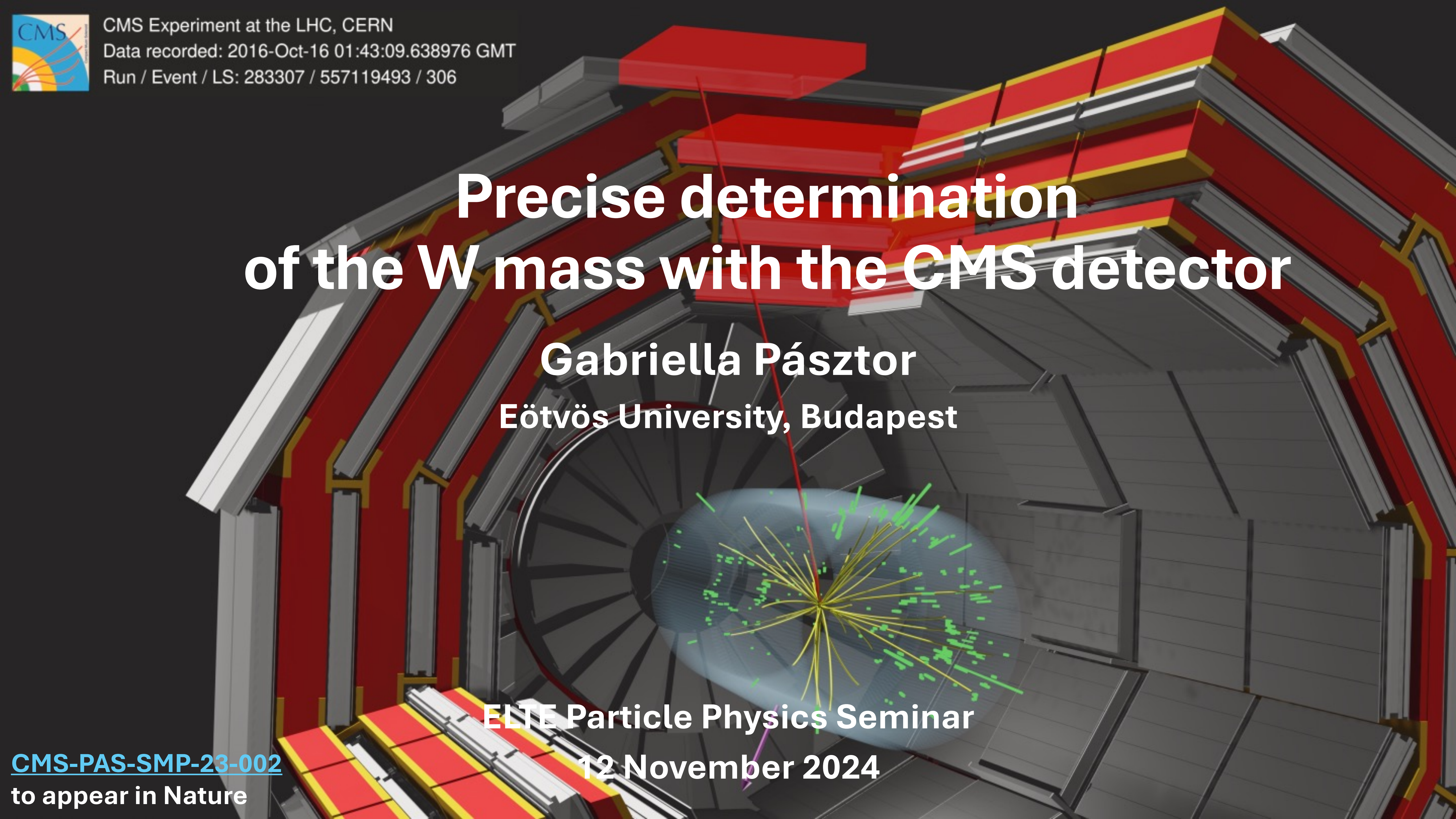


Precise determination of the W mass with the CMS detector

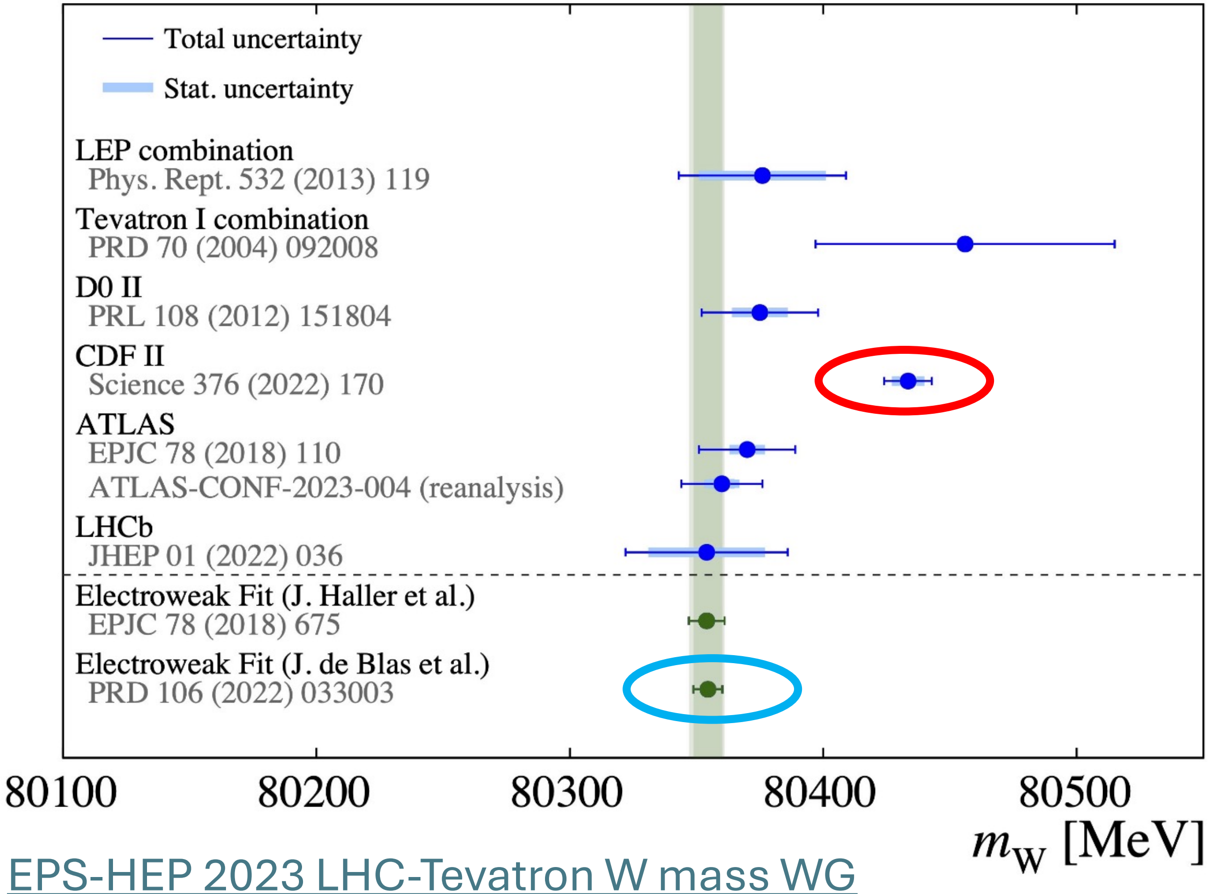
Gabriella Pásztor
Eötvös University, Budapest

ELTE Particle Physics Seminar
12 November 2024

[CMS-PAS-SMP-23-002](CMS-PAS-SMP-23-002)
to appear in Nature

Motivation

- W mass – fundamental parameter of SM – least precisely measured
- Closely related to the Z mass and the weak mixing angle ($M_W = M_Z \cos\theta_w$)
- New physics can change the relations via quantum loops
- Z mass measured to 2.1 MeV ($2.3 \cdot 10^{-5}$ precision) at LEP using 17M Z decays
- W mass more challenging
- Global SM fit: $\sigma(m_W) \sim 6$ MeV (<0.01%)
  PRD 106 (2022) 033003
  - **better** than direct experimental determination
- Most precise result:
  $\sigma(m_W) = 9.4$ MeV by CDF II Science 376 (2023) 170
  - in clear **tension** with SM (~7σ) and other measurements
  - from global combination (except CDF II)
    $\sigma(m_W) = 13.3$ MeV EPJ C84 (2024) 451
- Improved experimental precision crucial
- The most demanding measurement at LHC

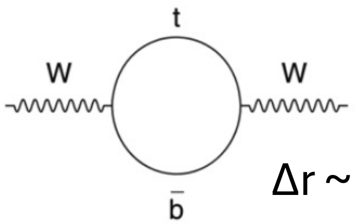


EPS-HEP 2023 LHC-Tevatron W mass WG

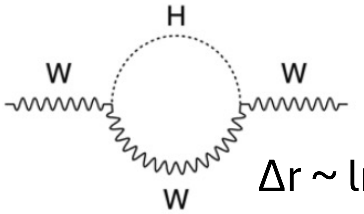
W mass in Standard Model

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{\mathrm{QED}}}{\sqrt{2}G_F}\times\frac{1}{1-\Delta r}$$

- Higgs discovery and precise mass measurement → EW sector over constrained
- Any conflict between direct and indirect determination of parameters? SM self-consistent?



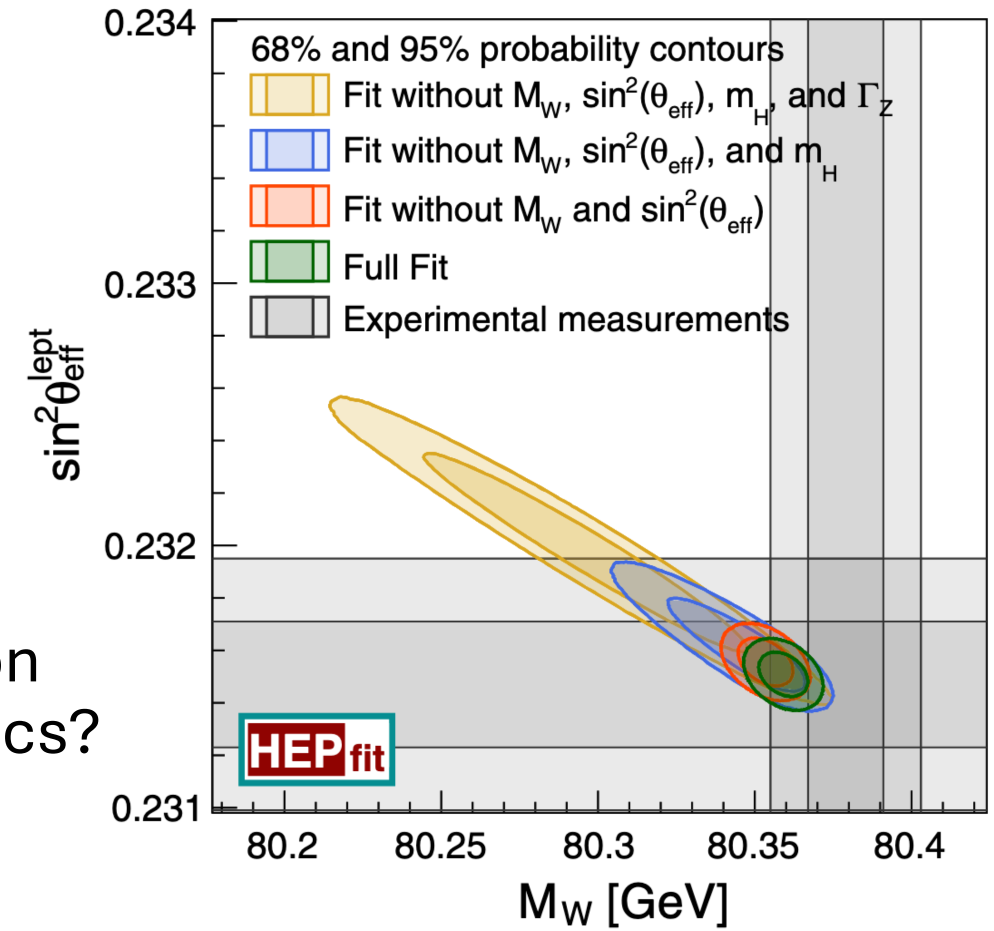
$\Delta r \sim m_{top}^2$

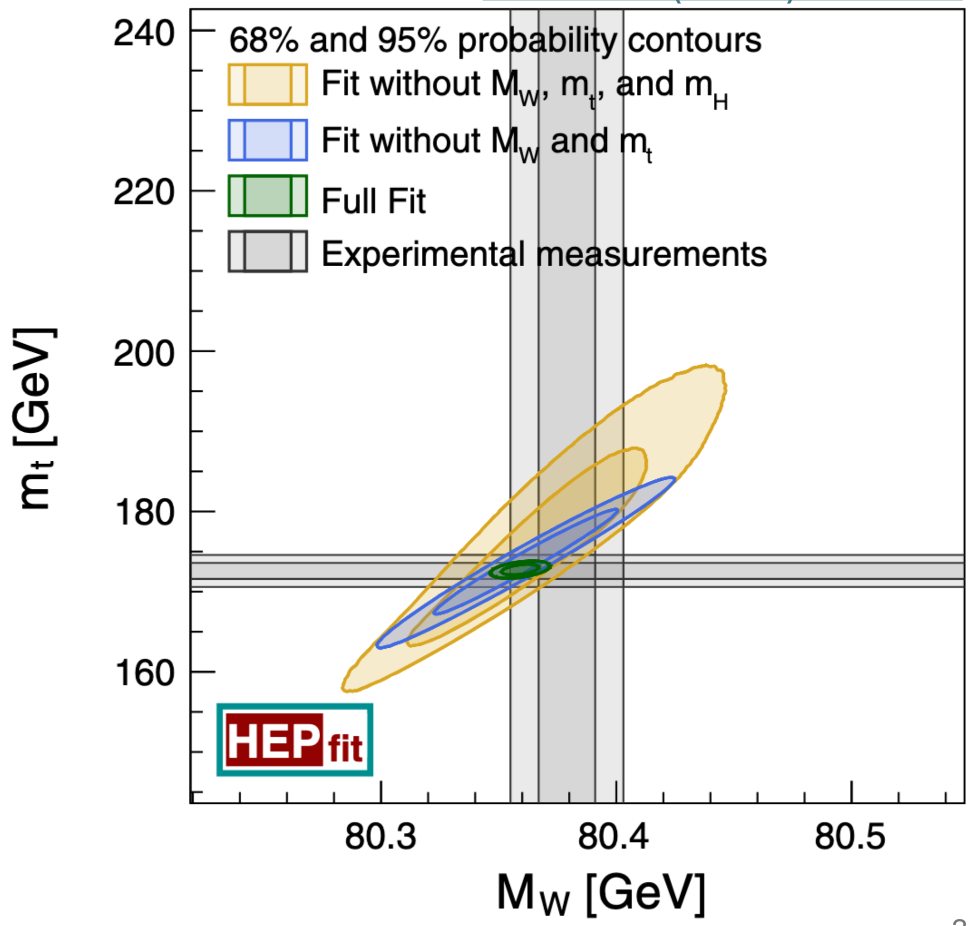


$\Delta r \sim \ln(m_H)$

- Any contribution from new physics?

