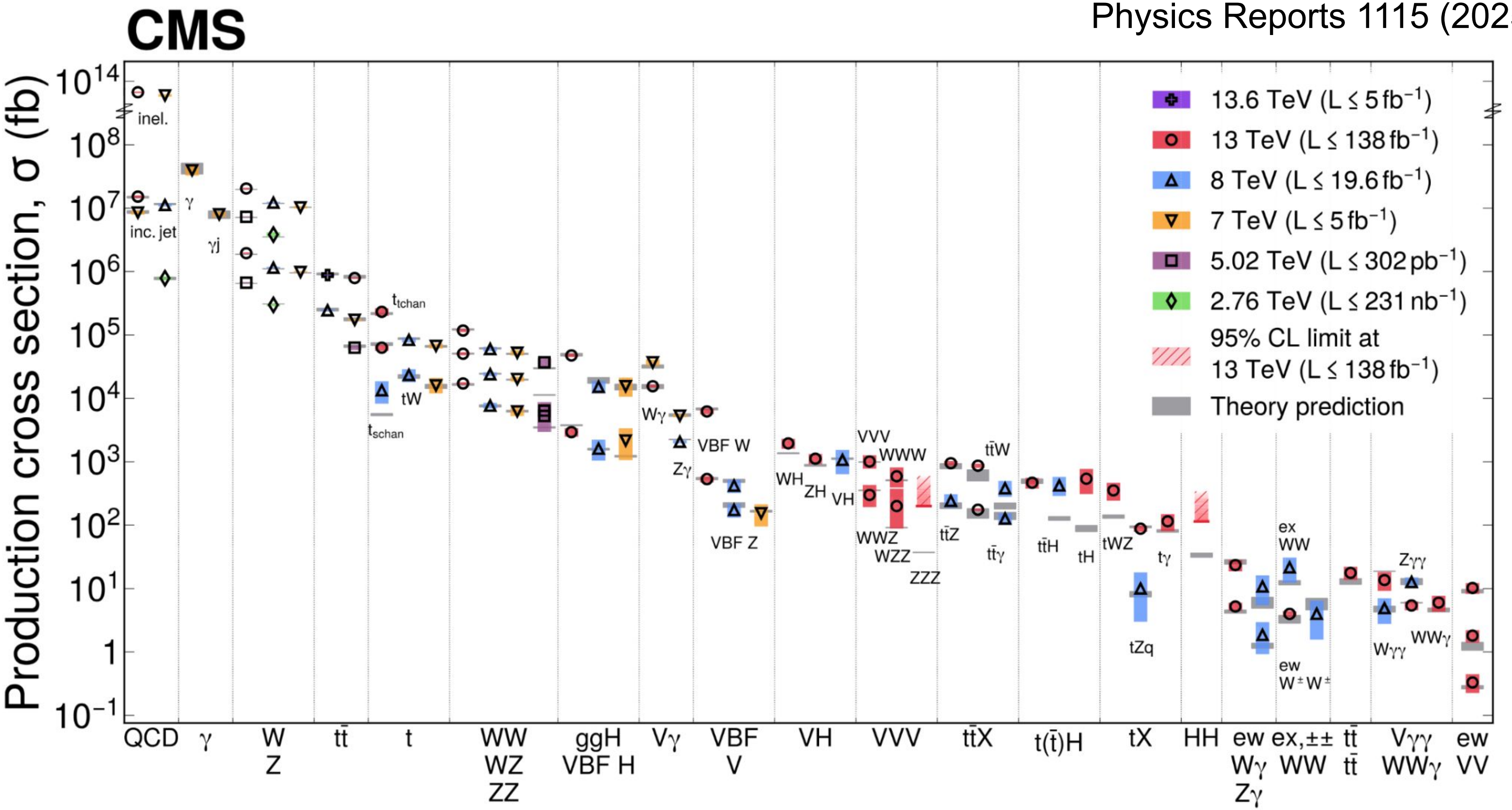
Recent Standard Model Measurements

Josh Bendavid (CERN)
EPS-HEP 2025
Marseille, France
Jul. 9, 2025

The Standard Model at the LHC

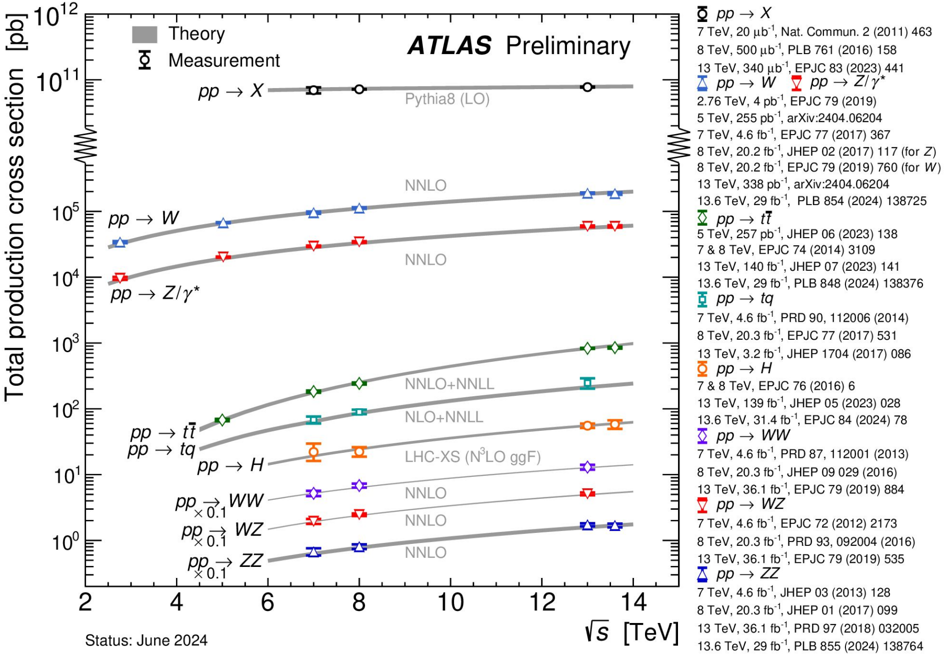
Physics Reports 1115 (2025) 3–115



Broad and spectacular confirmation of the Standard Model (and perturbative QCD/factorization)

Standard Model Measurements at the LHC

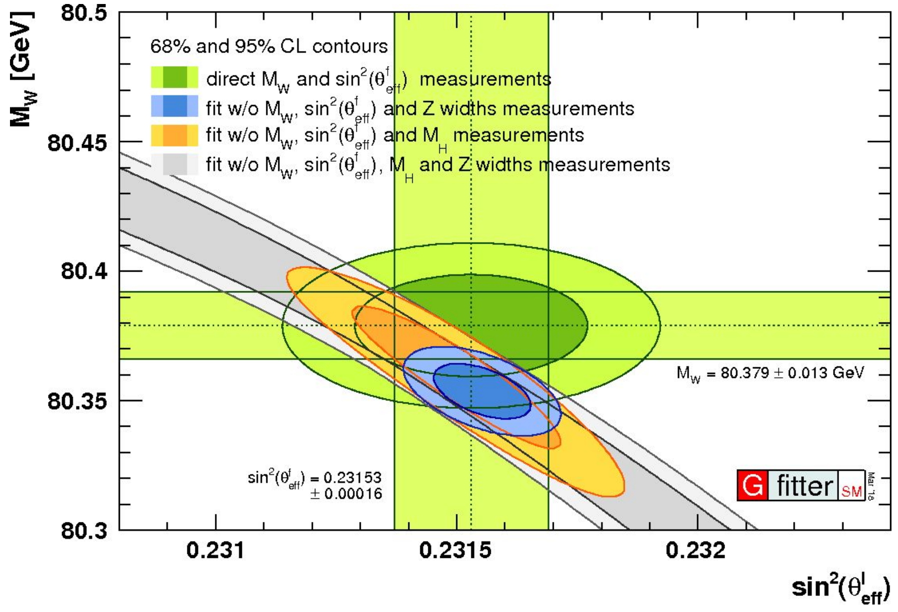
- Rich program at the LHC covers many aspects of the Standard Model
  - Non-perturbative QCD from soft physics and jet substructure
  - Perturbative QCD from jet physics (+ higher order corrections to all SM processes)
  - Tests/extraction of strong coupling constant and proton structure
  - Precision measurements of SM parameters (mW, mZ, sin2thetaW, mtop)
  - Measurements of rare processes and differential cross sections at high energies to probe vector boson and top couplings
- (Precision) measurements of Standard Model parameters and processes act as indirect searches for new physics
- (Higgs, flavour physics and direct BSM searches covered elsewhere)

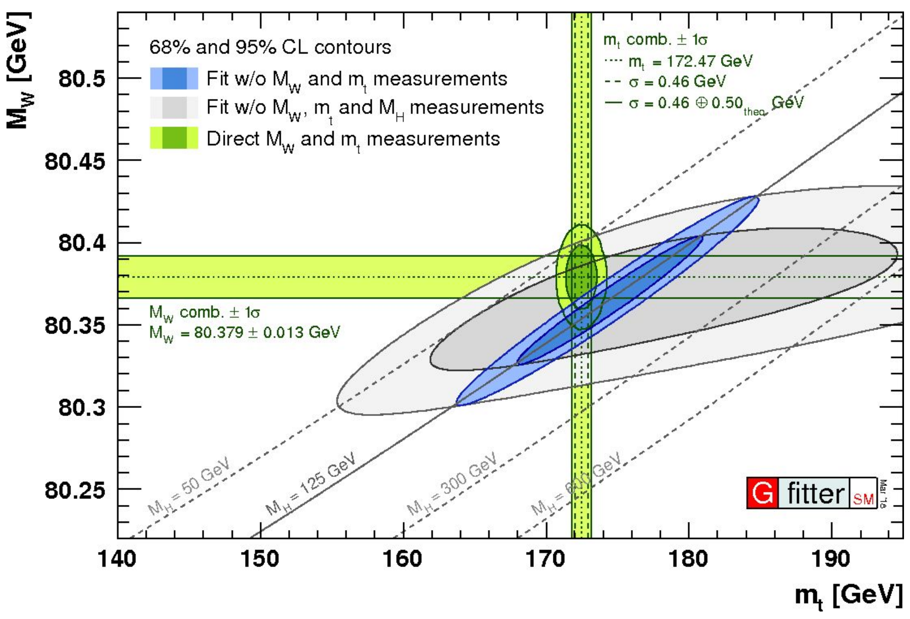


ATL-PHYS-PUB-2024-011

Electroweak Parameters

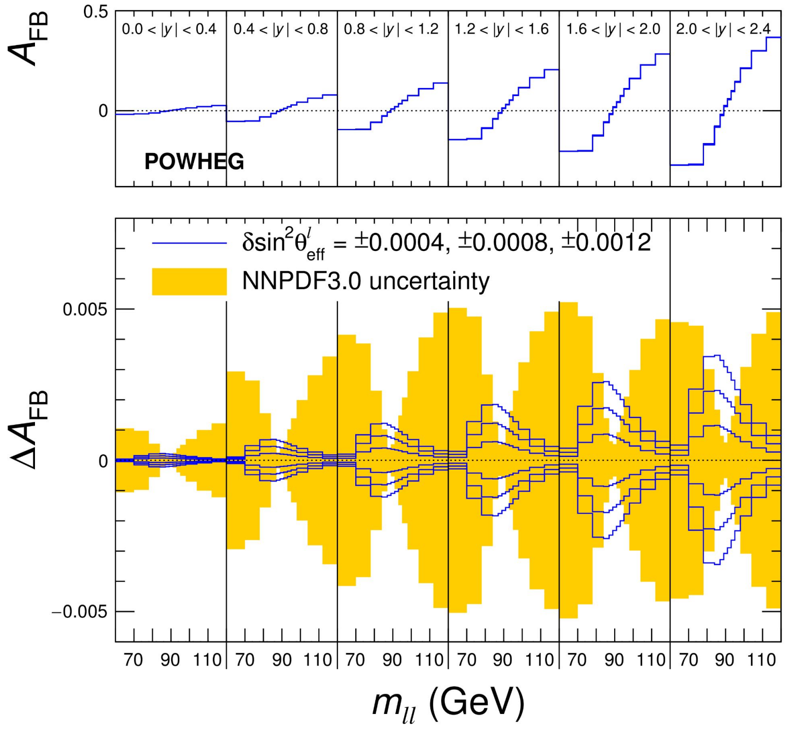
https://project-gfitter.web.cern.ch/Standard_Model/





- The discovery of the Higgs and the precise measurement of its mass provides the complete set of inputs needed to overconstrain the Standard Model
- Precision measurements are indirect searches for new physics

Weak Mixing Angle

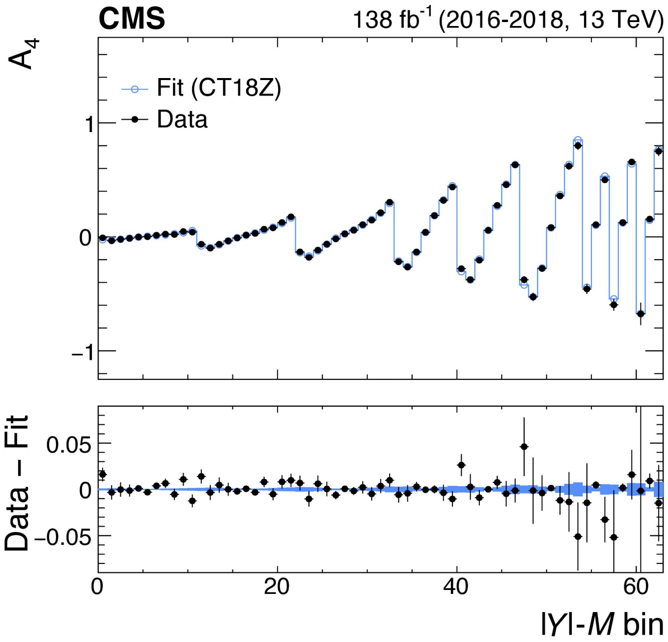


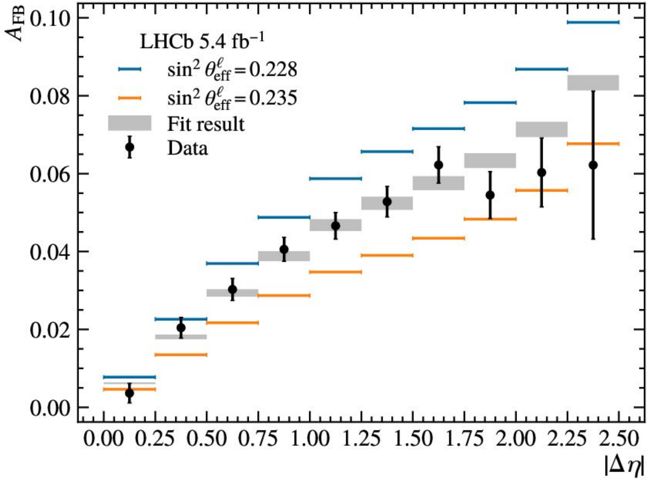
- sin2thetaW measured from forward-backward asymmetry in Z/gamma* -> ll events near the Z peak
- Incoming quark vs antiquark direction is not known per-event so direction of dilepton system is used as a proxy -> **significant dilution with strong dependence on PDFs**
- Dilution is reduced at high rapidity (high x)
- Differential measurement of Afb allows in-situ constraints on PDFs

