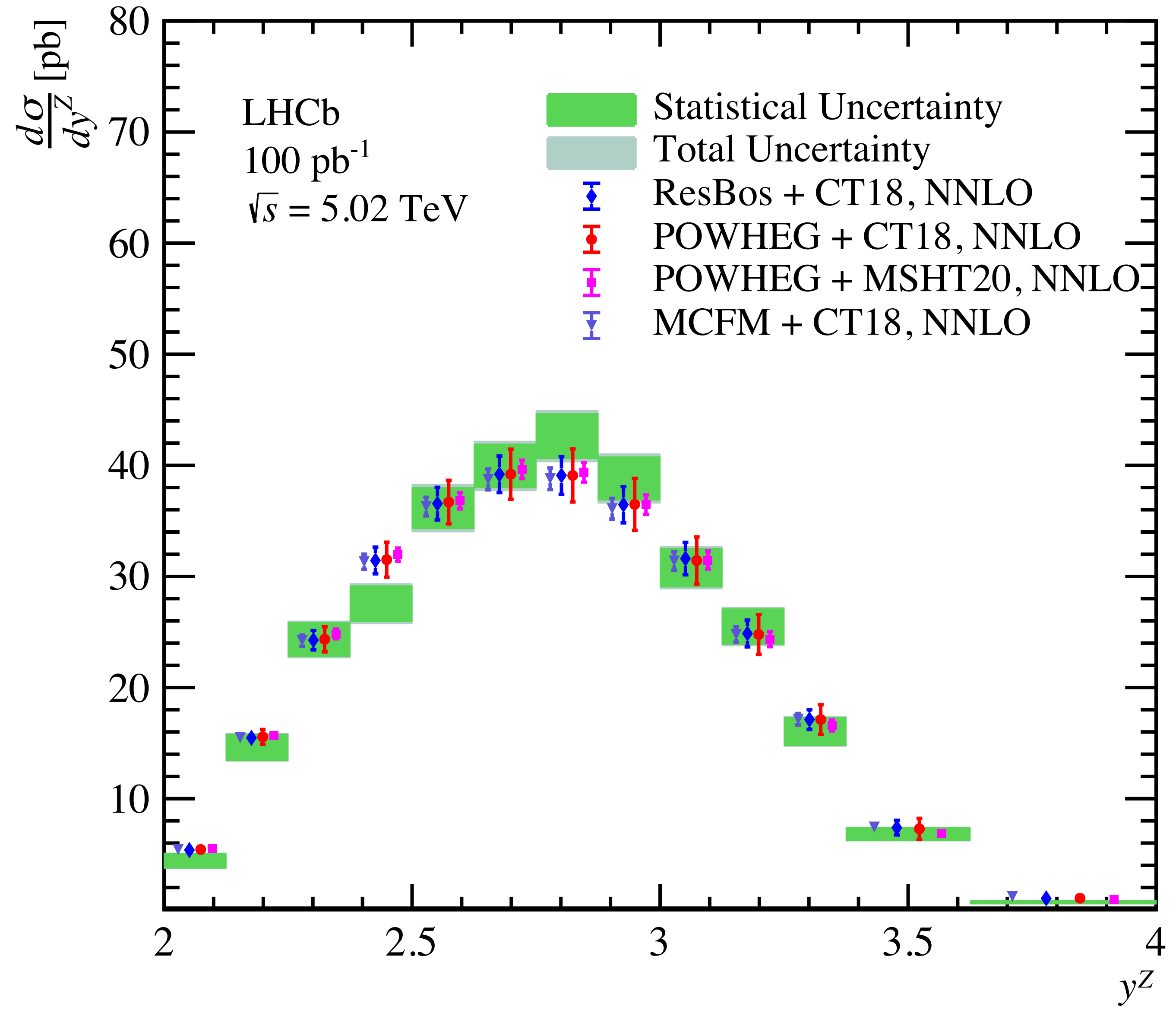


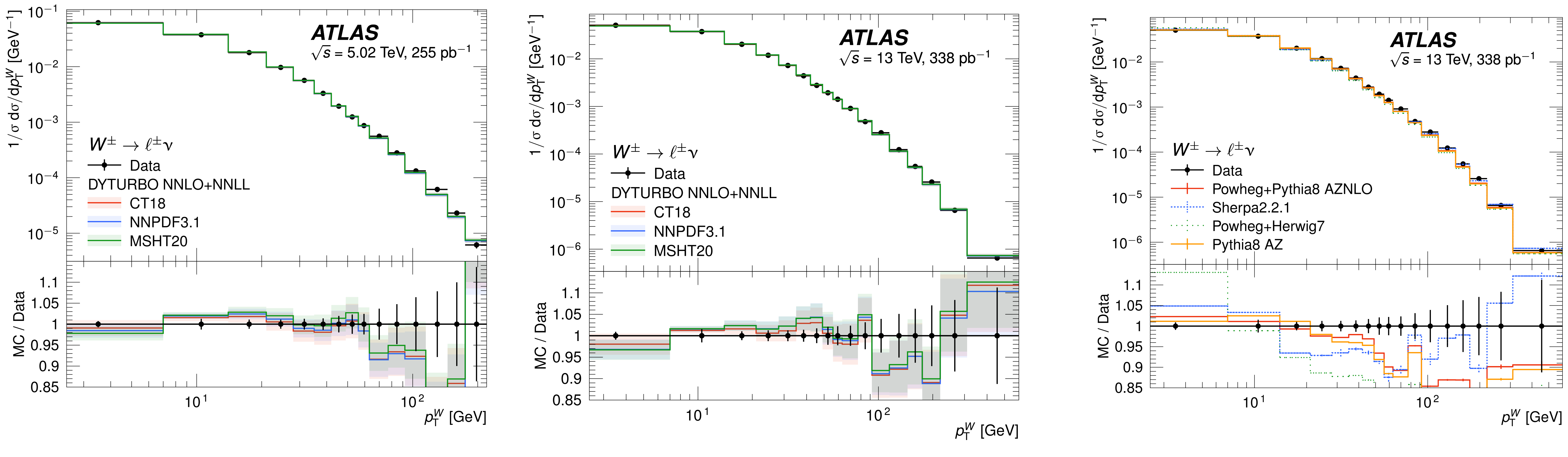


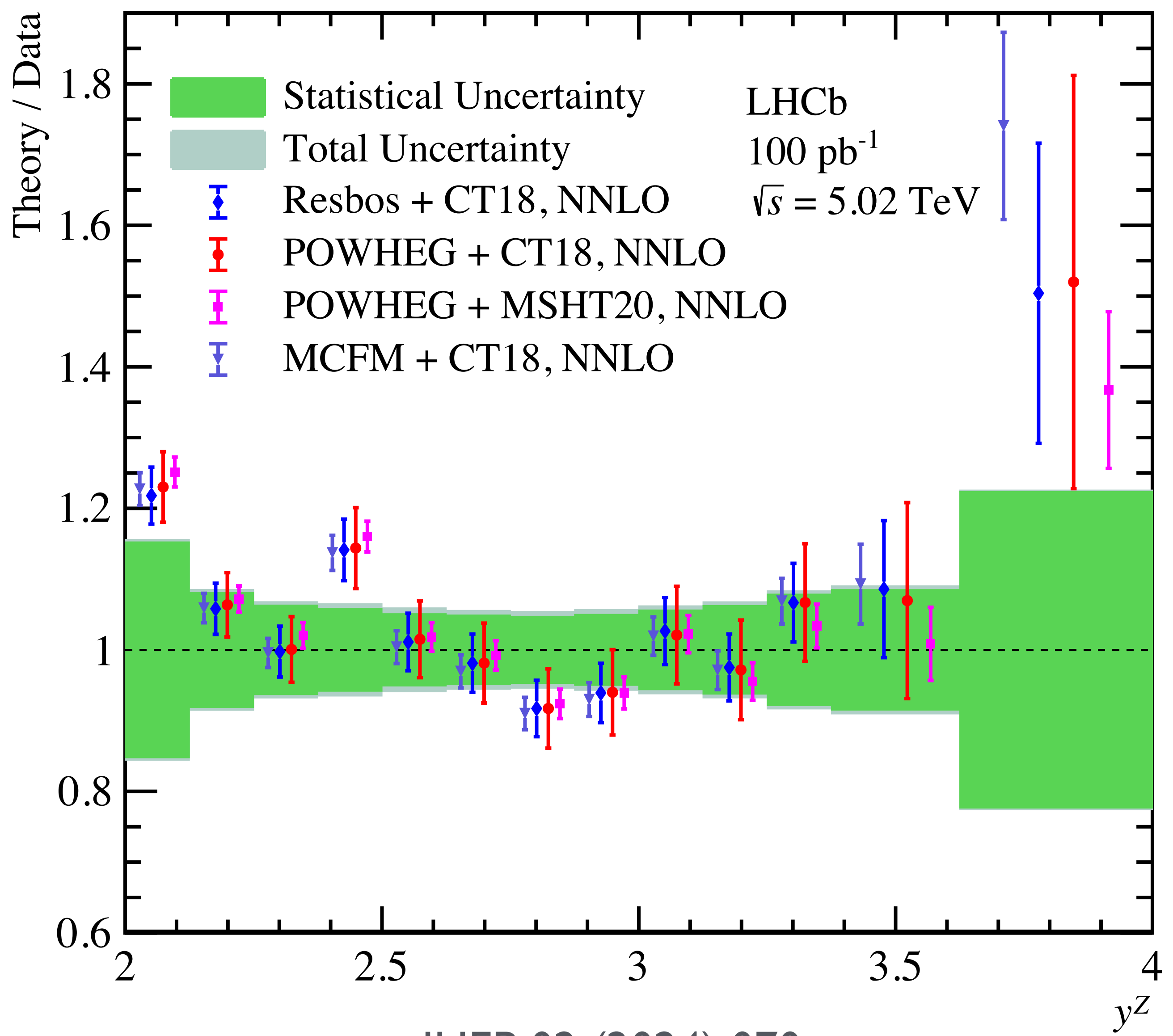
arXiv:2405.18661

W and Z cross sections

- **Special runs** with lower pile up can be used to make very precise measurements
  - Typical results include cross-sections, ratios, differential distributions
  - Provide theoretical validation of p_T^W useful for m_W measurements
- Geometry of the LHCb detector enables measurements up to **rapidity of 4**







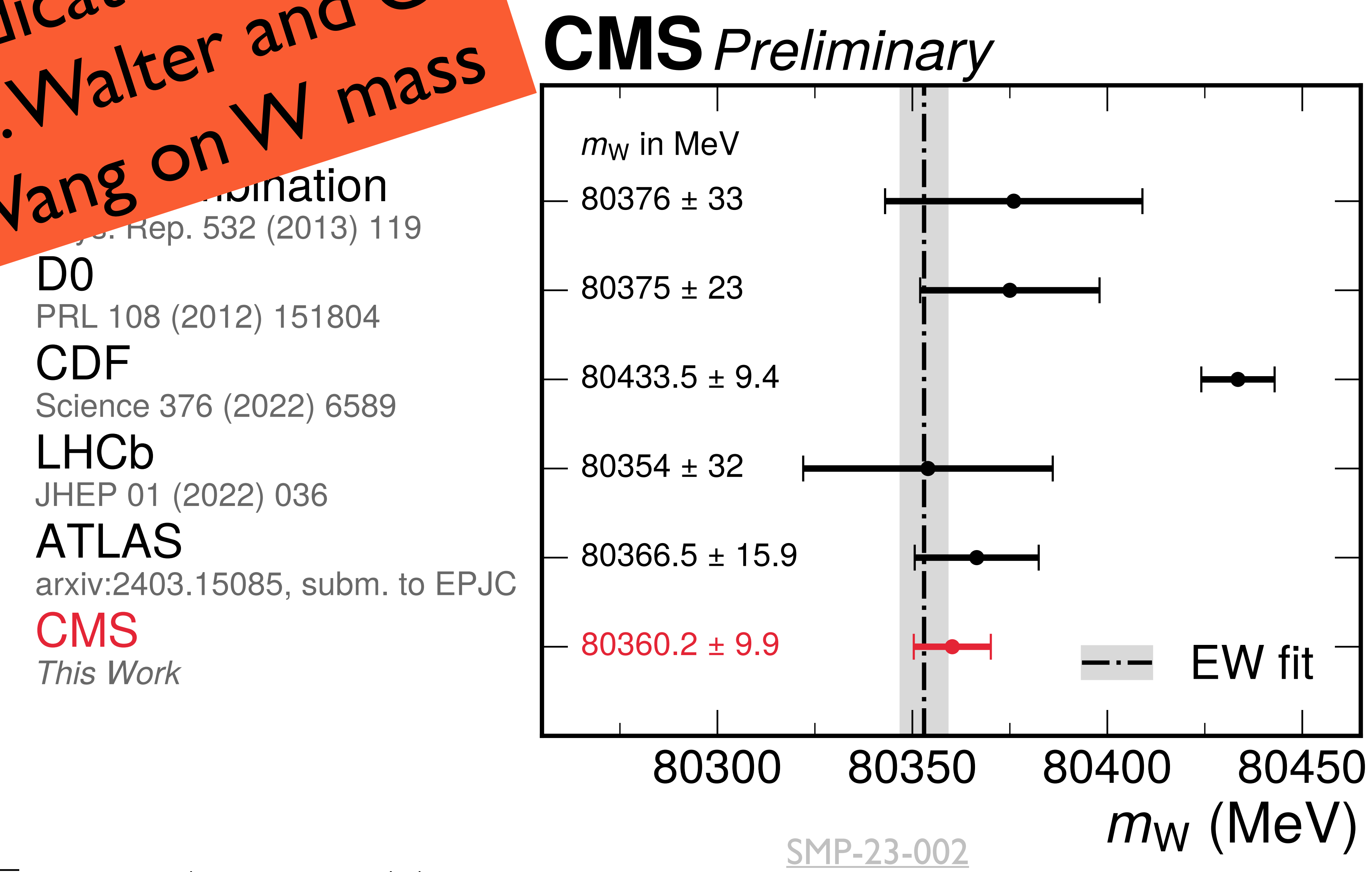
arXiv:2404.06204

JHEP 02 (2024) 070

W Boson Width

- First measurement of **W boson width** at the LHC from ATLAS
- Re-analysis of 7 TeV data performed together with W mass
- **Most precise single measurement** to date
- Within 2σ of SM prediction

