W and Z production and properties

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Building Blocks of the Standard Model: Vector Boson Studies

- **The LHC: A Vector Boson Powerhouse**
- **CMS Detector at the Center of the Action**

A wide range of studies using CMS are focusing on these particles — with several **new results ready to be shared.**

- **Bosons Offer Clean, Clear Signals**

Very clean experimental signature with lepton ID eff. uncertainty <1% and momentum scale uncert. ~ 0.1%

Why It Matters?

- **Putting Theory to the Test**

Probe for pQCD as well as npQCD in different regions

- **Looking Inside the Proton**

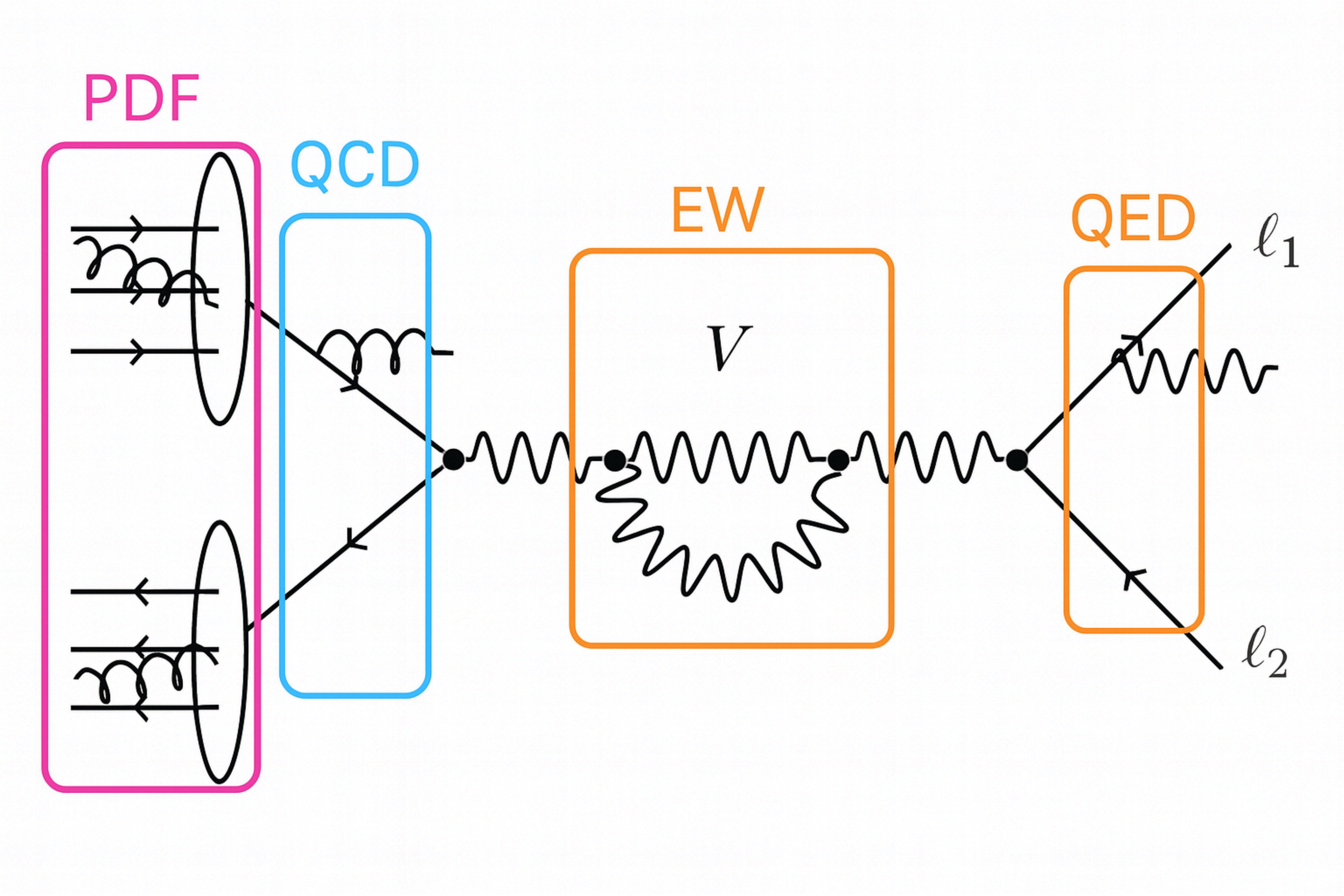
Important insights into the partonic structure of hadrons

- **Measuring the Fundamentals**

Used to determine key Standard Model parameters with great precision.

Tiny differences could matter - as measurement accuracy improves, even very small differences from predictions could signal something new.

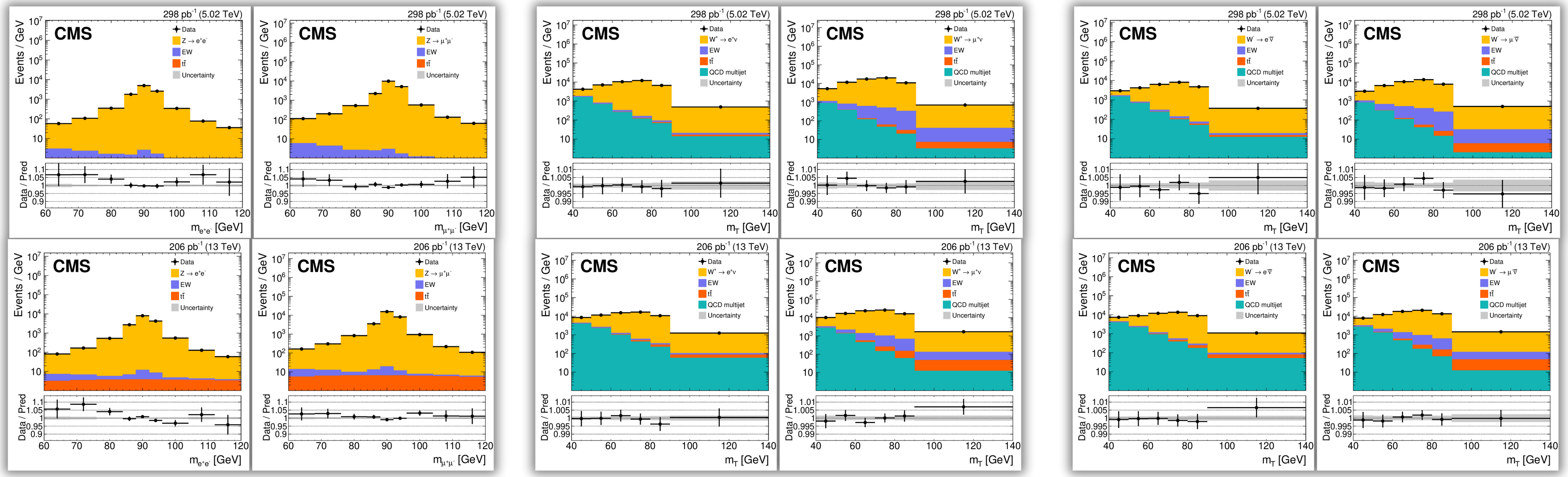
- **Background for other analyses**



Measurement of W and Z boson cross sections at 5.02 and 13 TeV

2017 DATA ● 298 ± 6 pb^{-1} at 5.02 TeV & 201 ± 3 pb^{-1} at 13 TeV ● TOTAL INCLUSIVE AND FIDUCIAL CROSS SECTIONS ● JHEP 04 (2025) 162

Low pile up



Event selection and background:

- Prompt, energetic and isolated lepton(s)
- Both electron and muon channels analysed
- EW and tt backgrounds from simulation
- For the W case, QCD multijets background from control region in data (invert m_T cut)

	$W^+ \to e^+\nu$	$W^- \to e^-\bar{\nu}$	$Z \to e^+e^-$	$W^+ \to \mu^+\nu$	$W^- \to \mu^-\bar{\nu}$	$Z \to \mu^+\mu^-$
Observed	689131	561870	72040	1016318	796731	128889
Signal	591760 ± 770	467820 ± 680	71520 ± 270	923620 ± 960	708680 ± 840	128390 ± 360
EW	12150 ± 110	11450 ± 110	159 ± 13	38200 ± 200	33710 ± 180	271 ± 16
$t\bar{t}$	4768 ± 69	4780 ± 69	216 ± 15	6326 ± 80	6345 ± 80	360 ± 19
QCD multijet	80750 ± 280	77980 ± 280	—	47910 ± 220	47930 ± 220	—

Event yields, after the maximum likelihood fit, in the W$^+$, W$^-$, and Z boson signal regions for electron and muon final states at 13 TeV.