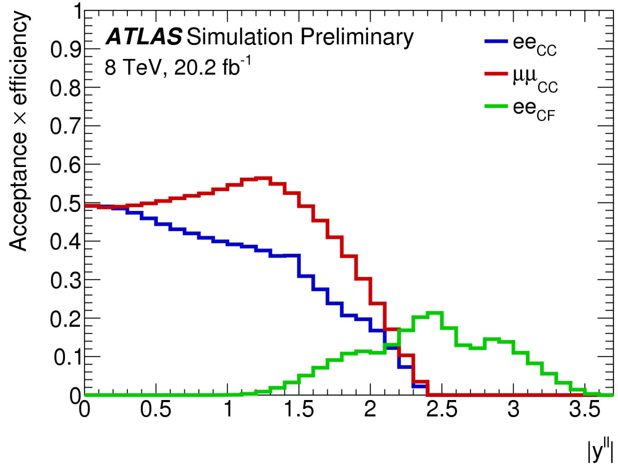
Eur. Phys. J. C (2018) 78: 701

Phys. Lett. B 866 (2025) 139526, ATLAS-CONF-2018-037, JHEP 12 (2024) 026

Weak Mixing Angle

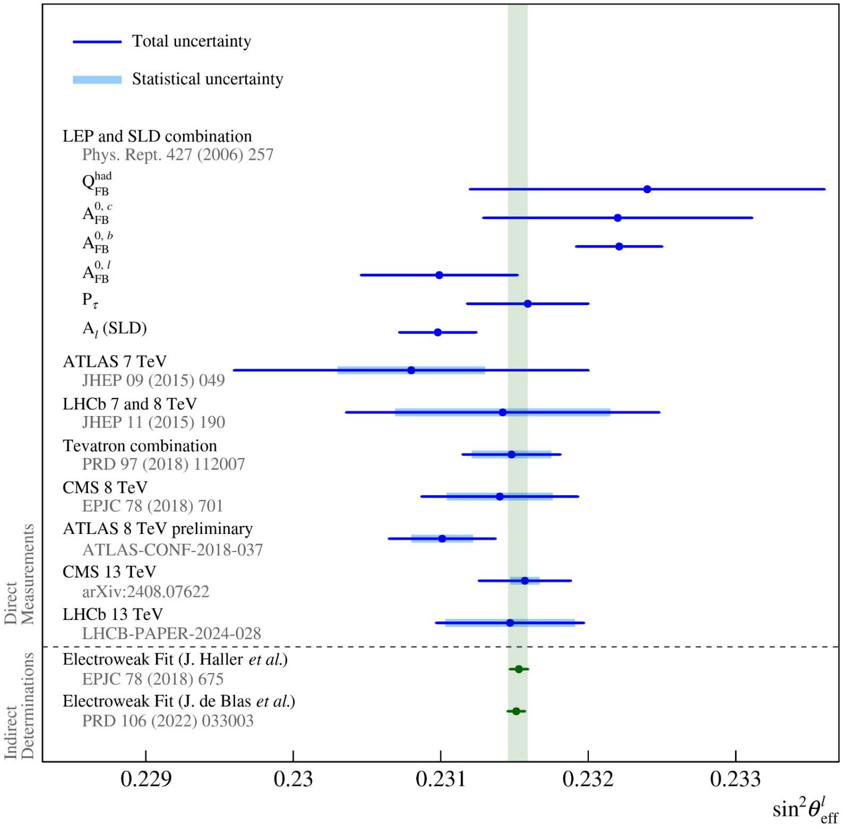


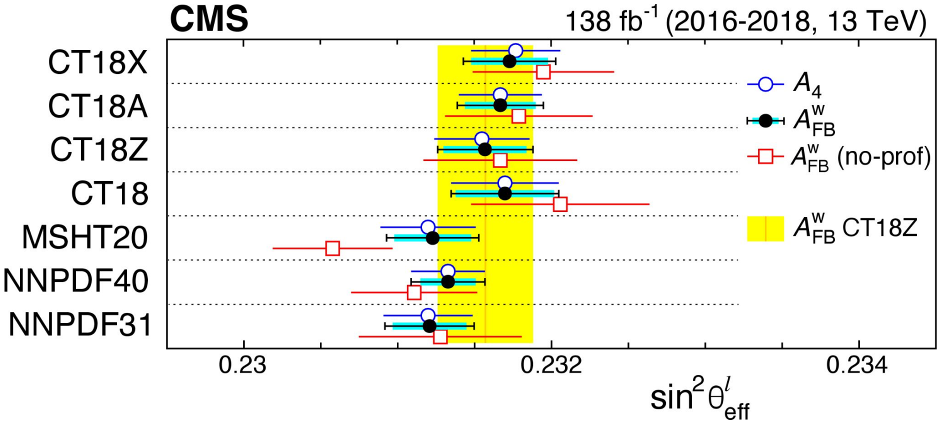




- ATLAS and CMS improve sensitivity through inclusion of forward electrons
- LHCb has forward rapidity coverage, but less integrated luminosity

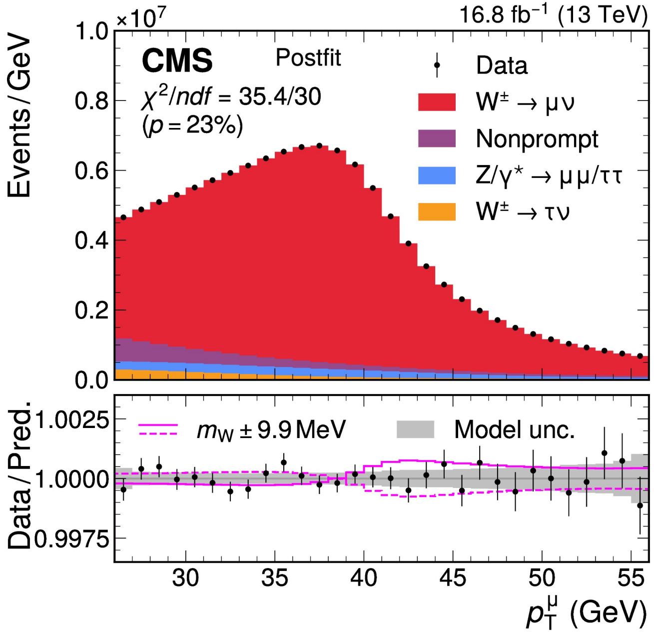
Weak Mixing Angle

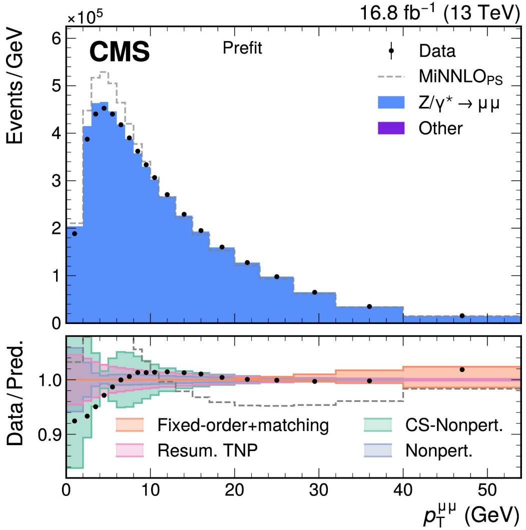


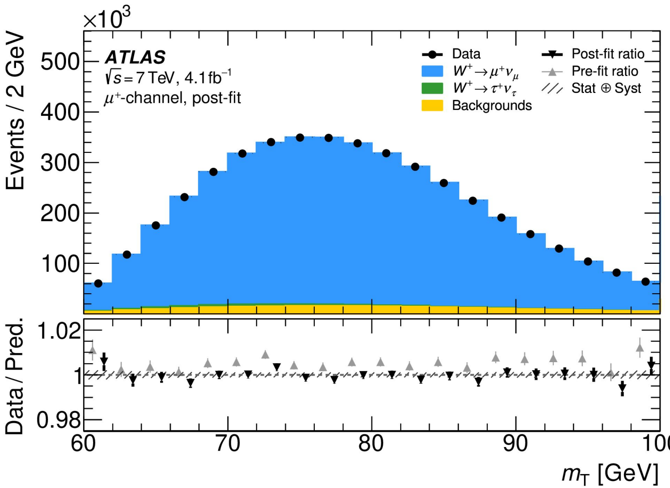


- LHC measurements now competitive with LEP/SLD
- For recent CMS measurement PDFs are largest uncertainty
- Non-negligible PDF dependence for result (though reduced by profiling)
- LHCb measurement is statistically dominated

W mass



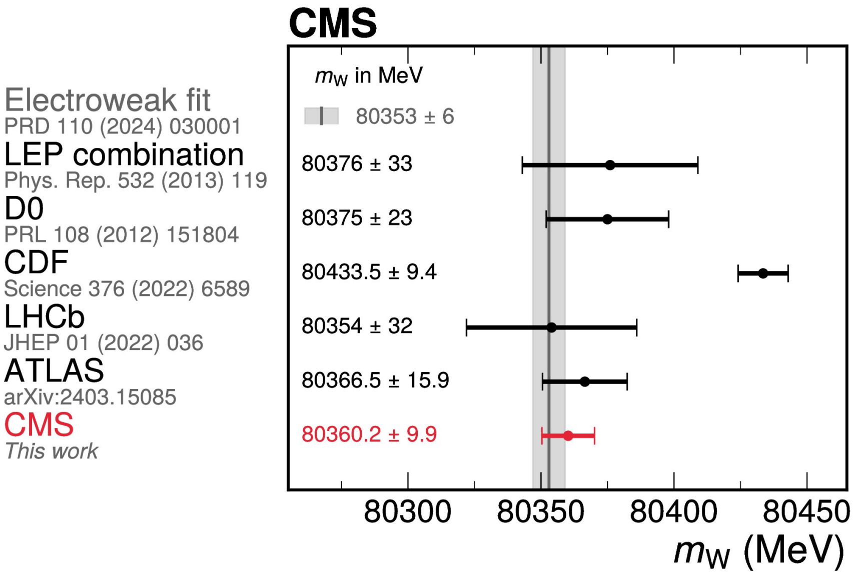




- W mass at LHC measured from charged lepton kinematics and/or transverse mass distributions
- Extreme control needed over experimental and theoretical modeling
- Significant PDF uncertainty through W polarization and acceptance
- Theory challenges in modeling effect of soft gluon emissions
- Z->ll events are an essential standard candle for calibration and/or validation

arXiv:2412.13872, Eur. Phys. J. C 84 (2024) 1309, JHEP 01 (2022) 036

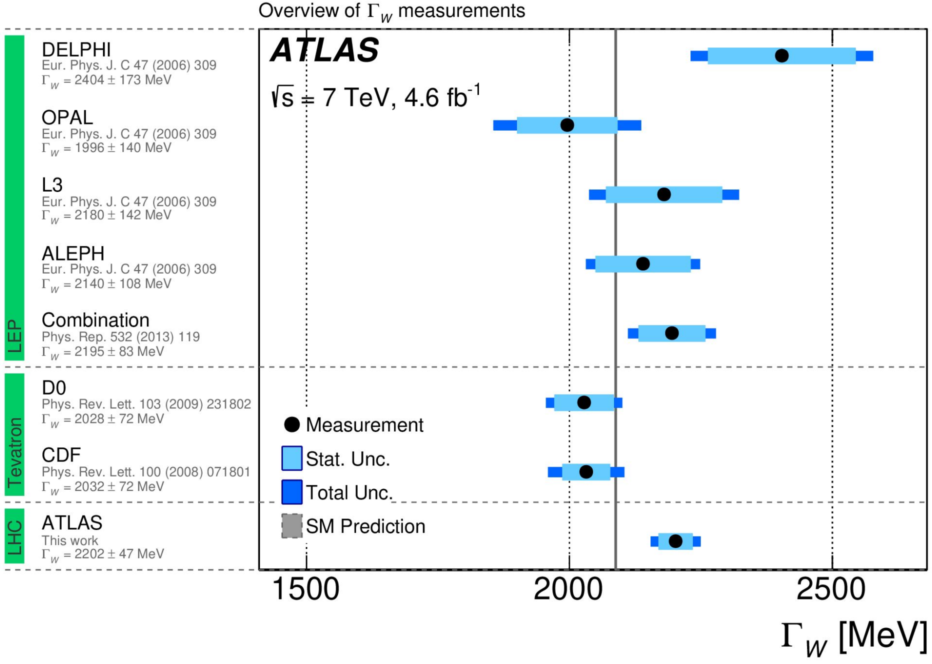
W mass

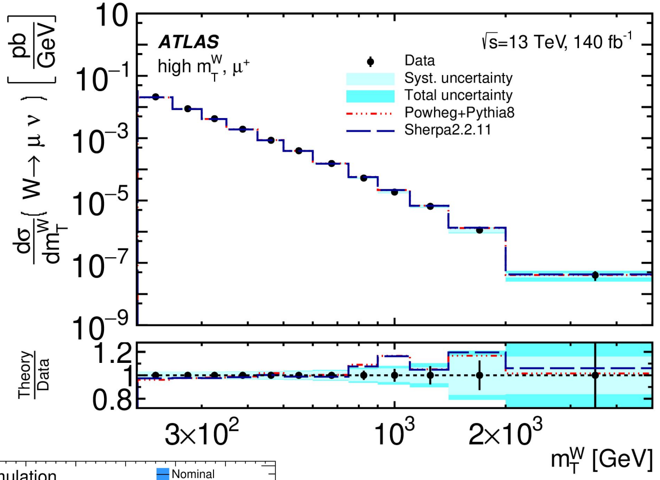


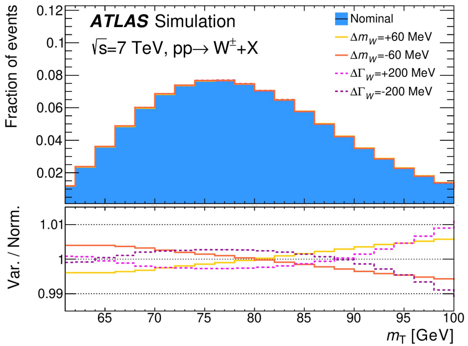
Source of uncertainty	Impact (MeV) Nominal	Impact (MeV) Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4	6.0
Total uncertainty	9.9	9.9

- Recent CMS measurement is the most precise at the LHC, approaching quoted CDF precision, compatible with SM prediction and other measurements
- Exploits strong in-situ constraints to reduce PDF/QCD uncertainties
- Clear tension with CDF measurement