Dedicated talks by D.Walter and C. Wang on W mass



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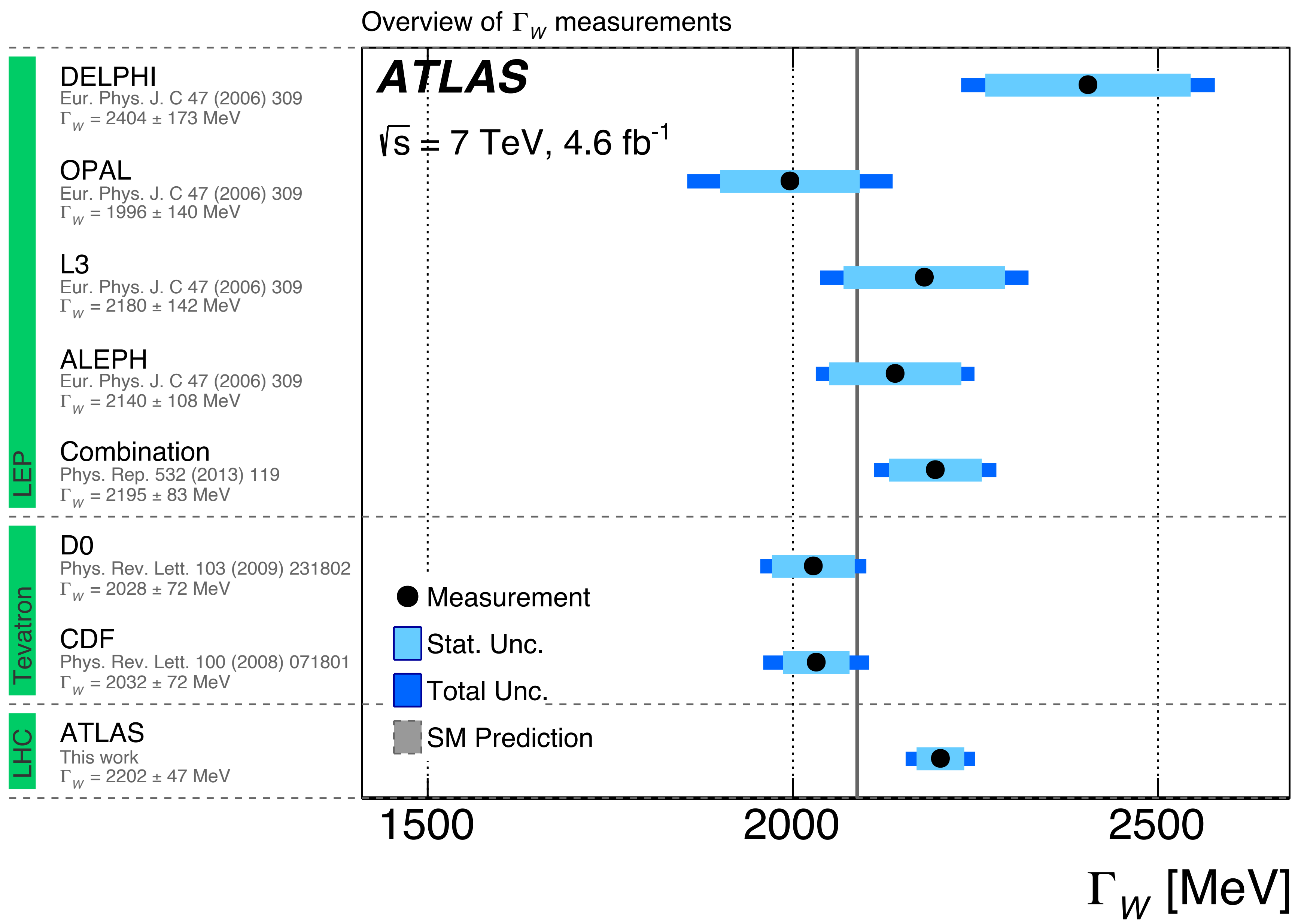
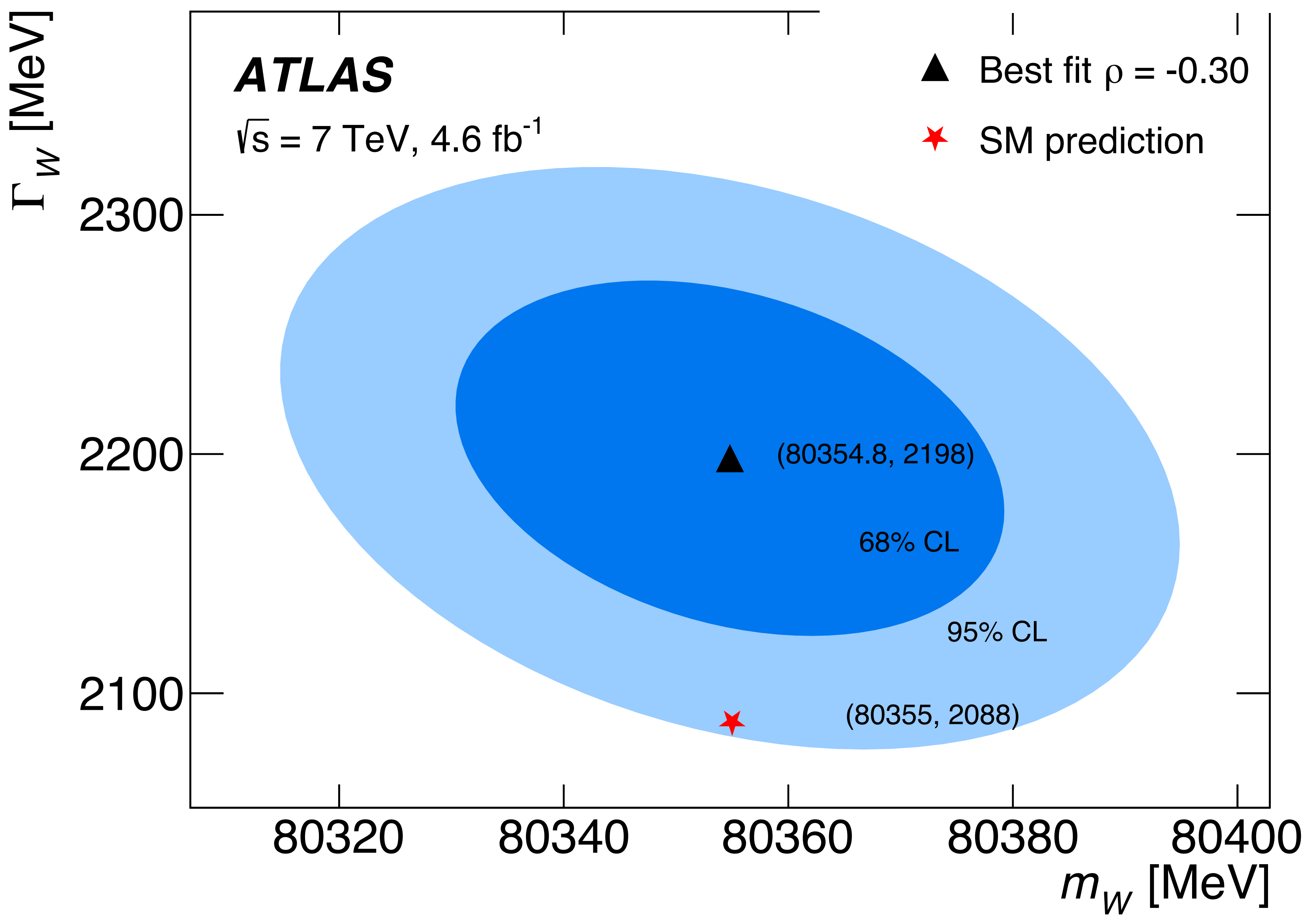


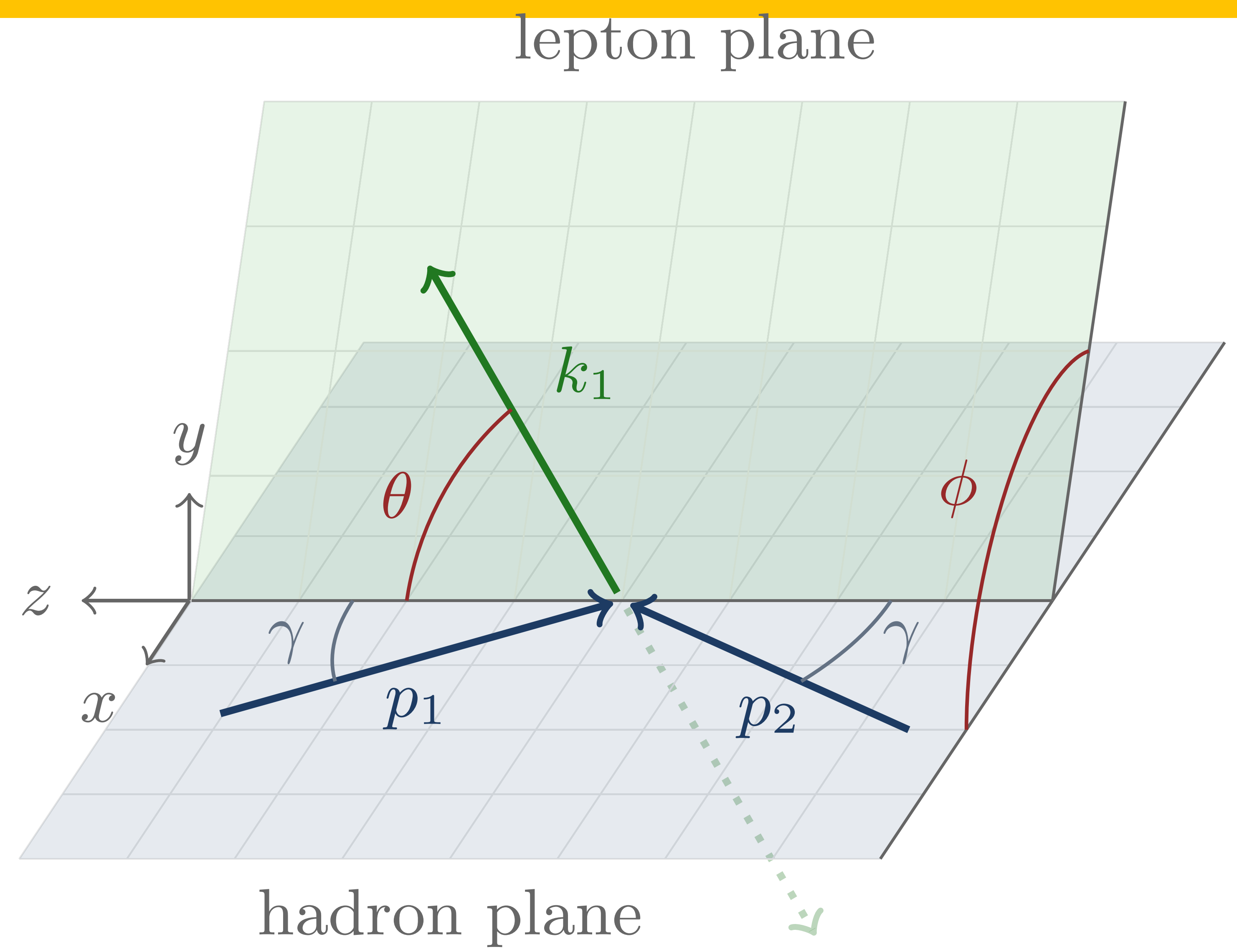


arXiv:2403.15085

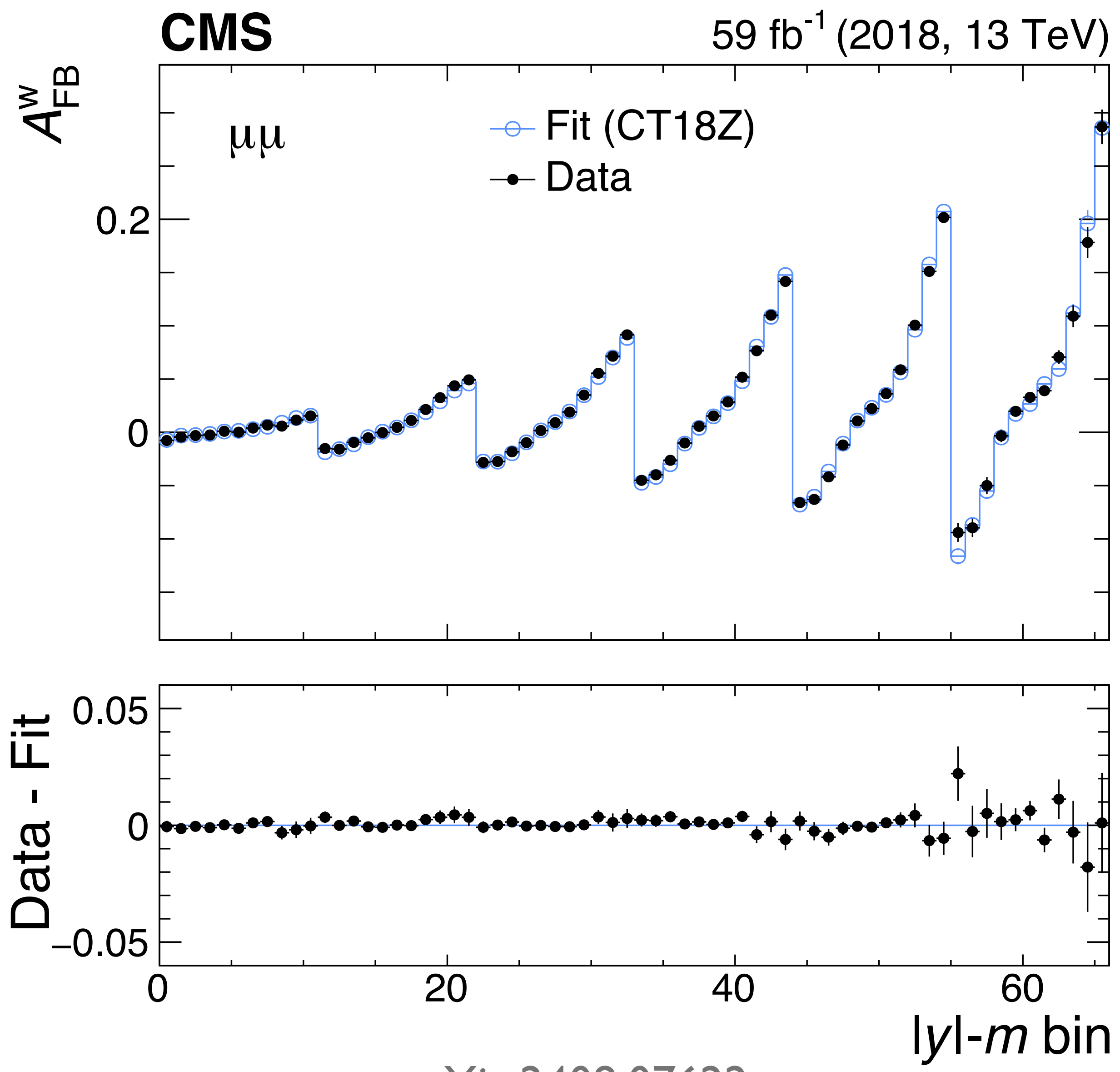
Small interplay between m_W and Γ_W

Effective Weak Mixing Angle

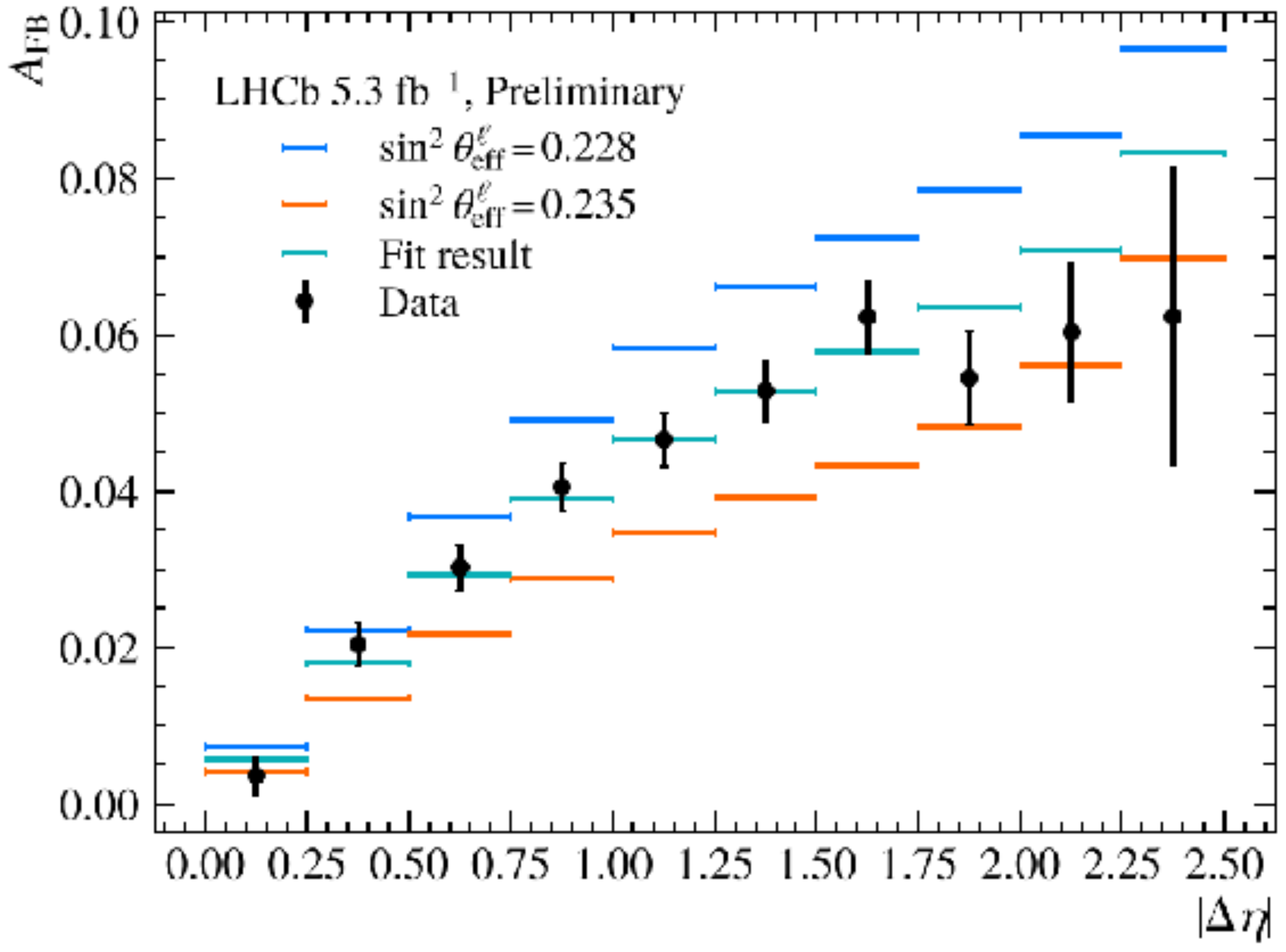
- Weak mixing angle probes **mixing of W and B fields**
- Measured using $pp \to \ell^+\ell^-$ forward backward asymmetry
- Determine $\sin^2\theta^\ell_{\text{eff}}$
  - $\dfrac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta + \dfrac{1}{2}A_0(1 - 3\cos^2\theta) + A_4\cos\theta$
  - $(\Delta A)_{FB} = \dfrac{3}{8}A_4$