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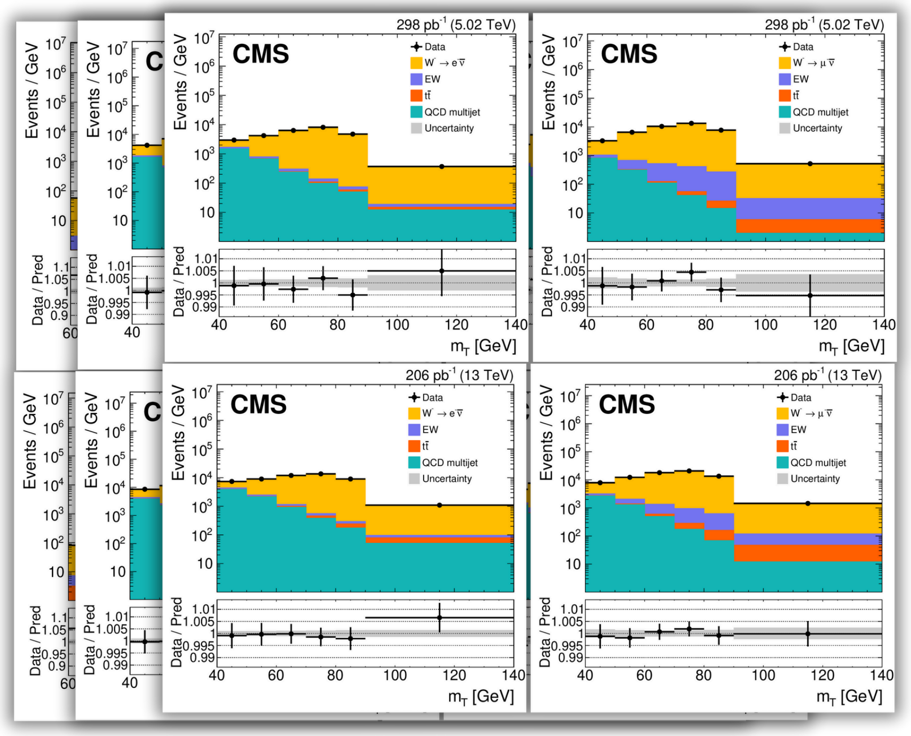
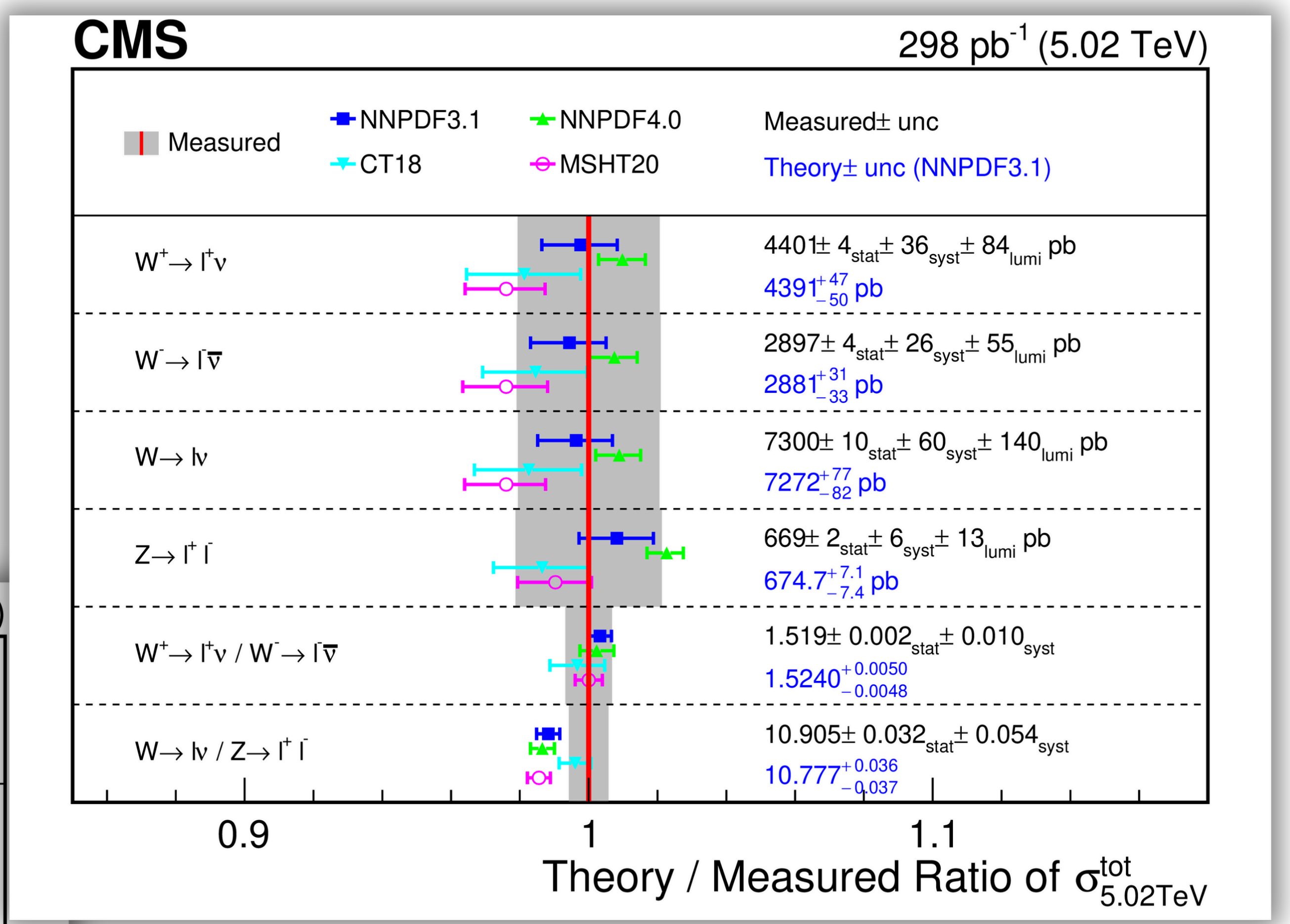
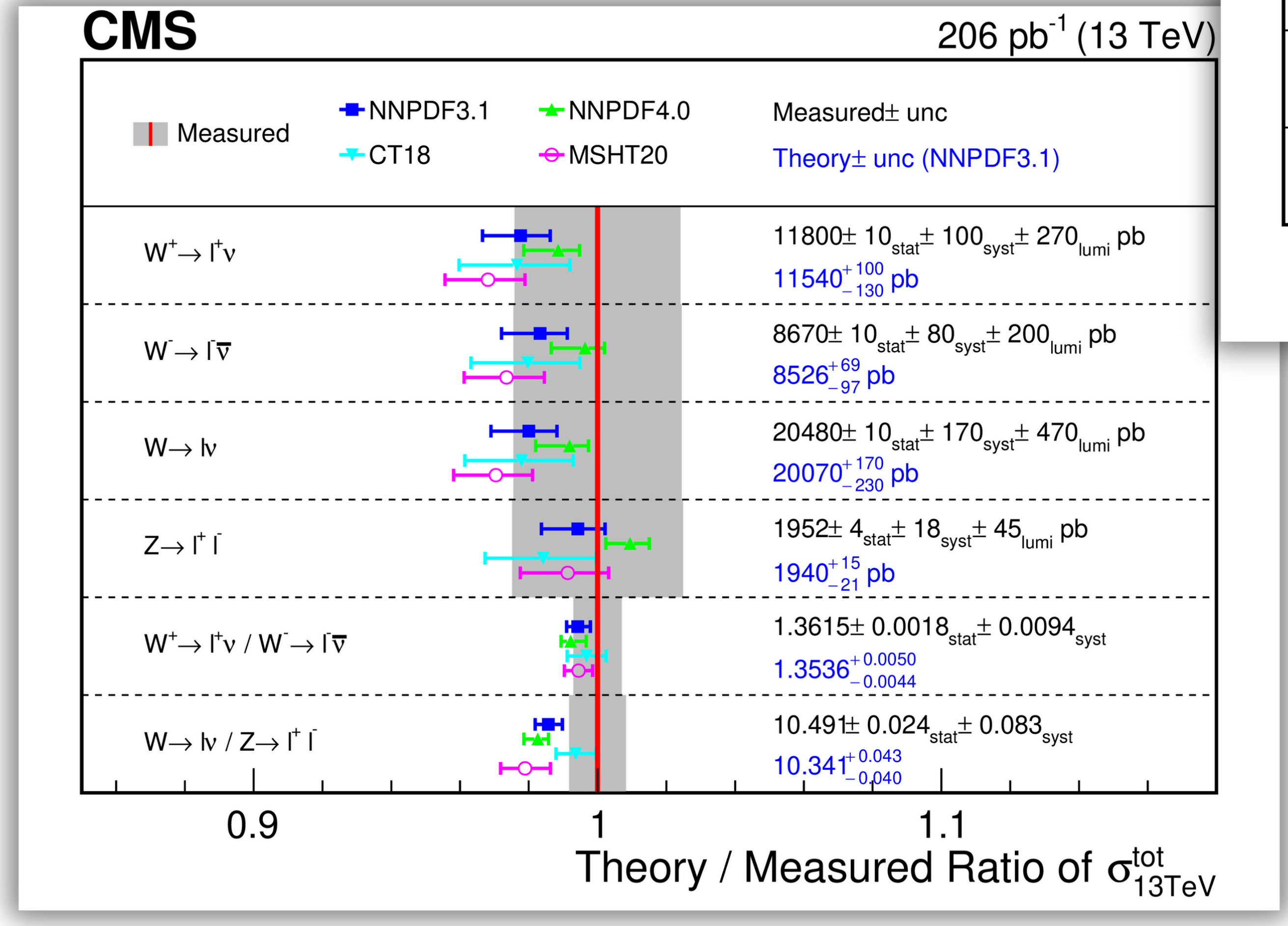


- Cross-section and cross-section ratios from fitting m_{ll} and m_T distributions from Z and W bosons



Theoretical predictions:

- NNLO and N3LO in QCD
- NLO in electroweak corrections



Important for:

- Testing higher-order perturbative QCD
- Evaluating electroweak radiative corrections
- Constraining parton distribution functions (PDFs)

- Luminosity unc. at 5.02 TeV (13 TeV) 1.9% (2.3%), other experimental unc. ~0.3%
- Luminosity and other systematic unc. cancel out for the ratios - improved agreement with theory