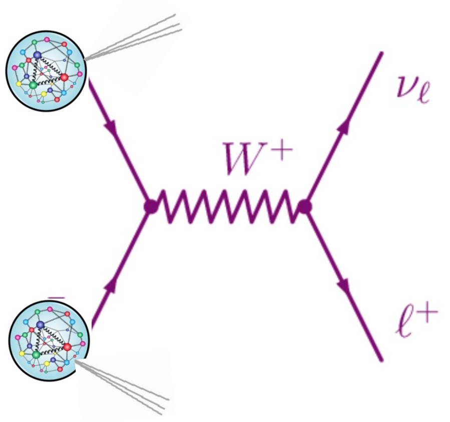
PRD 106 (2022) 033003





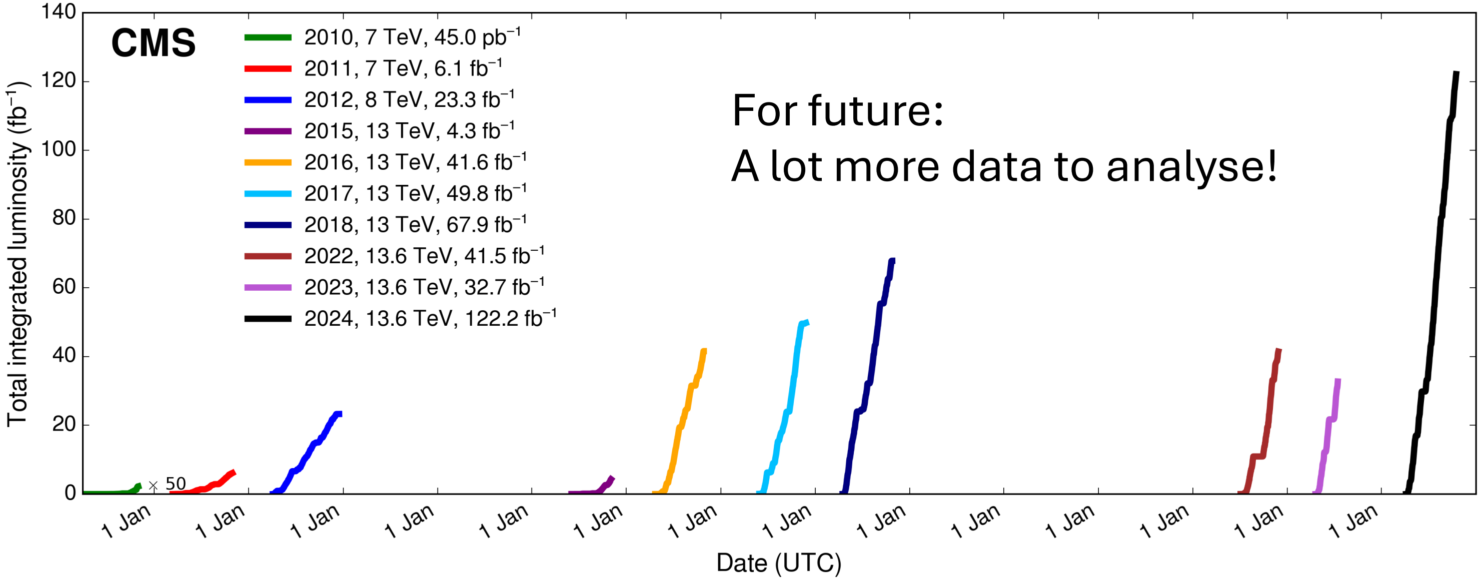
Data sample

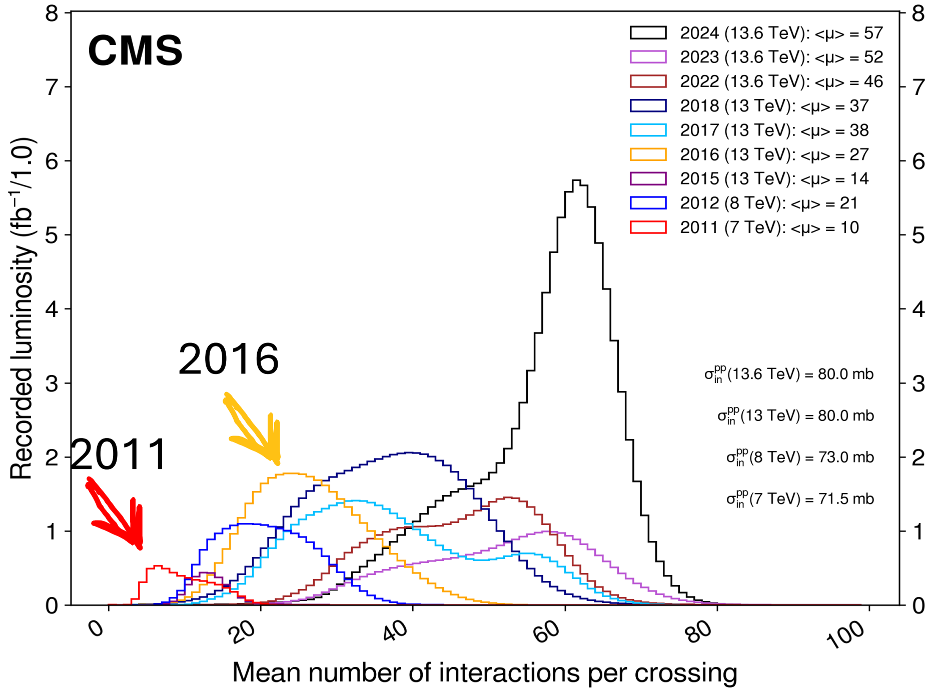
- 2016 pp @ 13 TeV
- Last ~40% of data with improved tracker performance: L_{int} = 16.8 ± 0.2 fb^{-1}
- Average pileup <PU> ~ 25 (tail up to 44)
- Hadronic decay not accessible (large background, jet energy scale)
- In $W \to \ell\nu$, neutrino takes away momentum giving unbalanced events (missing p_T: $-\Sigma \mathbf{p}_{T,i}$)
  - Difficult to measure / model at high PU: only used in event selection!
- **>100M $W \to \mu\nu$ events binned in muon (p_T^μ, η^μ, q^μ)**



For comparison

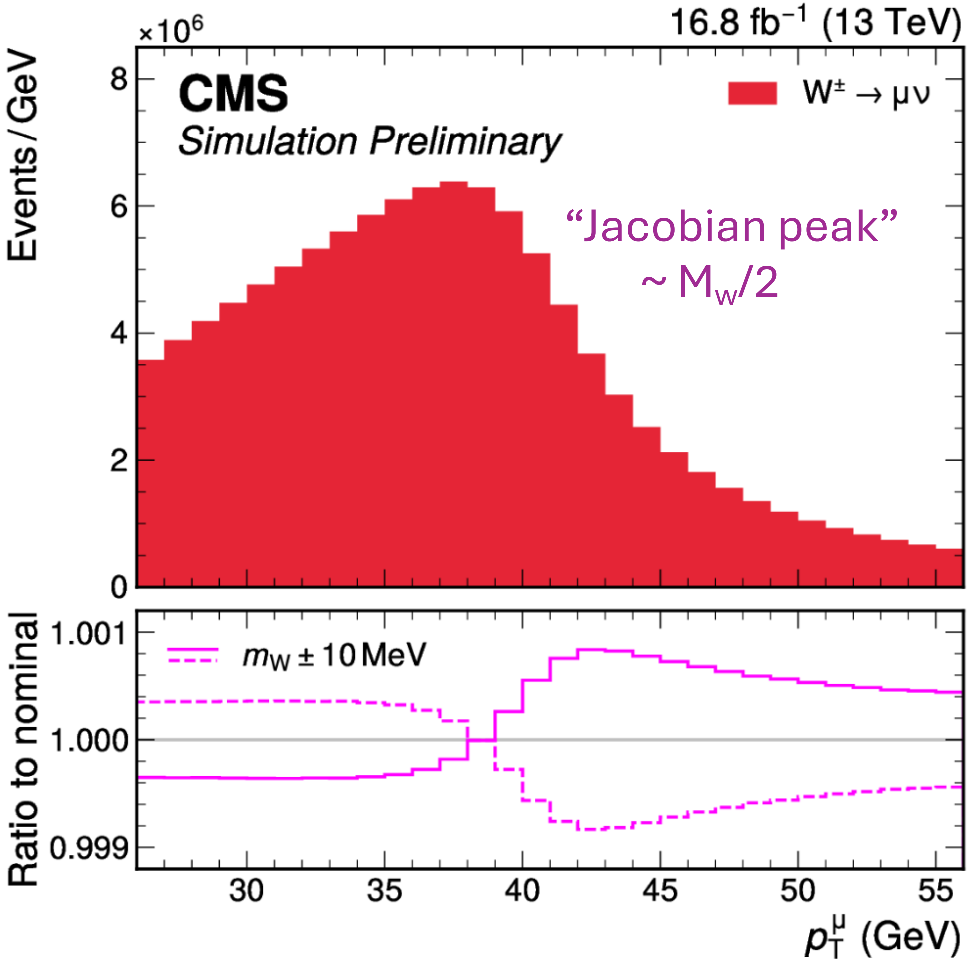
- **ATLAS** 2011 pp @ 7 TeV, PU ~ 9
  L_{int} =4.6, 4.1 fb^{-1} , $W \to e\nu$,$\mu\nu$
  2403.15085
- **CDF** $p\bar{p}$ @ 1.96 TeV, PU ~ 2
  L_{int} = 8.8 fb^{-1} , $W \to e\nu$,$\mu\nu$
  Science 376 (2023) 170

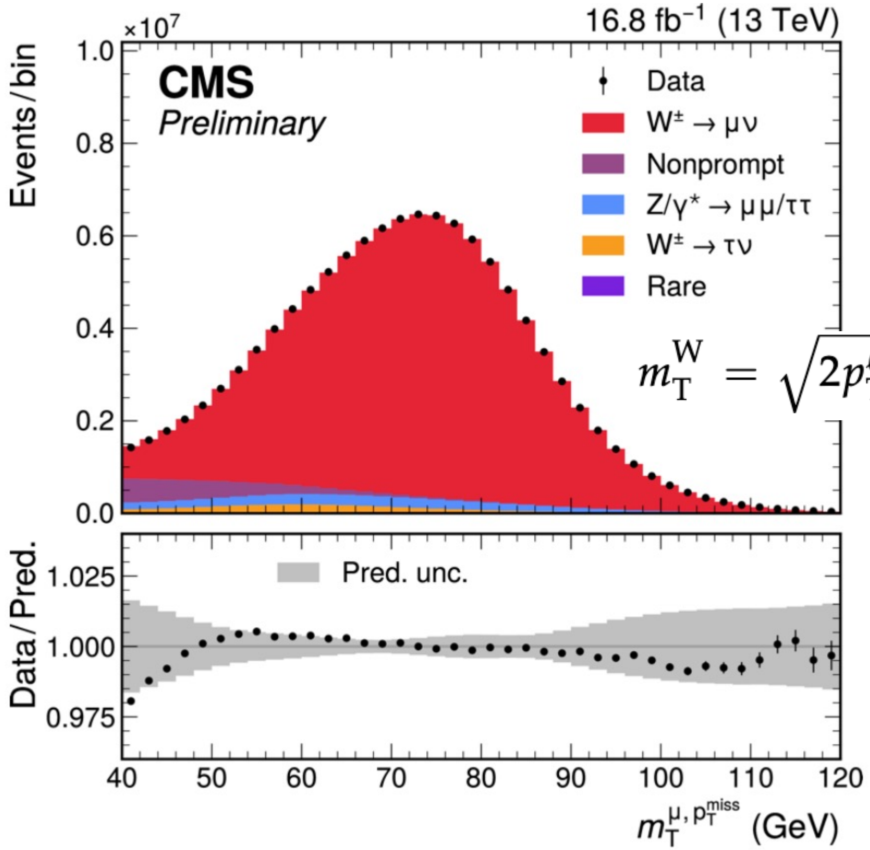




m_W measurement strategy

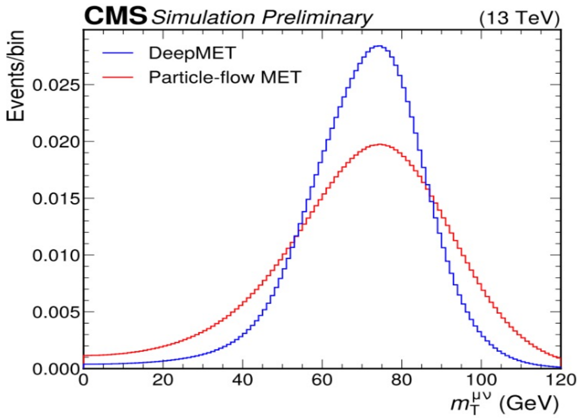
- From partial information
  - lepton p_T^{ℓ} → muons best measured, electrons higher syst
  - transverse mass m_T of *lepton - missing p_T system*
  - p_T^{miss} (hadronic recoil reco) challenging at high PU
    - for future