arXiv:1708.00008



arXiv:2408.07622



LHCb

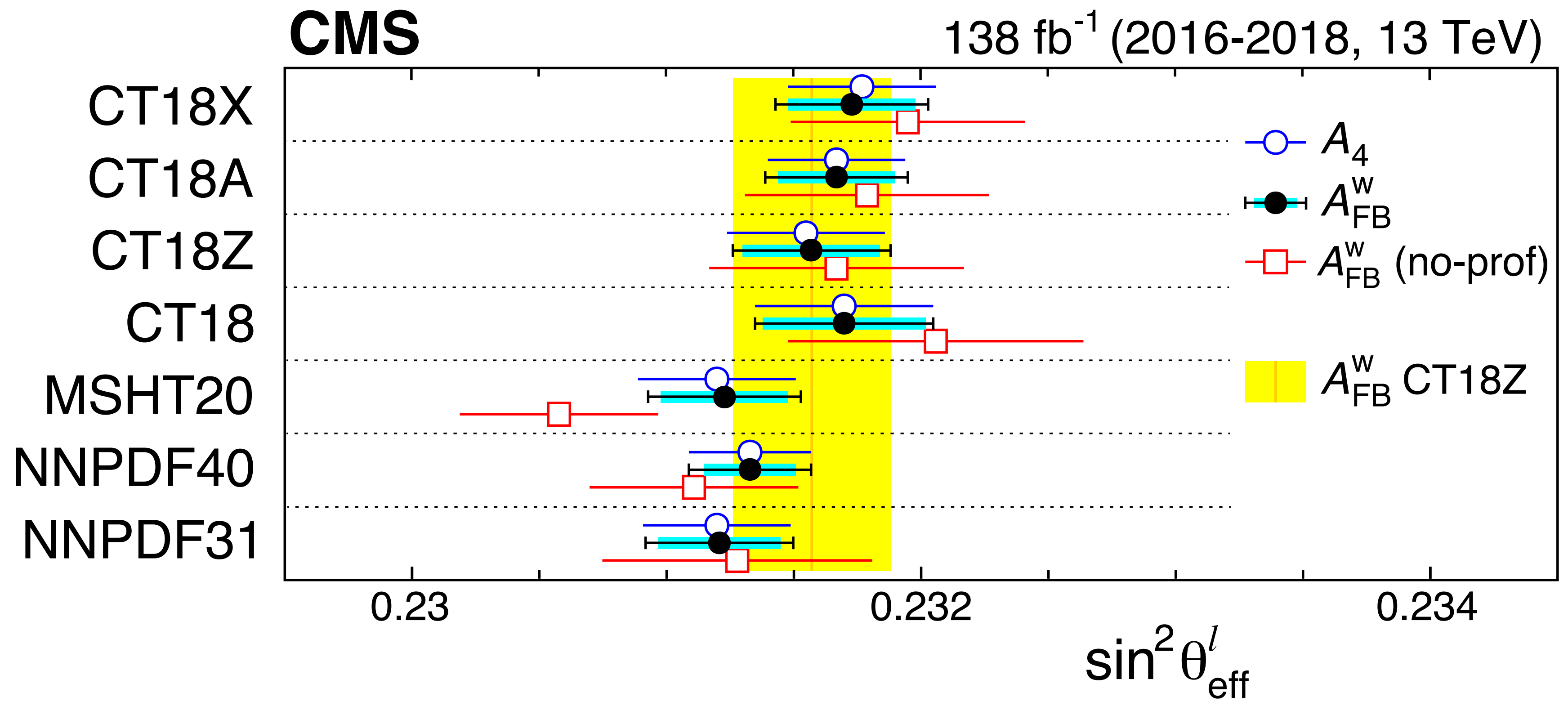
- Asymmetry increases with **rapidity**
- Also resolves ambiguity in quark-proton association
- CMS extended **electron reconstruction** to $|\eta| < 4.36$
- LHCb result for $2.0 < |\eta| < 4.5$

Effective Weak Mixing Angle Results

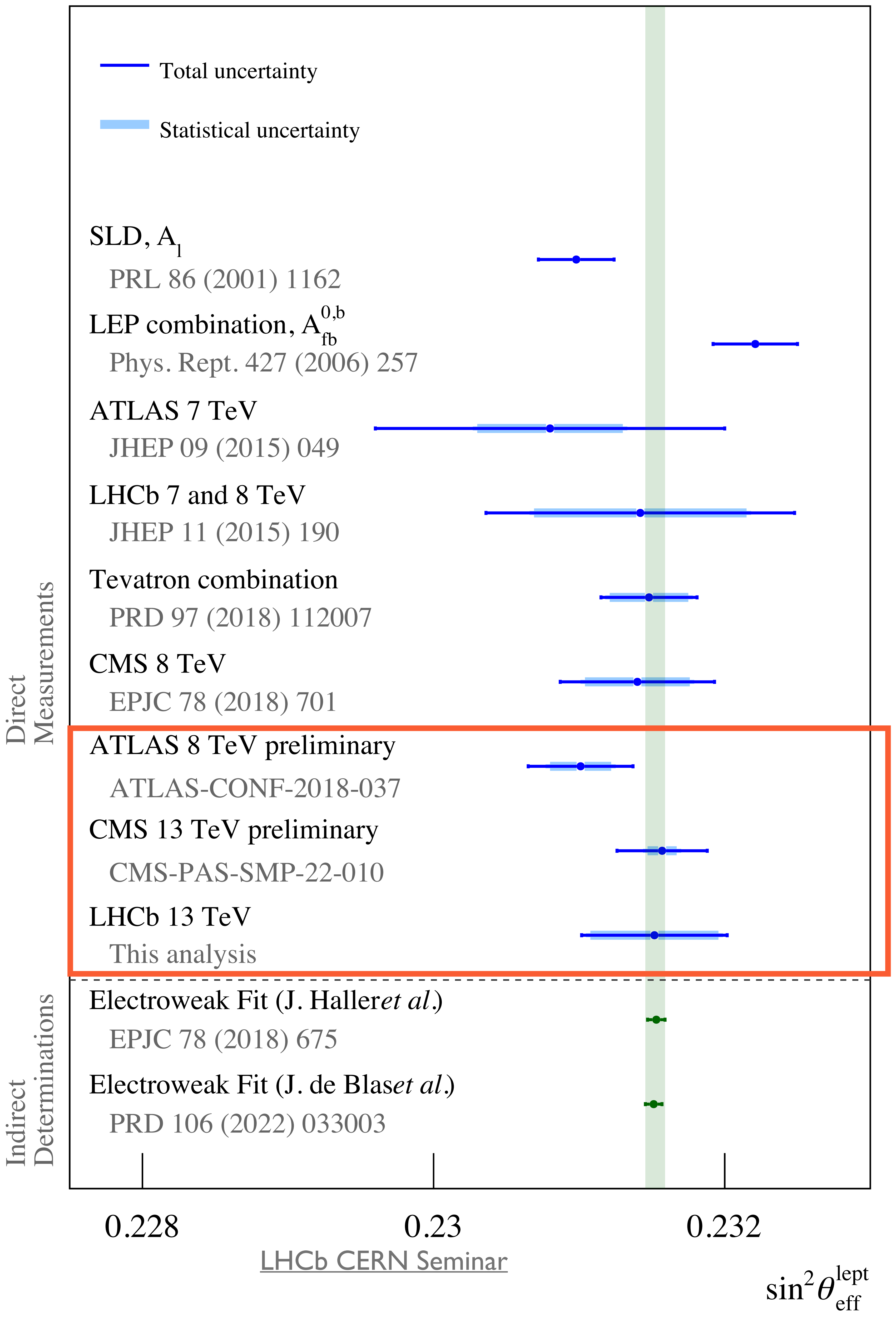
- Best **hadron collider measurement** approaching LEP and SLD

	$\sin^2\theta^{\ell}_{eff}$	stat ($\times 10^{-5}$)	syst ($\times 10^{-5}$)	th ($\times 10^{-5}$)	PDF ($\times 10^{-5}$)
CMS	0.23157	10	15	9	27
LHCb	0.23152	44	5	22	

- Profiling PDF uncertainties in the fit reduces uncertainties and leads to better consistency with global fits



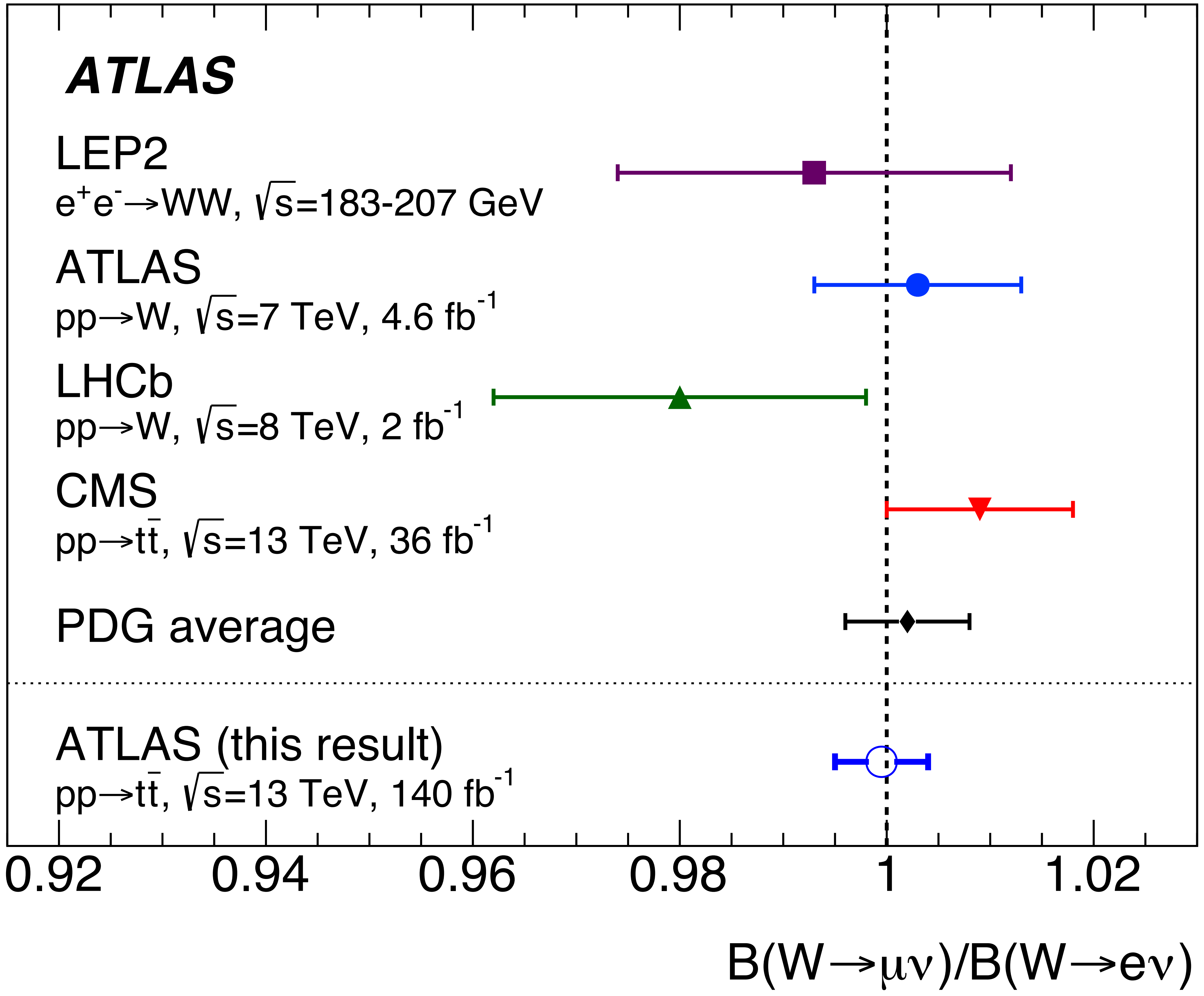
arXiv:2408.07622



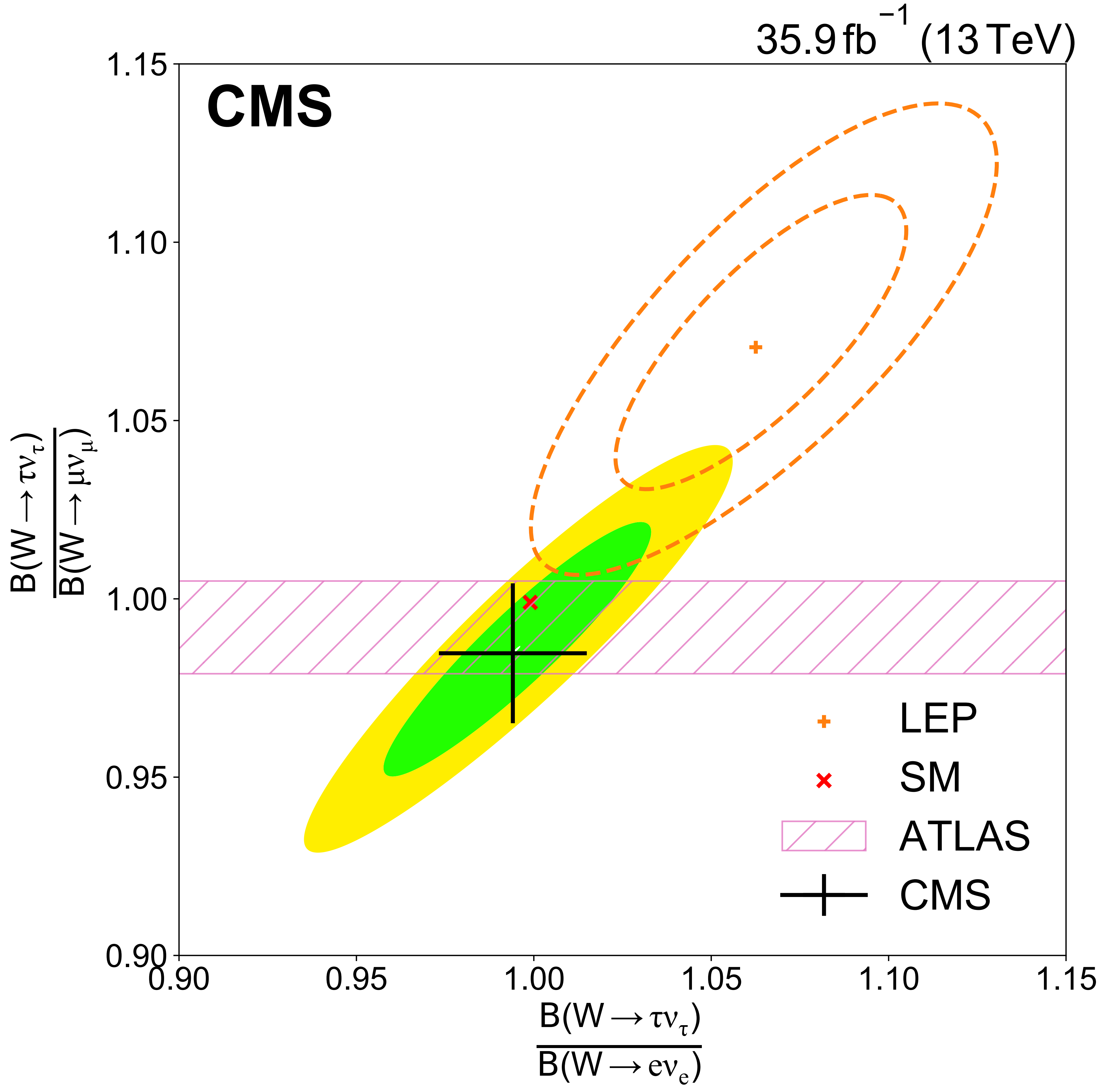
LHCb CERN Seminar

W Boson Decay Branching Fractions

- Precise measurements of W boson decays using **$t\bar{t}$ events**
- **Leptonic decay branching fractions** probe **lepton universality** of the weak interaction
  - Consistent with SM; ~1% precision