- Good agreement with NNLO predictions

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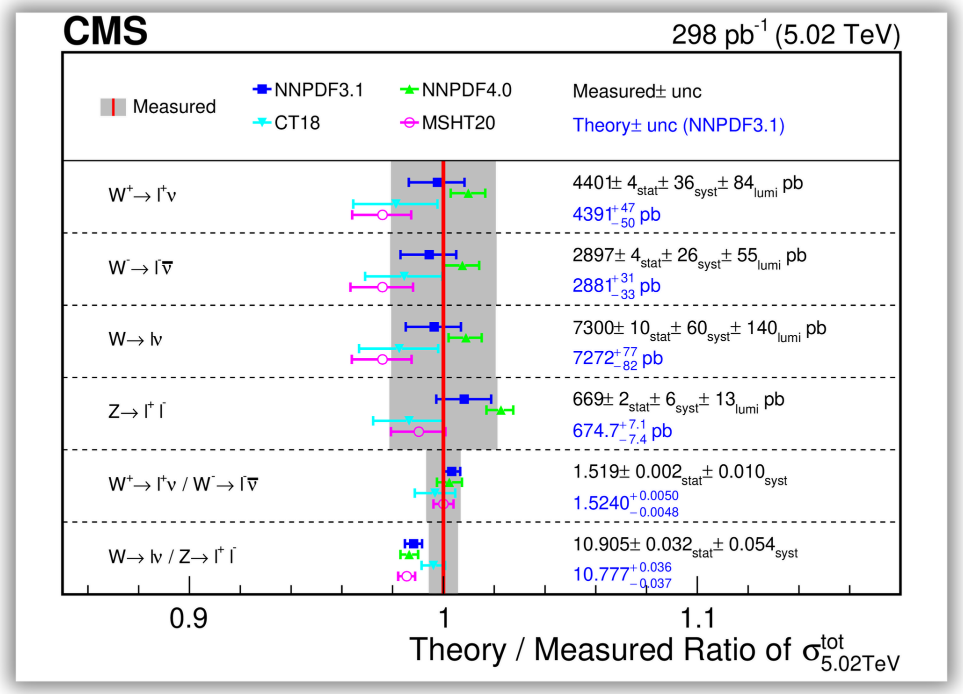
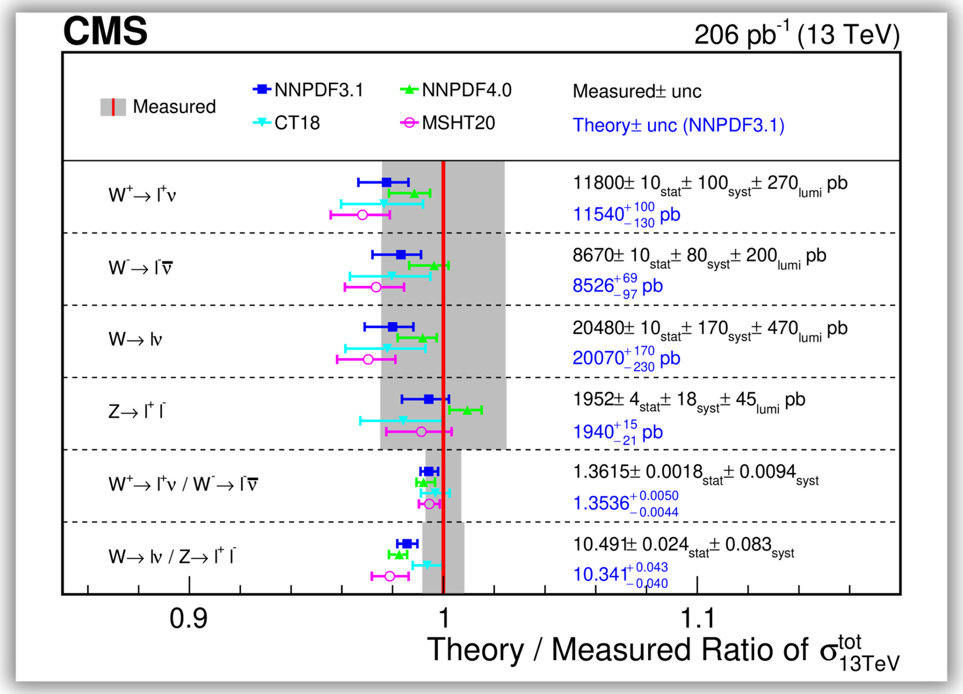
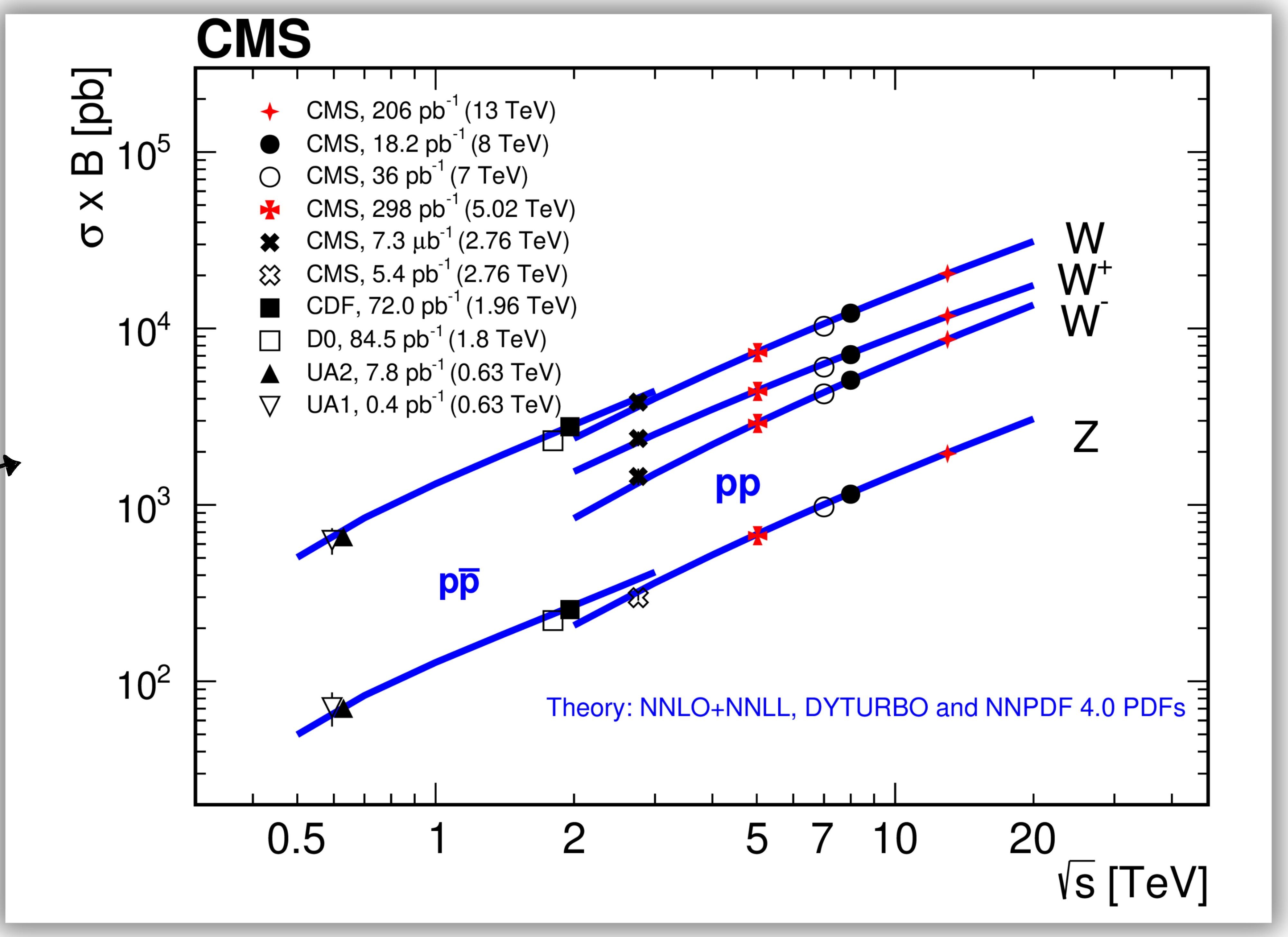