W width and off-shell production





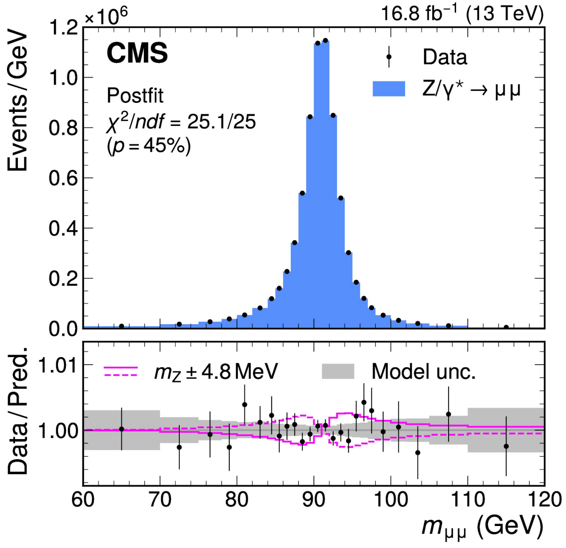


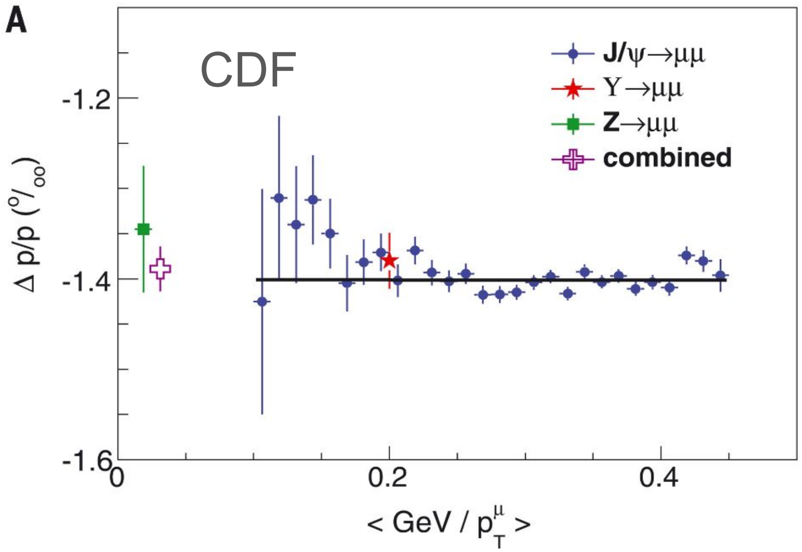
- W width is also predicted by the SM given mW and other parameters
- Updated ATLAS mW measurement includes most precise determination of the W width
- Sensitivity driven by the transverse mass distribution
- Recent cross section measurement also at high transverse mass

Eur. Phys. J. C 84 (2024) 1309, arXiv:2502.21088

Z mass

arXiv:2412.13872, *Science* 376 (2022) 6589, 170-176





$$\mathbf{m_Z - m_Z^{PDG} = -2.2 \pm 4.8\ MeV}$$

$$M_Z = 91,192.0 \pm 6.4_{\rm stat} \pm 4.0_{\rm syst}\ \mathrm{MeV}$$

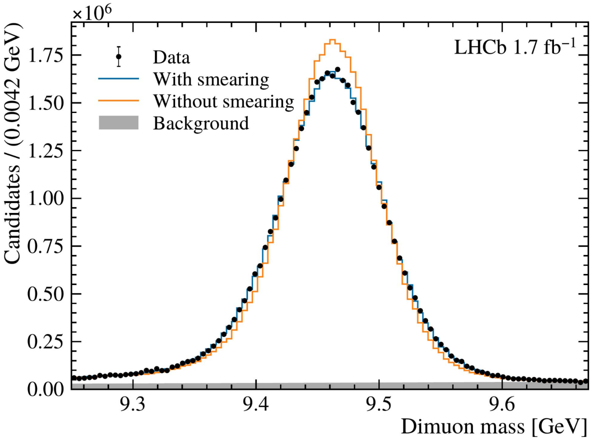
- mW measurement at hadron colliders requires very precise calibration of lepton energy/momentum scale
- Calibration with quarkonium can be used for an independent measurement of the Z mass
- CMS Z mass validation not quite an independent measurement since consistency with the LEP Z mass was used to define the final systematic uncertainties (and not fully blind during validation of the J/psi calibration)
- CDF Z mass measurement from J/psi + Upsilon 1S calibration is included in the PDG value (though with small weight compared to 2.1 MeV uncertainty from LEP)

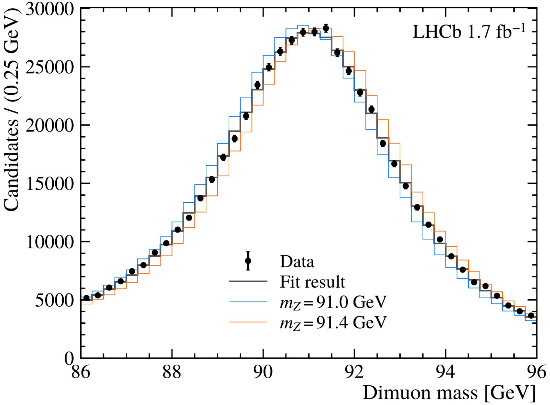
Z mass

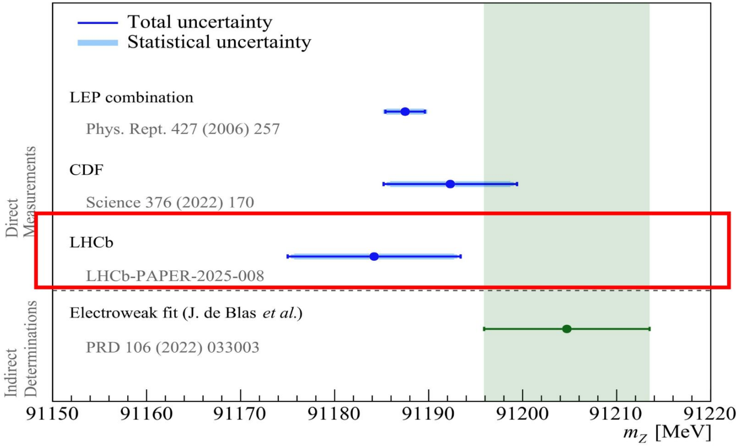
arXiv:2505.15582

Source	Uncertainty [MeV]
Momentum calibration	3.6
Signal final-state radiation	0.8
Parton distribution functions	0.7
Detection efficiency	0.1
Total systematic uncertainty	3.8

$$p \to (1 + \alpha + \beta/p - q\delta p)\, p,$$



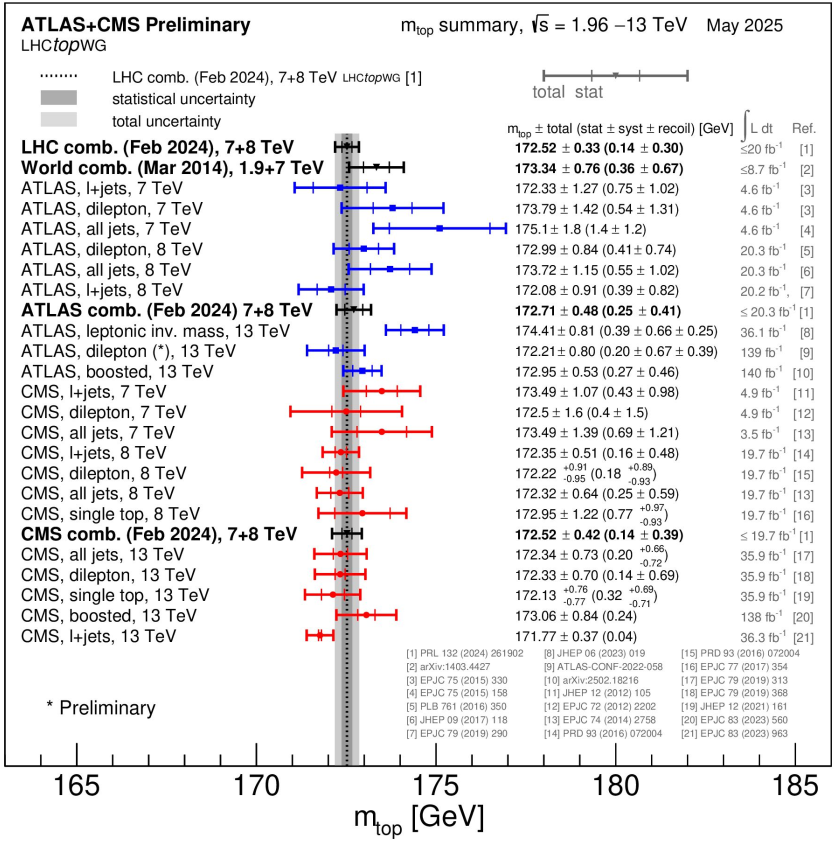


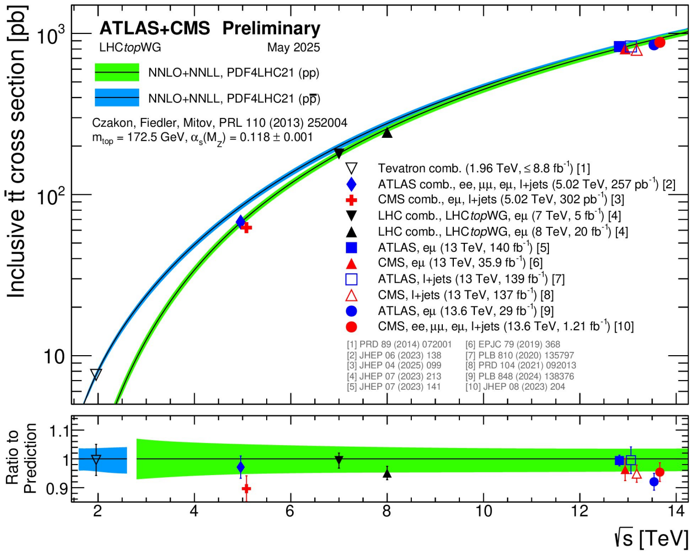


$$m_Z = 91184.2 \pm 8.5 \pm 3.8\,\mathrm{MeV}$$

- LHCb Z mass measurement in dimuon final state: **first at the LHC**
- Muon momentum scale calibrated from Upsilon 1S, independent validation with J/psi
- Dedicated calibration steps and/or uncertainties for B-field-like, energy loss/material, and alignment terms: **linearity of momentum scale crucial in extrapolation from Upsilon to Z**
- Measurement is statistically dominated for now, but systematic uncertainty approaching LEP precision

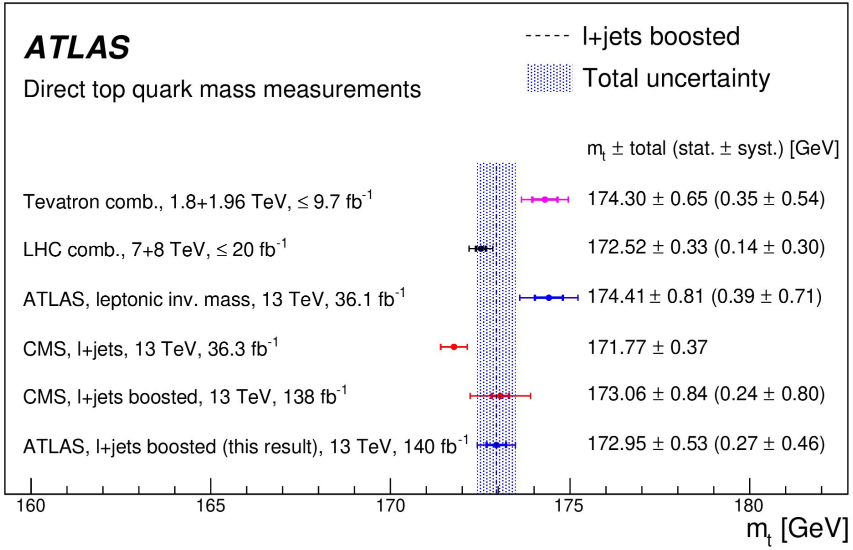
Top Mass

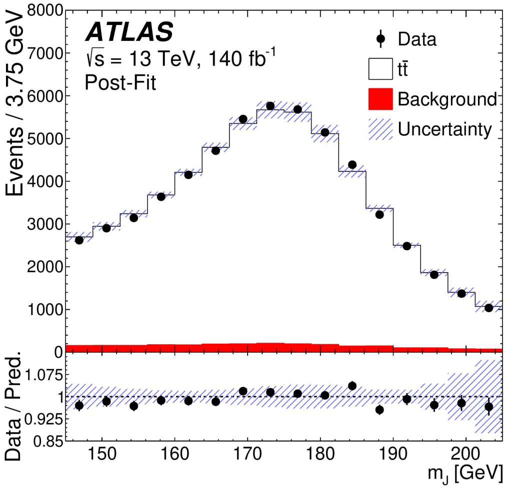


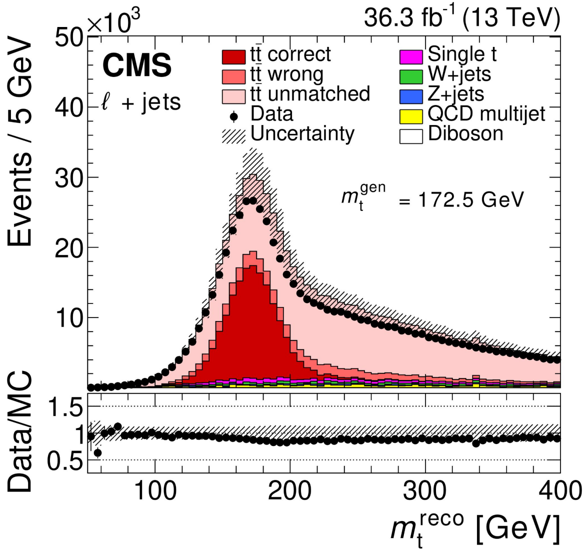


- Top mass at LHC measured most precisely from direct reconstruction of decay products, but with some theoretical ambiguity
- Pole-mass can be measured from production cross sections
- Important to test/establish consistency across many methods

Direct top mass measurements



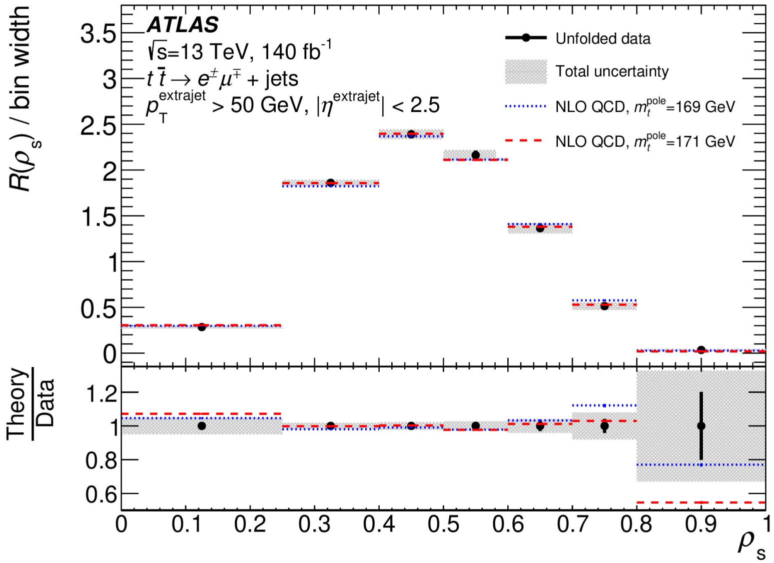


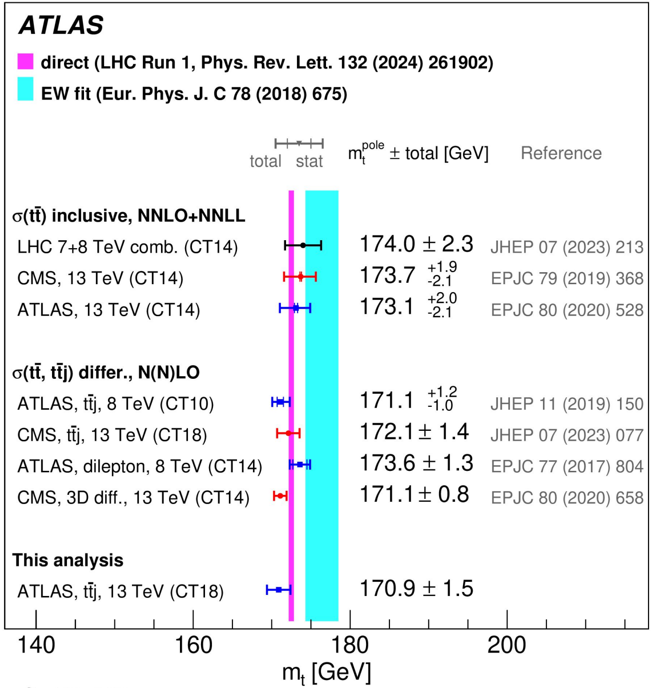


- Most precise measurements from direct reconstruction of hadronic top decays in l+jets events
- Both resolved and merged/boosted topologies can be used
- Aside intrinsic theoretical ambiguity, both theory modeling and Jet Energy/Mass scale uncertainties are relevant
- Boosted jet substructure/reconstruction also plays an important role in Higgs physics and direct BSM searches