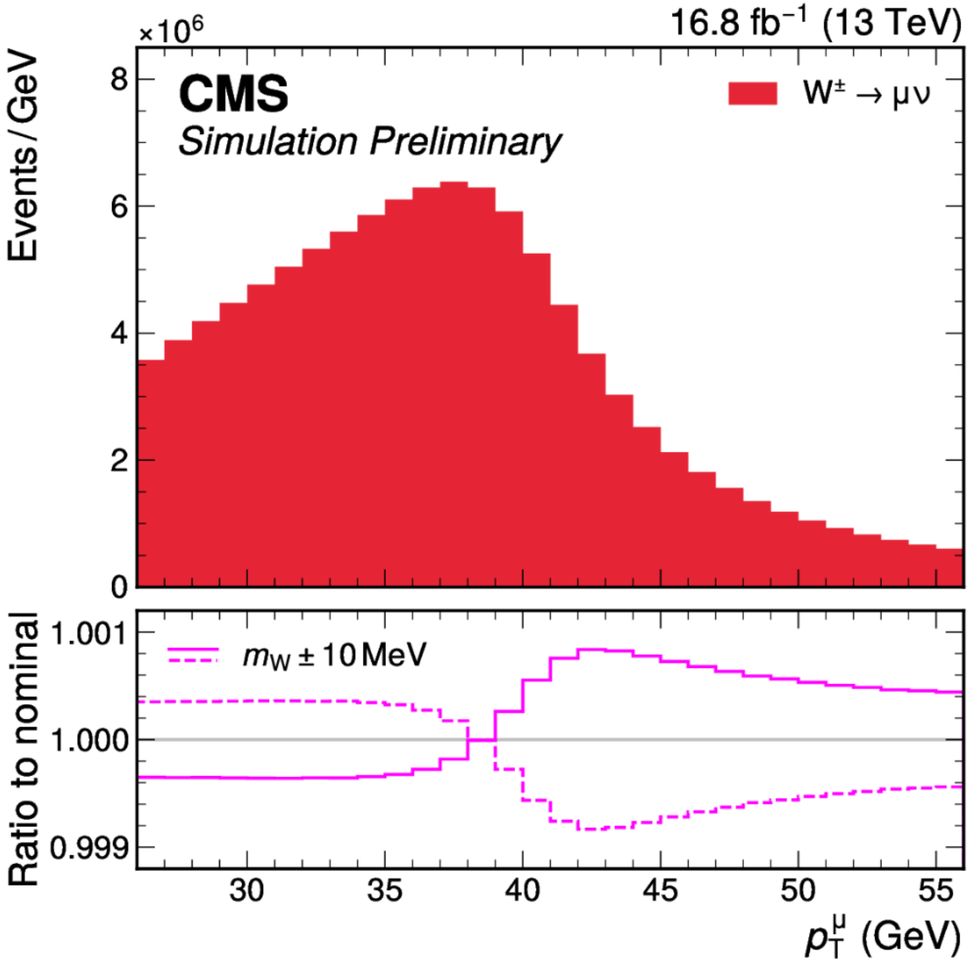
$$m_T^W = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\phi_{\ell\nu})}$$

Event selection: m_T > 40 GeV
p_T^{miss} based on deep neural net, corrected using $Z \to \mu^+\mu^-$ events



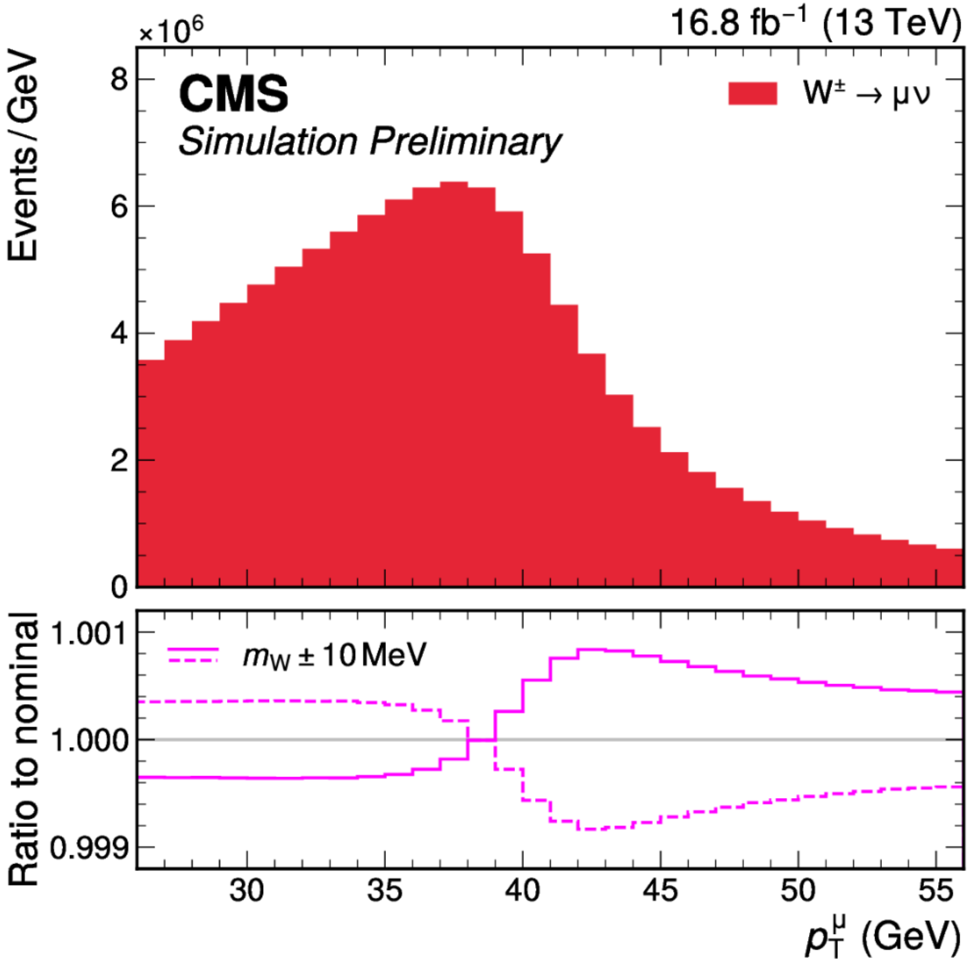
m_W measurement strategy

- From partial information
  - lepton p_T^ℓ → muons best measured, electrons higher syst
  - transverse mass m_T of *lepton - missing p_T system*
  - p_T^{miss} (hadronic recoil) challenging at high PU, for future
    - only in event selection
- **CMS strategy:**
  reconstruct muon kinematics to (sub) per mille precision
  - $\sigma(p_T^\ell)/p_T^\ell \sim 10^{-4} \Rightarrow \sigma(m_W) \sim 10$ MeV
  - precise control necessary for experimental (and theory) biases
  - well-understood data set, event selection, background estimation
  - in-situ muon efficiency correction with high granularity
  - muon momentum scale derived from J/ψ data, independent of Z and W data set
    - verified using Z events

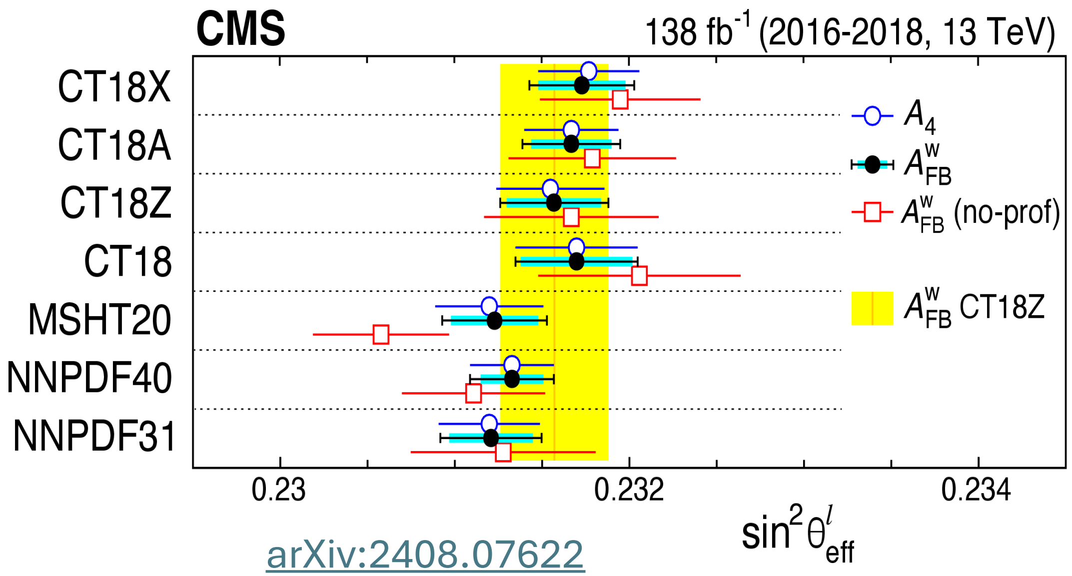


m_W measurement strategy

- p_T^{ℓ} in W (and Z) decays affected by theoretical uncertainties (also p_T^{miss} and m_T)
  - Initial state: parton distribution functions (pdf)
  - higher order pQCD corrections → $p_T^{W\,(Z)}$ model
    - large logs at low W (Z) pT
  - non-perturbative low-pT effects, like intrinsic transverse momentum of partons (k_T) in proton
  - electroweak corrections
  - …



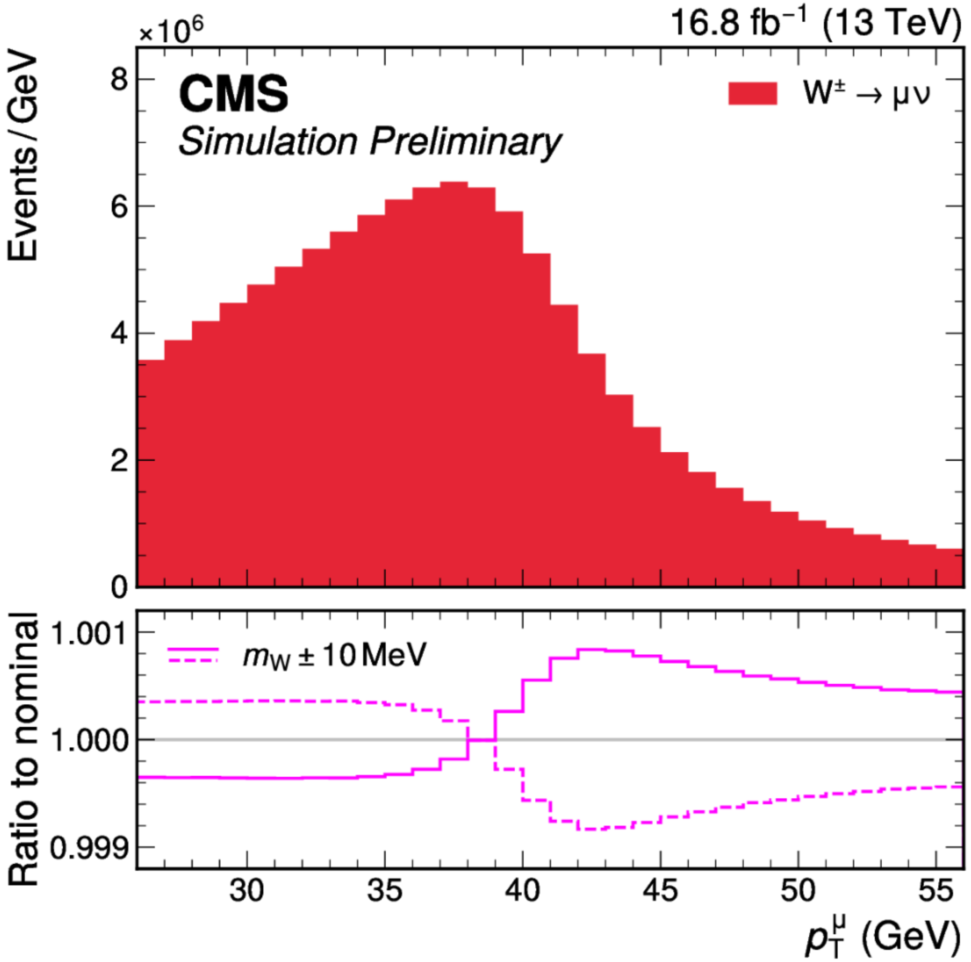
Experimental results often depend more on pdf set choice than expected from given pdf set uncertainties



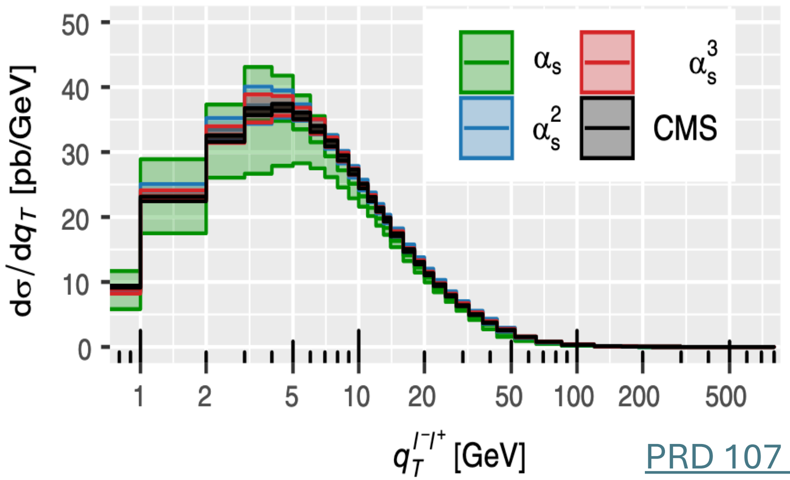
arXiv:2408.07622

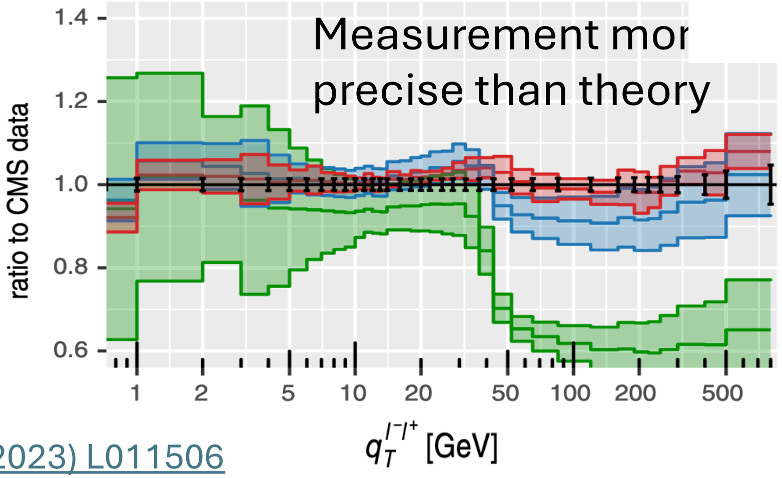
m_W measurement strategy

- p_T^{ℓ} in W (and Z) decays affected by theoretical uncertainties (also p_T^{miss} and m_T to a lesser extent)
  - Initial state: parton distribution functions (pdf)
  - higher order pQCD corrections → $p_T^{W(Z)}$ model
    - large logs at low W (Z) p_T
  - non-perturbative low-pT effects, like intrinsic transverse momentum of partons (k_T) in proton
  - electroweak corrections
  - …