arXiv:2403.02133, Nature Phys. 17 (2021) 813

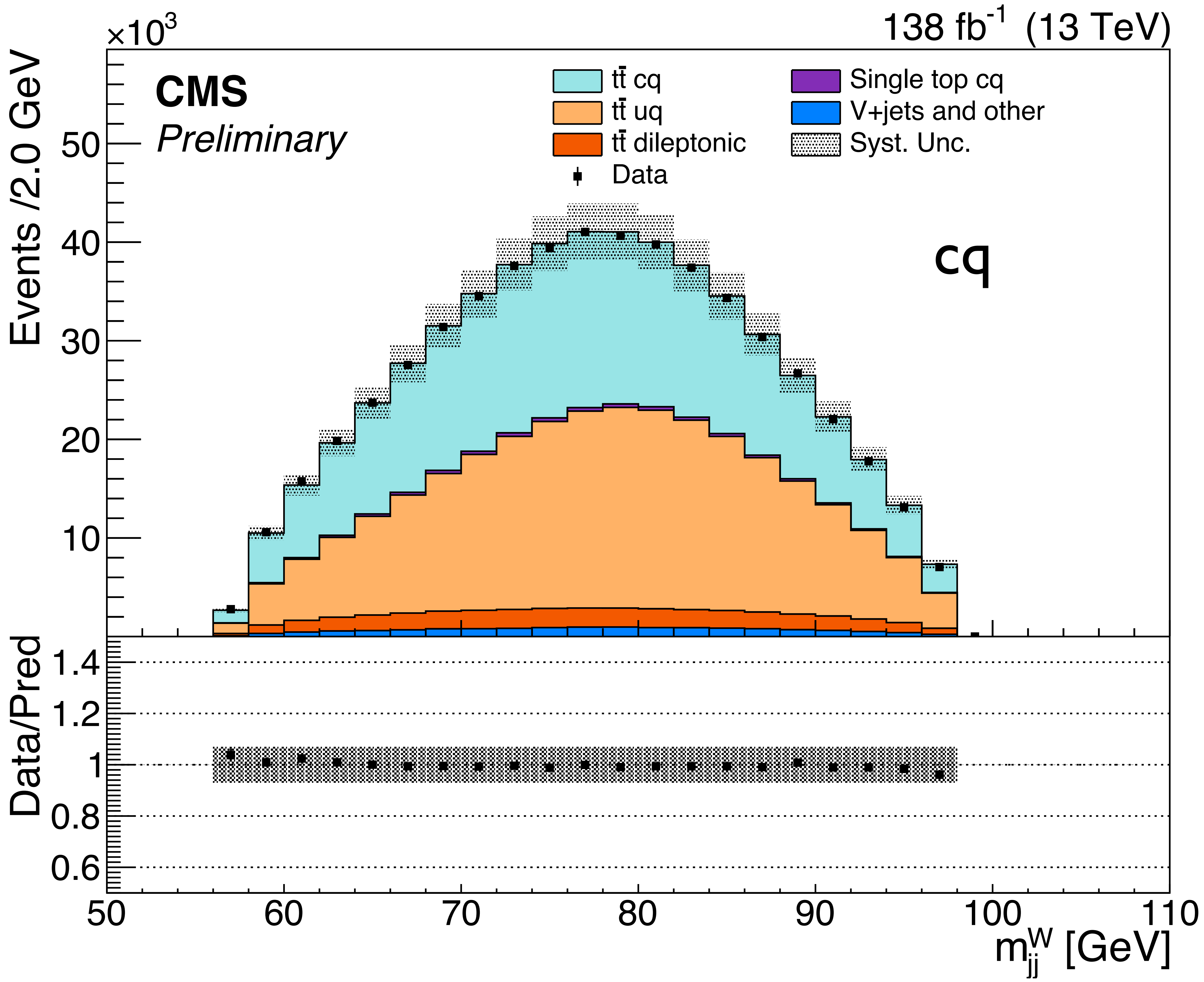


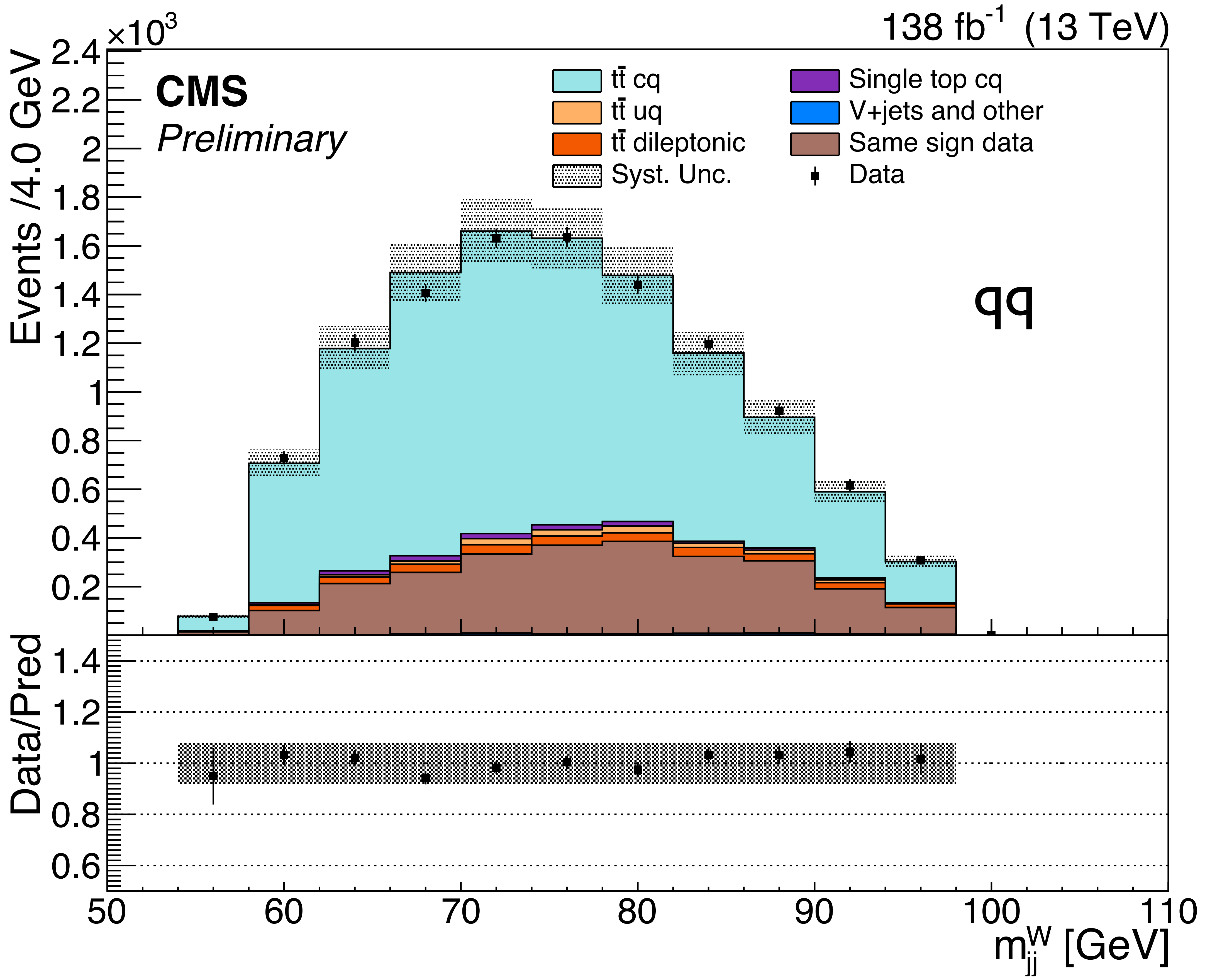
PRD 105 072008

W Boson Decay Branching Fractions

- **Hadronic decay branching fractions** $(W \rightarrow cs)$ to probe the CKM matrix
- $R_c^W = 0.489 \pm 0.005(\text{stat}) \pm 0.019(\text{syst}) \rightarrow |V_{cs}| = 0.959 \pm 0.021$

4% precision

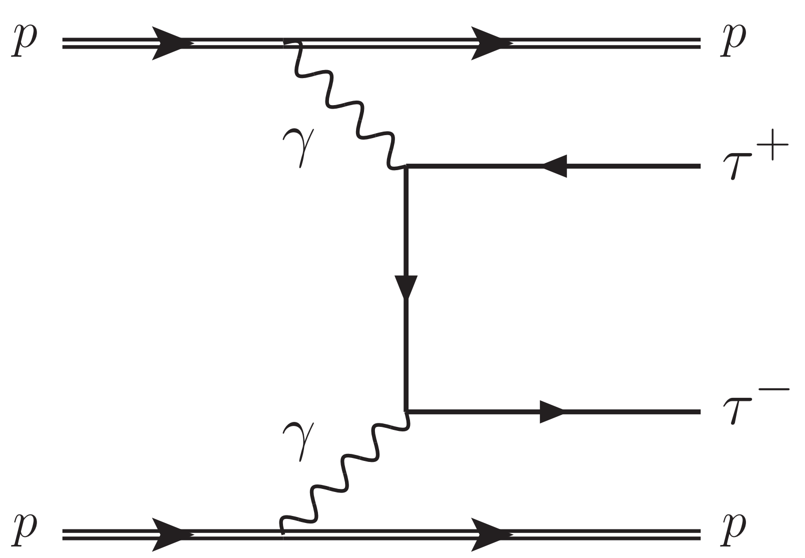


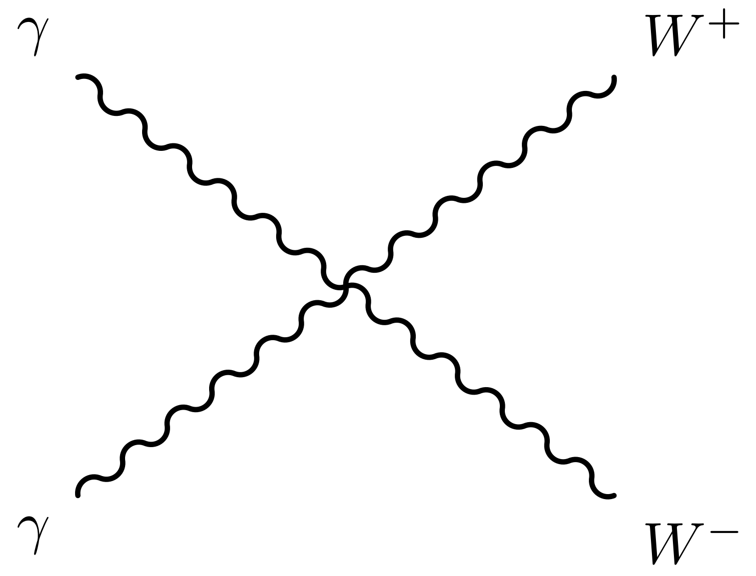


CMS-PAS-SMP-24-009

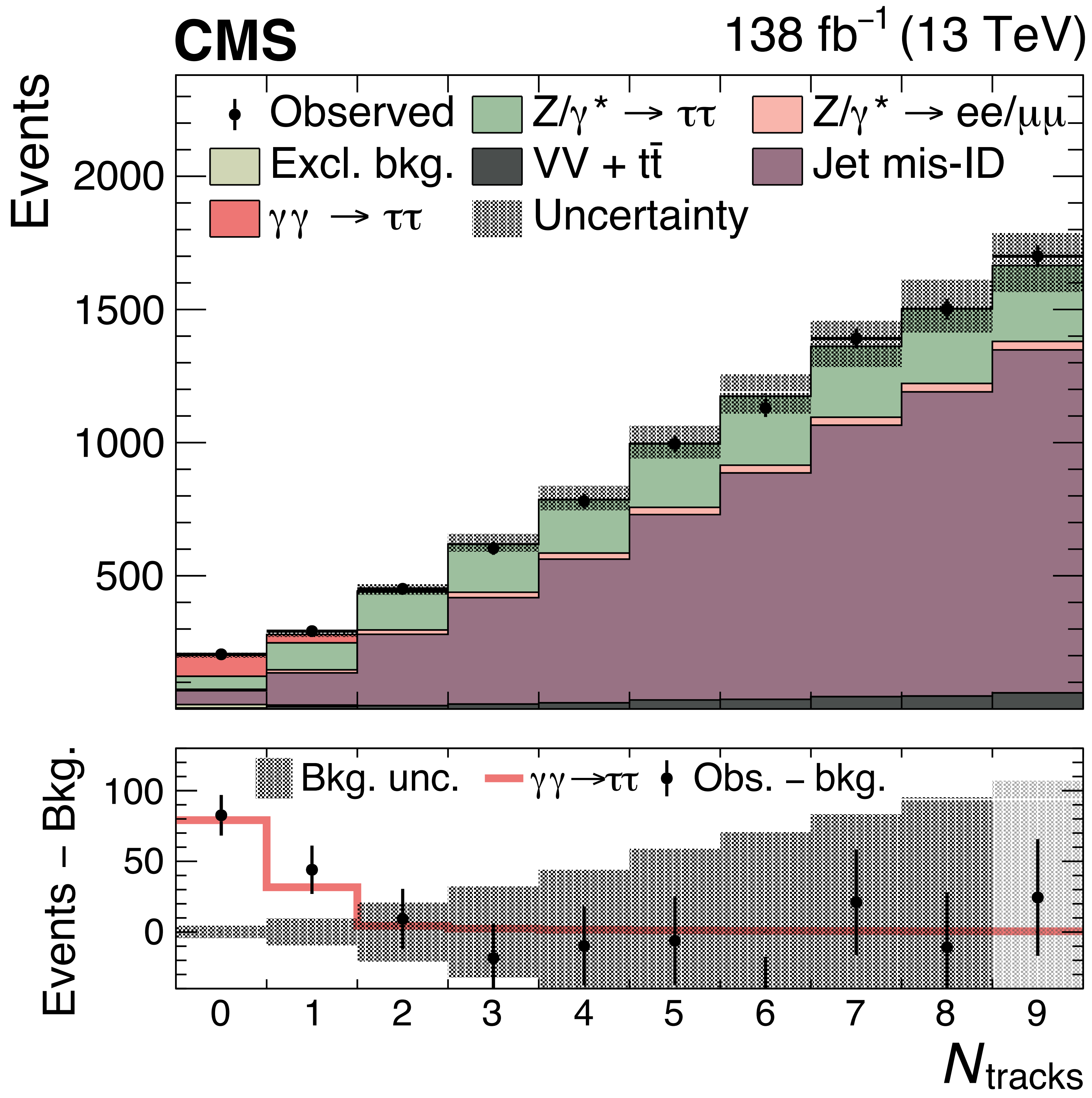
Photon-Photon Fusion

- Photon-photon fusion provides a **pure test of QED**
  - Precise theoretical calculations (<1%)
- Typically measured in **UPC heavy-ion collisions**