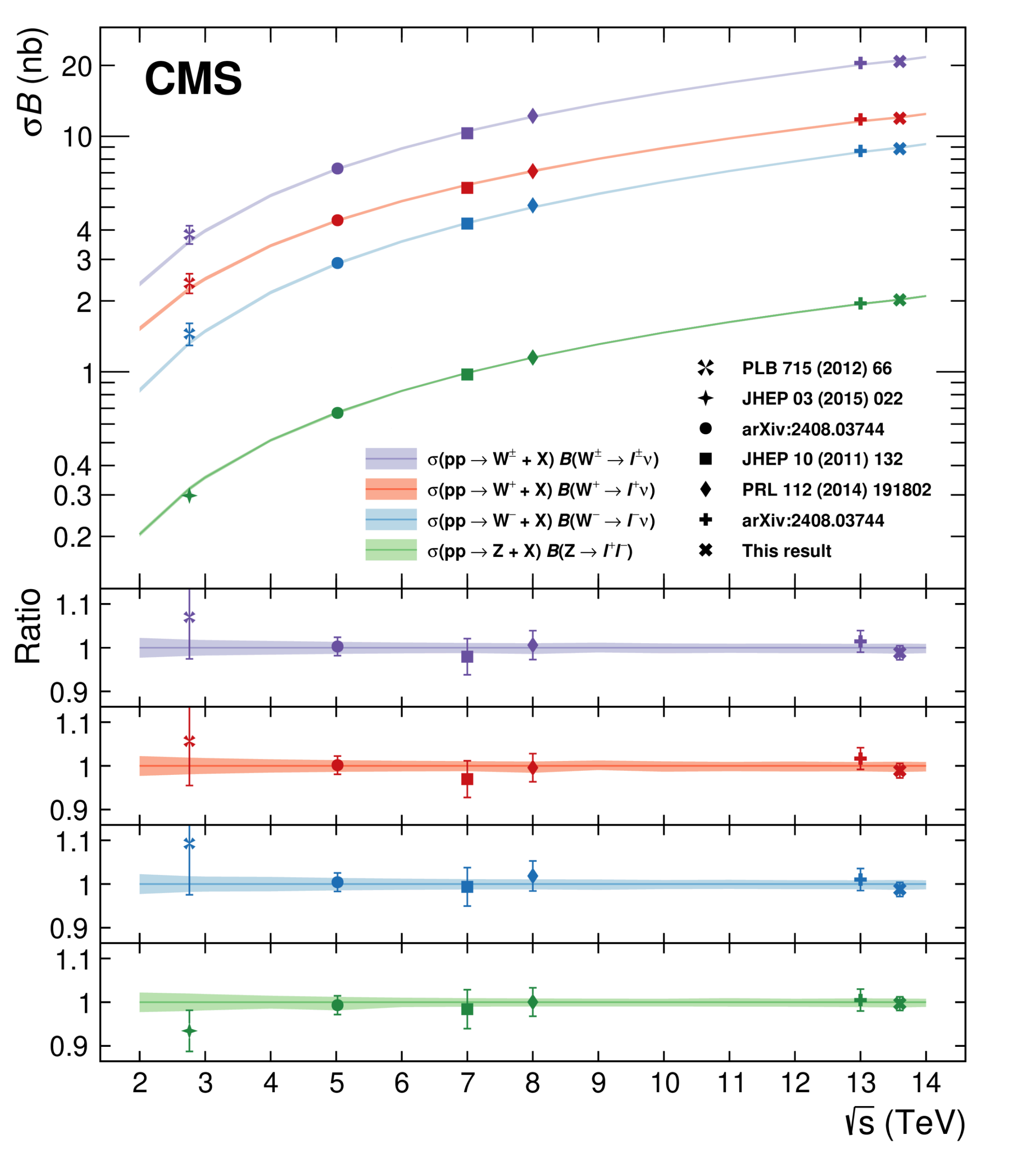




Summary of the measurements of the total W^+, W^-, W, and Z production cross sections times branching fractions versus center-of-mass energy for CMS and experiments at lower-energy colliders.

Measurement of the W and Z production cross section at 13.6 TeV

2022 DATA • 5.04 fb^{-1} • TOTAL INCLUSIVE AND FIDUCIAL CROSS SECTIONS • CMS PAS SMP-22-017



Uncertainty source	Uncertainty in $\sigma_{\text{fid}}\mathcal{B}$ (in %) for			
	W^+	W^-	$W^\pm$	Z
Muon efficiency	0.28	0.29	0.29	0.40
Finite size of MC samples (bin-by-bin)	0.27	0.27	0.25	0.08
QCD background	0.53	0.49	0.49	0.07
PDF, scales, and parton shower	0.25	0.25	0.25	0.06
Muon momentum correction	0.01	0.02	0.01	0.03
Recoil correction	0.09	0.08	0.08	0.02
EWK background normalization	0.05	0.05	0.05	0.02
Z boson p_T correction	0.03	0.04	0.03	0.01
$t\bar{t}$ background normalization	0.01	0.03	0.02	0.01
Pileup	0.01	0.02	<0.01	<0.01
Total	0.68	0.66	0.65	0.42
Integrated luminosity	1.4	1.4	1.4	1.4
Statistical uncertainty	0.03	0.03	0.02	0.06

- Muon decay modes considered
- Maximum likelihood fit to m_{ll} and m_T
- Luminosity unc. 1.4%, among other experimental unc. muon efficiency is dominating
- Good agreement with theory predictions

Drell-Yan forward-backward asymmetry and of the effective leptonic weak mixing angle at 13 TeV

2016–2018 DATA • **138 fb^{-1}** • **Phys. Lett. B 866 (2025) 139526**

- Key parameter in the electroweak sector

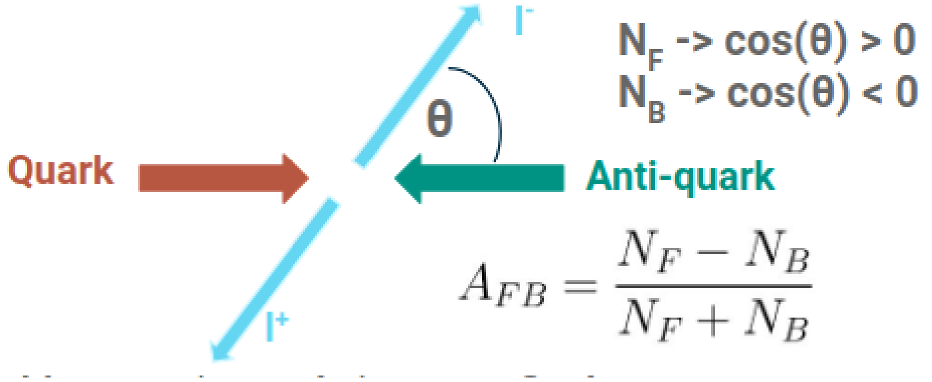
$$\sin^2\theta^l_{eff} = k_f\left(1 - \frac{m_W^2}{m_Z^2}\right)$$

- Connects the masses of electroweak bosons and determines the strength of the electroweak interaction
- The effective mixing angles for different fermions can be precisely computed in the SM
  - any significant deviation can be seen as evidence for new physics
- Currently, the most precise measurements from LEP and SLD differ in central values by 3.2 standard deviations
- This measurement exceeds the sensitivity of all previous hadron collider measurement and achieves equivalent precision to the LEP and SLD measurements.

- Drell–Yan dimuon and dielectron events
  - Electrons divided according to eta
- Asymmetry in lepton decay angle distribution

$$\sim 1 + \cos^2\theta + 0.5A_0(1 - 3\cos^2\theta) + A_4\cos\theta$$

$$\Rightarrow A_{FB} = \frac{3}{8}A_4$$



  - Collins-Soper frame in order to reduce theoretical and experimental uncertainties
  - Definition of positive z relies on sign of pair rapidity
    - Significant y-dependent dilution & pdf errors

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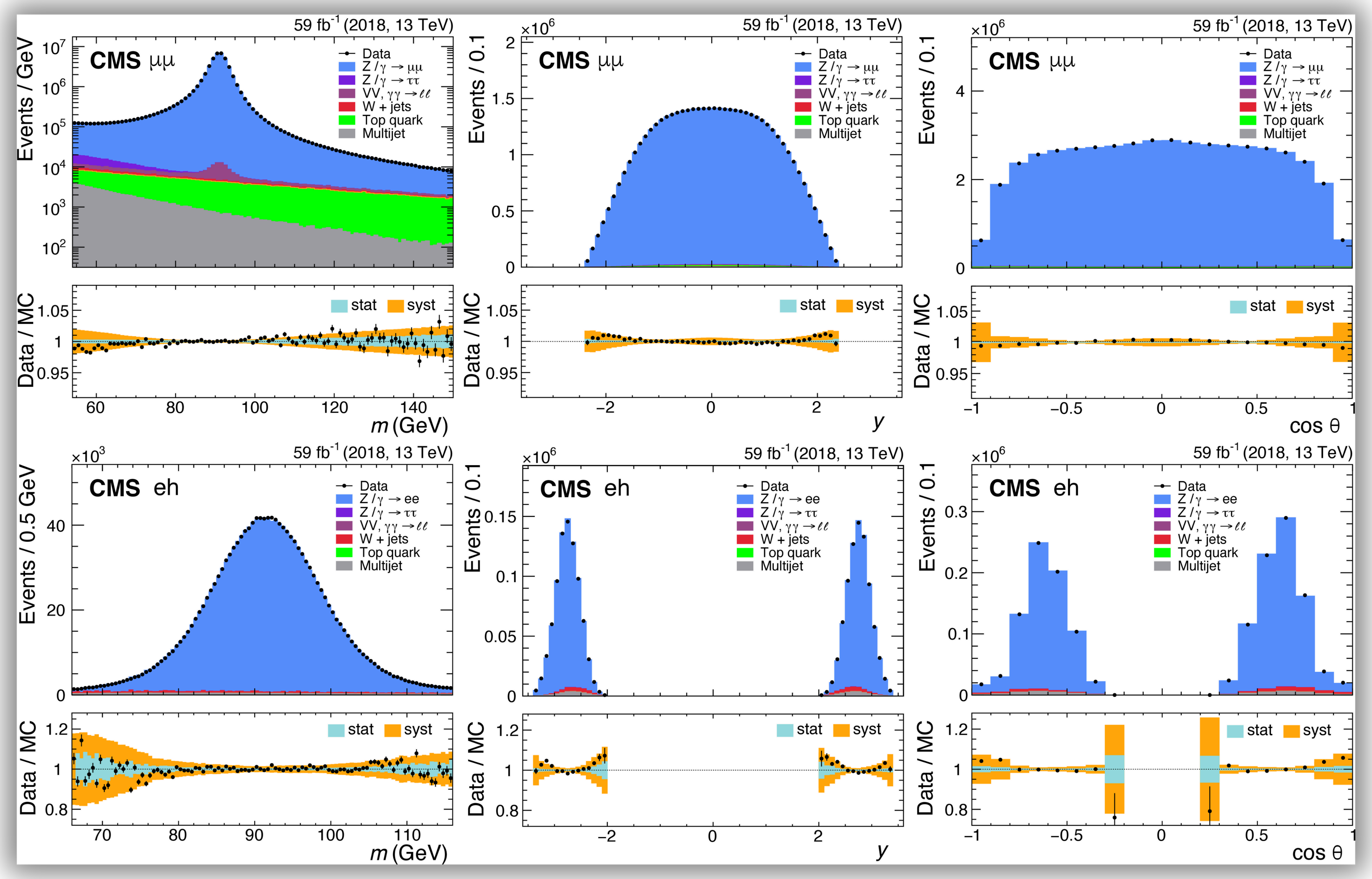