Theoretical description: NNLO in pQCD + N^{3}LL (important if $p_T^{W(Z)} < M_{W(Z)}$) + model for non-perturbative effects





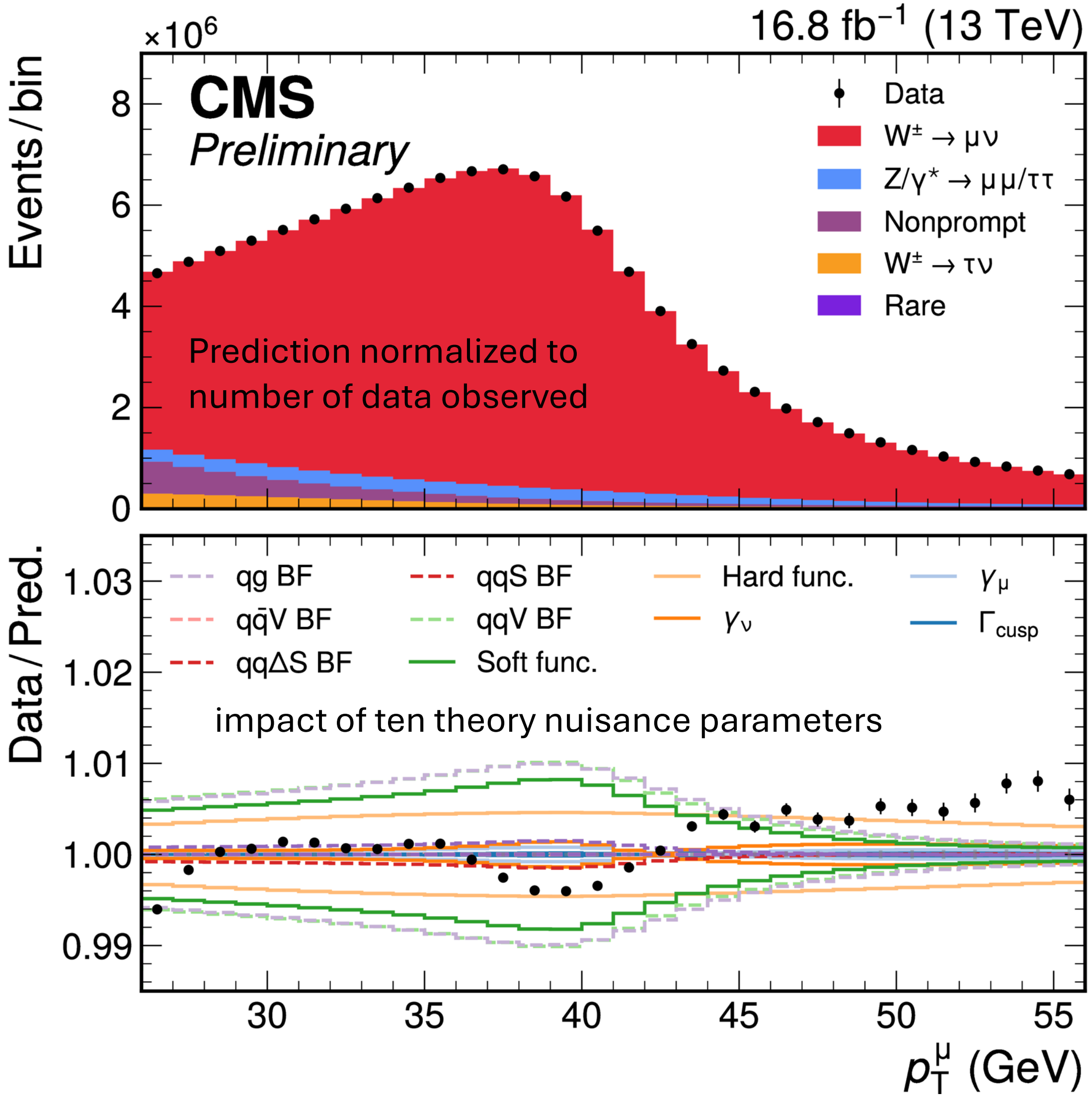
Measurement more precise than theory

PRD 107 (2023) L011506

What was done before?
Previous measurements (CDF, ATLAS) used the "precisely" measured $Z \to \ell^+\ell^-$ p_T^Z spectrum to tune the theoretical prediction
BUT validation is difficult if Z already used!

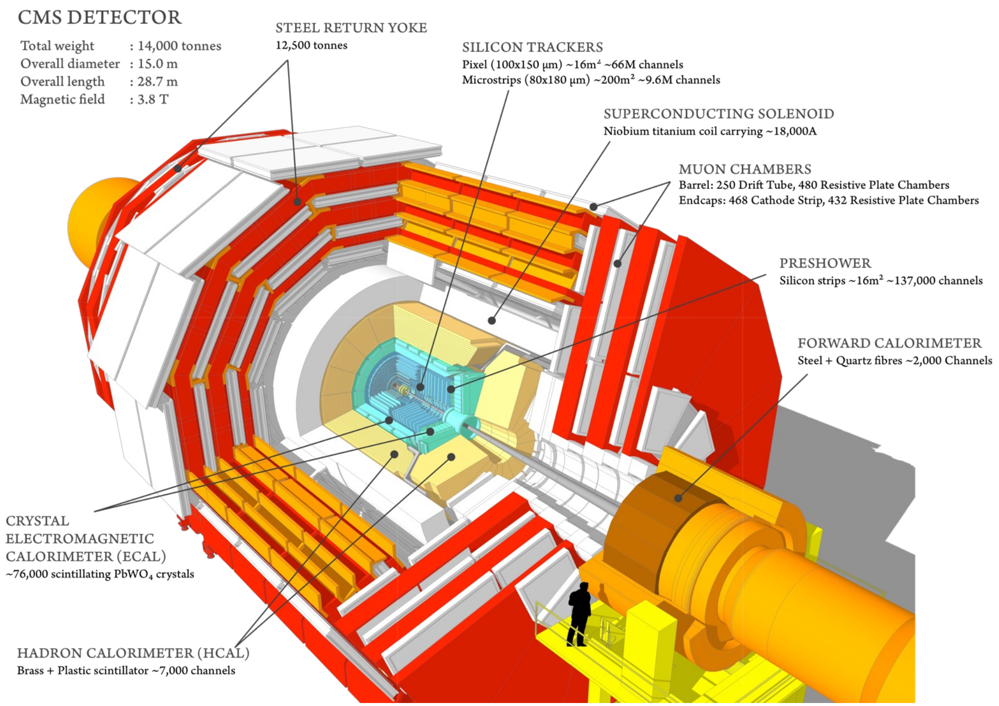
m_W measurement strategy

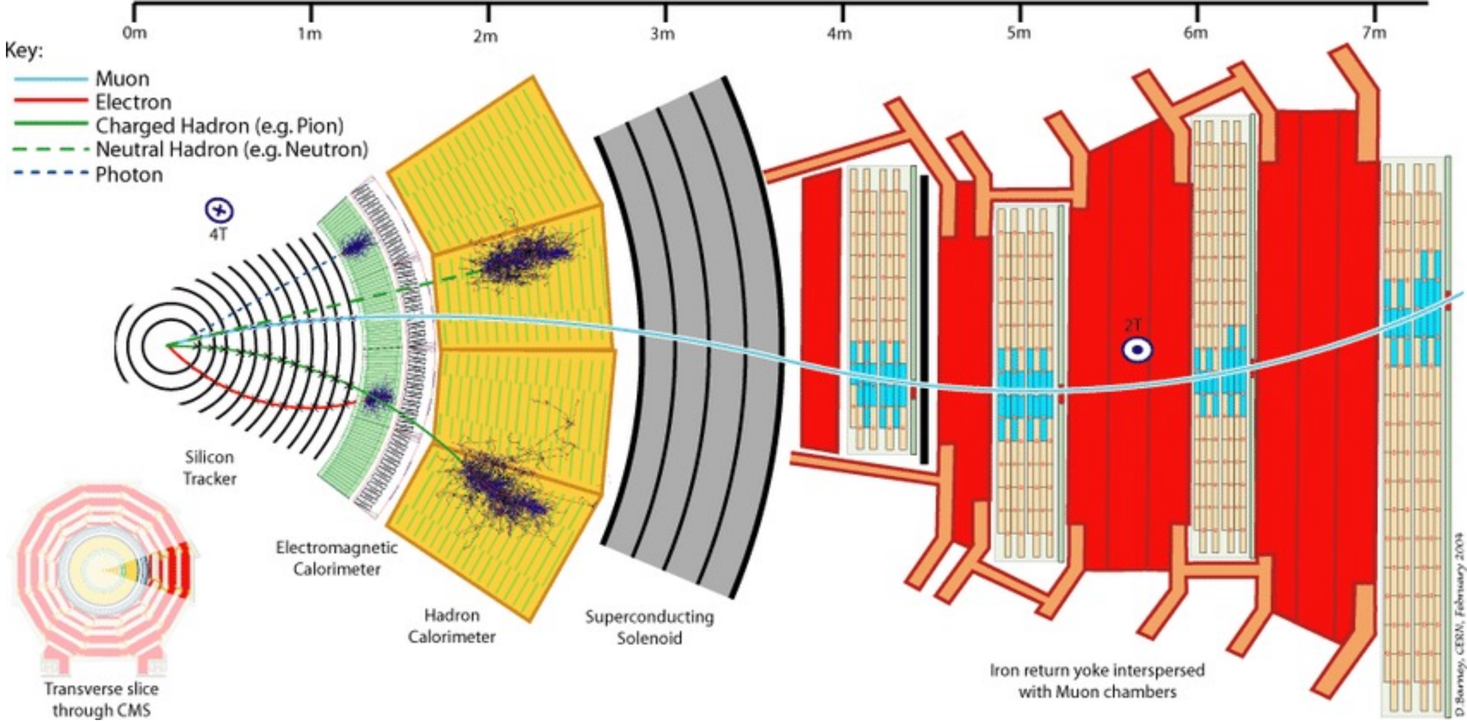
- **In-situ constraint of theory and pdf description from W data thanks to high-statistics and finely-binned fit in (p_T^μ, η^μ, q^μ)**
- State-of-the-art theory and pdf descriptions
  - 7 modern pdf sets
- W-like Z mass measurement (removing a muon)
  - **Z data not used to tune theory, but to perform independent cross check of the description**
- Crosscheck with less theory dependent helicity amplitude fit: simultaneous extraction of M_W and angular coefficients
- A decade of "blind" M_W measurement program
- Going through a W-like M_Z (2016) and W rapidity-helicity (2020) measurements

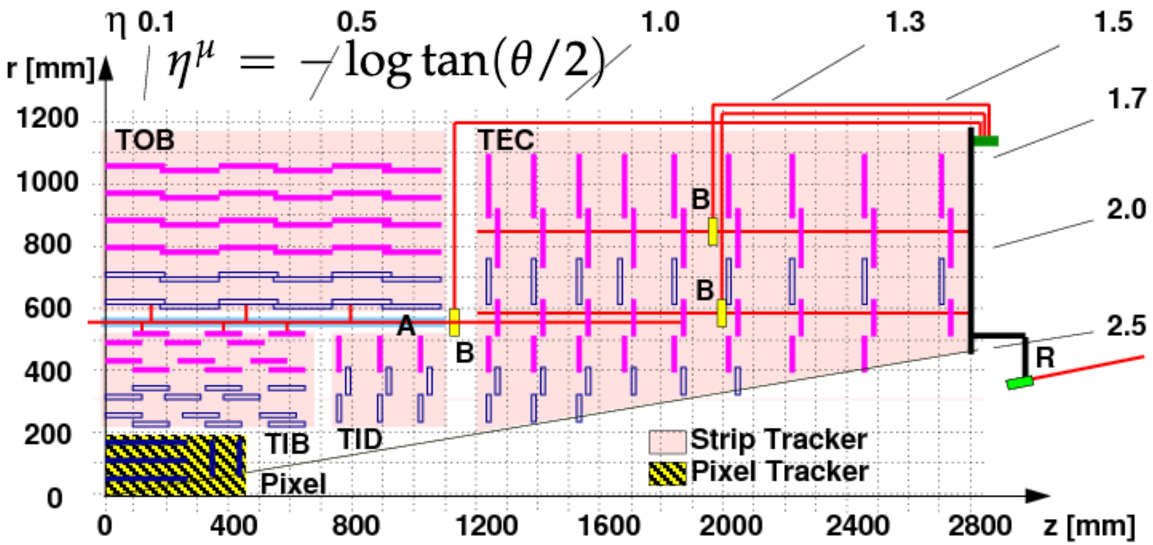


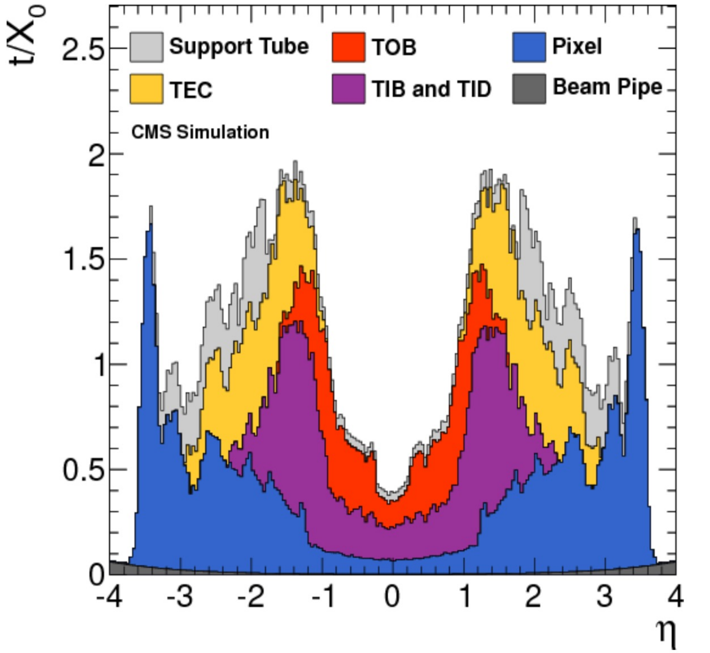
[CMS-PAS-SMP-14-007](#)
[Phys. Rev. D 102 (2020) 092012](#)