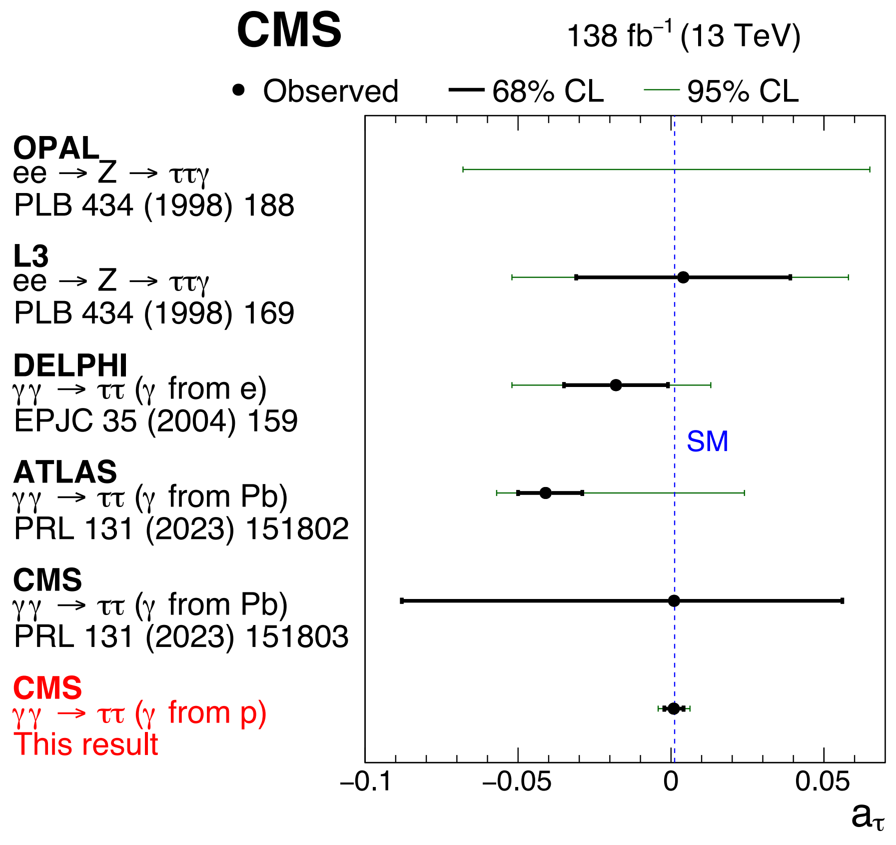


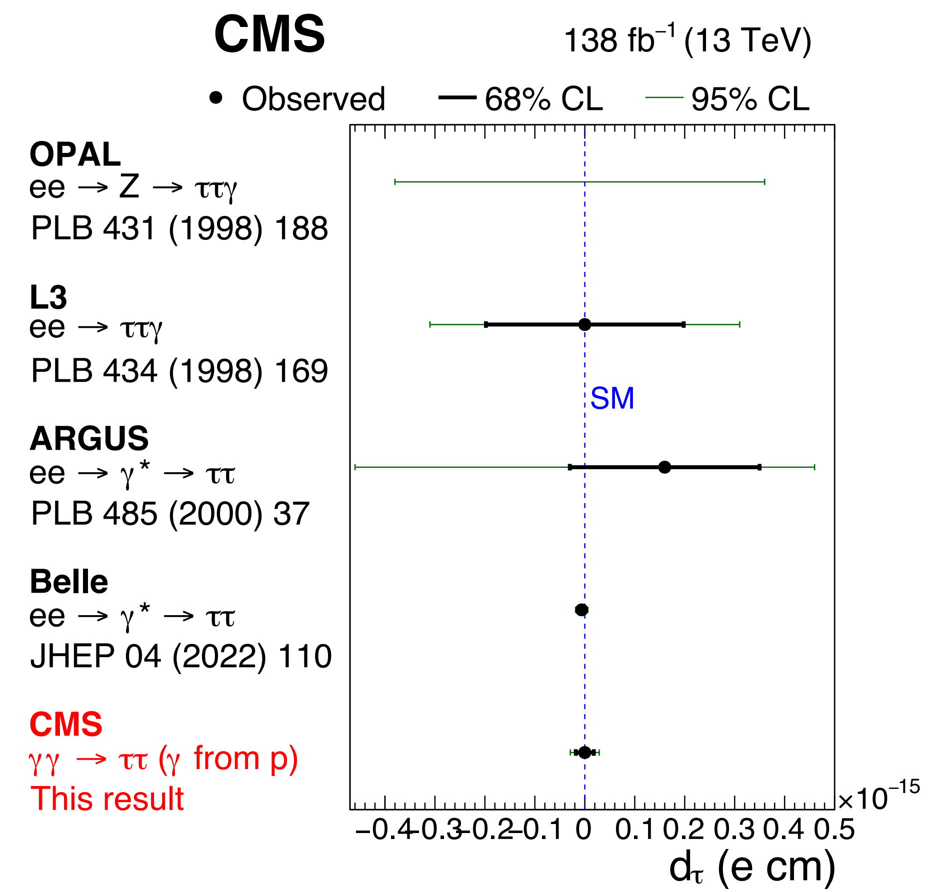


First measurement $\gamma\gamma \to \tau\tau$ in pp; constraints on anomalous EM moments of τ