Good data/MC agreement across the phase space

Drell-Yan forward-backward asymmetry and of the effective leptonic weak mixing angle at 13 TeV

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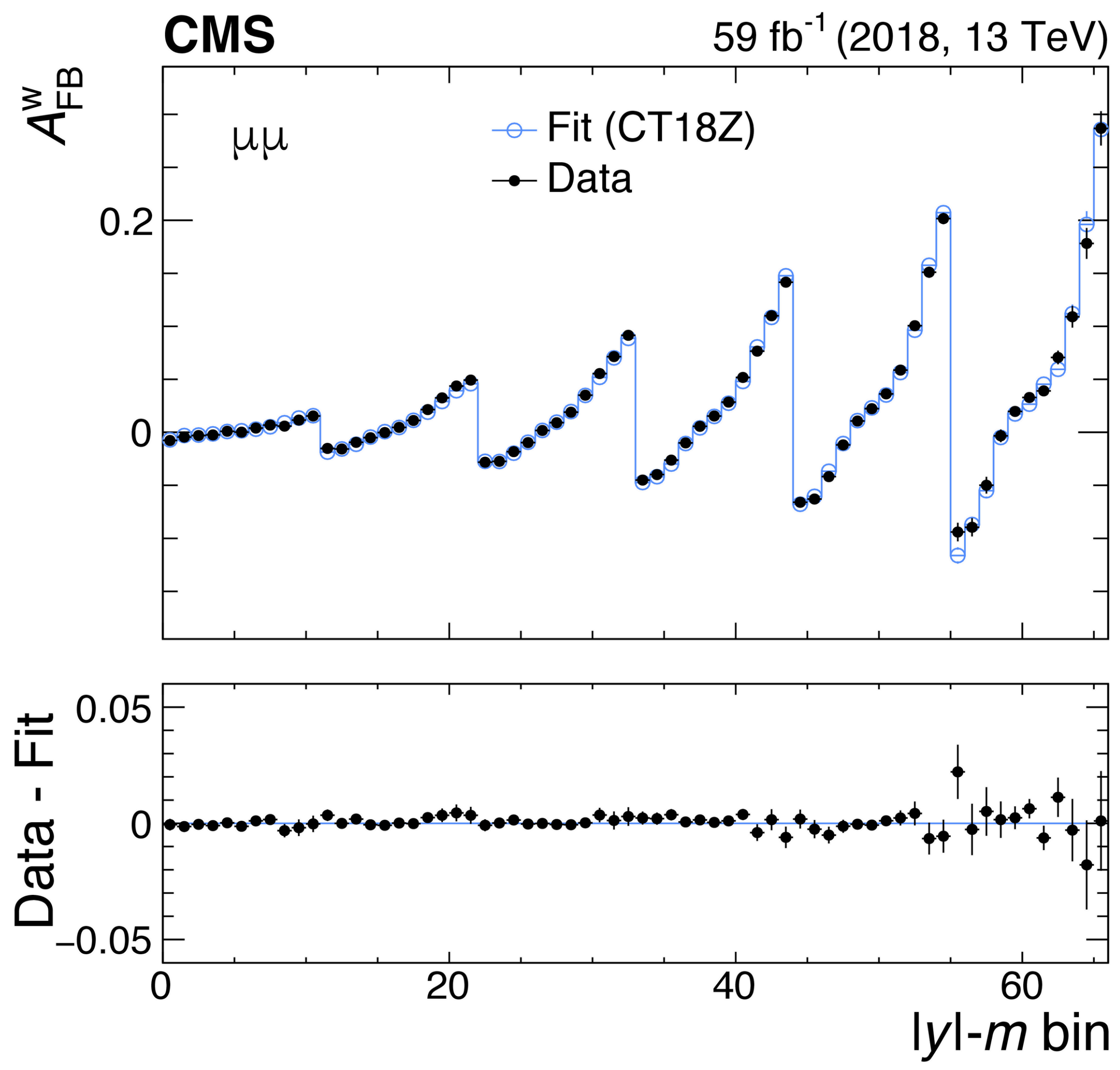
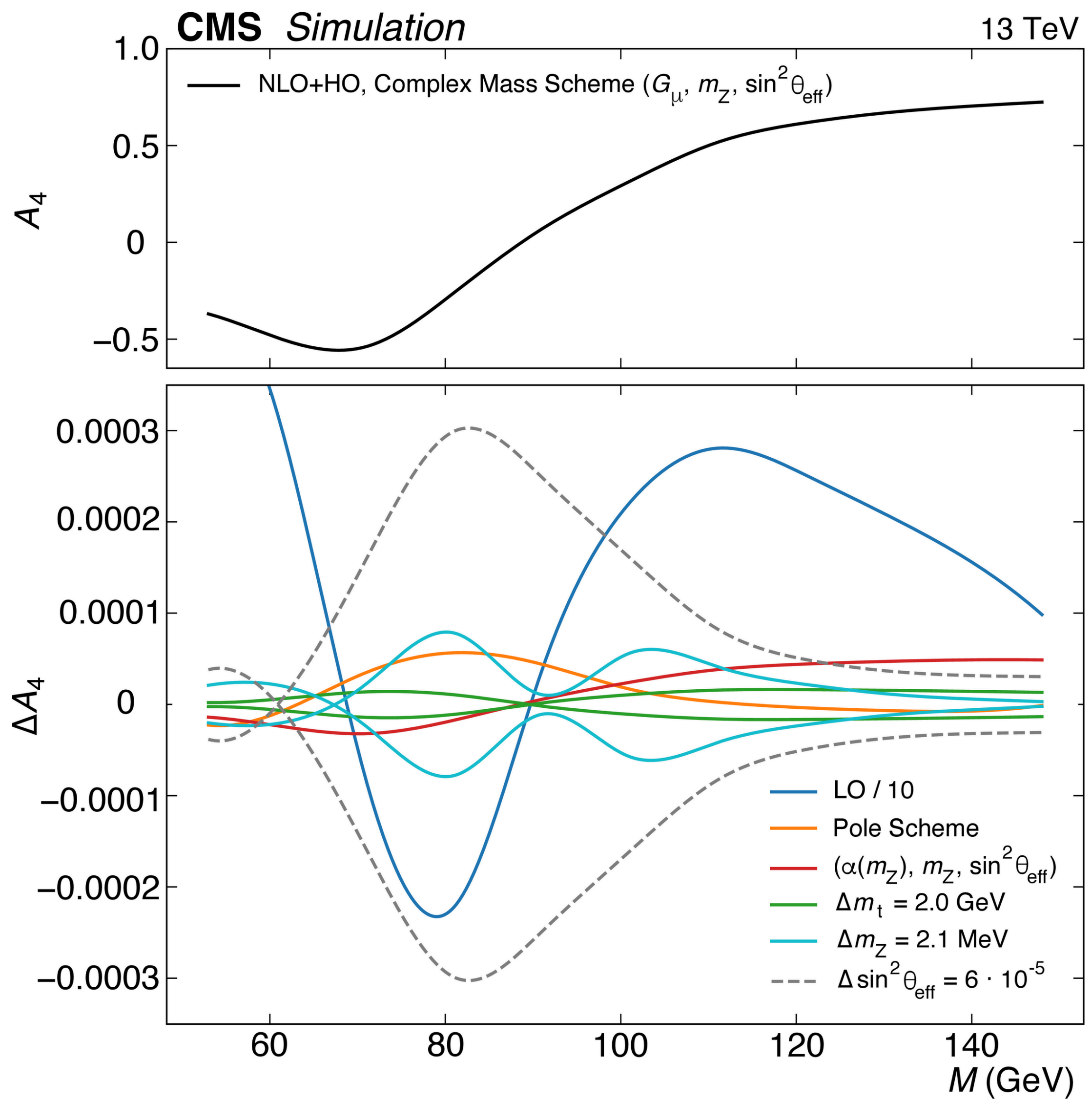
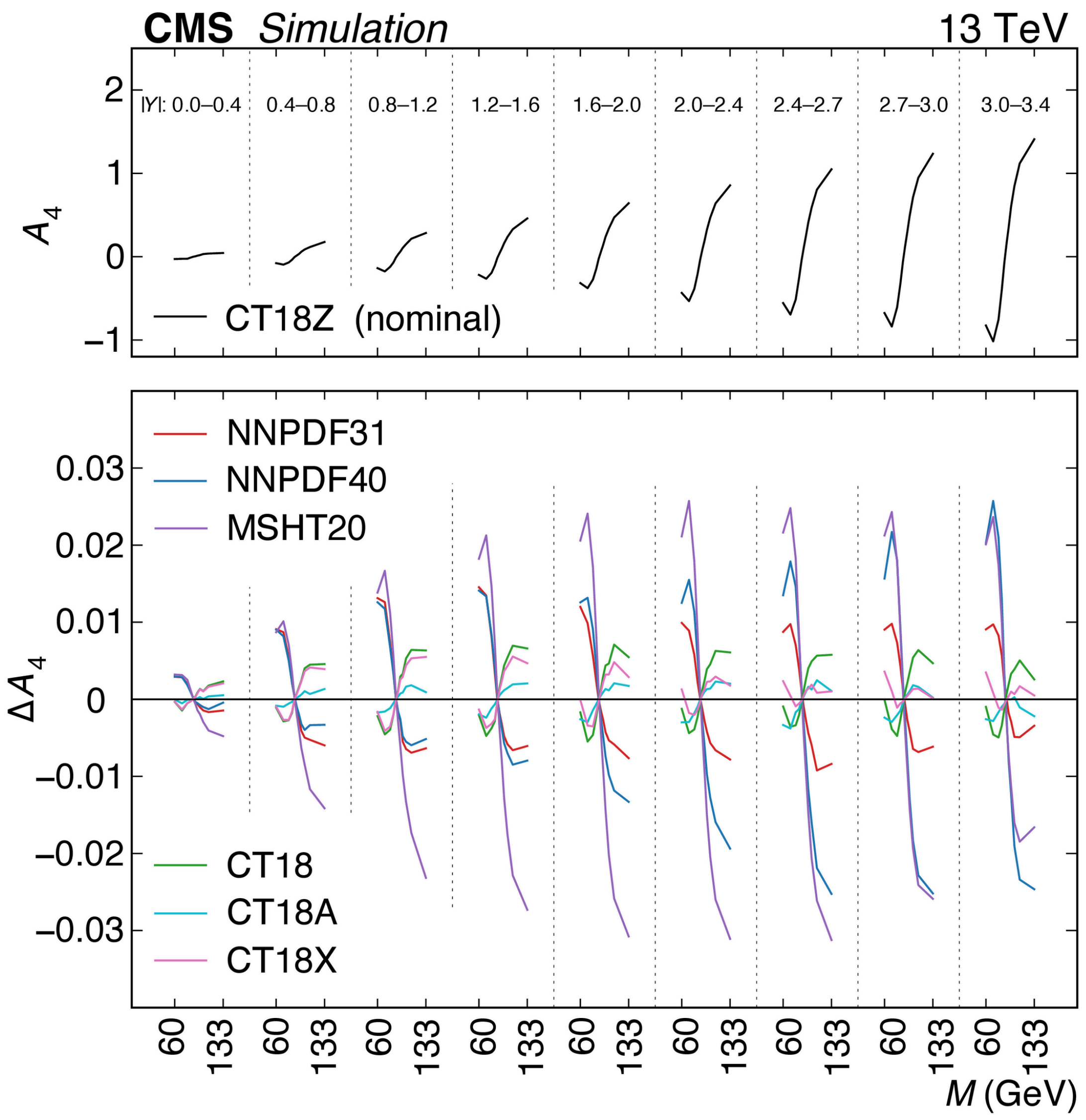
- Baseline model: POWHEG MiNNLO + Pythia8 + PHOTOS
- Extract of the effective leptonic weak mixing angle from template fits of A_{FB} depending on mass and rapidity
- Dependence on rapidity -> valence quarks are important
  - A_{FB} measurement is sensitive to the PDF