CMS detector





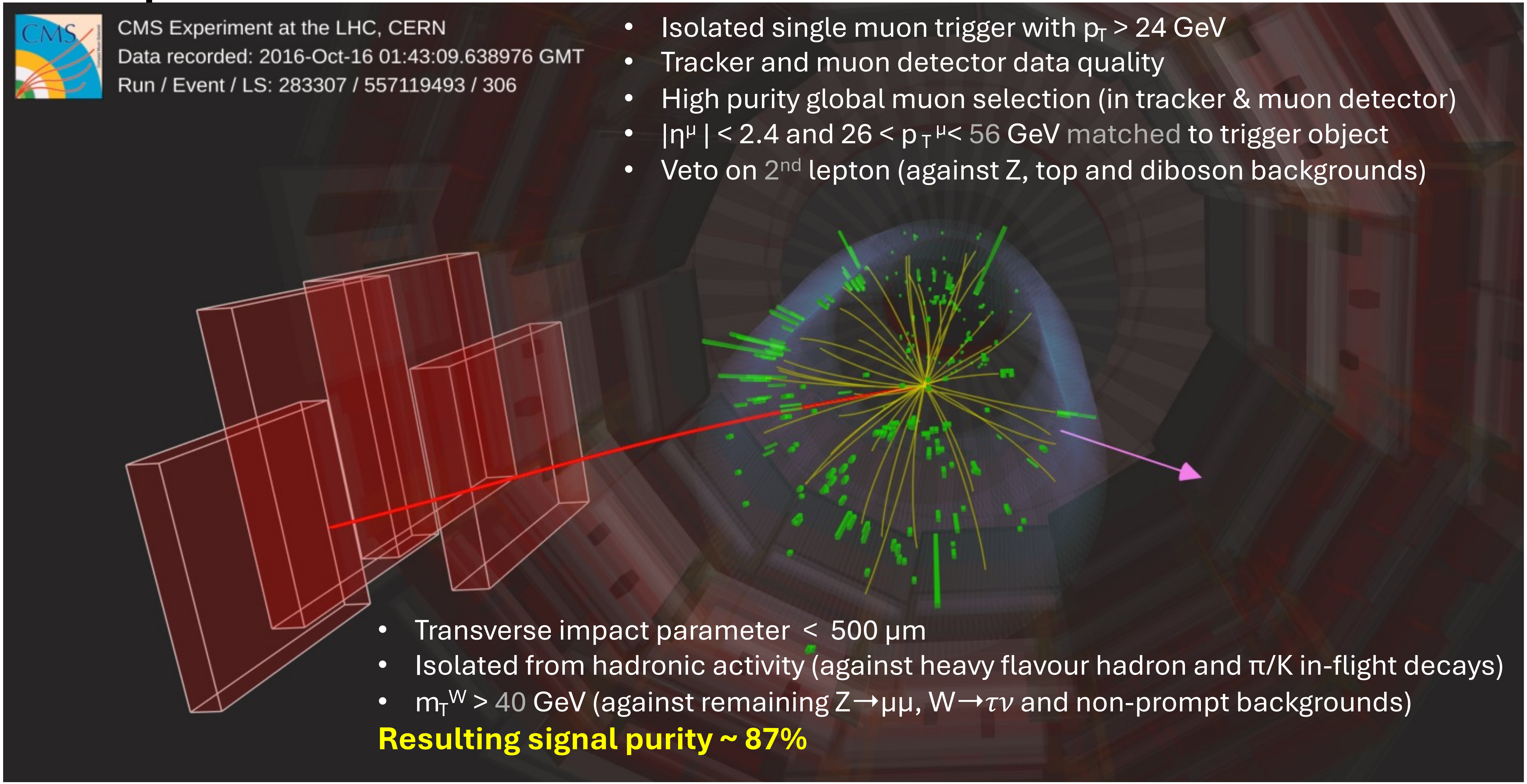




- Trigger and identify muons using the outer muon detectors
- Measure momentum in the inner tracker alone (muon detectors important for higher p_T range than used in analysis but bring lots of complications for precise calibration)
- Corrections finely binned in pseudorapidity

W→μν selection

Only slight modifications for W-like Z →μ⁺μ⁻ event selection with extra requirements on opposite charge and $m_{\mu\mu}$ range



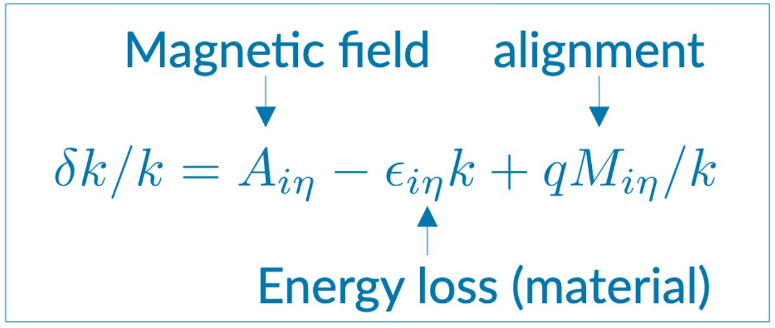
- Isolated single muon trigger with $p_T > 24$ GeV
- Tracker and muon detector data quality
- High purity global muon selection (in tracker & muon detector)
- $|\eta^{\mu}| < 2.4$ and $26 < p_T^{\mu} < 56$ GeV matched to trigger object
- Veto on 2nd lepton (against Z, top and diboson backgrounds)

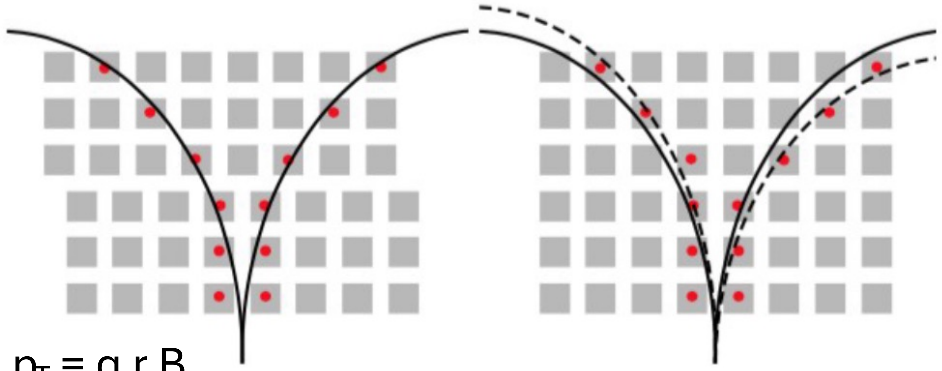
- Transverse impact parameter < 500 μm
- Isolated from hadronic activity (against heavy flavour hadron and π/K in-flight decays)
- $m_T^W > 40$ GeV (against remaining Z→μμ, W→$\tau\nu$ and non-prompt backgrounds)

Resulting signal purity ~ 87%

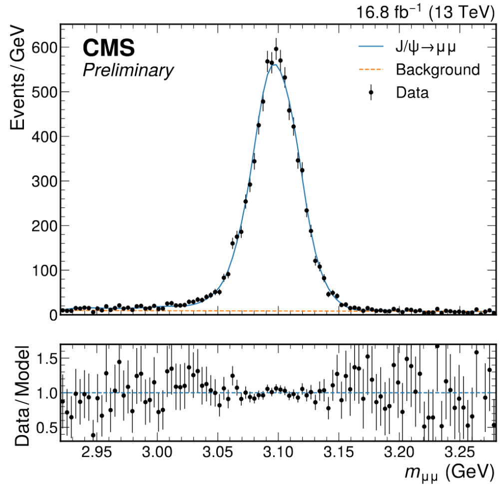
Muon momentum calibration

- Momentum from curvature of muon track in magnetic field in silicon tracker
- Momentum calibration depends on magnetic field (B), detector alignment, material distribution inducing energy loss (dE/dx) and multiple scattering
- Improved track fit, stringent pixel hit quality, new parametrization for local hit positions in endcap, detailed magnetic field map
- Dedicated alignment (position, orientation of detector elements) using fine granularity corrections for B and dE/dx, correcting also for weak modes (coherent misalignments)
- Residual scale bias derived using $J/\psi \to \mu^+\mu^-$ events relying on well-known mass of J/ψ
- Extrapolated based on physics-motivated model as a function of curvature: $k \equiv 1/p_T$