Top pole mass

arXiv:2507.02632

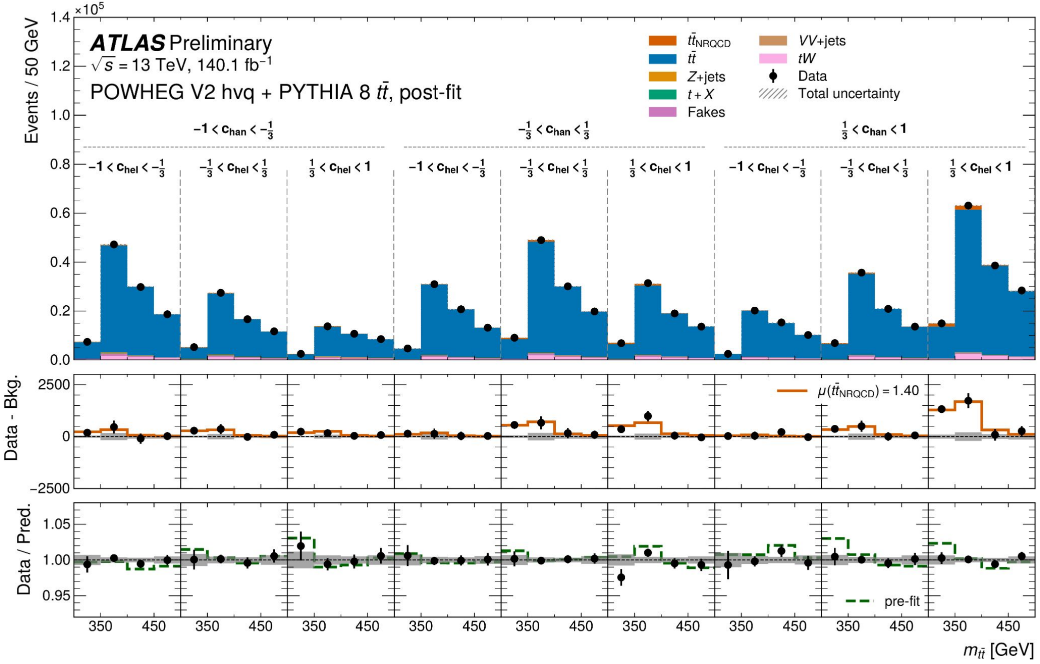


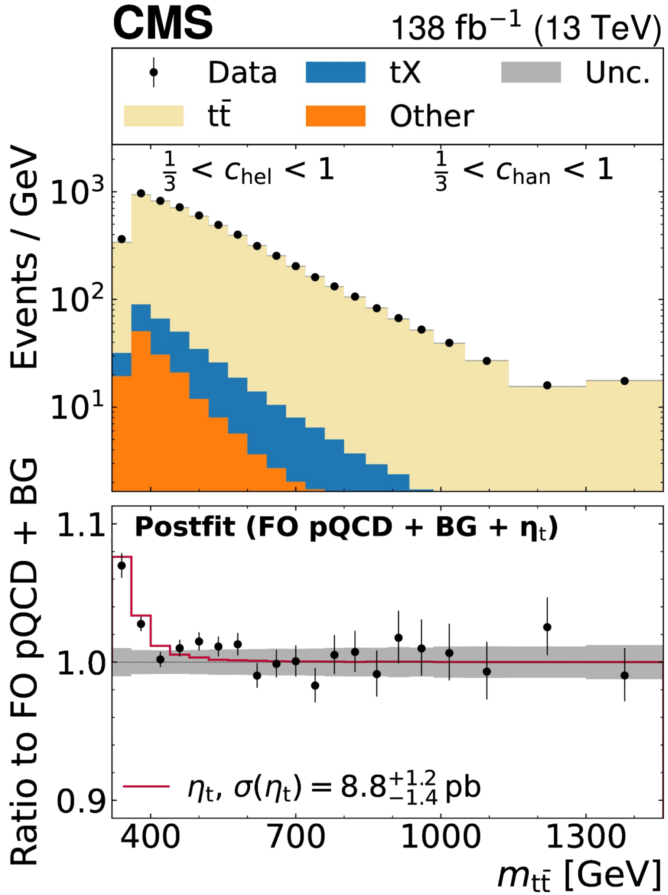


$$m_t^{\text{pole}} = 170.73 \pm 0.33\ (\text{stat.}) \pm 1.36\ (\text{syst.})\ ^{+0.28}_{-0.34}\ (\text{scale})\ ^{+0.24}_{-0.24}\ (\text{PDF} + \alpha_s)\ \text{GeV}$$

- Use of differential cross sections reduces theory uncertainties
- Presence of an additional jet enhances sensitivity to top mass and avoids theoretically difficult threshold production
- Largest uncertainties are related to parton shower modeling

Top Production at threshold

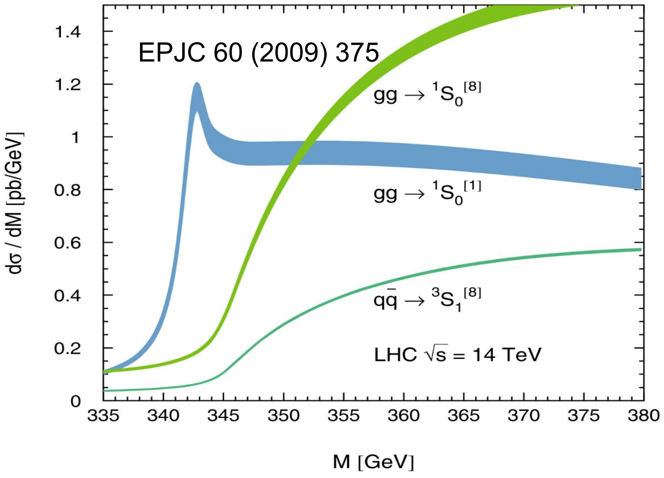




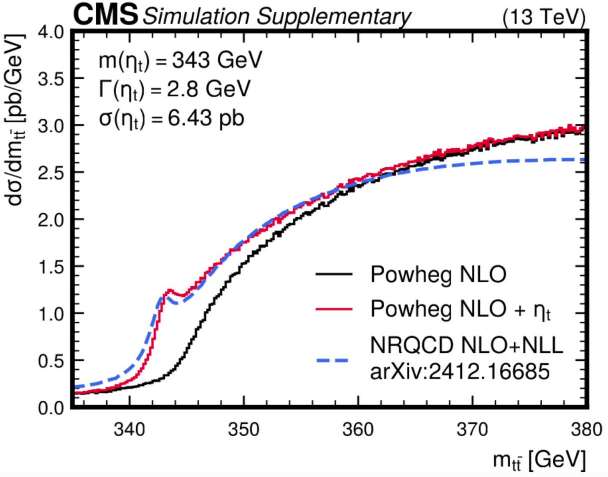
- Excess in ttbar production at threshold compared to perturbative QCD prediction in both ATLAS and CMS at > 5 sigma
- Further subdivided according to angular distributions sensitive to spin/parity
- Can be interpreted as a quasi-bound toponium state in NR-QCD

arXiv:2503.22382, ATLAS-CONF-2025-008

Top production at threshold



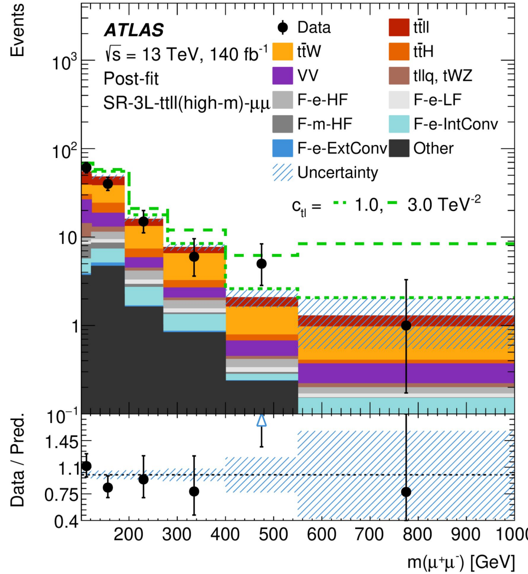
Experiment	Model	Cross Section (pb)
ATLAS	**NR-QCD**	**9.0 +- 1.2 (stat) +- 0.6 (syst)**
ATLAS	Pseudoscalar	13.4 +- 1.7 (stat) +- 1.0 (syst)
CMS	**Pseudoscalar**	**8.8 +- 0.5 (stat) +- 1.2 (syst)**

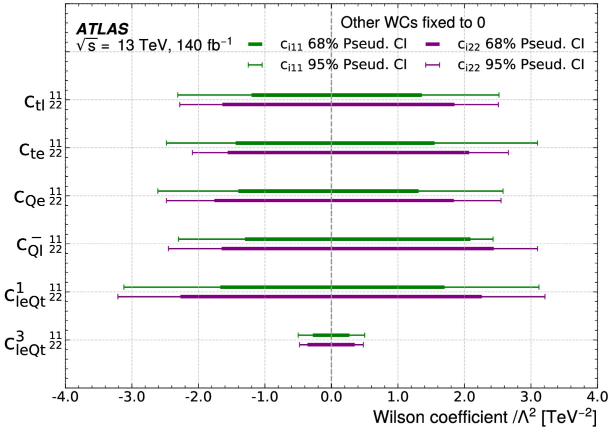


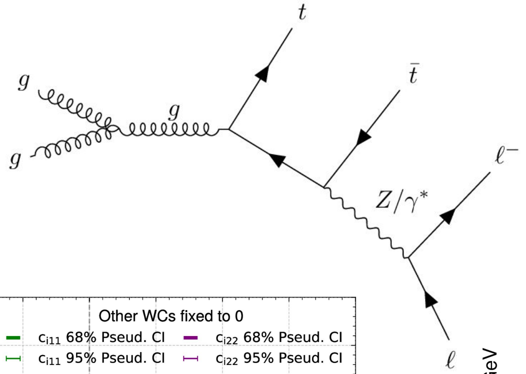
- NR-QCD quasi-bound state can also be approximated with a simplified model: pseudoscalar resonance with appropriate mass/width/coupling
- Nominal cross sections for additional state agree between ATLAS and CMS, but with different signal models
- Non-negligible theory modeling uncertainties in both cases (but different methods used for uncertainty breakdowns)
- More theoretical study needed for improved interpretations in the future

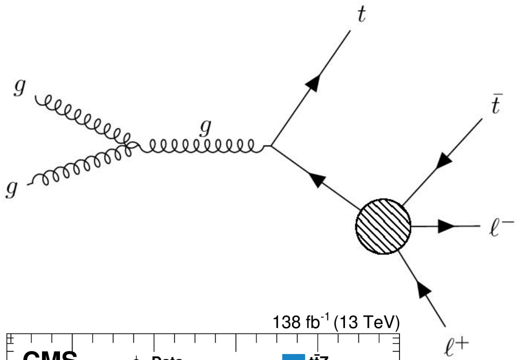
arXiv:2503.22382, ATLAS-CONF-2025-008

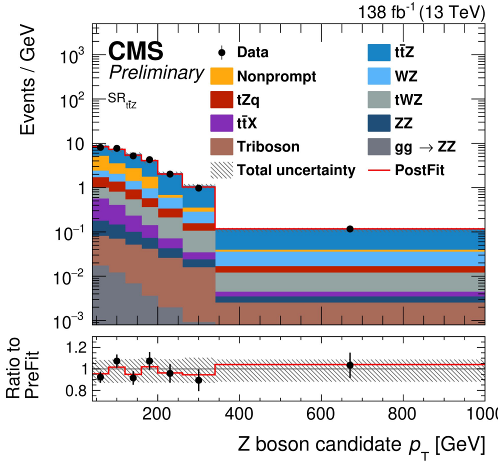
Top couplings: Z/leptons







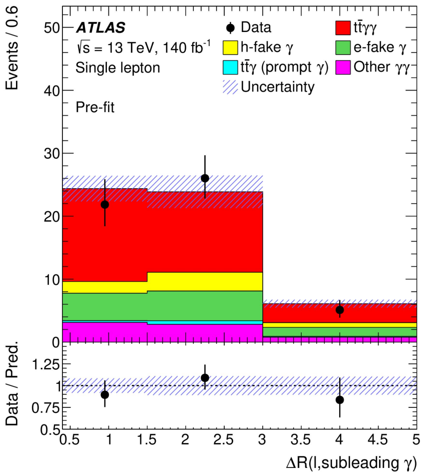


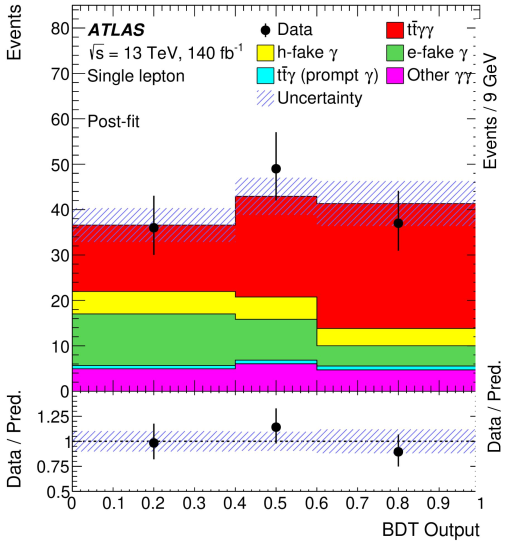


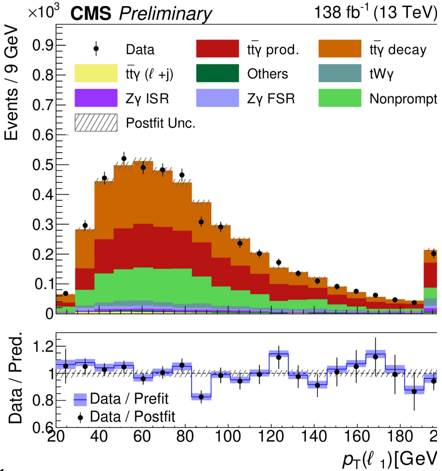
- ttbar + dilepton production can be interpreted either in an SM or SMEFT context
- Also sensitive to flavour-dependent dim-6 operators
- Recent ATLAS and CMS results consistent with SM