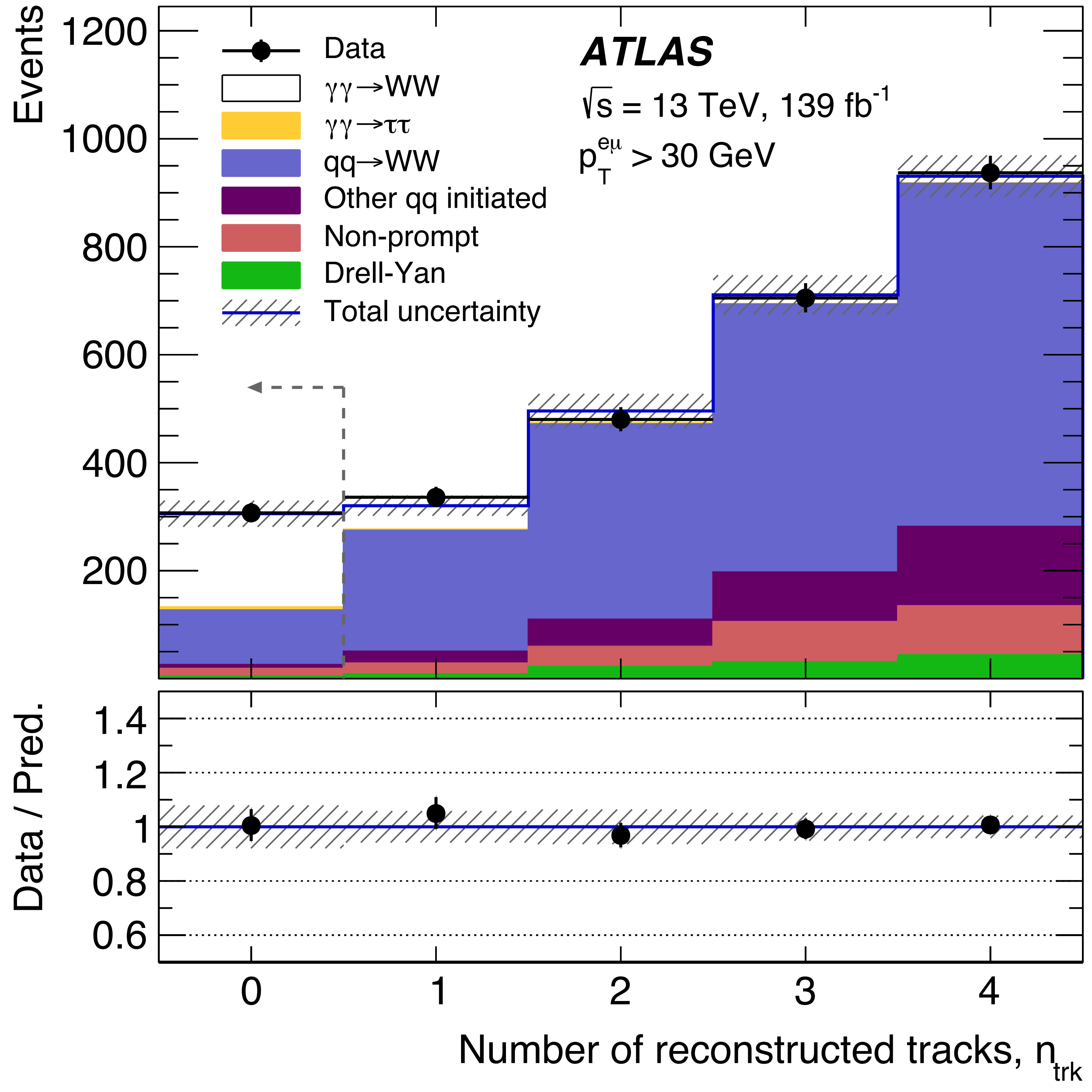


arxiv:2406.03975





Observation of $\gamma\gamma \to WW$



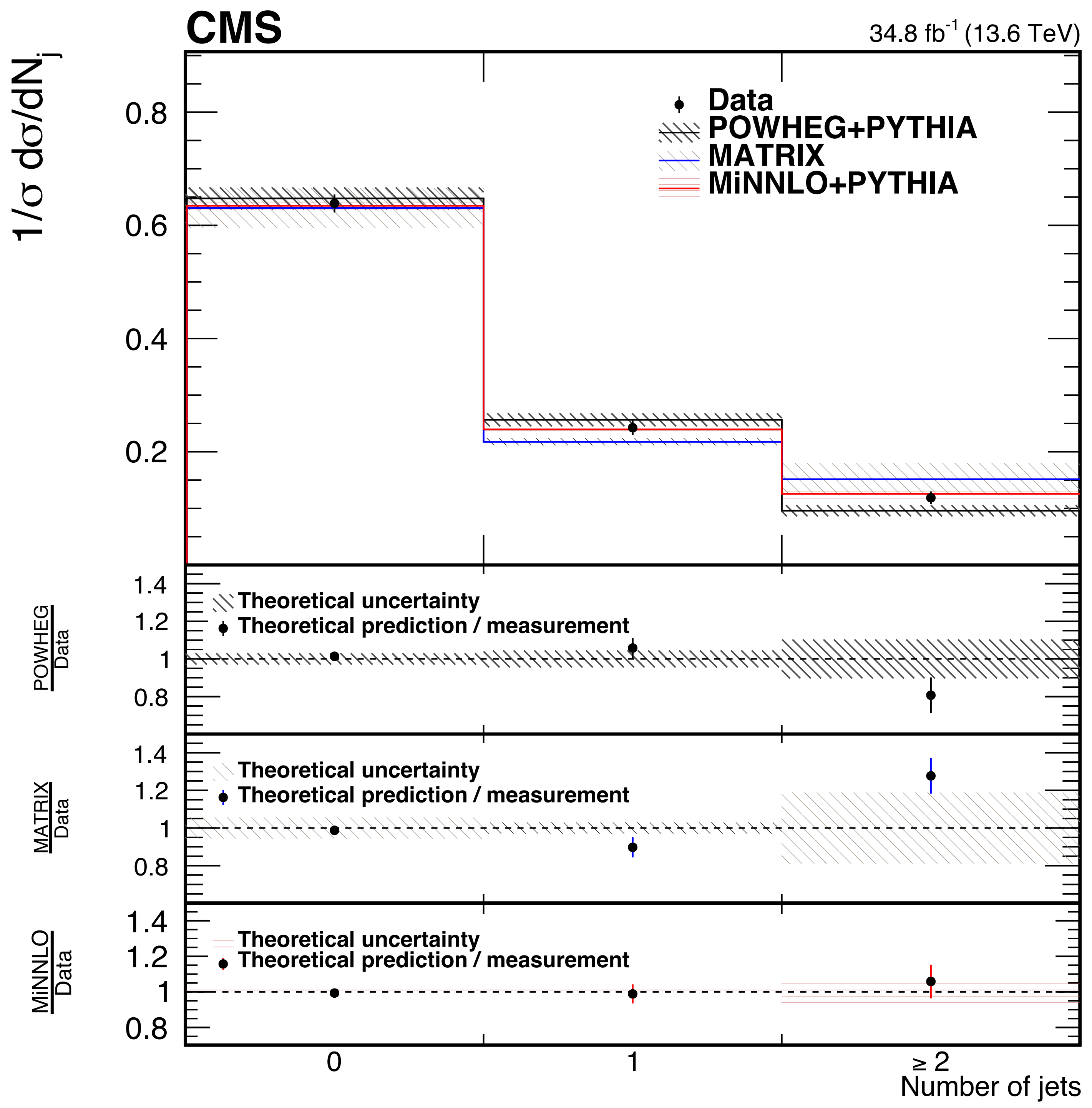
Phys. Lett. B 816 (2021) 136190

Multiboson Production at High-Energy

Image Source

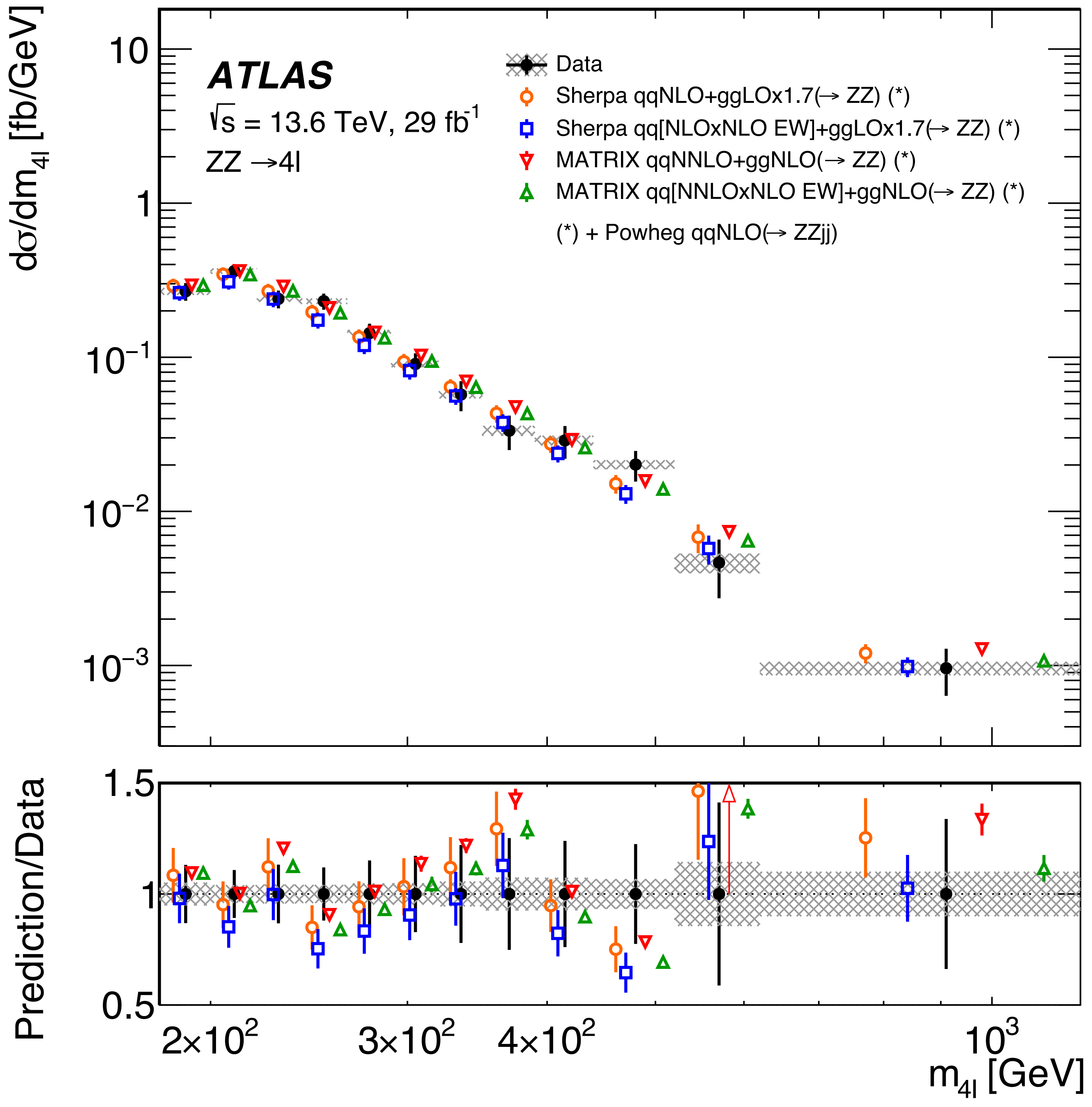
Diboson Production at 13.6 TeV

$pp \to WW$



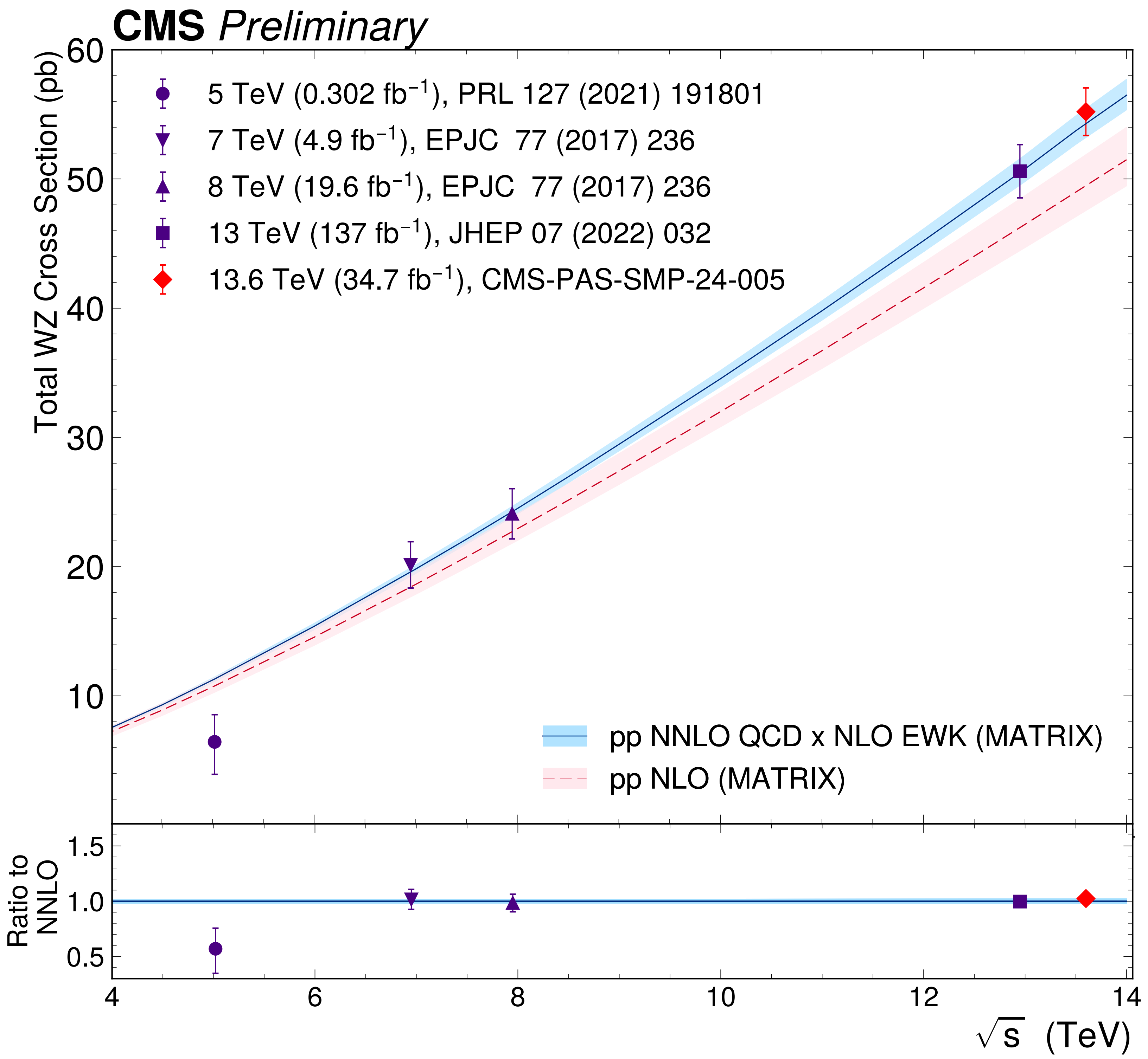
arXiv:2406.05101

$pp \to ZZ$



PLB 855 (2024) 138764

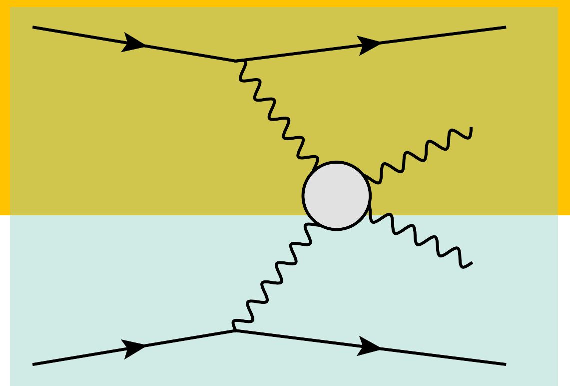
$pp \to WZ$

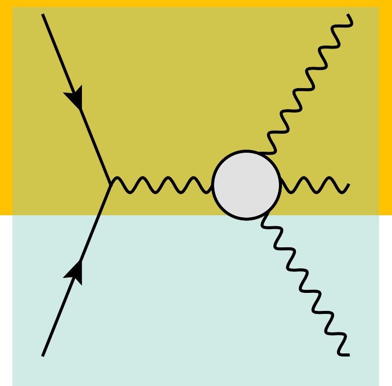


CMS-PAS-SMP-24-005

Typical precision <5%

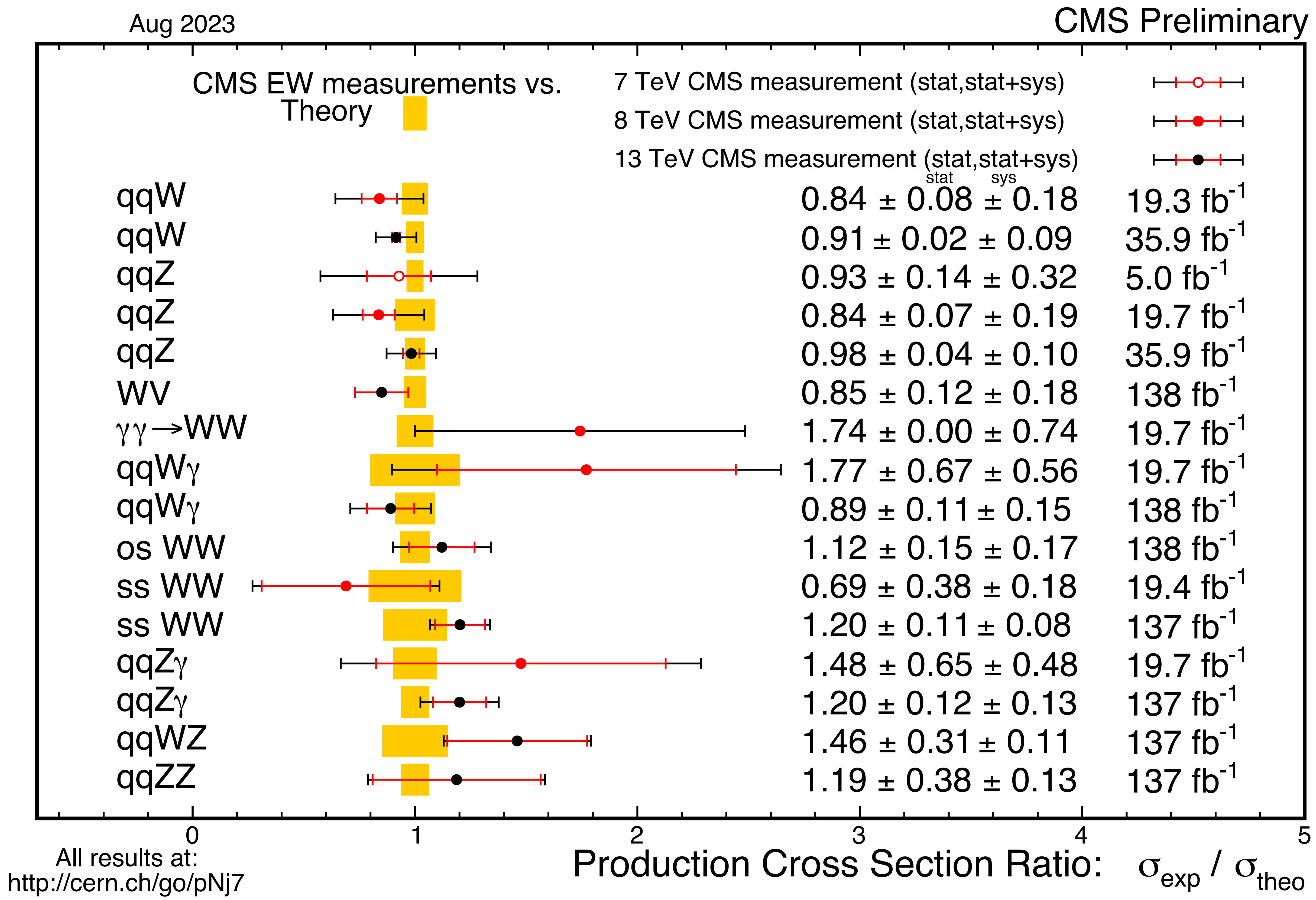
Quartic Electroweak Couplings