Alignment effect



- Validated using Y(1S) and Z events

$p_T = q\,r\,B$

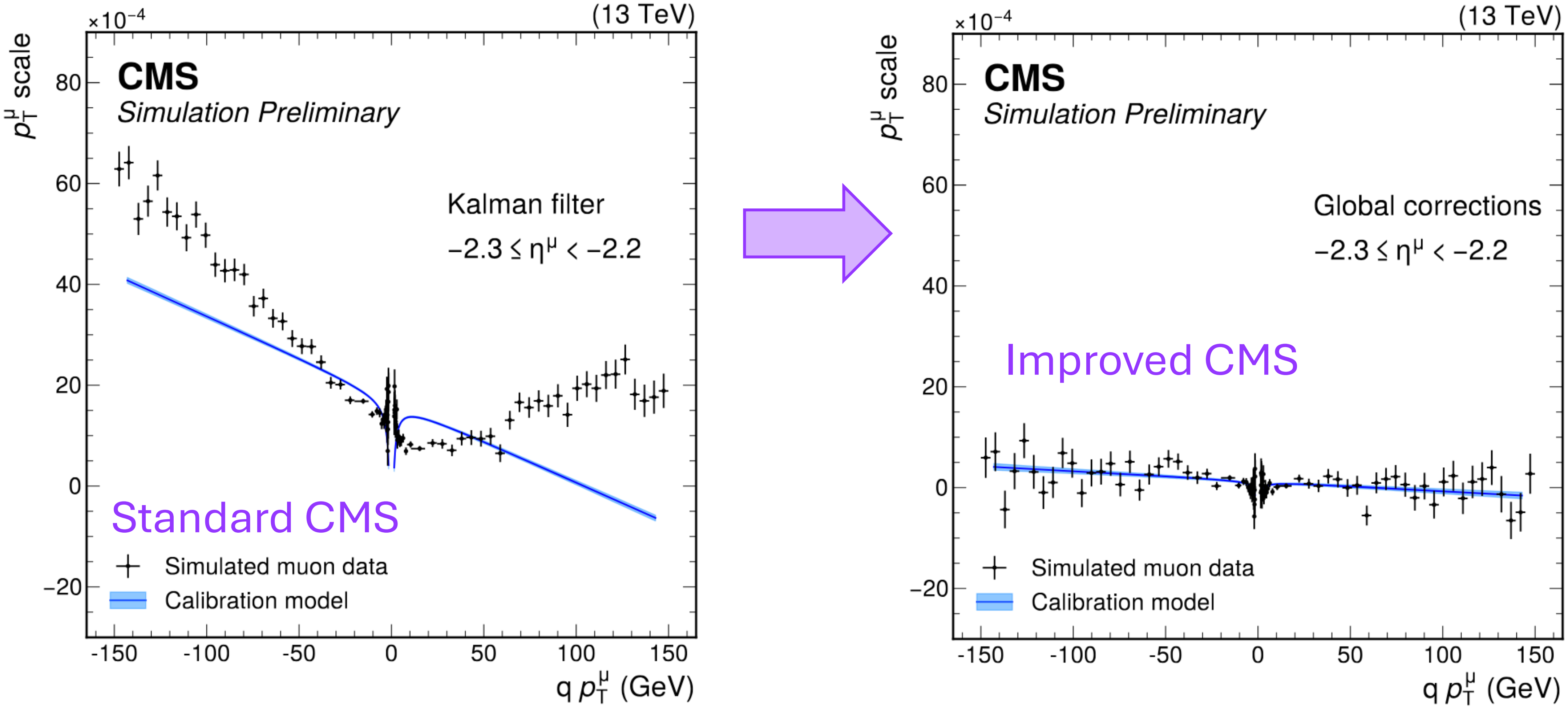
Muon momentum calibration

Validation of extrapolation model

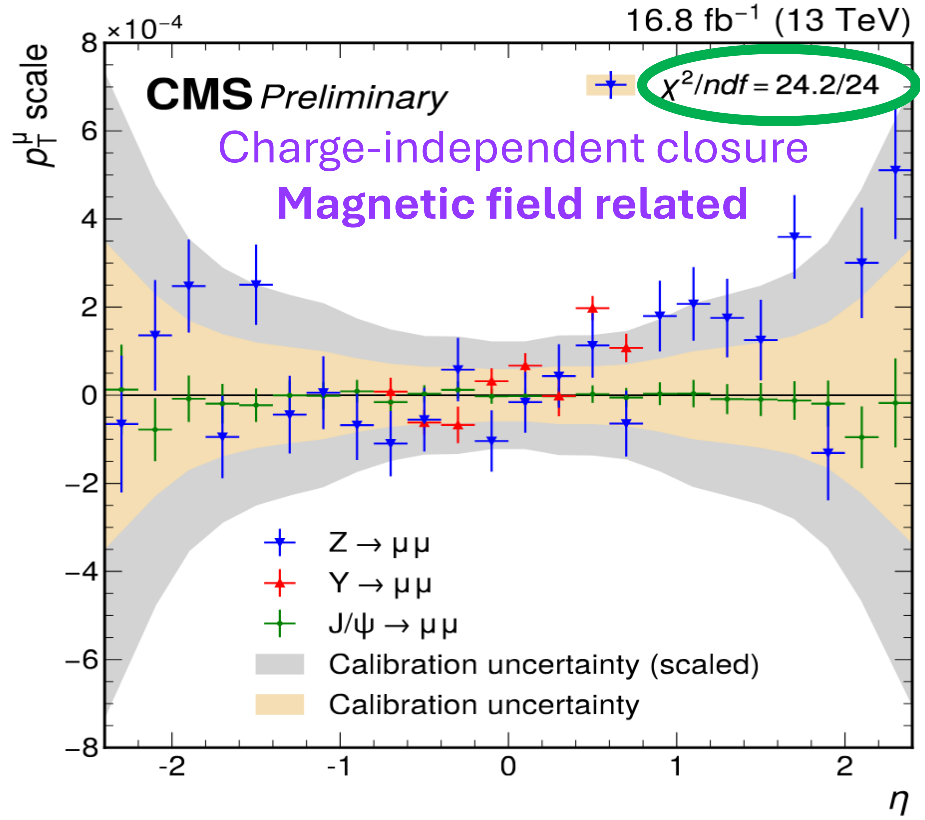
Magnetic field ↓ alignment ↓

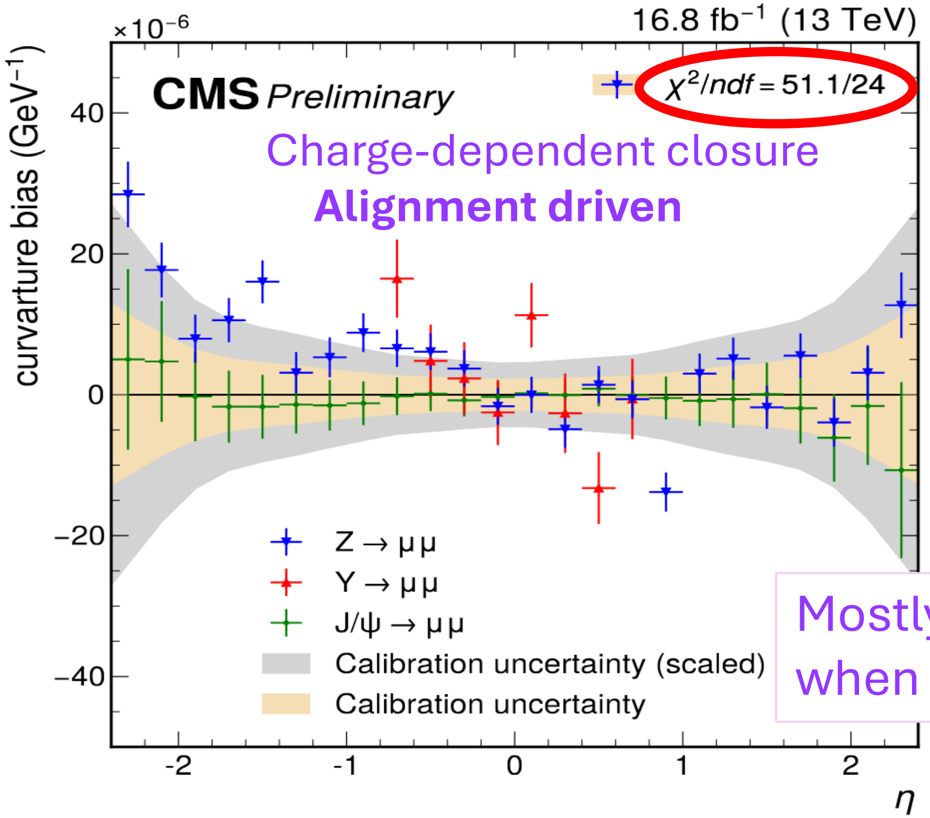
$$\delta k/k = A_{i\eta} - \epsilon_{i\eta} k + qM_{i\eta}/k$$

↑ Energy loss (material)



Muon momentum calibration closure





Closure measures remaining systematic effects, related to weak modes with different sensitivity in J/ψ and Z events, trigger biases, or other sources

Mostly cancels out in M_W when both charges used

Statistical uncertainty scaled up by 2.1 to account for closure χ^2/dof for various binnings and assumptions for η symmetry, etc.

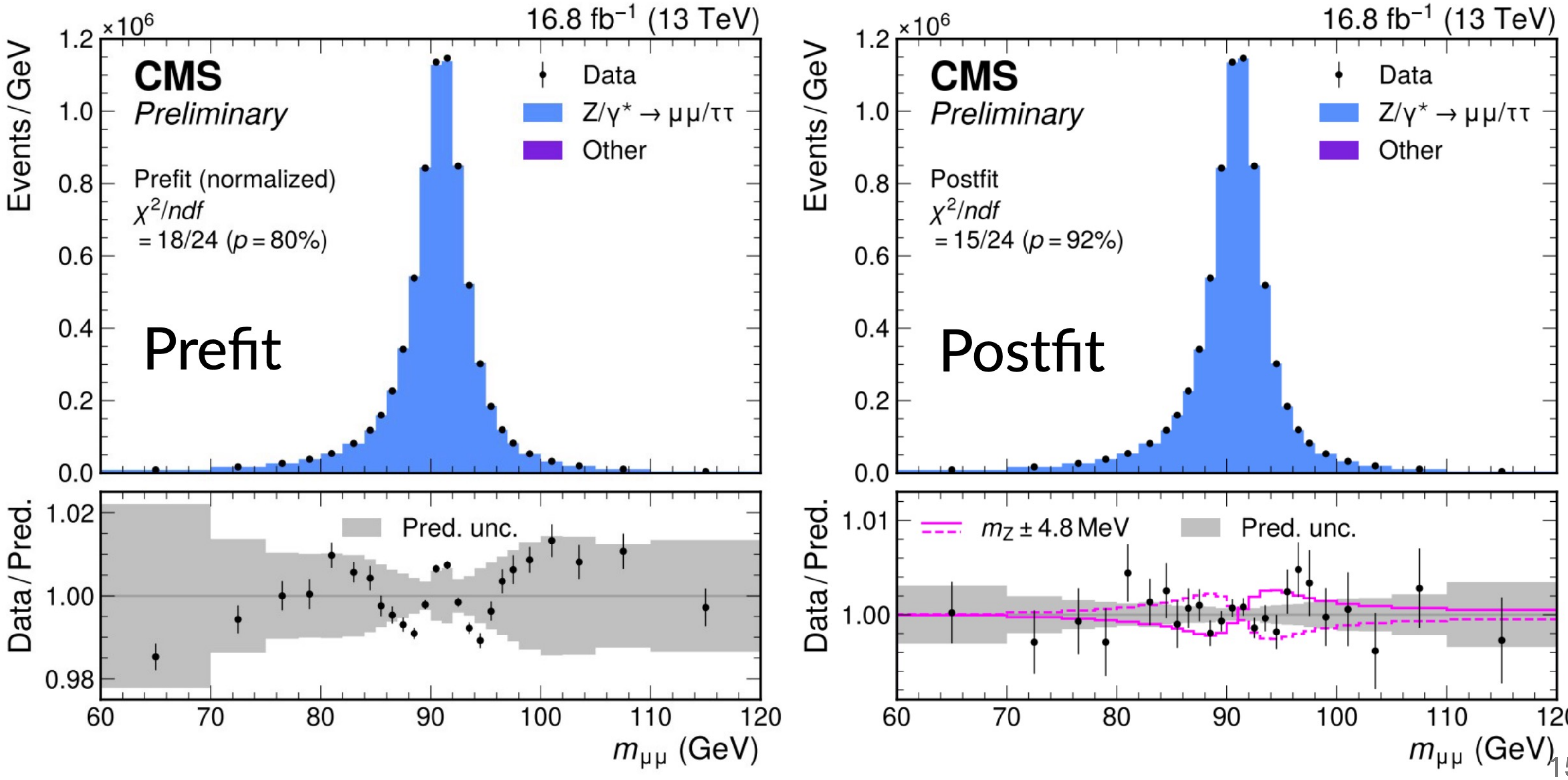
Source of uncertainty	Nuisance parameters	Uncertainty in m_W (MeV)
J/ψ calibration stat. (scaled ×2.1)	144	3.7
Z closure stat.	48	1.0
Z closure (LEP measurement)	1	1.7
Resolution stat. (scaled ×10)	72	1.4
Pixel multiplicity	49	0.7
Total	314	4.8

Scale validation with Z mass extraction

- 2D profile-likelihood fit in $m_{\mu\mu}$ and η of the most forward muon:

$$\mathbf{m_Z - m_Z^{PDG} = -2.2 \pm 4.8\ MeV} = -2.2 \pm 1.0\ \text{(stat)}\ \pm 4.7\ \text{(syst)}\ \text{MeV}$$

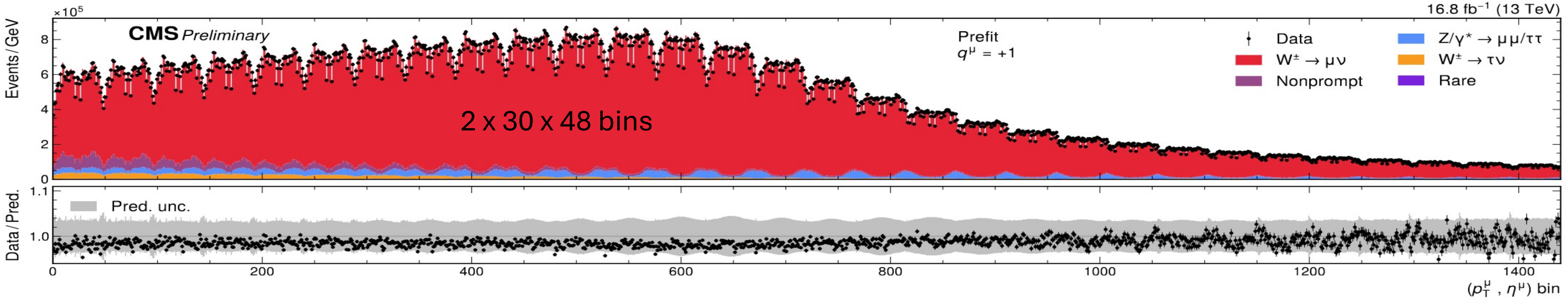
- Dominated by calibration uncertainty
- Not an independent M_Z measurement (yet): Z closure used to tune calibration and enters the uncertainty model
- Competitive future measurement feasible

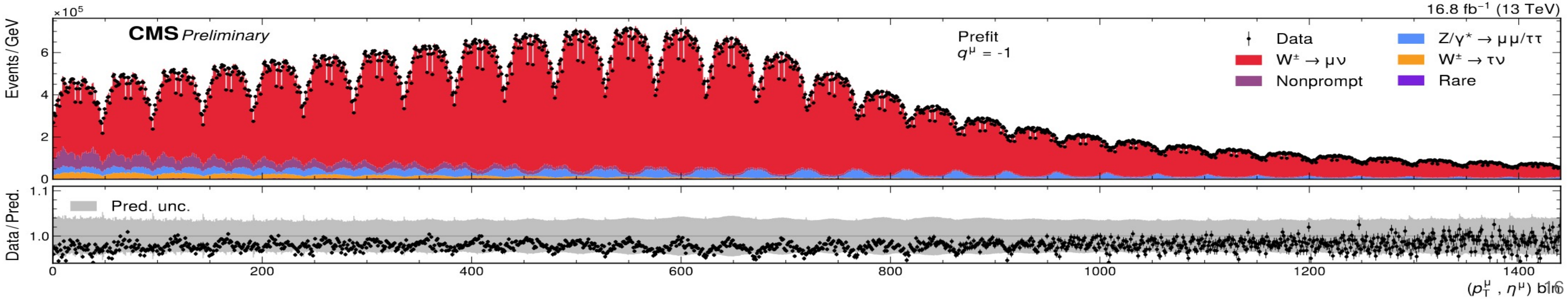


Measured "prefit" spectra (2880 bins)

- Two-dimensional distributions "unrolled" for each charge
- Each bin on represents one (p_T^μ, η^μ) cell
- Differences from prediction, uncertainties before fit to the data

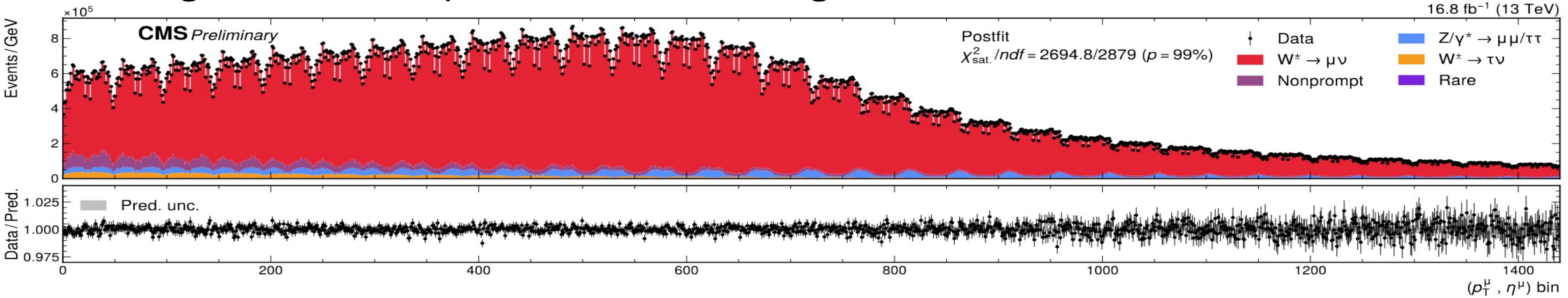
- **Non-prompt background from data** using the extended ABCD method (using muon isolation and m_T)
- Other contributions from simulation with data-driven correction as for signal