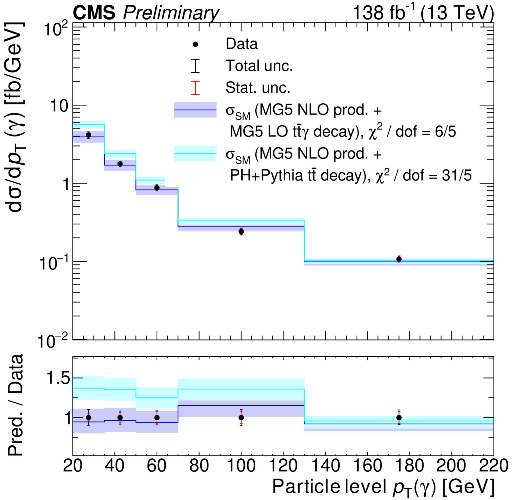
arXiv:2504.05919, CMS-PAS-TOP-23-009

Top couplings: photons









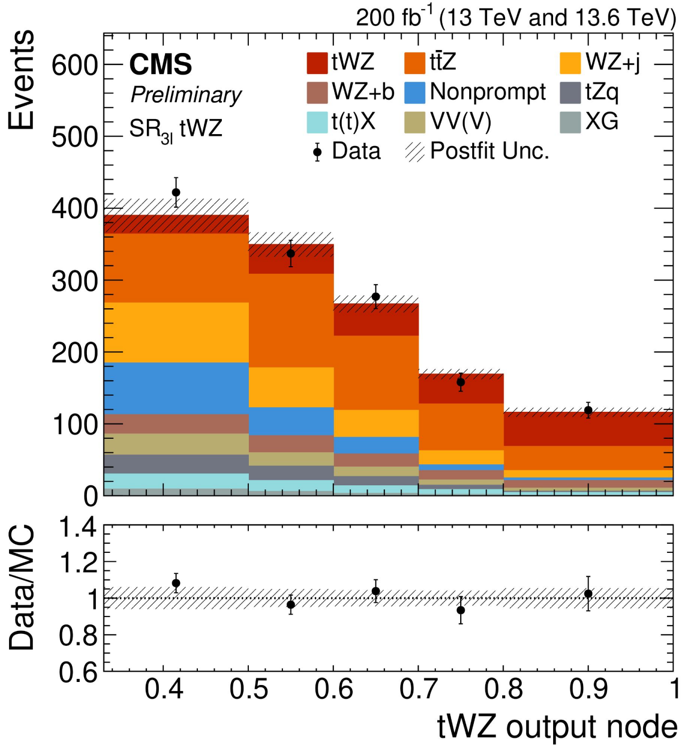
First observation of ttγγ

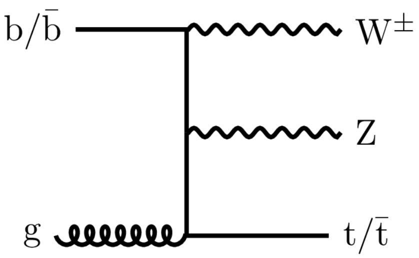
Differential measurements of ttγ production

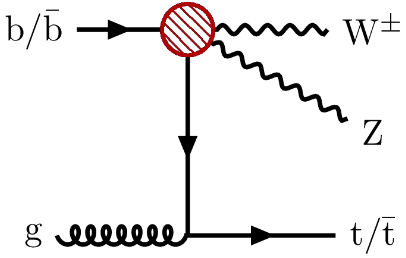
arXiv:2506.05018,
CMS-PAS-TOP-23-002

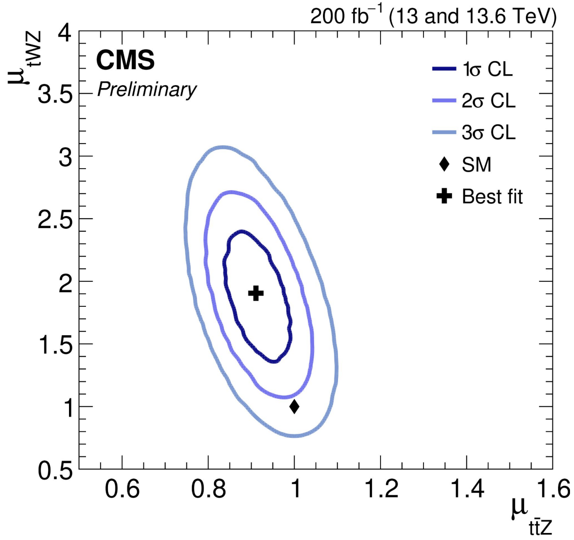
CMS-PAS-TOP-24-009

Top couplings: Rare processes



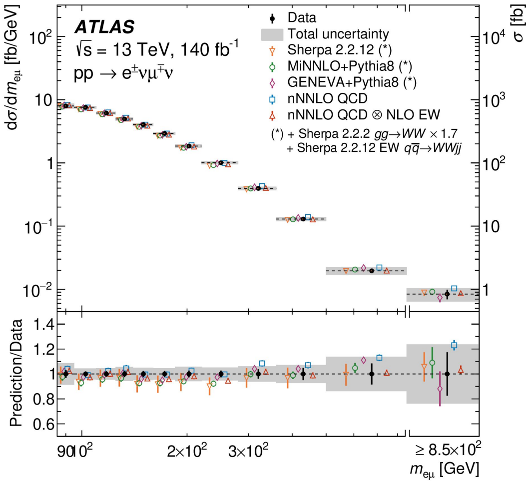


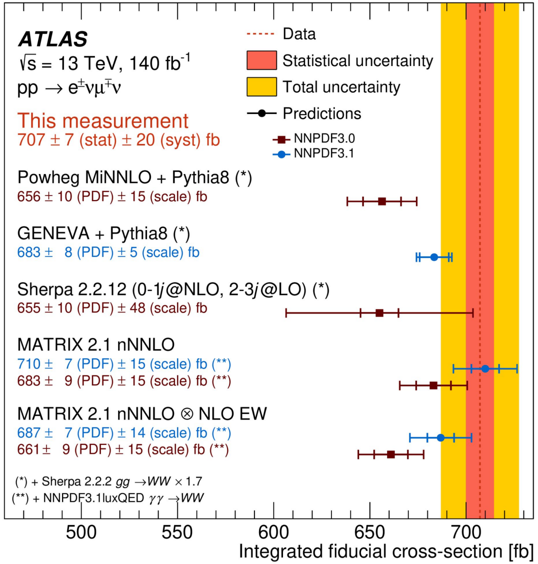


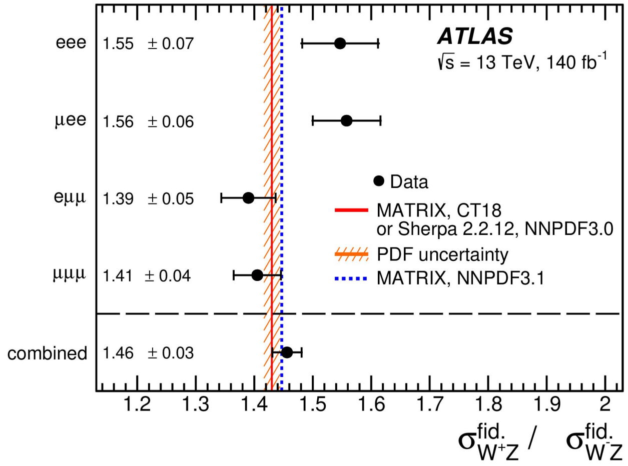


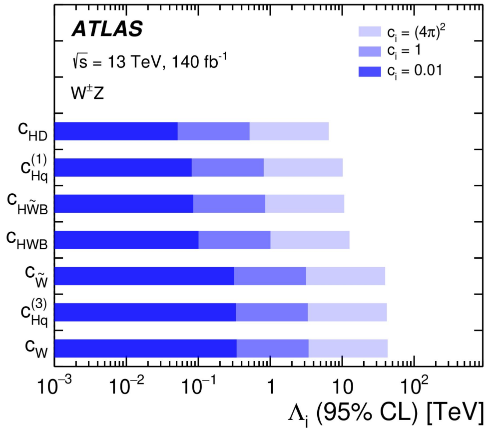
- First observation of tWZ production

Diboson Production







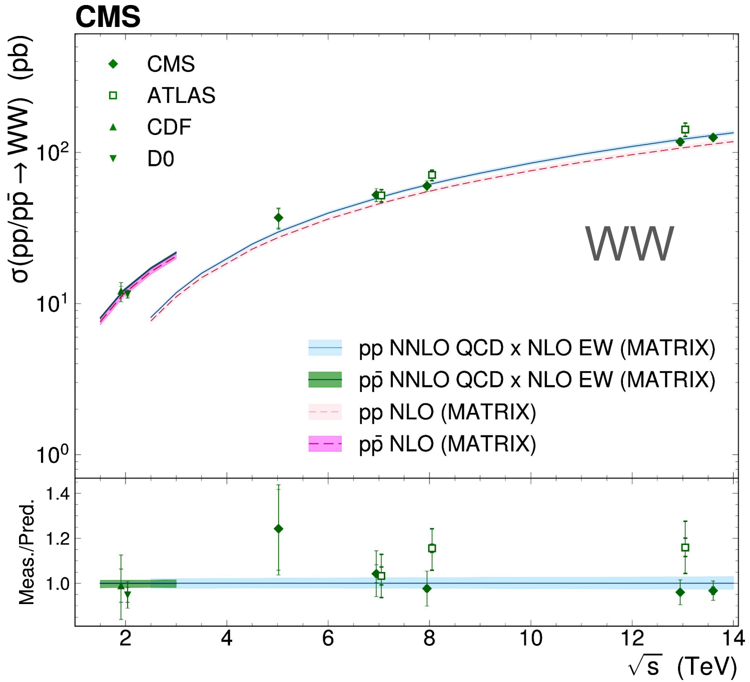


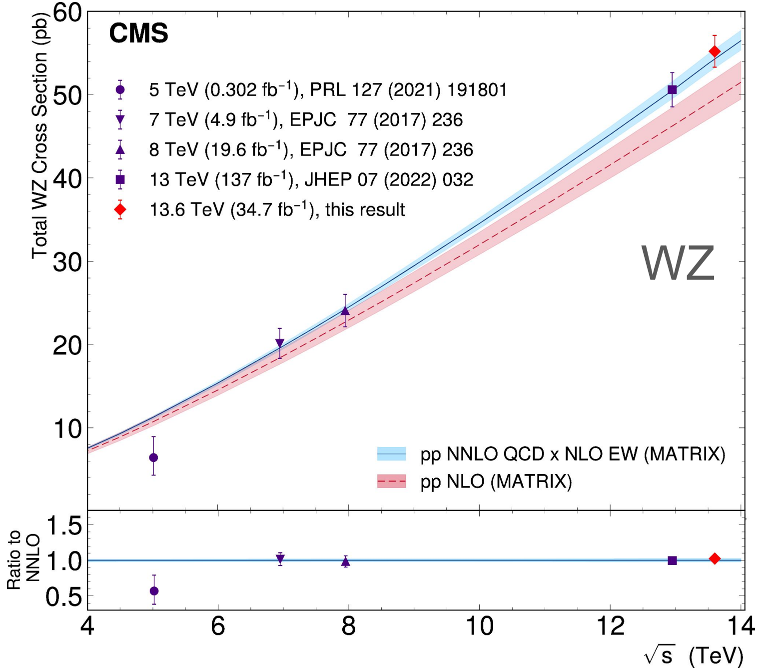
- Comprehensive measurement of WW and WZ production cross sections, asymmetries, with EFT interpretation

arXiv:2505.11310, arXiv:2507.03500

Phys. Lett. B 861 (2025) 139231, JHEP 04 (2025) 115

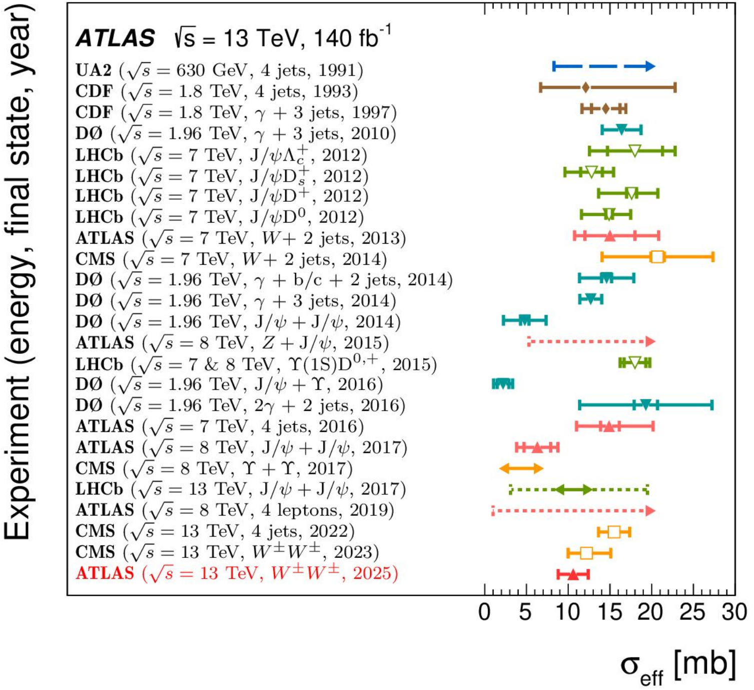
Diboson production



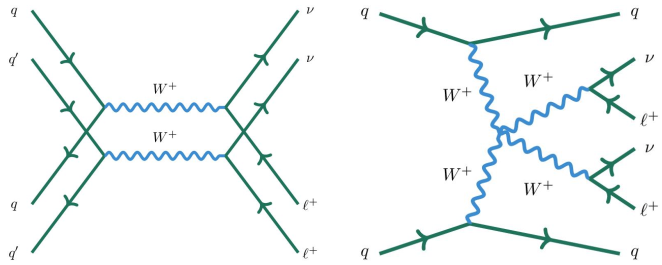


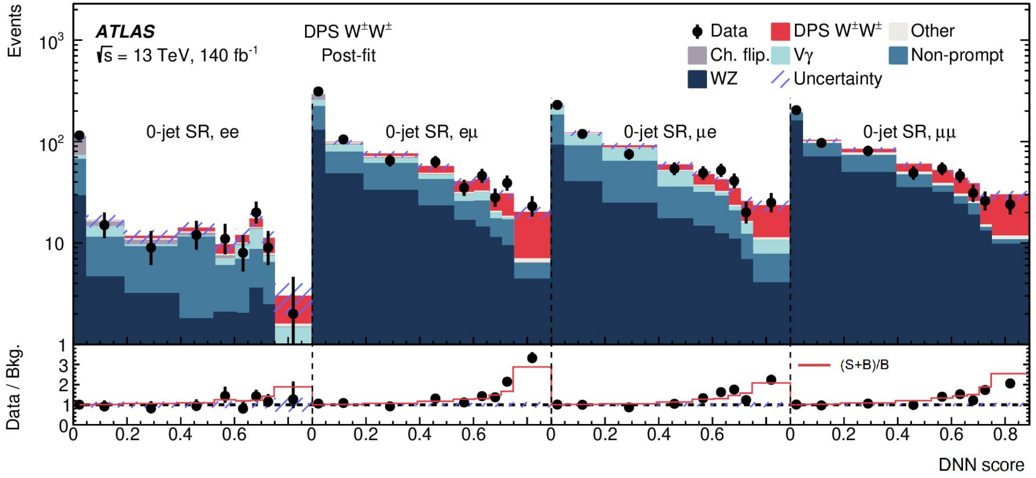
- Diboson production cross sections have been measured over a wide range of center of mass energy up to 13.6 TeV
- Effect of higher order corrections clearly visible

Dibosons: Double Parton Scattering



$$\sigma_{AB}^{DPS} = \frac{1}{1+\delta_{AB}} \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