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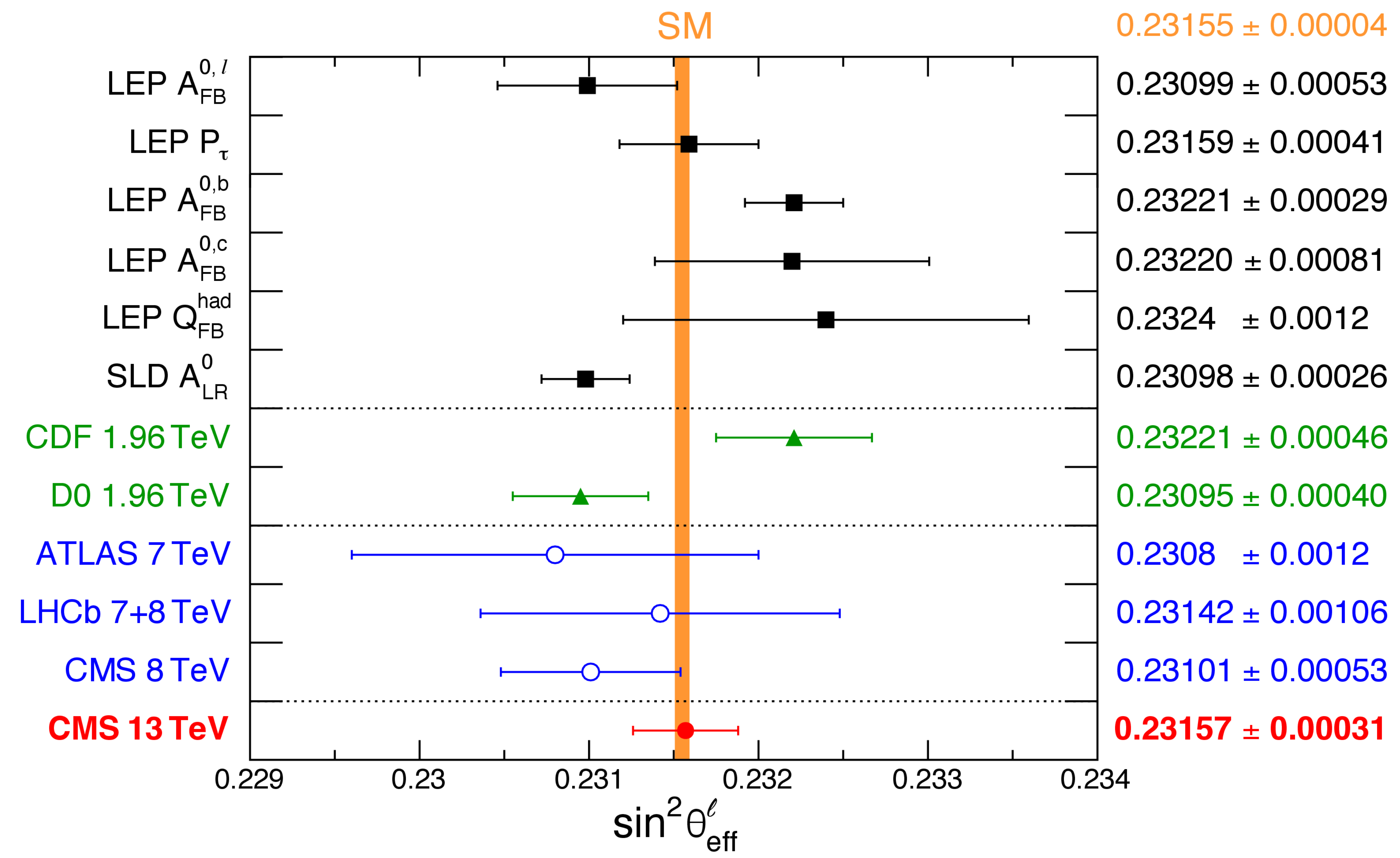
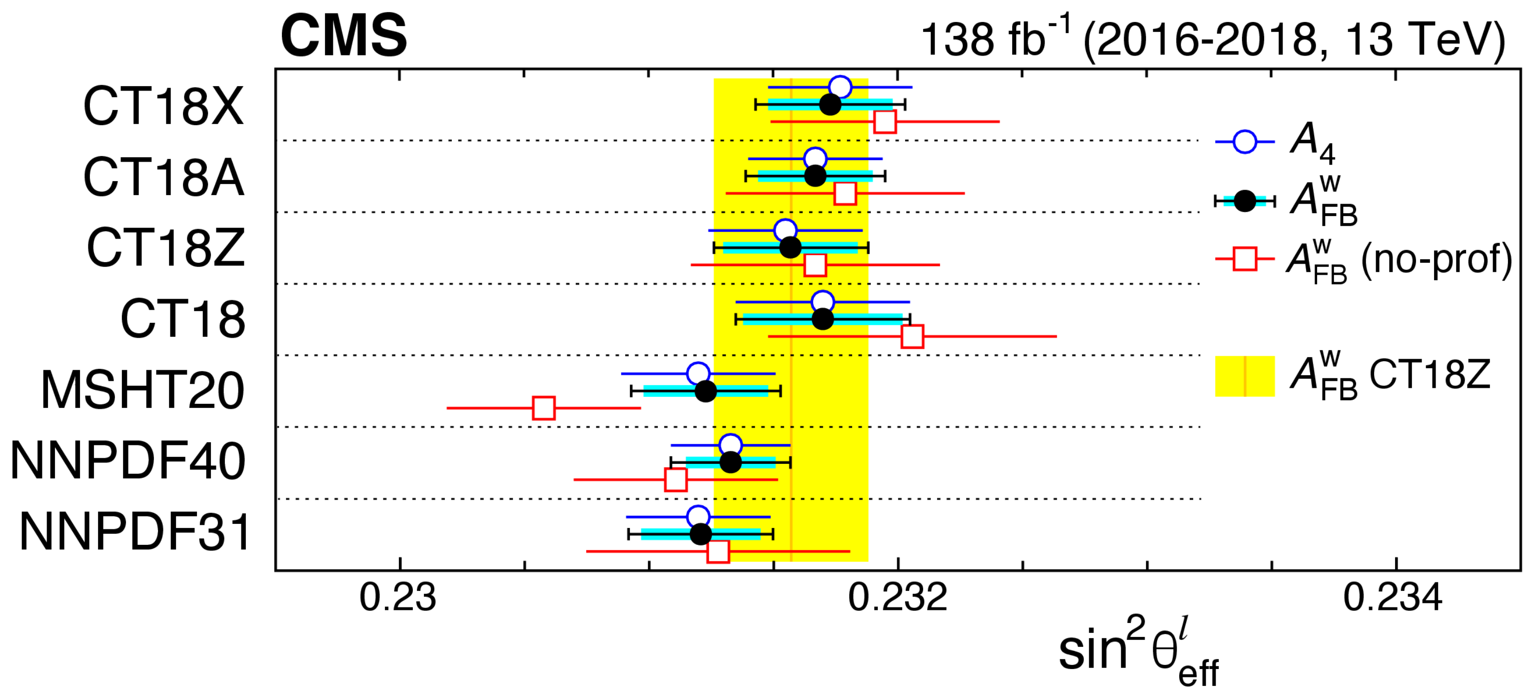