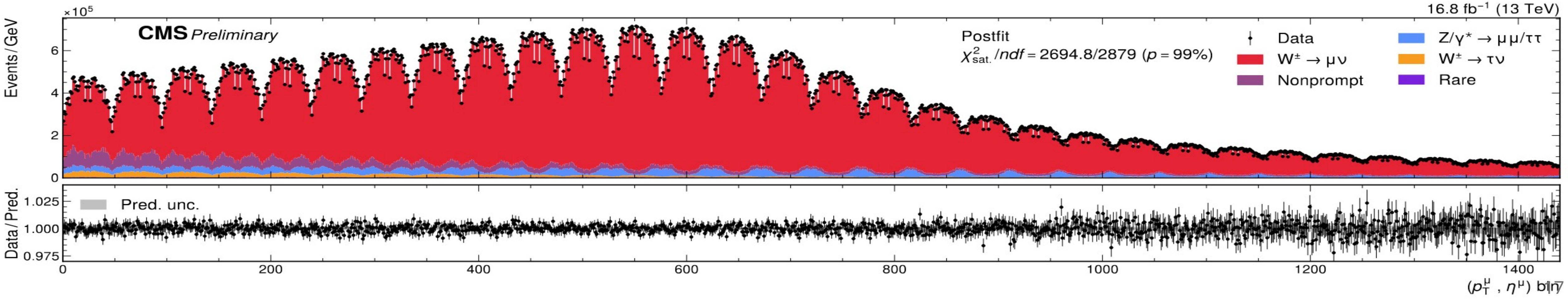




Measured "postfit" spectra

- Two-dimensional distributions "unrolled" for each charge
- Each bin on represents one (p_T^μ, η^μ) cell
- Good agreement with prediction after fitting biases from data, uncertainties after fit





Theoretical model

- More than 4B simulated events with state-of-the-art model of Z and W production
  - $\text{MiNNLO}_{\text{PS}}$ ($O(\alpha_s^2)$) + Pythia8 (fragmentation/hadronization) + Photos++ (QED radiation)
  - Unpolarized cross section corrected to resummed SCETLIB + DYTurbo (NNLO+N^3LL)
- Differential cross section as fuction of muon kinematics described in terms of angular coefficients $A_i(p_T^V, M_V, y_V)$:

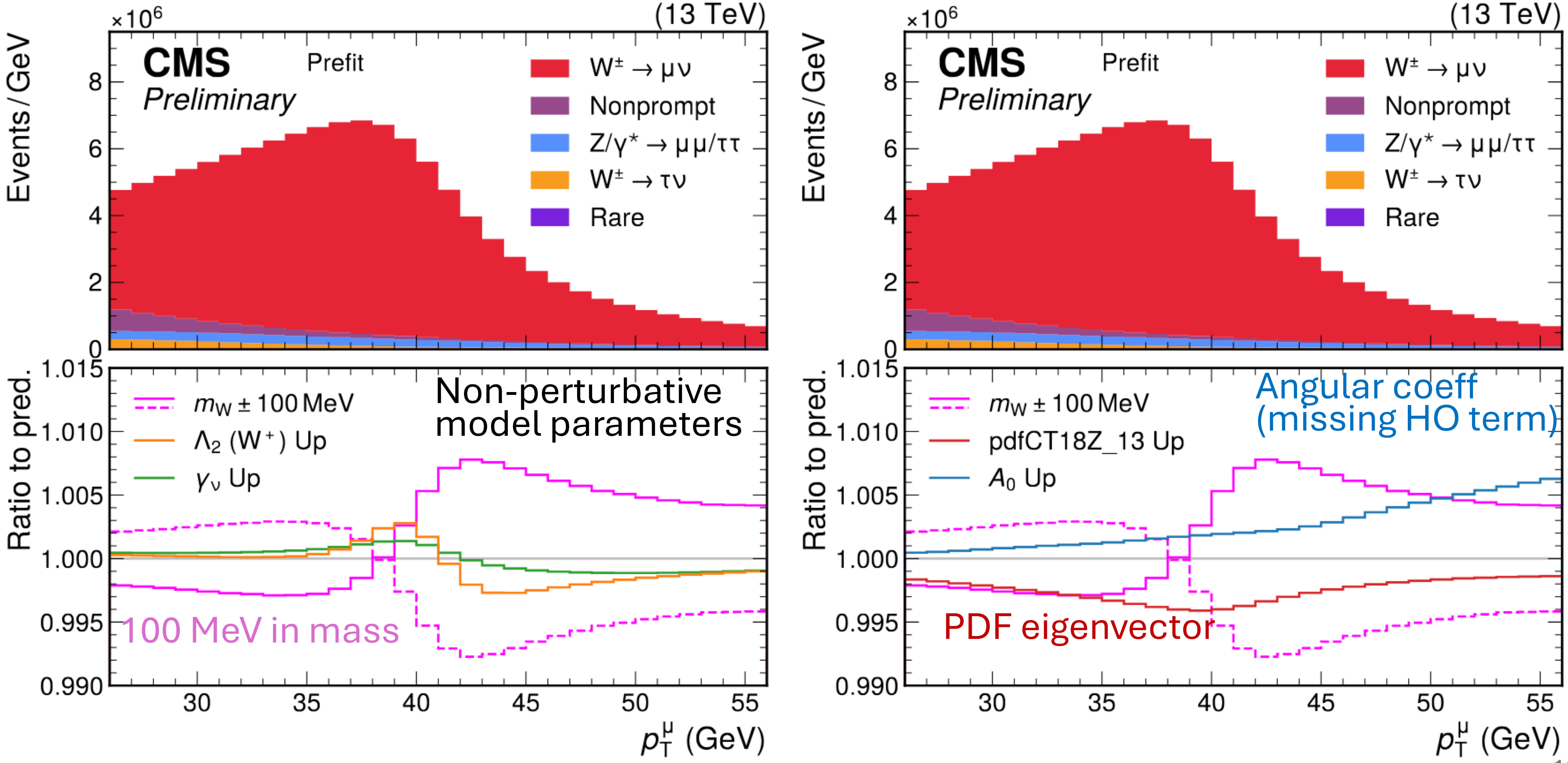
unpolarized cross section

$$\frac{d^5\sigma}{dq_T^2\, dy\, dm\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d^3\sigma^{U+L}}{dq_T^2\, dy\, dm}\Big[(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+ \frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

  - Using spherical harmonics, cross section decomposed into nine helicity-dependent states
- Use "theory nuisance parameters" (TNP) exploiting the universal structure of the resummation to parametrize the impact of unknown perturbative corrections (F. Tackmann)
  - Defines correlation model between different bins and W and Z

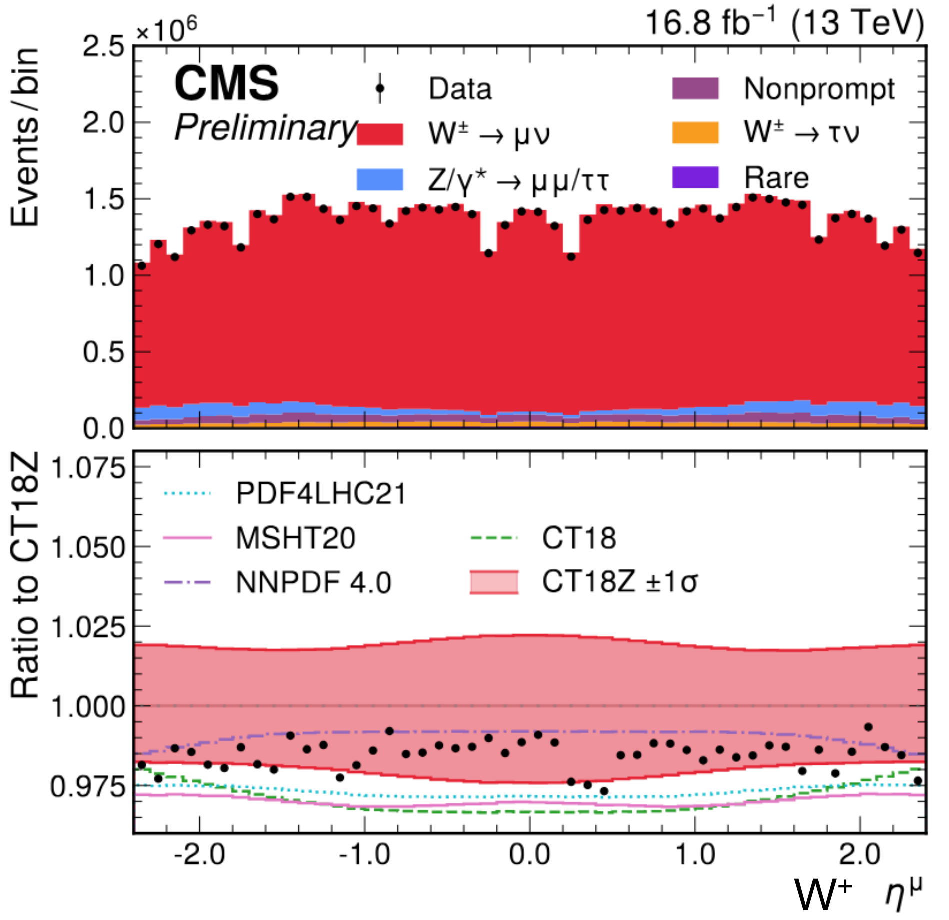
Constraining the theoretical model

- Change in m_W has a different effect on lepton kinematics (p_T^{ℓ}) than variations in p_T^W, rapidity or decay angles due to QCD uncertainties and PDFs
- Different shapes of biases → p_T^W and PDF uncertainties can be constrained in-situ by the data
- p_T^{ℓ} sensitive to m_W
- Use of η and charge enhances in-situ constraints on theory model (PDFs…)



Theoretical uncertainties: PDFs

- PDFs impact boson kinematics → measured m_W
- Uncertainty evaluated using Hessian eigenvectors of given PDF set which fully captures correlations across bins and processes
- Different sets frequently do not agree within uncertainties
  → using pseudo data generated using the central values of other sets, inflate the prefit uncertainties of the set studied to cover the m_W prediction



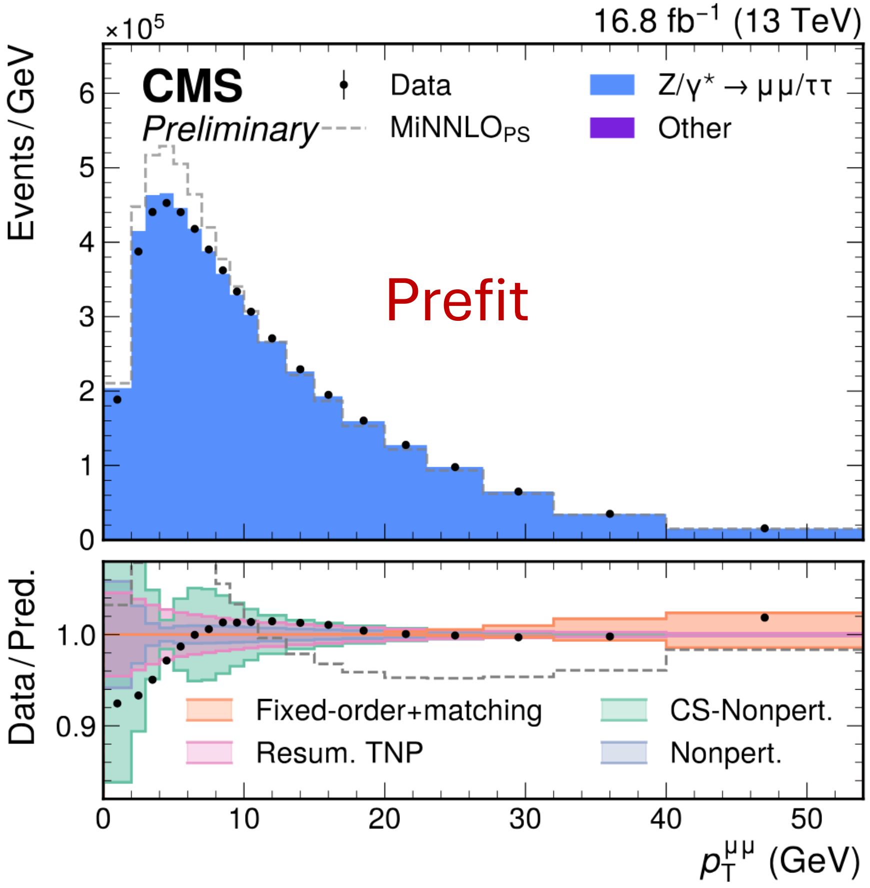
PDF set	Scale factor	Impact in m_W (MeV)	
		Original σ_{PDF}	Scaled σ_{PDF}
CT18Z	–	4.4	
CT18	–	4.6	
PDF4LHC21	–	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0

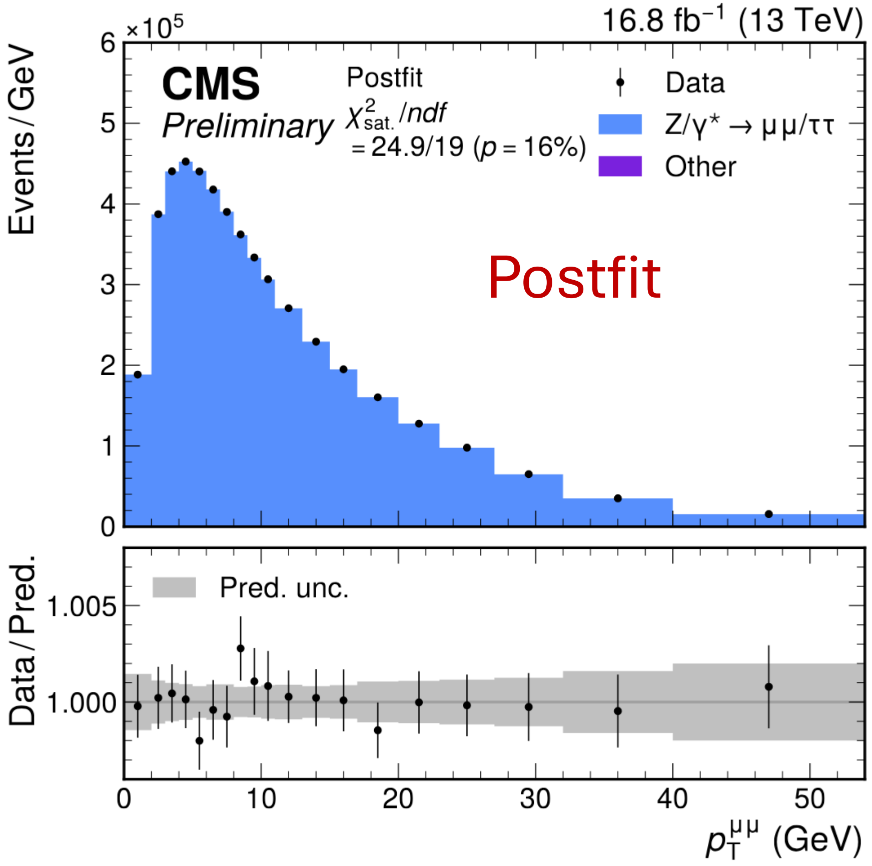
CT18Z chosen as nominal

- covers the others without scaling, with small uncertainty
- among largest nominal uncertainties