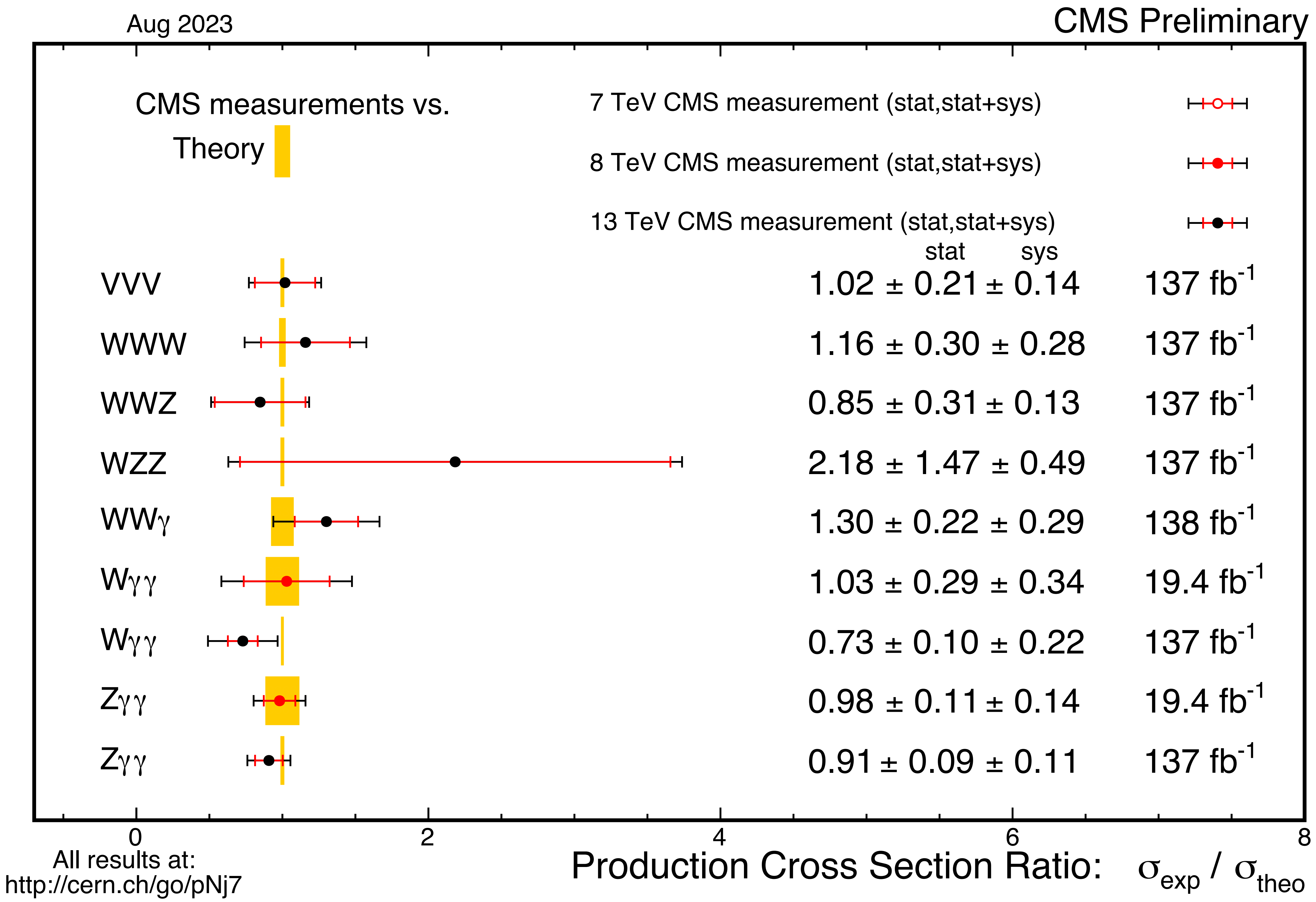




Vector boson scattering observed in all channels

Triboson production is experimentally more challenging

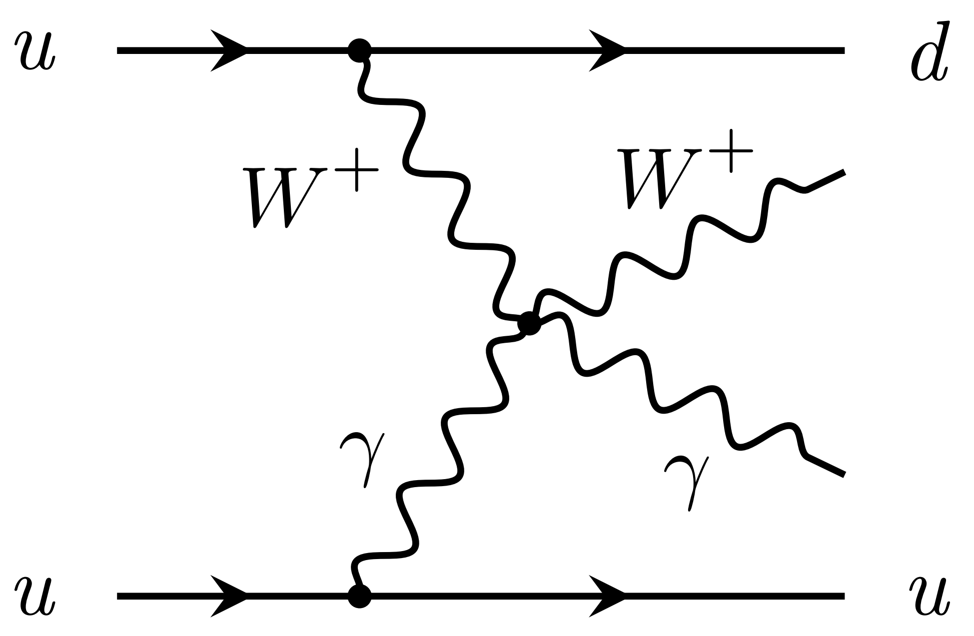




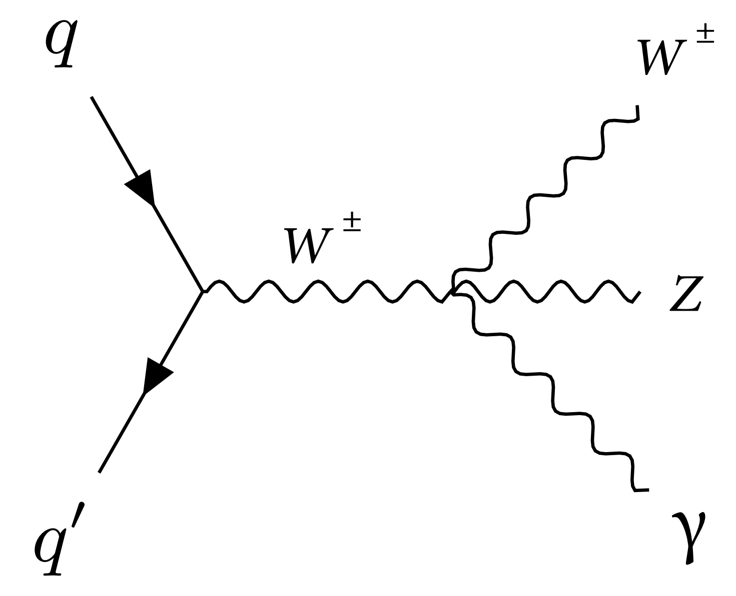
CMS Summary Plots Webpage

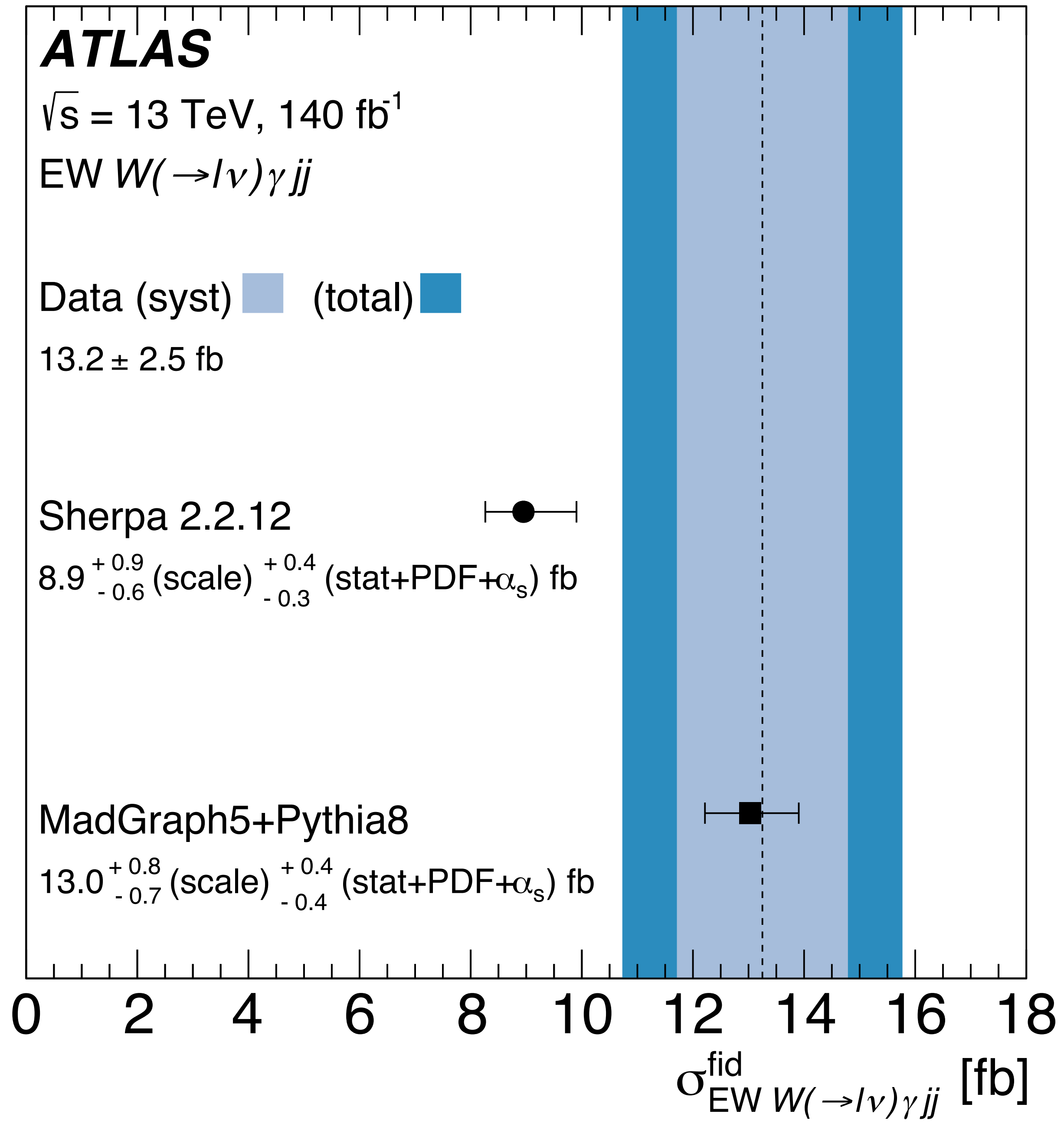
Recent Examples of Quartic Coupling

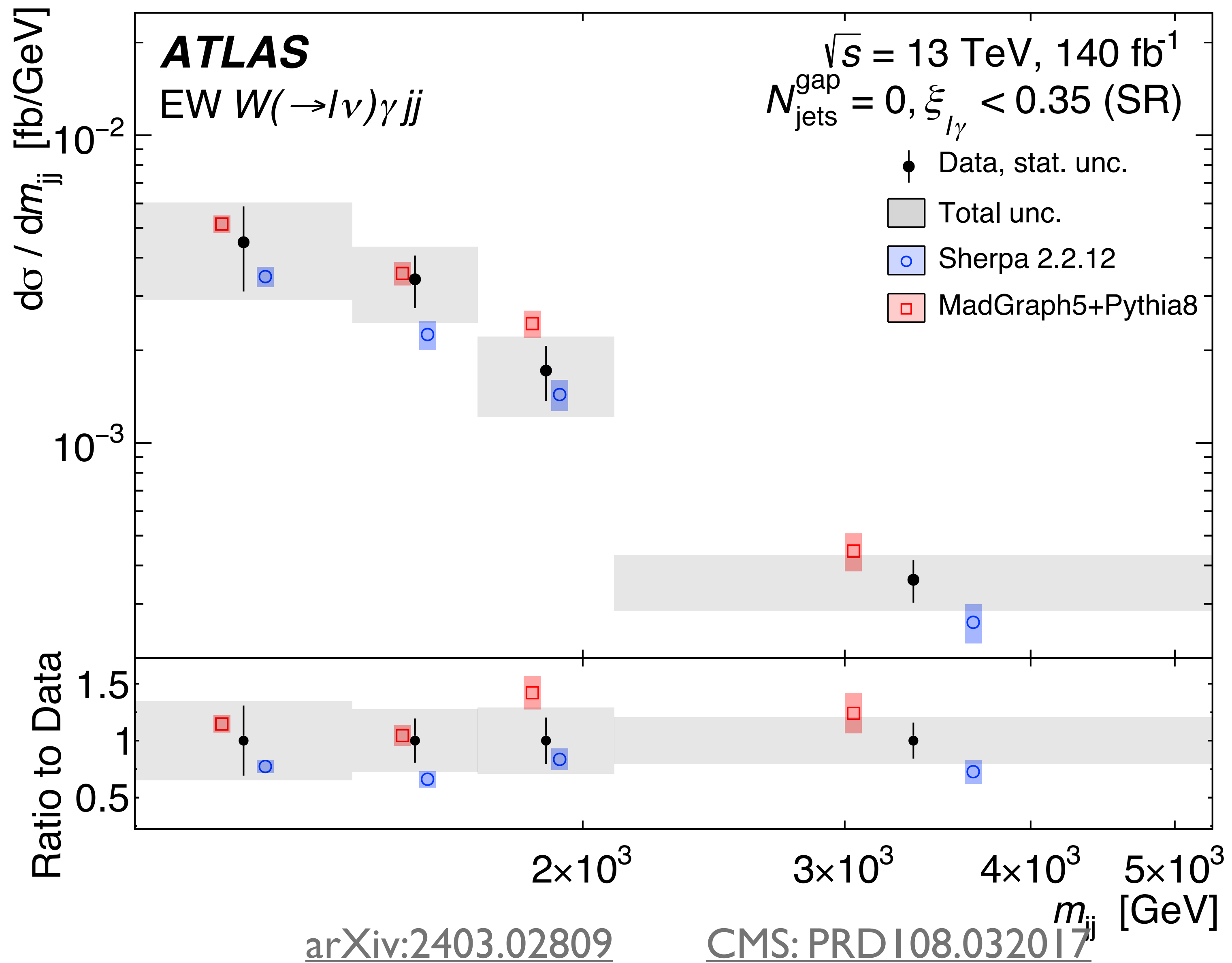
- **>6σ** observation of $W\gamma jj$ using a neural network
- Consistent with Madgraph5+Pythia prediction

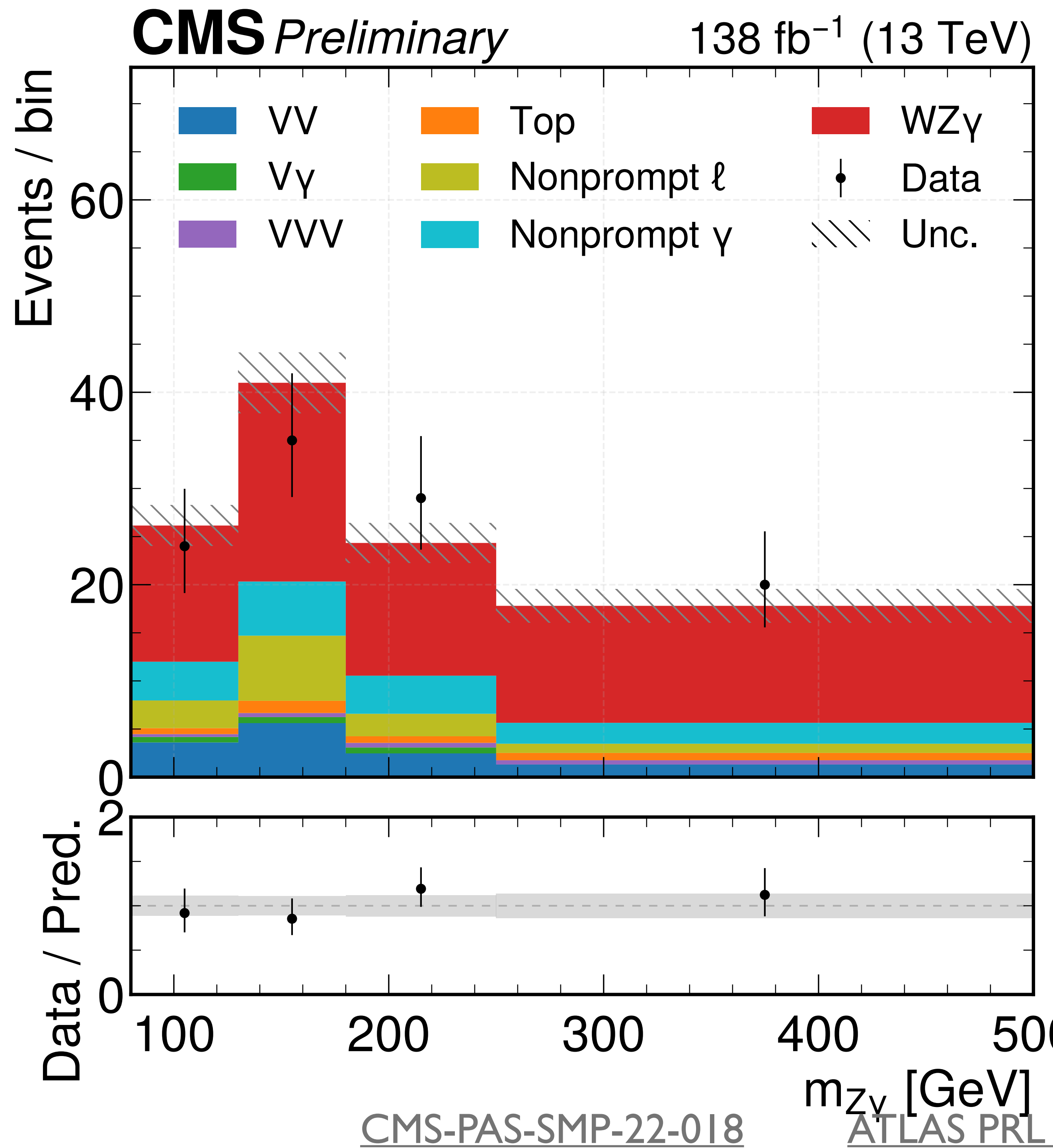


- **5.4σ** observation of $WZ\gamma$ using $M_{Z\gamma}$ fit
- Higher than NLO theory prediction: $\mu = 1.47^{+0.33}_{-0.29}$