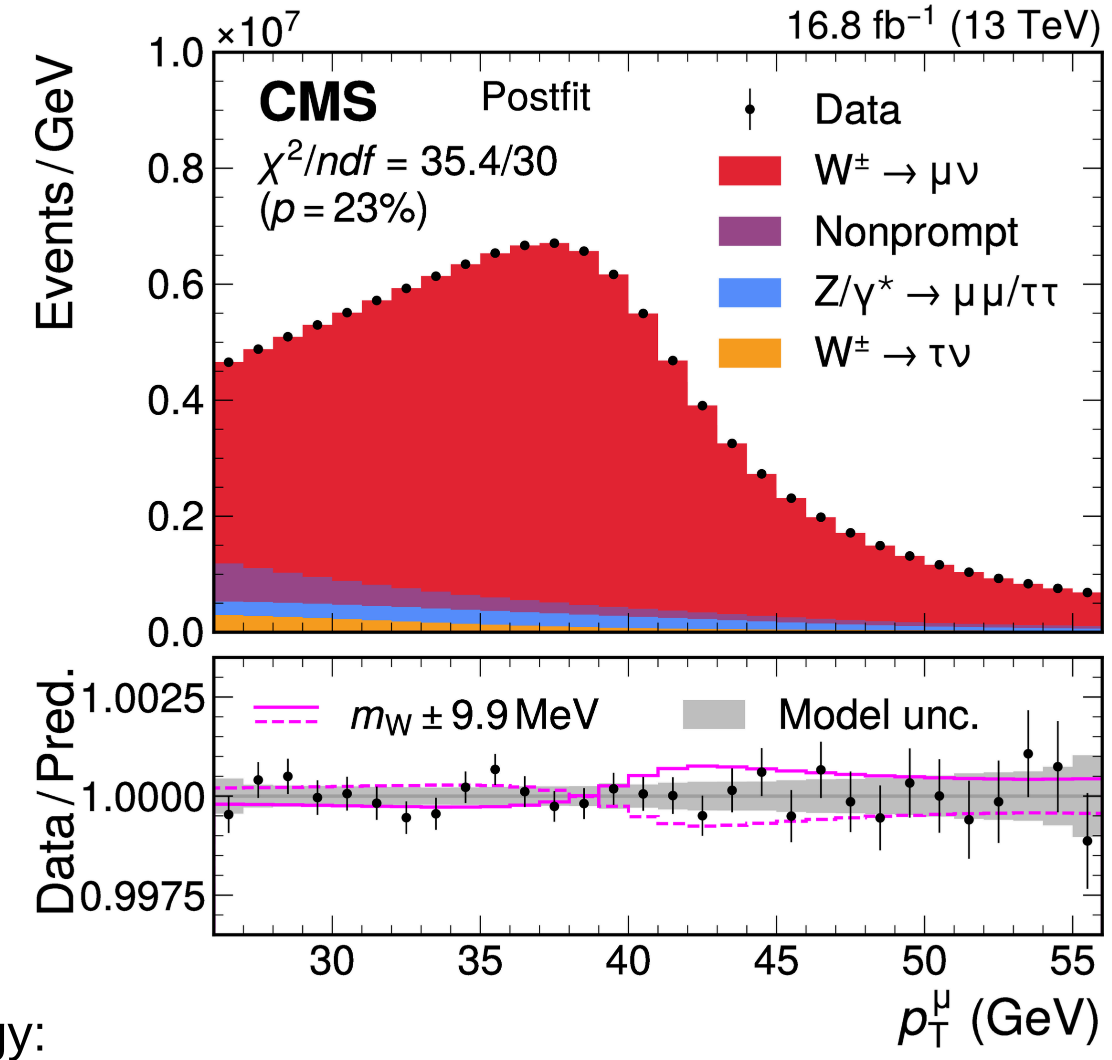
- All years and channels combined
- Uncertainties dominated by PDF
- CT18Z as default result, its uncertainty covers best other central values
- Best hadron collider measurement
- Precision also comparable with LEP and SLD measurements

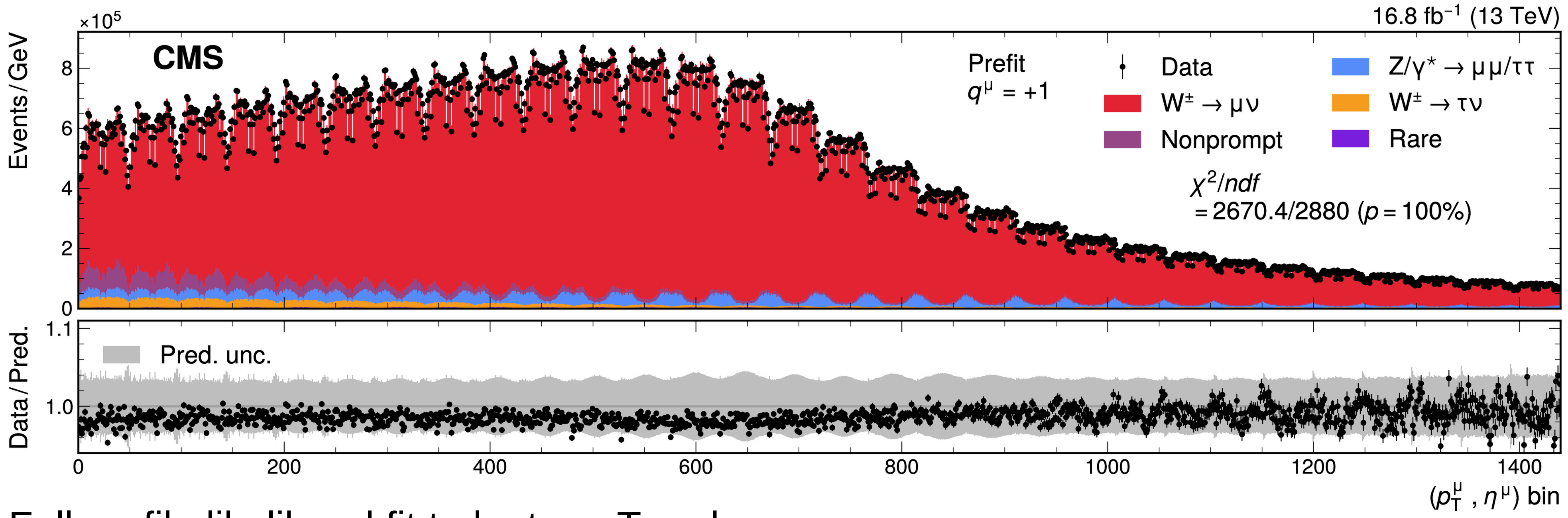
$$\sin^2\theta^{\ell}_{\text{eff}} = 23157 \pm 10\ (\text{stat.}) \pm 15\ (\text{syst.}) \pm 9\ (\text{theo.}) \pm 27\ (\text{PDF}) \times 10^{-5}$$

High-precision measurement of the W boson mass

2016 DATA • **16.8 pb⁻¹** • **SMP-23-002**

- **Goal:** Precision measurement of the W boson mass (m_W)
  - Hadronic channel: Not feasible due to huge QCD backgrounds
  - Focus on leptonic channel: Full W reconstruction not possible because of the undetected neutrino but can be inferred from the missing transverse momentum
  - Muon channel only:
    - Less affected by systematics than electrons
  - Traditionally, m_T is the preferred variable for the m_W measurement
    - More robust wrt theoretical calculations, but resolution limited at high pileup environments
  - Muon p_T is more precisely measured than m_T
    - Sensitive to theoretical uncertainties (PDFs and W p_T)





Full profile likelihood fit to lepton pT and η

- Fit Strategy:
  - 3D fit using muon p_t, η, and charge
  - ~2,880 bins in total
  - ~5,000 systematic variations evaluated
  - ~4 billion simulated events
  - ~100 million selected data events → largest ever dataset for mW