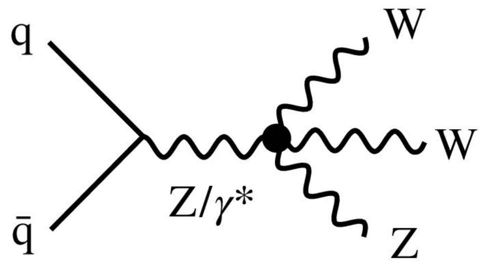


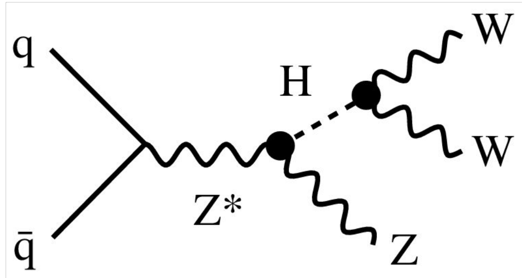


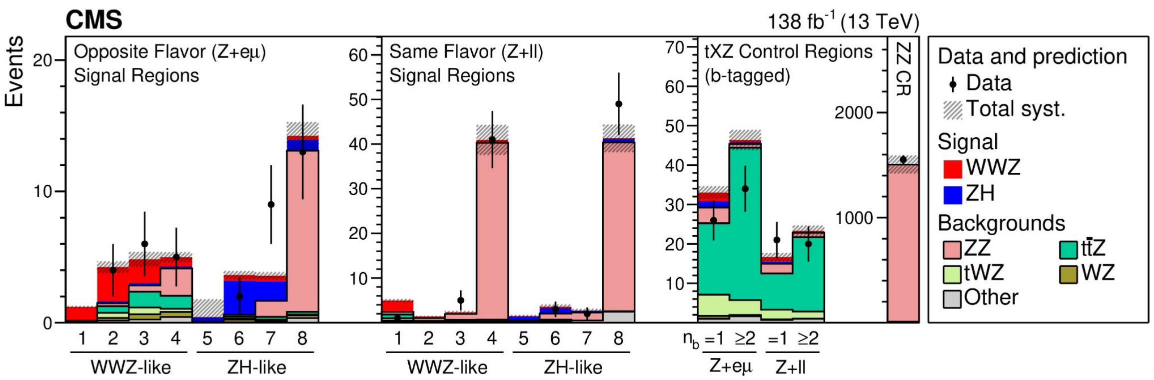
- Same-sign WW production from single parton scattering is heavily suppressed
- Unique probe of double parton scattering at high scales
- Complements existing CMS measurement

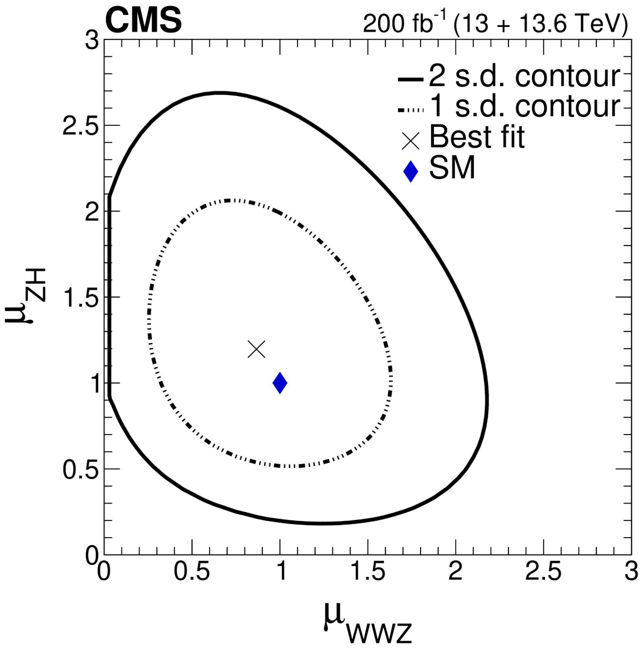
arXiv:2505.08313

Triboson Production



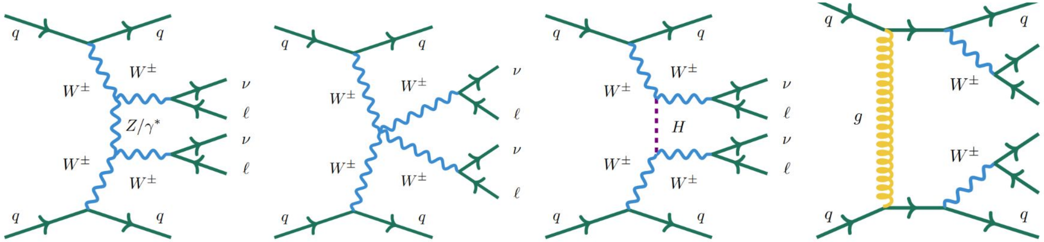


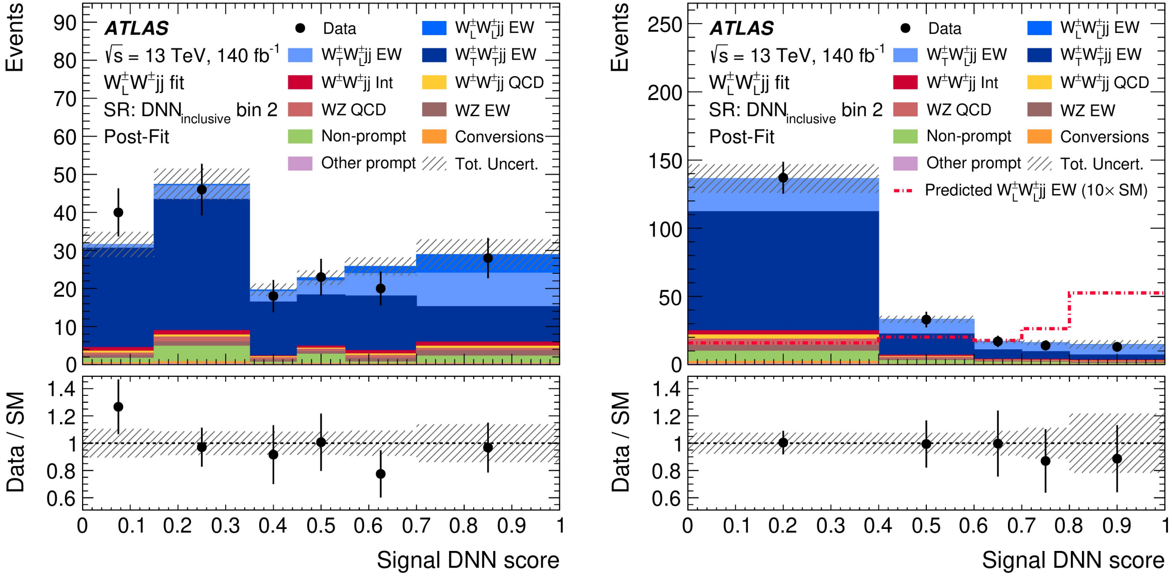




- WWZ production measured in events with 4 leptons (+ missing energy)
- Continuum contribution separated from ZH
- Results consistent with SM using Run 2+3 data

Longitudinally Polarized Vector Boson Scattering

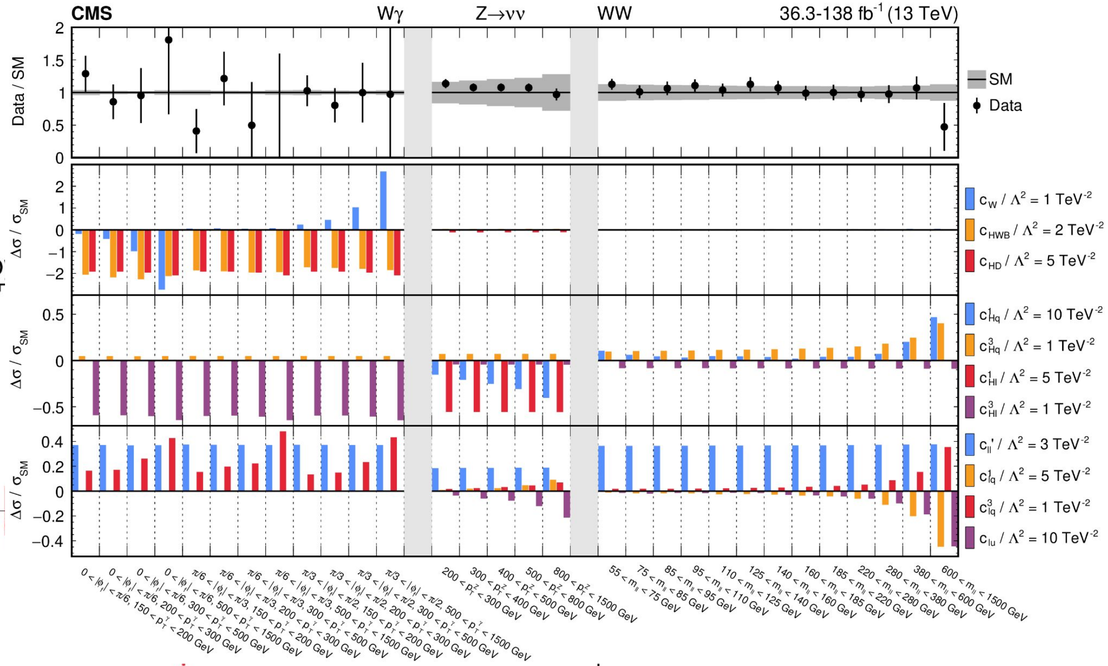


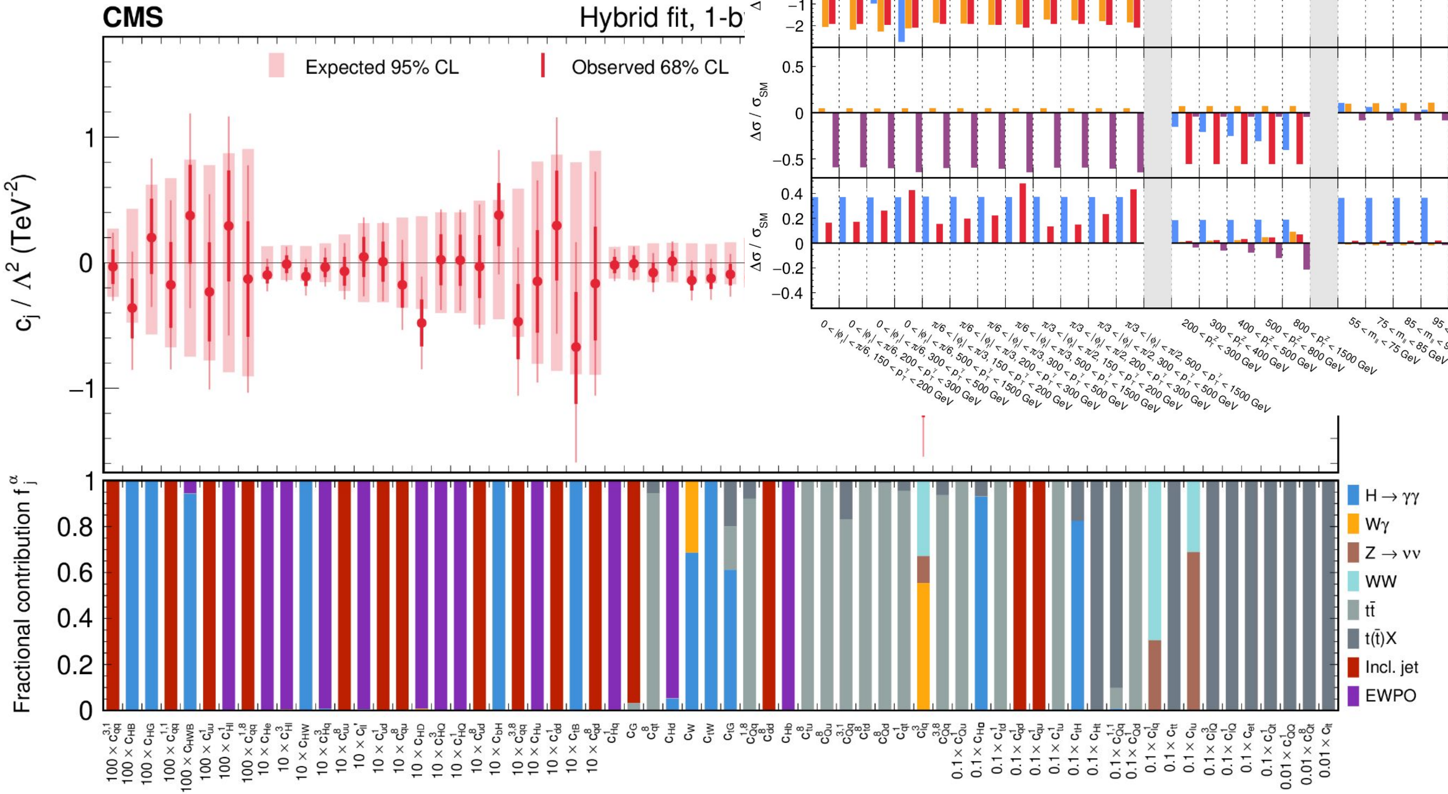


- Longitudinal polarization of vector bosons and the unitarity of vector boson scattering is closely related to EW symmetry breaking
- First evidence of scattering with at least one longitudinally polarized W in recent ATLAS result
- Previous CMS results on this subject

arXiv:2503.11317

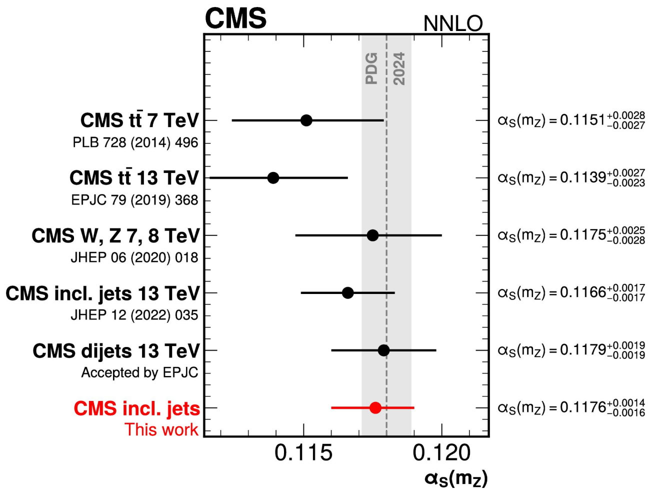
EFT Interpretation

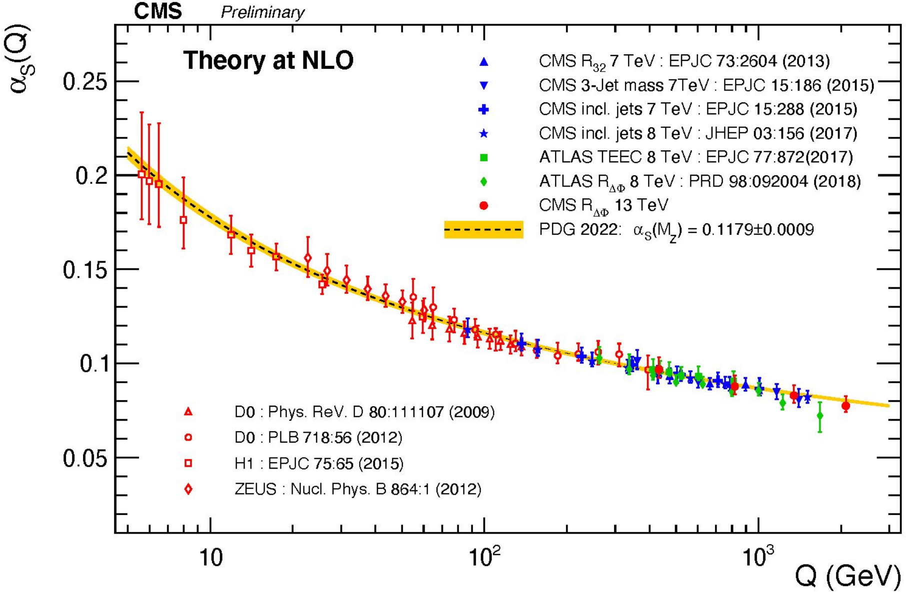




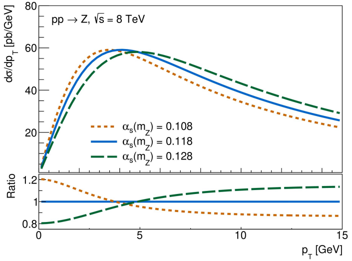
arXiv:2504.02958

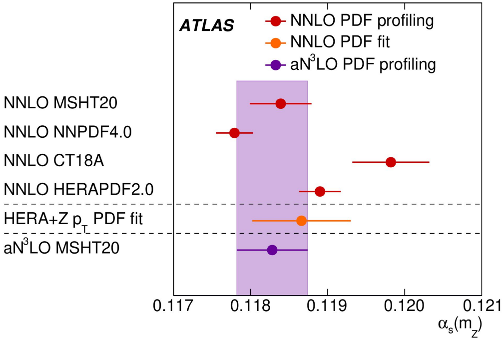
Strong coupling Constant





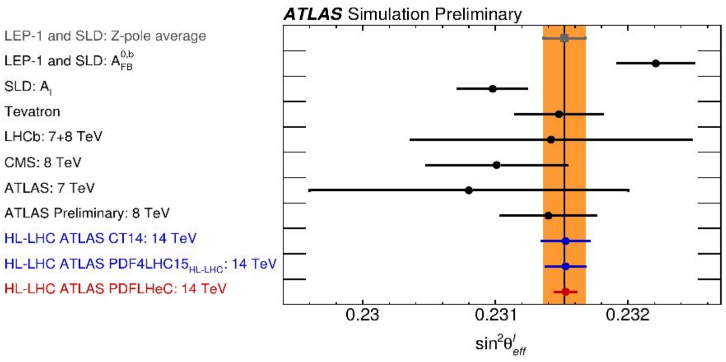
- Measurement of strong coupling constant from many different observables across a range of scales at the LHC
- Strong interplay with PDFs