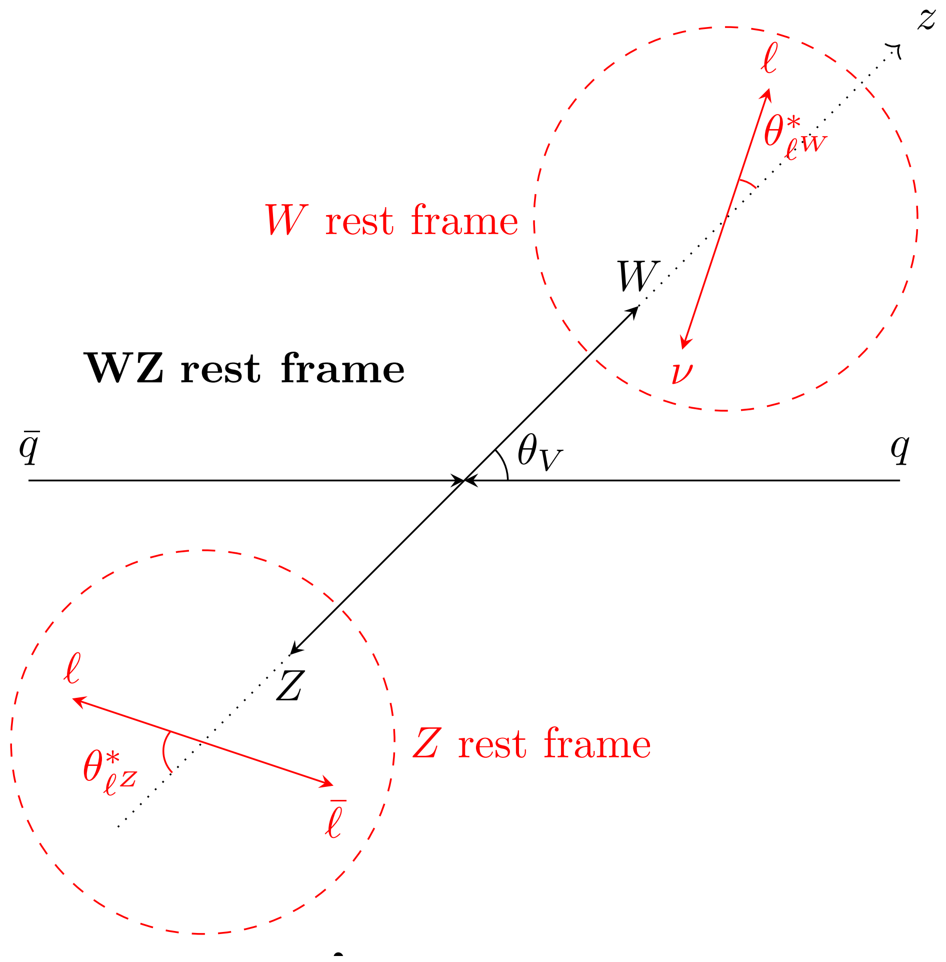


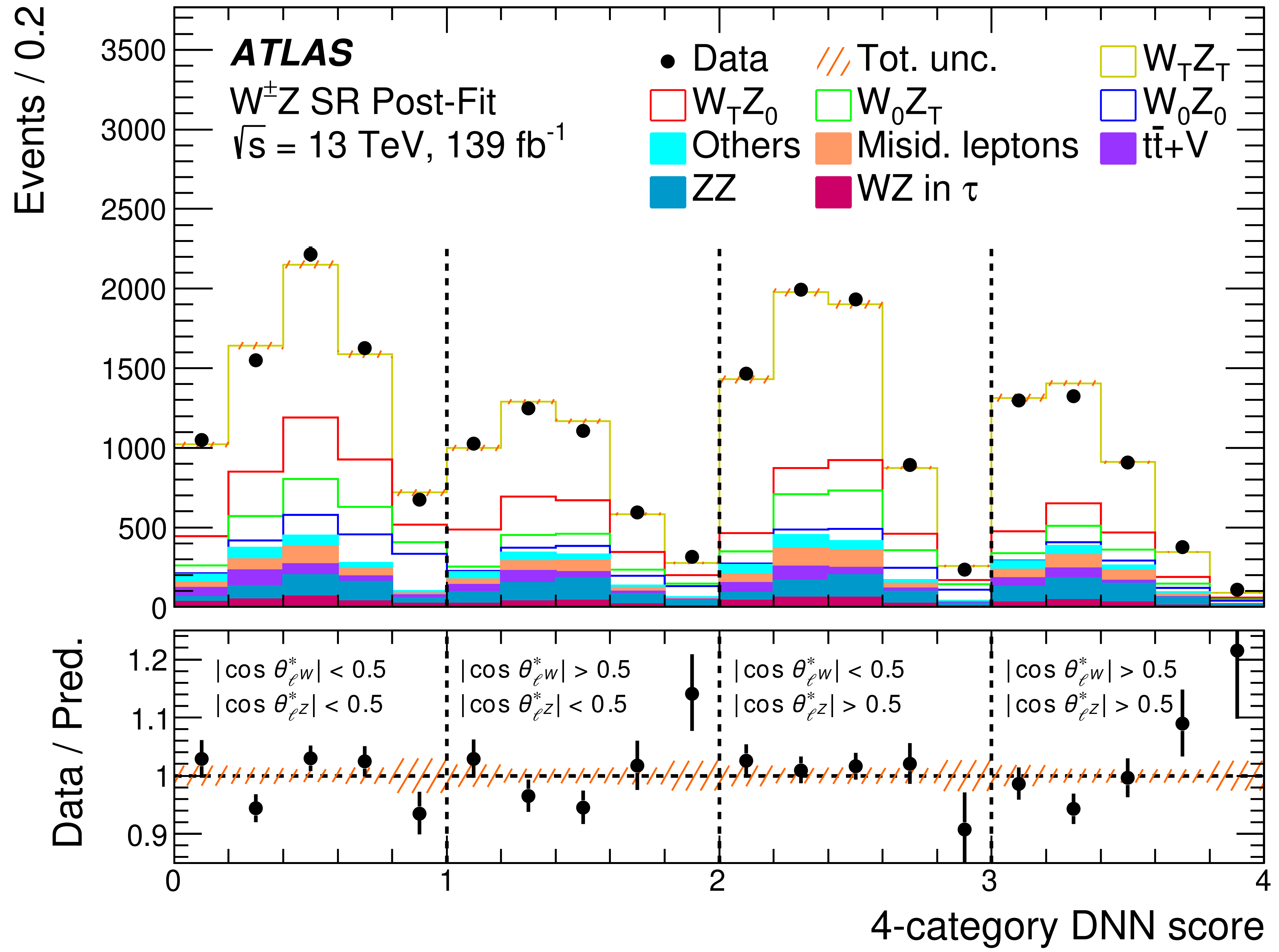


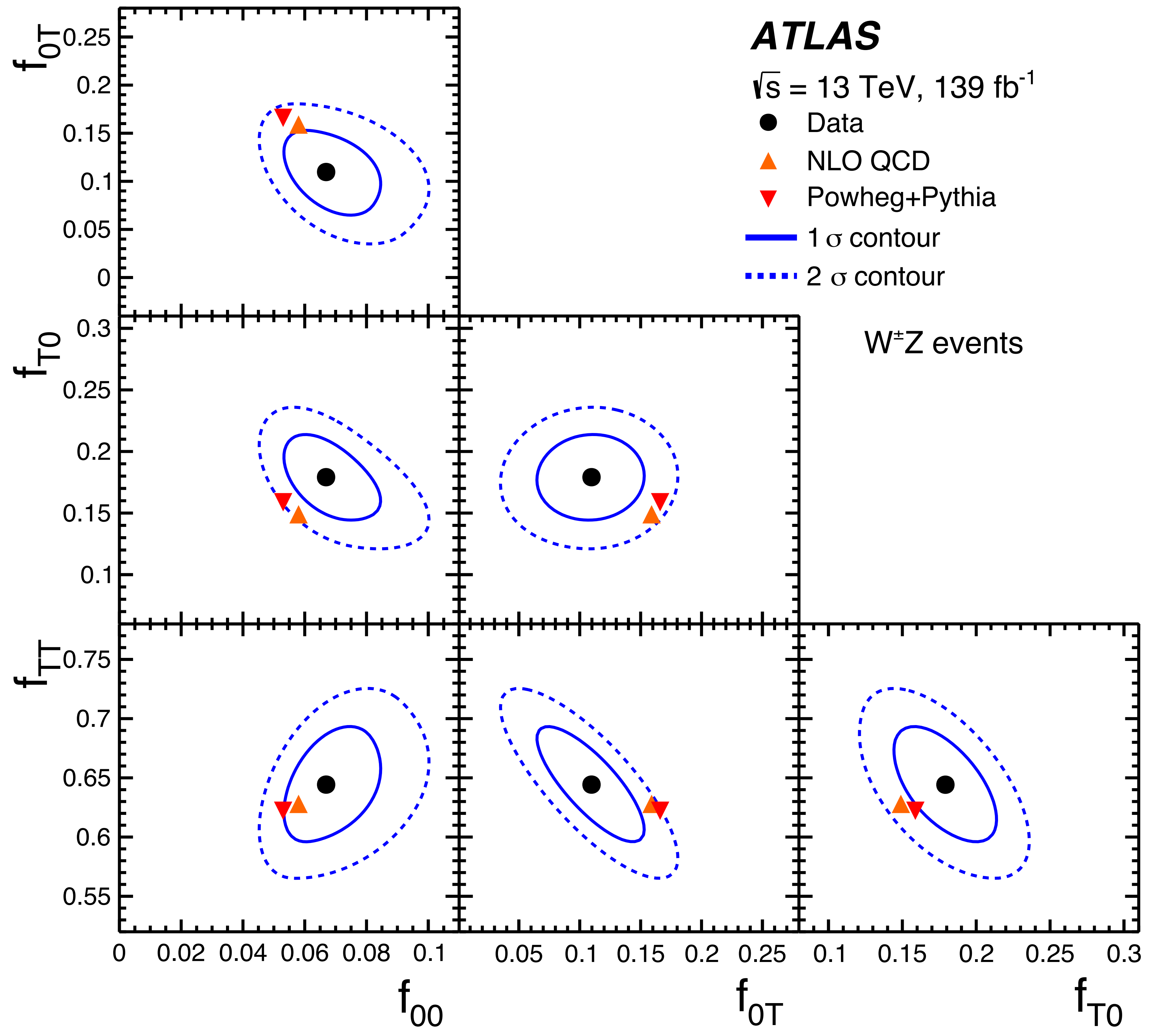
arXiv:2403.02809 CMS: PRD108.032017 CMS-PAS-SMP-22-018 ATLAS PRL 132.021802

Diboson Polarization

- **Longitudinal polarization** of dibosons generated by EWSB
- Measured from **decay angles of leptons** from vector boson decays
- Recent observation of **joint polarization** builds on measurements of individual polarization [PLB 843 (2023) 137895, JHEP 07 (2022) 032]
- Measure 4 components: $f_{00}, f_{TT}, f_{0T}, f_{T0}$



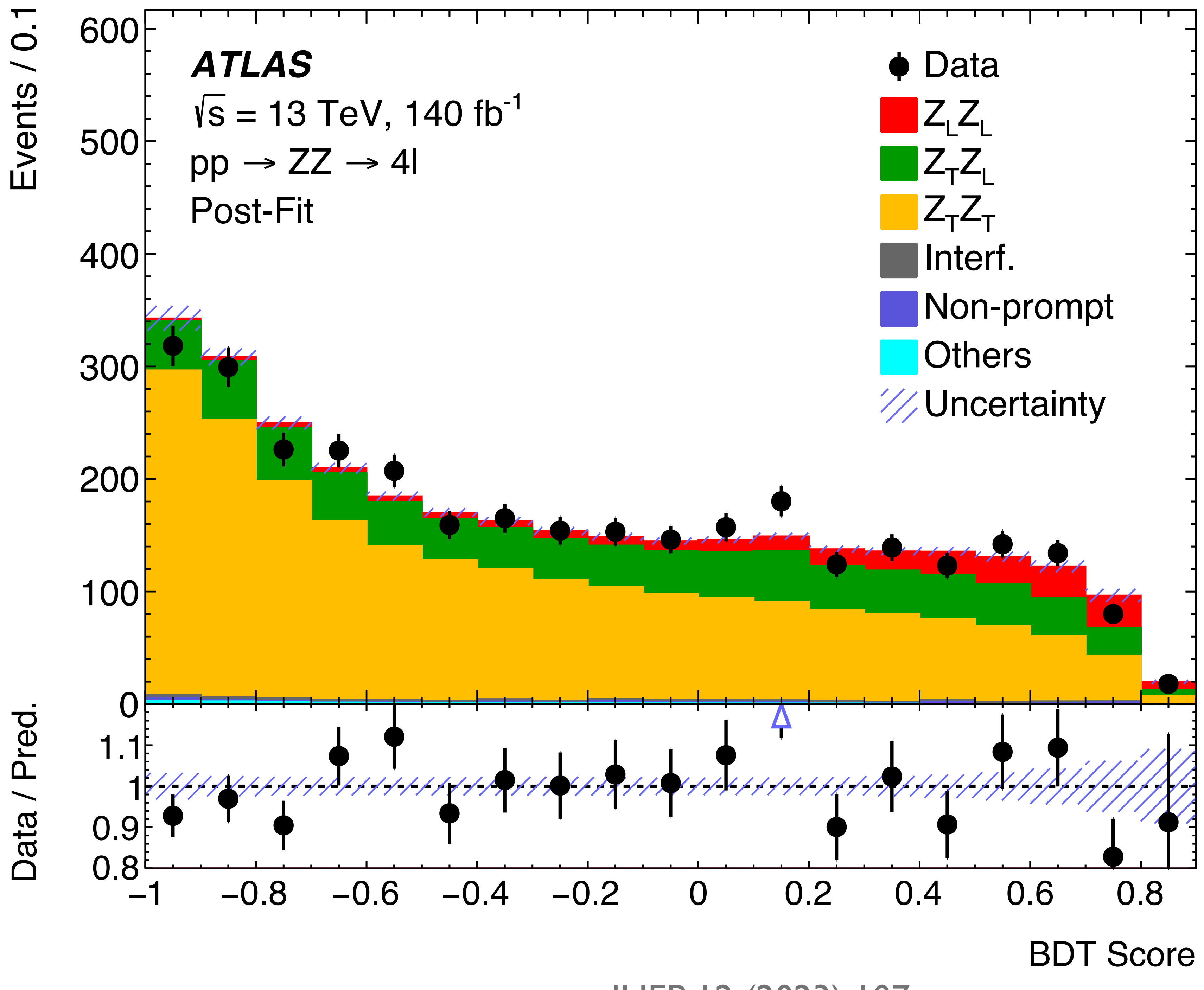




Diboson Polarization Results

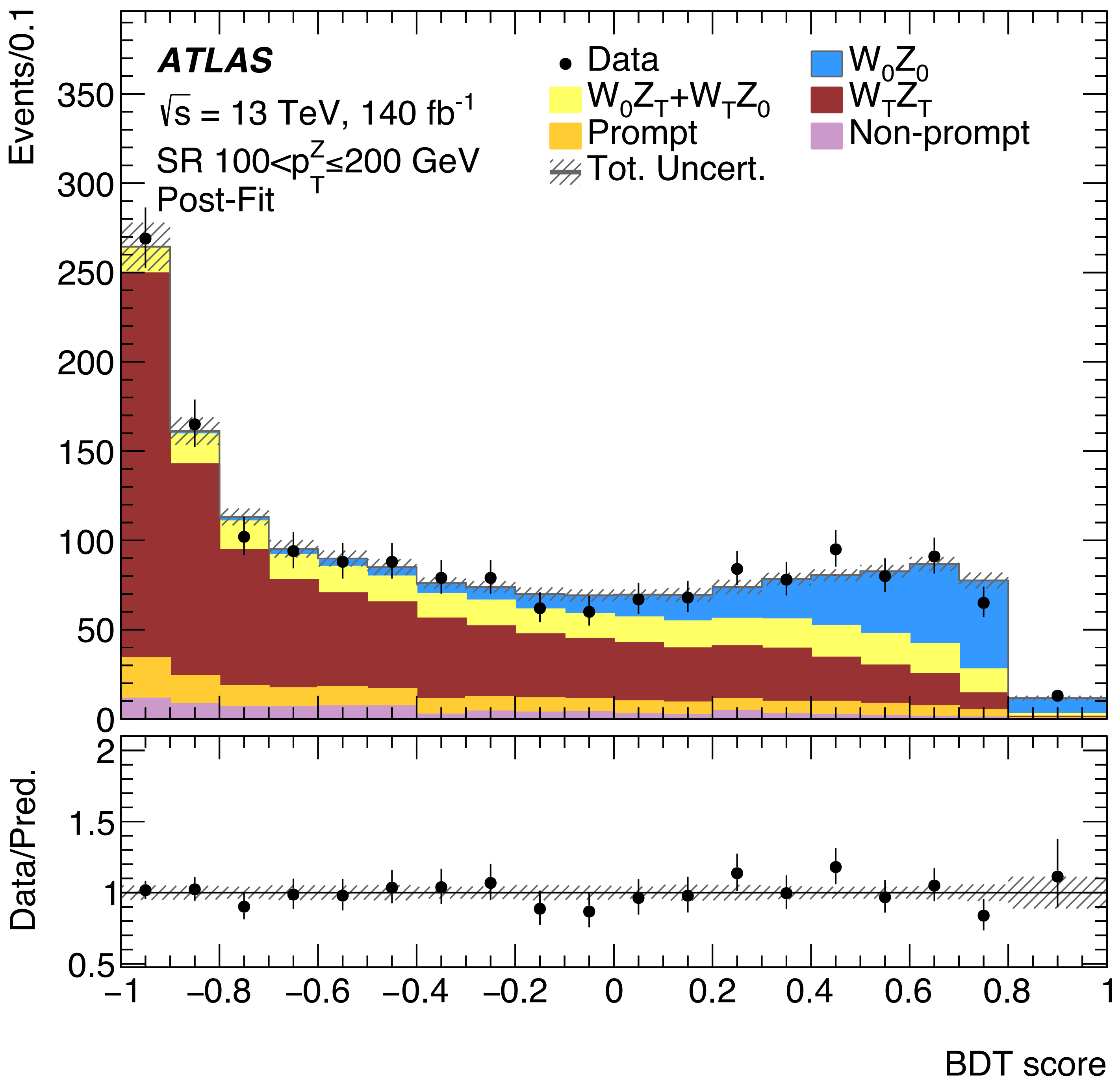
- LHC experiments are starting to become sensitive to $V_L V_L$ production
  - Initial studies of **energy dependence**, e.g. with WZ
- Eagerly awaiting $V_L V_L$ **scattering** at the HL-LHC as critical test of EW symmetry breaking

$Z_L Z_L$: 4.3σ



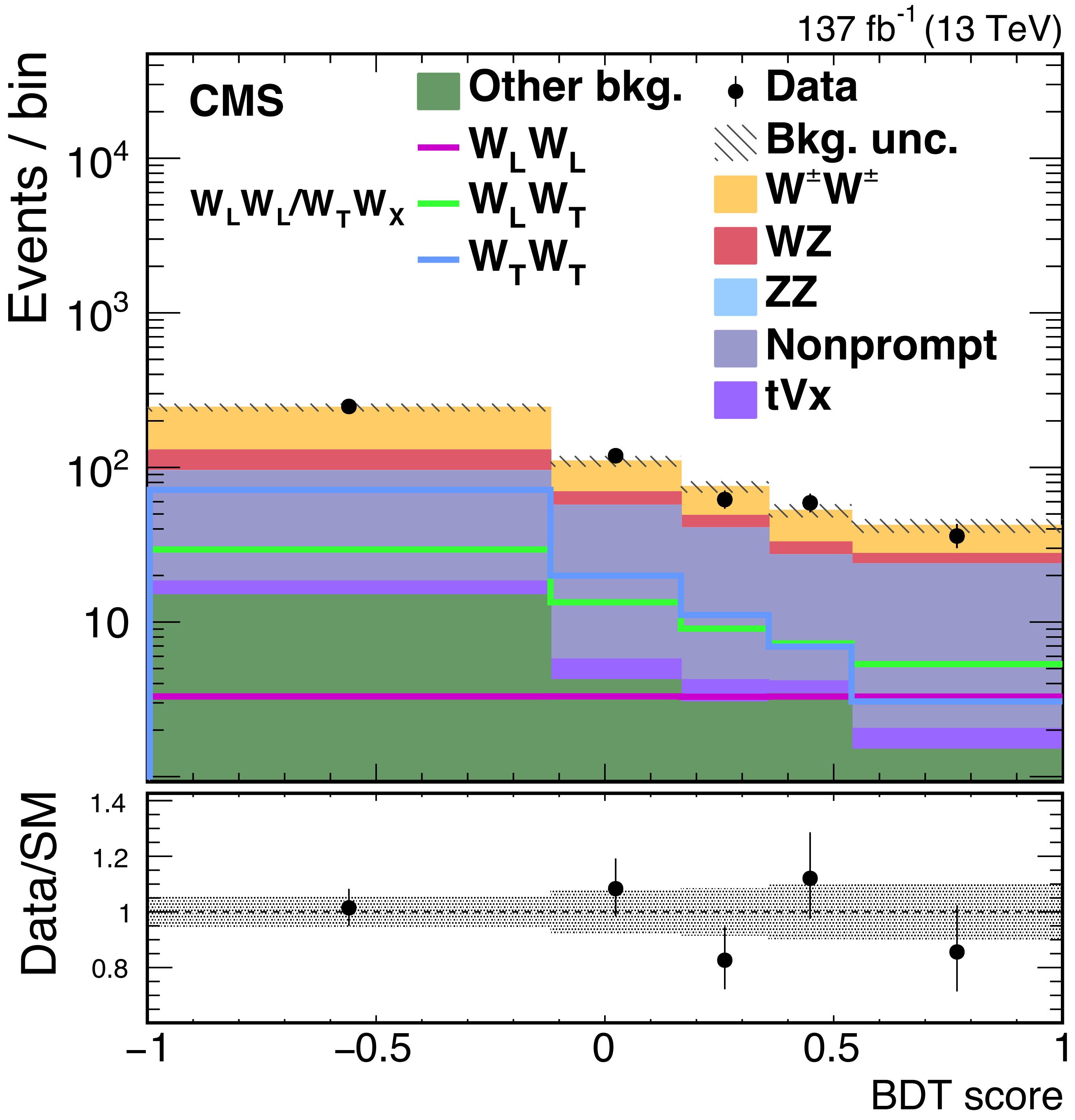
JHEP 12 (2023) 107

$W_L Z_L$: 3.2σ ($p_T > 200$ GeV)



PRL 133 (2024) 101802

VBS $W_L^\pm Z_L^\pm jj$: $< 1\sigma$



PLB 812 (2020) 136018

Conclusion

- LHC is proving to be precision machine for **electroweak physics**
- Already **surpassing precision** of previous accelerators in many cases
- Relies on large datasets, detailed detector understanding, dedicated reconstruction techniques, advanced analysis methods (including AI/ML) and accurate theoretical predictions
- Recent **highlights** includes
  - W boson mass and width
  - Weak mixing angle
  - Lepton couplings
- Multiboson measurements are being used to test **electroweak theory** at high energies
  - Looking ahead towards a full exploration of electroweak symmetry breaking at the upcoming HL-LHC