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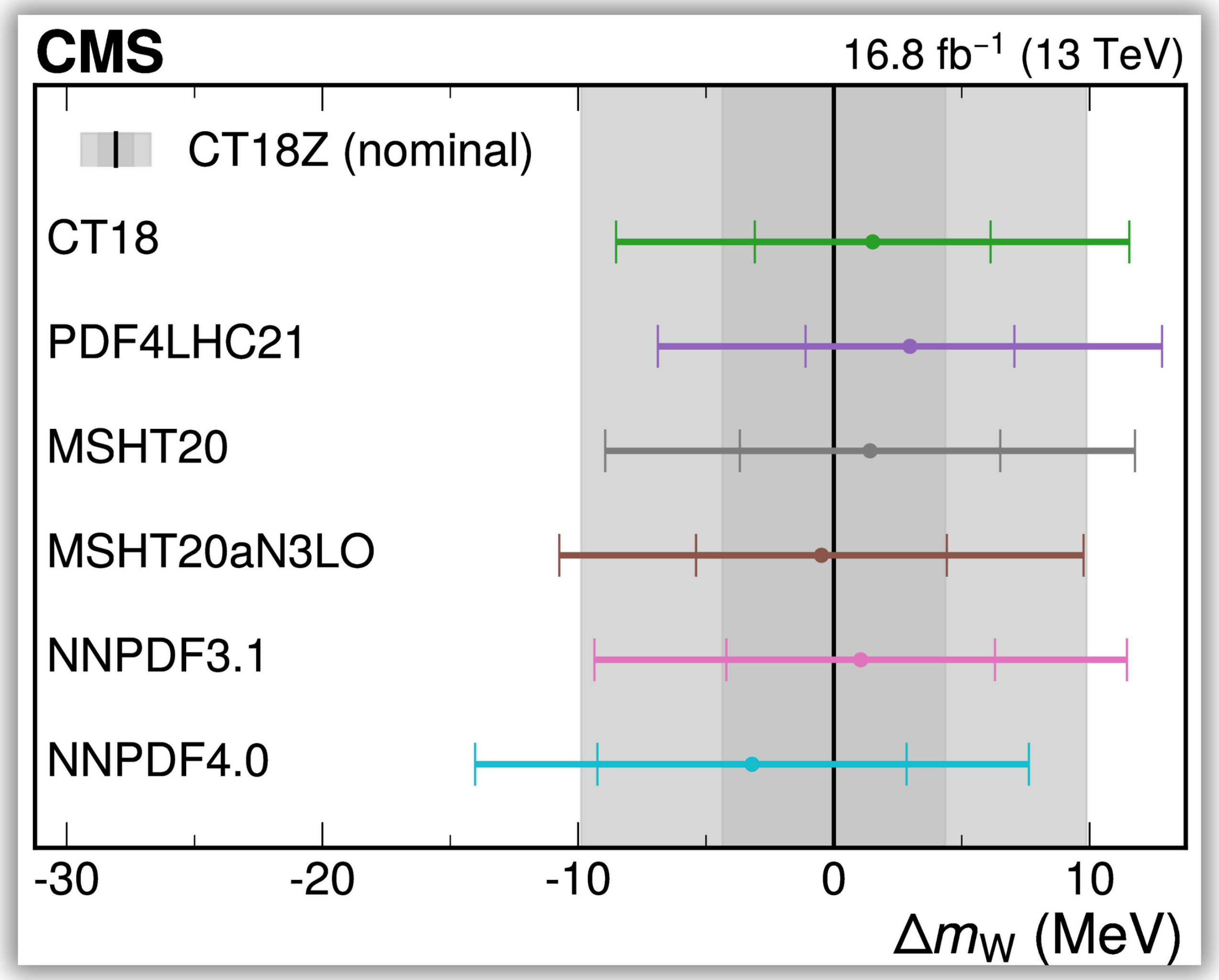

- Considered seven modern sets of PDFs
- Performed bias test on m_W
  - Taking one PDF as prediction and the other as pseudo data
  - Determine inflation factors needed to cover the other PDF set
- CT18Z used as nominal PDF, cover other sets within its original uncertainty
- Impact on m_W ~4.4 MeV

PDF set	Scale factor	Impact on m_W (MeV) Original σ_{PDF}	Impact on m_W (MeV) 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

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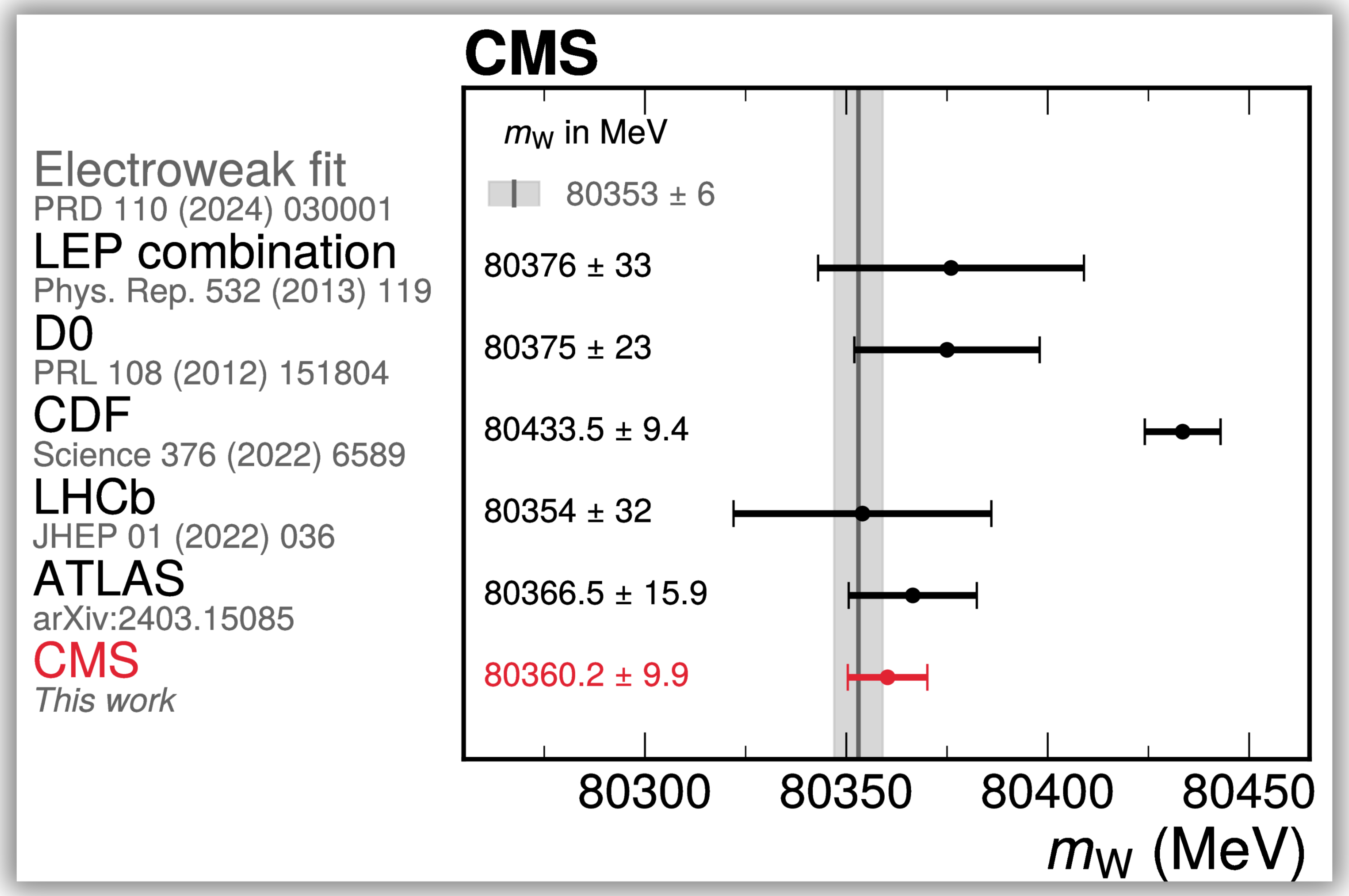
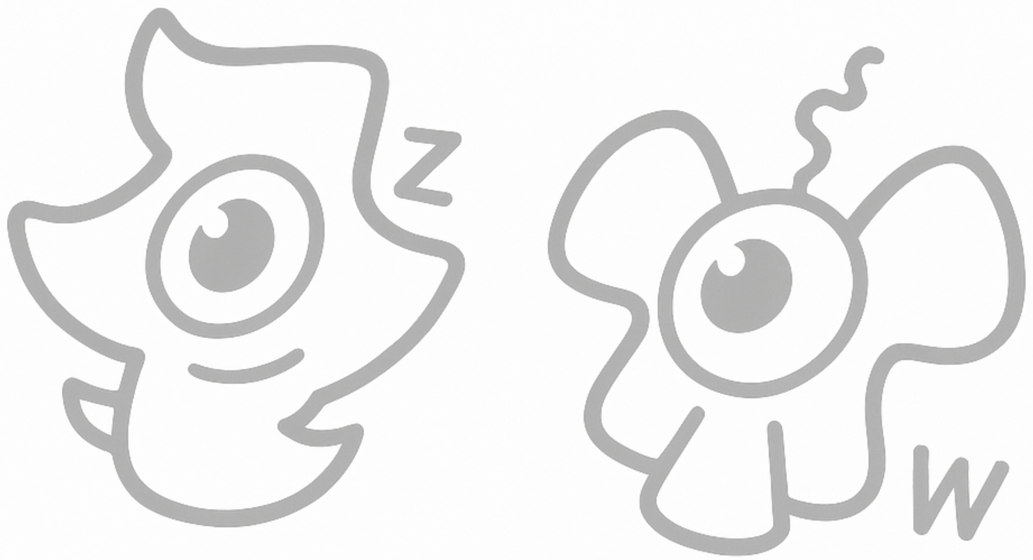


- First W mass measurement by CMS
- Most precise at the LHC
- Precision comparable to CDF
- Excellent agreement with Standard Model prediction
- Tension with CDF result
- Acts as a benchmark for future electroweak precision measurements

Summary

- Overview of recent precision measurements involving W and Z bosons
- Results obtained with CMS detector
- Results shown for several center of mass energies
- Comparison with several theory predictions
- Aim for better understanding of the QCD
- Precision today, discovery tomorrow!



Thank you!