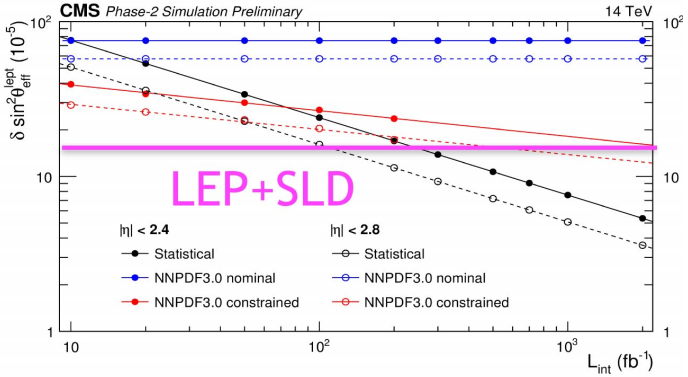




Phys. Lett. B 868 (2025) 139651, arXiv:2309.12986

Future

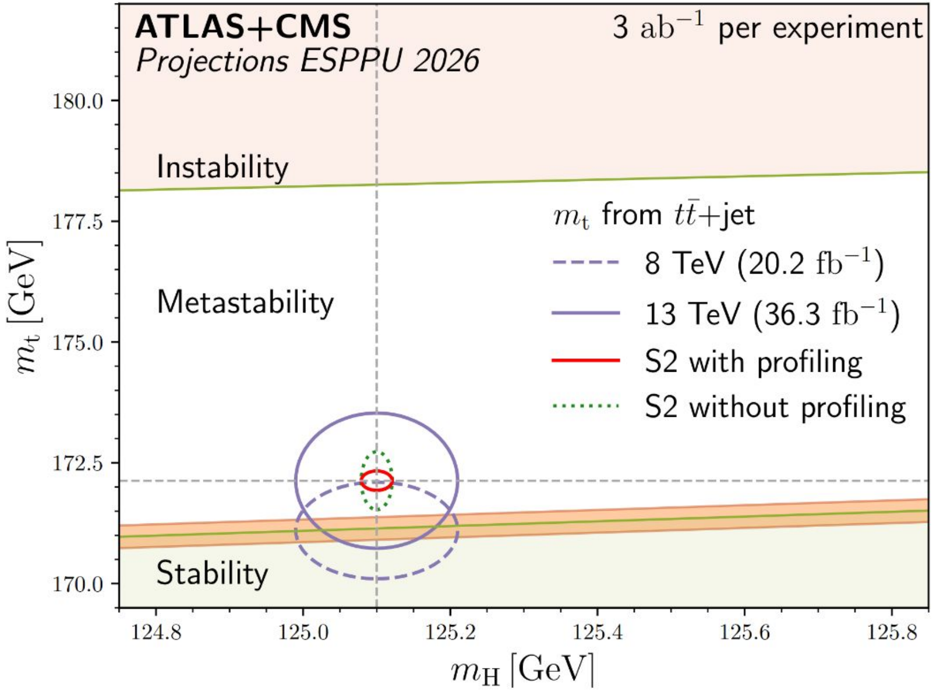




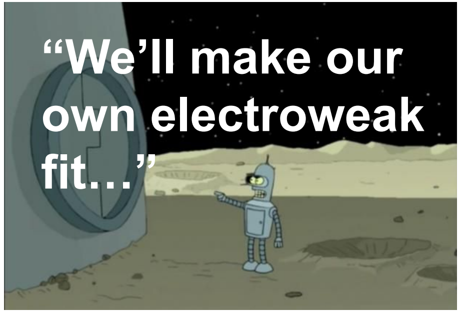
- Next:
  - Full exploitation of LHC Run 2 and Run 3 data
  - High Luminosity LHC
- **Weak mixing angle** benefits from both higher statistics and upgraded detectors (and improved external knowledge of PDFs) -> surpass LEP+SLD precision
- **W mass:** More data, additional observables, improved theory and calibrations, low PU data, combination of experiments: < 5 MeV precision achievable
- **Z mass:** Measurements competitive with LEP conceivable with more data, improved calibration samples and methodology
  - This also has synergy with precise tracking and calibration for e.g. FCC-ee detectors
- Analysis preservation/re-interpretability key to incorporate e.g. improved PDFs from future electron-proton collider, improved parametric inputs from FCC-ee, etc

Future: Top Mass

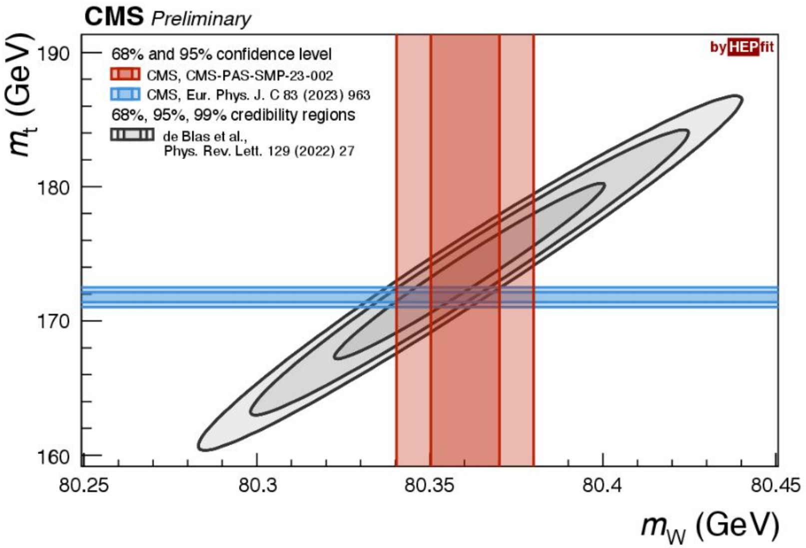
- HL-LHC projections for top mass precision range from 200-600 MeV depending on theoretical interpretation, and degree of control over systematic uncertainties

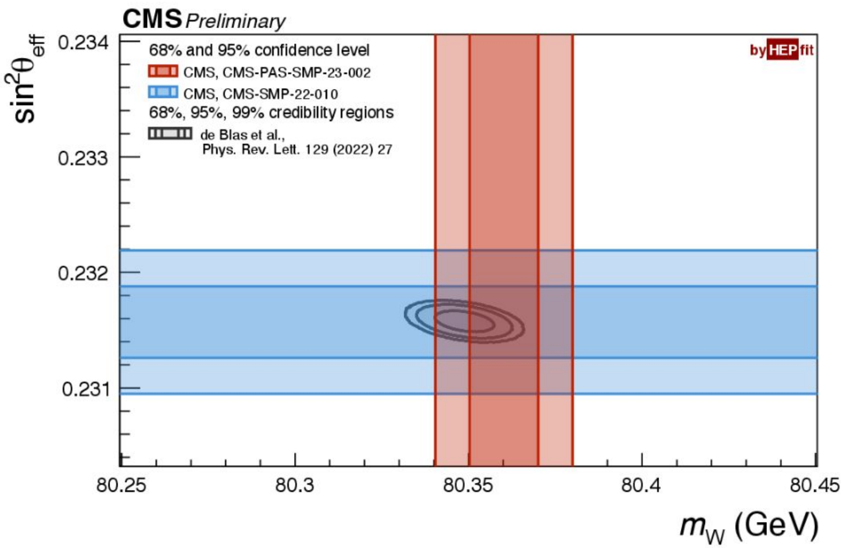


Electroweak Parameters

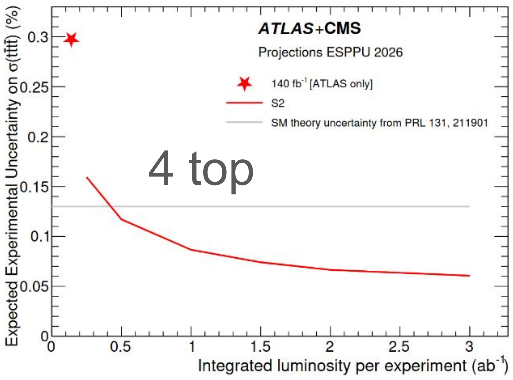


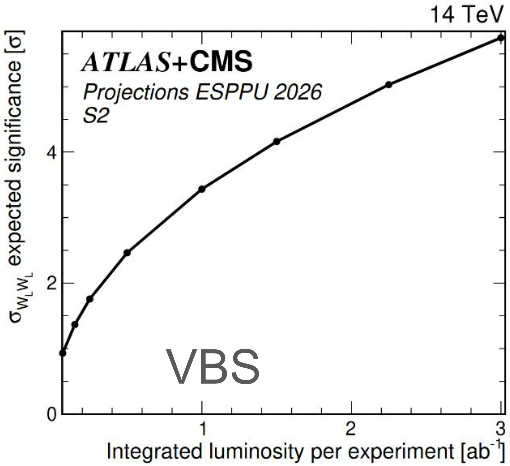
- LHC measurements approaching global EW fit precision and will have increasing importance in tests of the SM moving forward



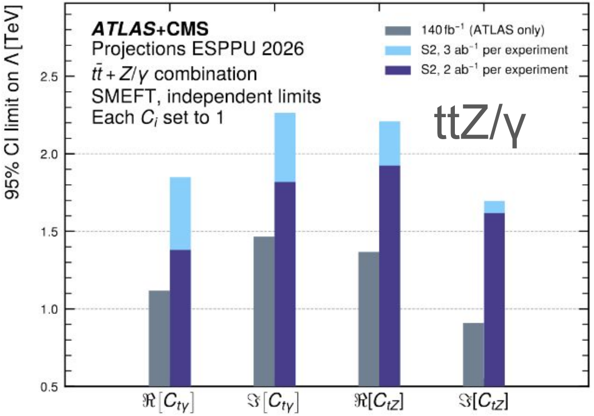


Future





- HL-LHC gives access to longitudinally polarized vector boson scattering to directly probe electroweak symmetry breaking
- Unprecedented reach for anomalous couplings from top, vector boson production



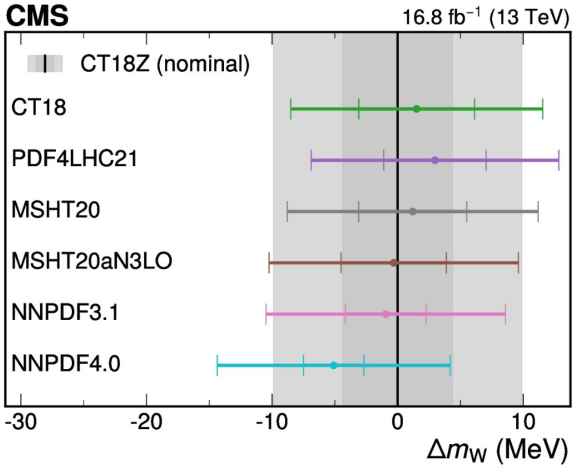
Conclusions

- LHC has a comprehensive program of QCD, precision electroweak measurements, broad probe of vector boson and top production up to high energies as tests of the Standard Model and indirect searches for new physics
- LHC precision and reach has already greatly exceeded projections and expectations in many areas
- Greatly improved precision and reach will come from the full exploitation of LHC and HL-LHC data
- Future electron-positron colliders (especially FCC-ee): further orders of magnitude improvement possible
    - See ECFA/European Strategy session tomorrow afternoon

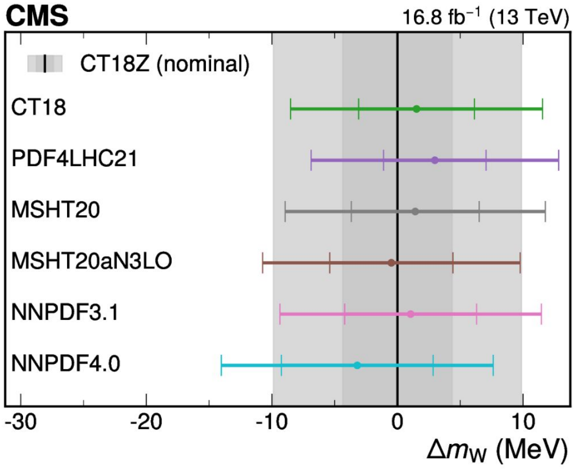
Backup

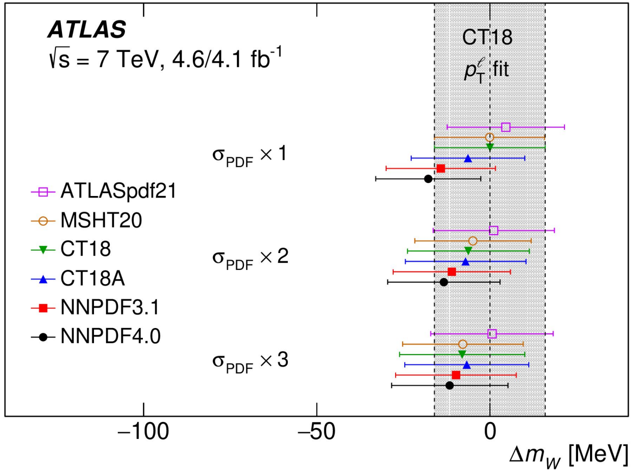
W mass: PDF Dependence

Unscaled



Scaled





- Dependence of mW measurement on PDF set can be minimized by “scaling” of PDF uncertainties to enforce consistency
- Better understanding of compatibility and uncertainties on PDFs would lead to more precise measurements in the future

PDF set	Extracted m_W (MeV) Original σ_{PDF}	Scaled σ_{PDF}
CT18Z	$80\,360.2 \pm 9.9$	
CT18	$80\,361.8 \pm 10.0$	
PDF4LHC21	$80\,363.2 \pm 9.9$	
MSHT20	$80\,361.4 \pm 10.0$	$80\,361.7 \pm 10.4$
MSHT20aN3LO	$80\,359.9 \pm 9.9$	$80\,359.8 \pm 10.3$
NNPDF3.1	$80\,359.3 \pm 9.5$	$80\,361.3 \pm 10.4$
NNPDF4.0	$80\,355.1 \pm 9.3$	$80\,357.0 \pm 10.8$

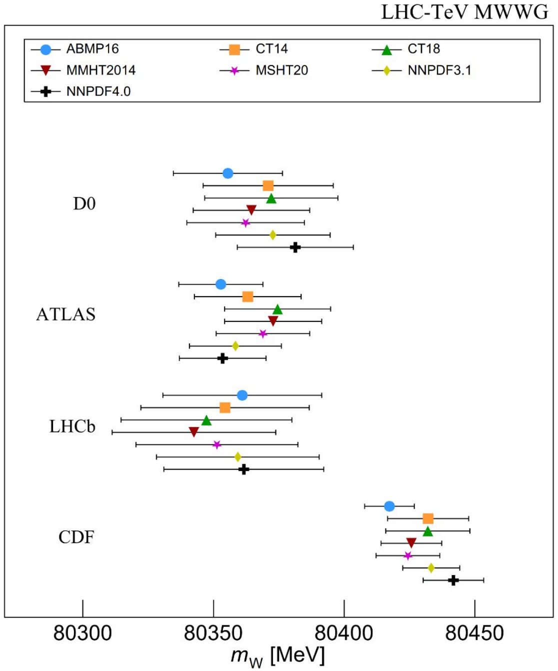
W mass: PDFs

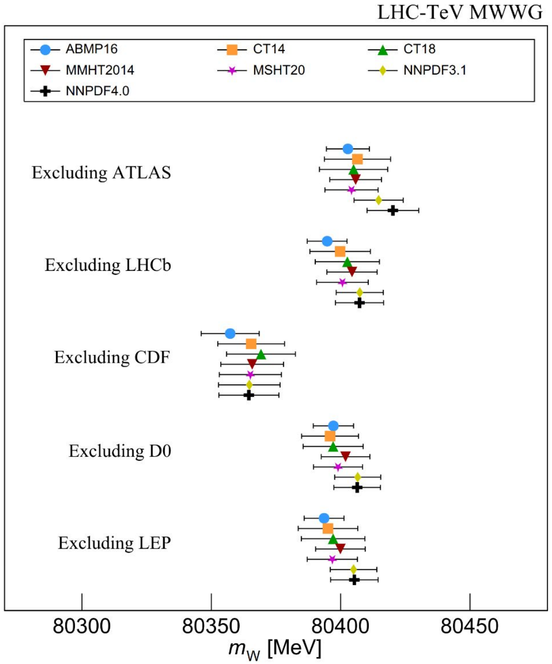
PDF set	Scale factor	Impact on m_W (MeV) Original σ_{PDF}	Scaled σ_{PDF}
CT18Z	—	4.4	
CT18	—	4.6	
PDF4LHC21	—	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0

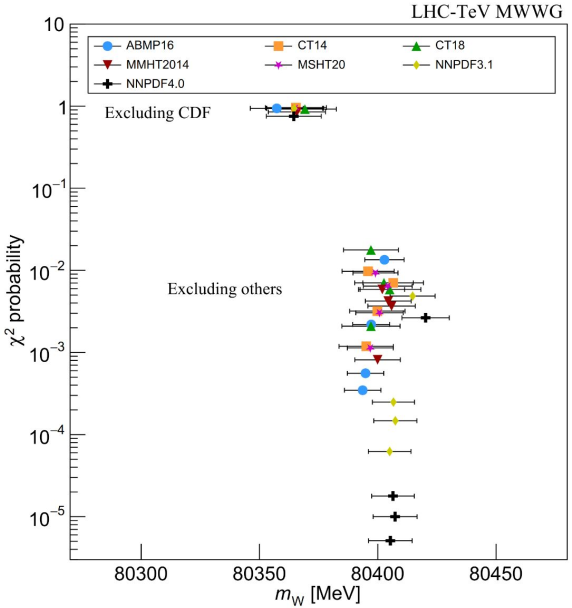
- **Strategy:** Scale prefit PDF uncertainties to ensure consistency between sets for measured m_W value
- This procedure does **not** prove that e.g. NNPDF4.0 uncertainty is underestimated, only that it's too small to cover the central value of the other sets
- CT18Z is chosen as the nominal since it covers the others without scaling and with small uncertainty
    - But note that this set is amongst the largest in terms of nominal uncertainty

Eur.Phys.J.C 84 (2024) 5, 451

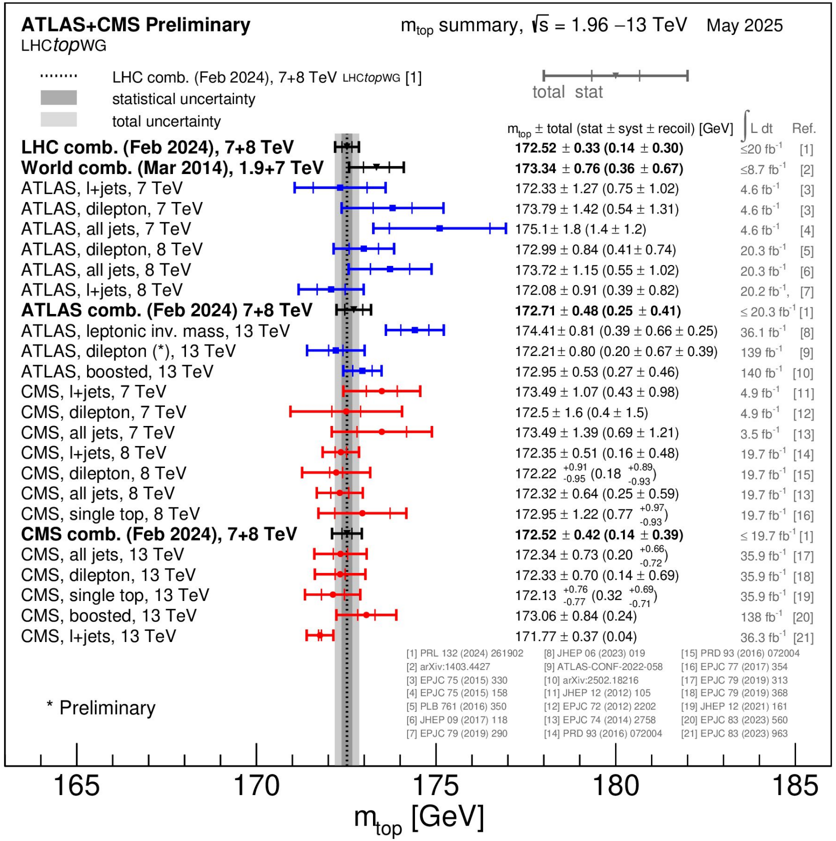
W mass combination

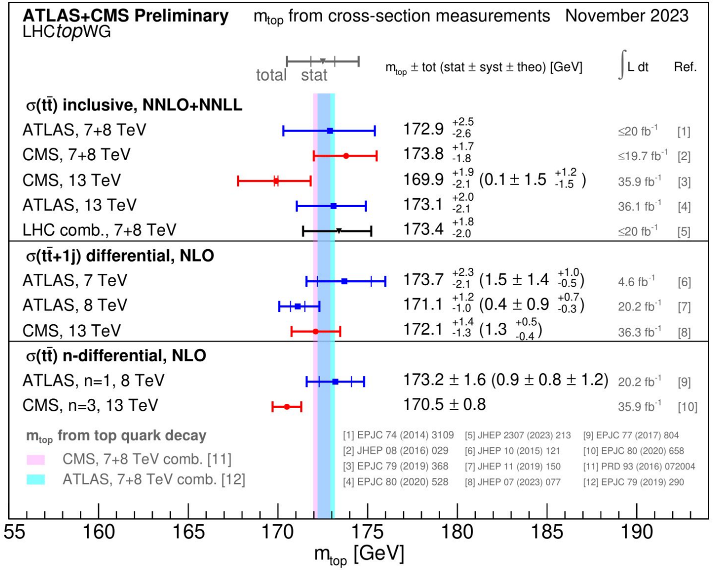






Top Mass

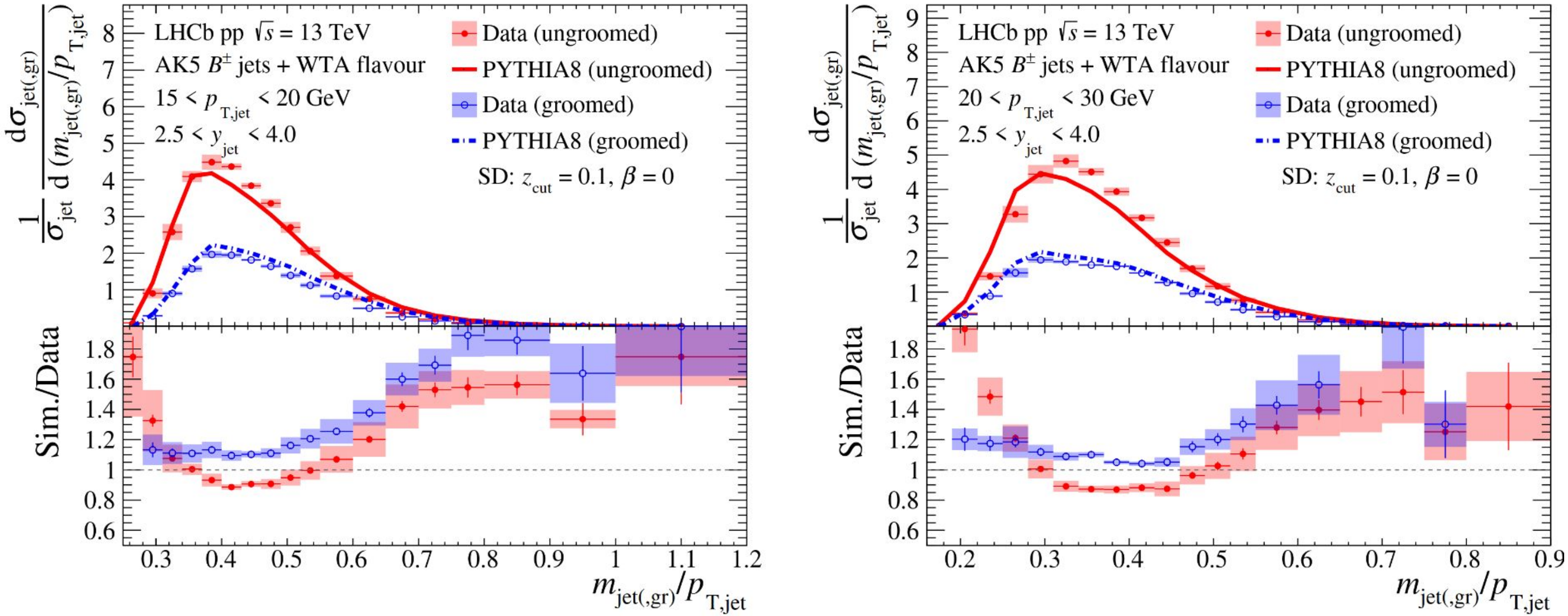




- Top mass at LHC measured most precisely from direct reconstruction of decay products, but with some theoretical ambiguity
- Pole-mass can be measured from production cross sections
- Important to test/establish consistency across many methods

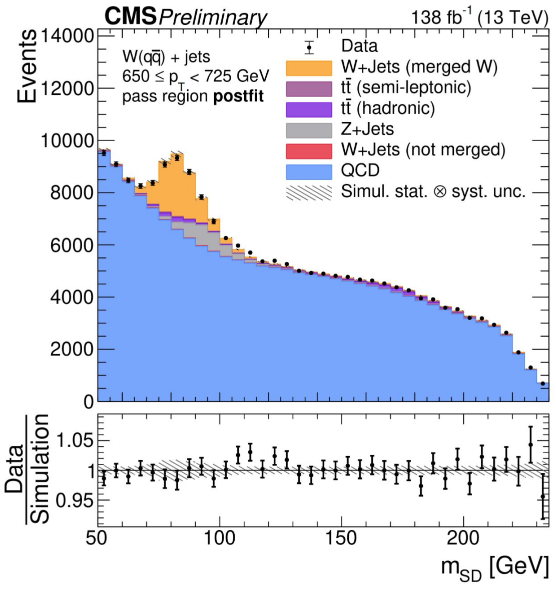
Jet Substructure: b-jets

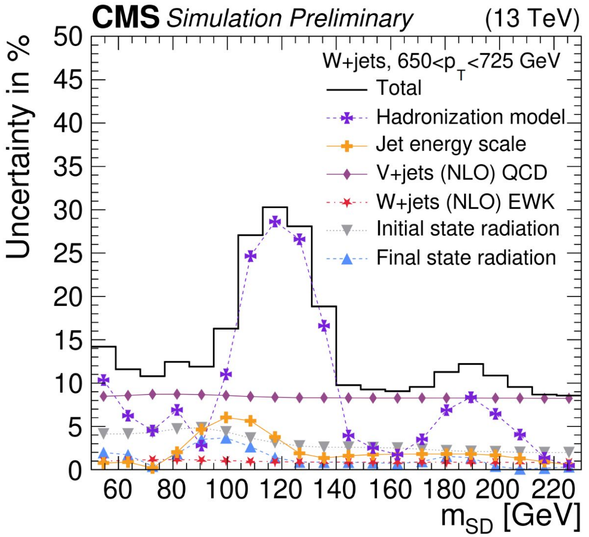
arXiv:2505.11955

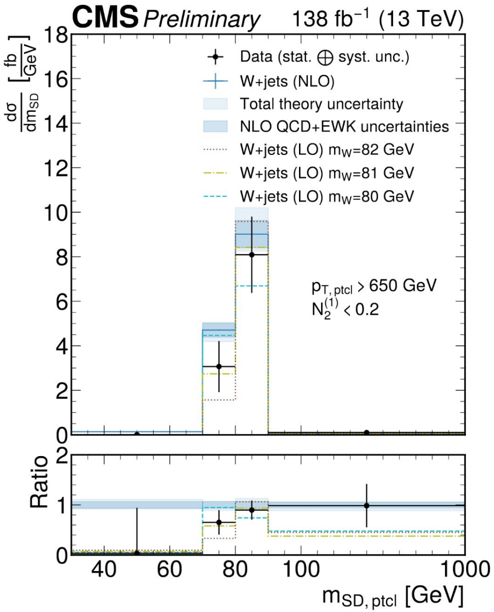


- Measurements of jet substructure useful for tuning of Monte Carlo, comparison with QCD predictions, improving modeling for measurements/searches with boosted objects
- Unique measurement from LHCb of soft drop mass in forward b-jets (with explicitly reconstructed B hadrons)

Jet Substructure: Hadronic W Decays







- Jet mass distribution measured from boosted hadronic W decays
- Unfolded cross sections for tuning and theory comparisons
- Can also be interpreted as a W mass measurement
  - **mW = 80.77 +- 0.36 (stat+bkg) +- 0.43 (syst) GeV**
  - Main systematic uncertainties for mass interpretation are Jet Energy Scale and QCD FSR modeling affecting the mass scale