Theory model validation using Z sample: dilepton p_T

- Fit theory model to dilepton p_T spectrum directly to validate that it
- O(10%) discrepancy originating from untuned non-perturbative parameters at low p_T fully absorbed: postfit agreement at 0.1% level





Non-perturbative: Intrinsic momentum of partons (transverse momentum dependent PDF), non-perturbative uncertainties in resummation

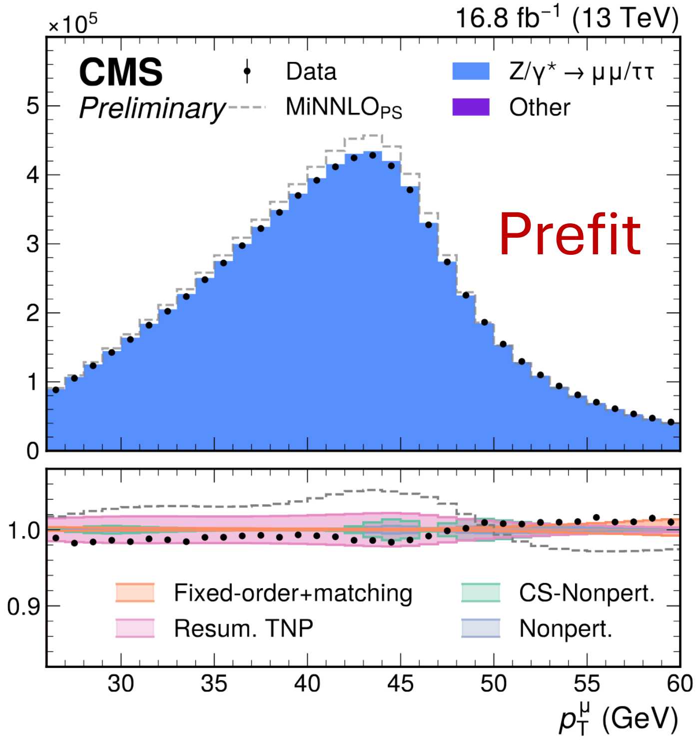
Resummation (perturbative): "Theory Nuisance Parameters" corresponding to coefficients in resummed calculations

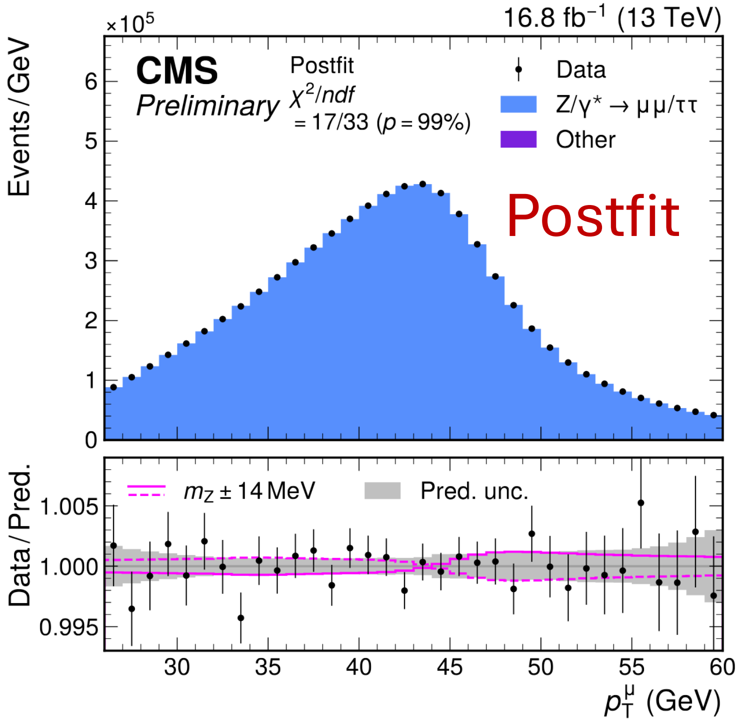
Matching: Variation in matching scale

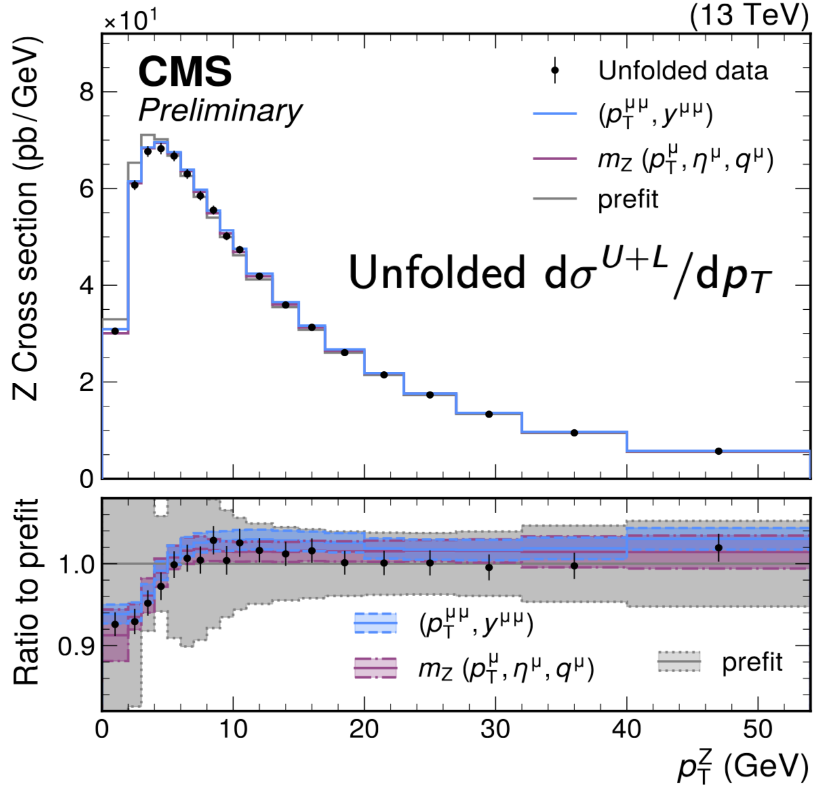
Fixed order: Missing higher orders assessed through μ_r, μ_f variations

Theory model validation using Z sample: W-like lepton p_T

- Remove one muon from Z events to perform W-like analysis
- In W-like fit to single muon (η, p_T, charge) spectrum, the model also precisely accommodates the muon pT distribution





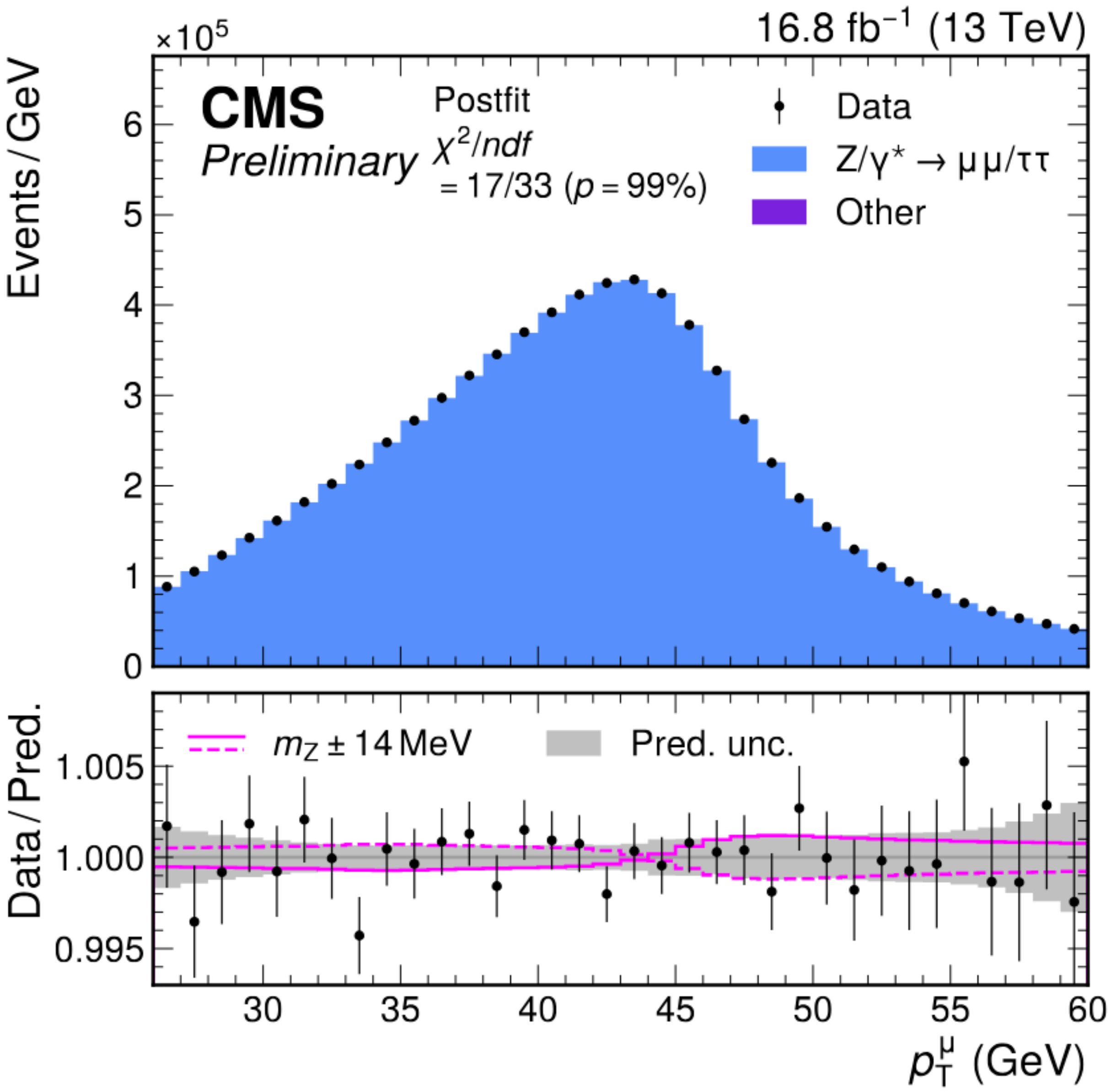


Compare direct p_T^Z measurement ("unfolded data") to the fitted p_T^Z from dimuon spectra (previous slide), and p_T^Z derived from W-like fit → strong constraints, excellent agreement

Method can be used for p_T^W (and m_W) extraction as well!

W-like Z mass measurement

3750 fit parameters!

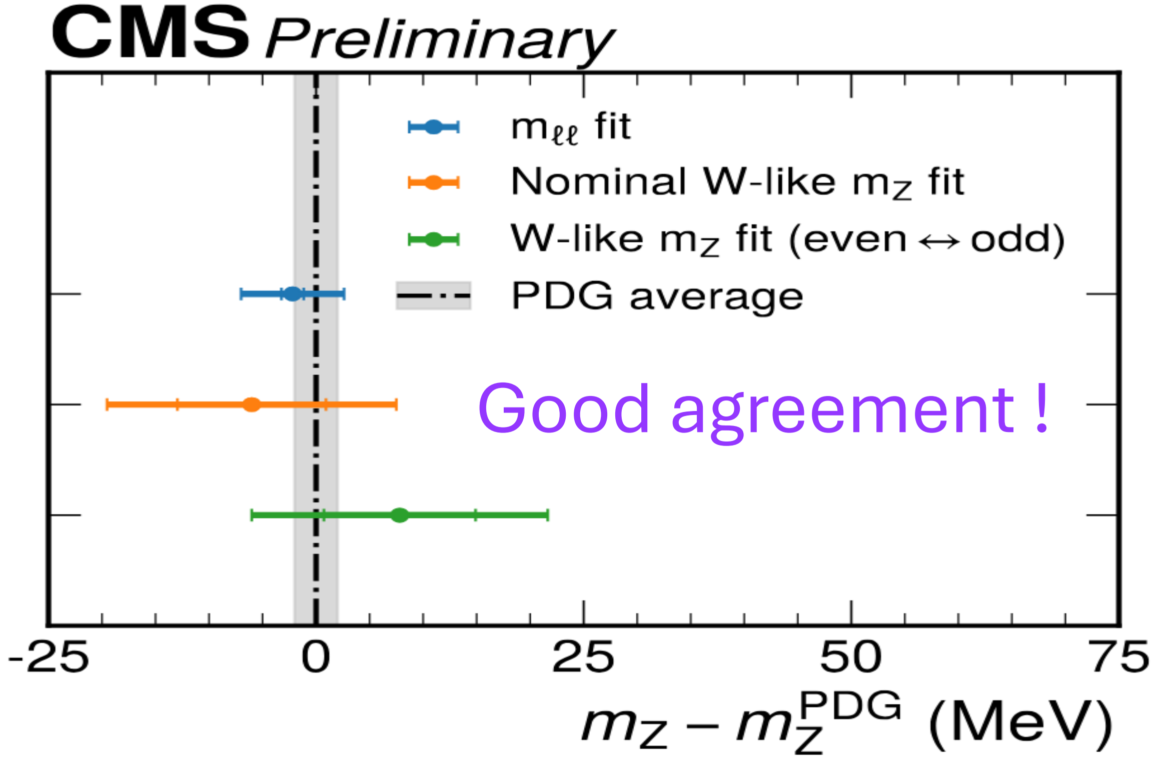


Dilepton: $\mathbf{m_Z - m_Z^{PDG} = -2.2 \pm 4.8\ MeV}$

W-like: $m_Z - m_Z^{\mathrm{PDG}} = -6 \pm 14\mathrm{MeV}$

Alternate muon choice (almost independent):

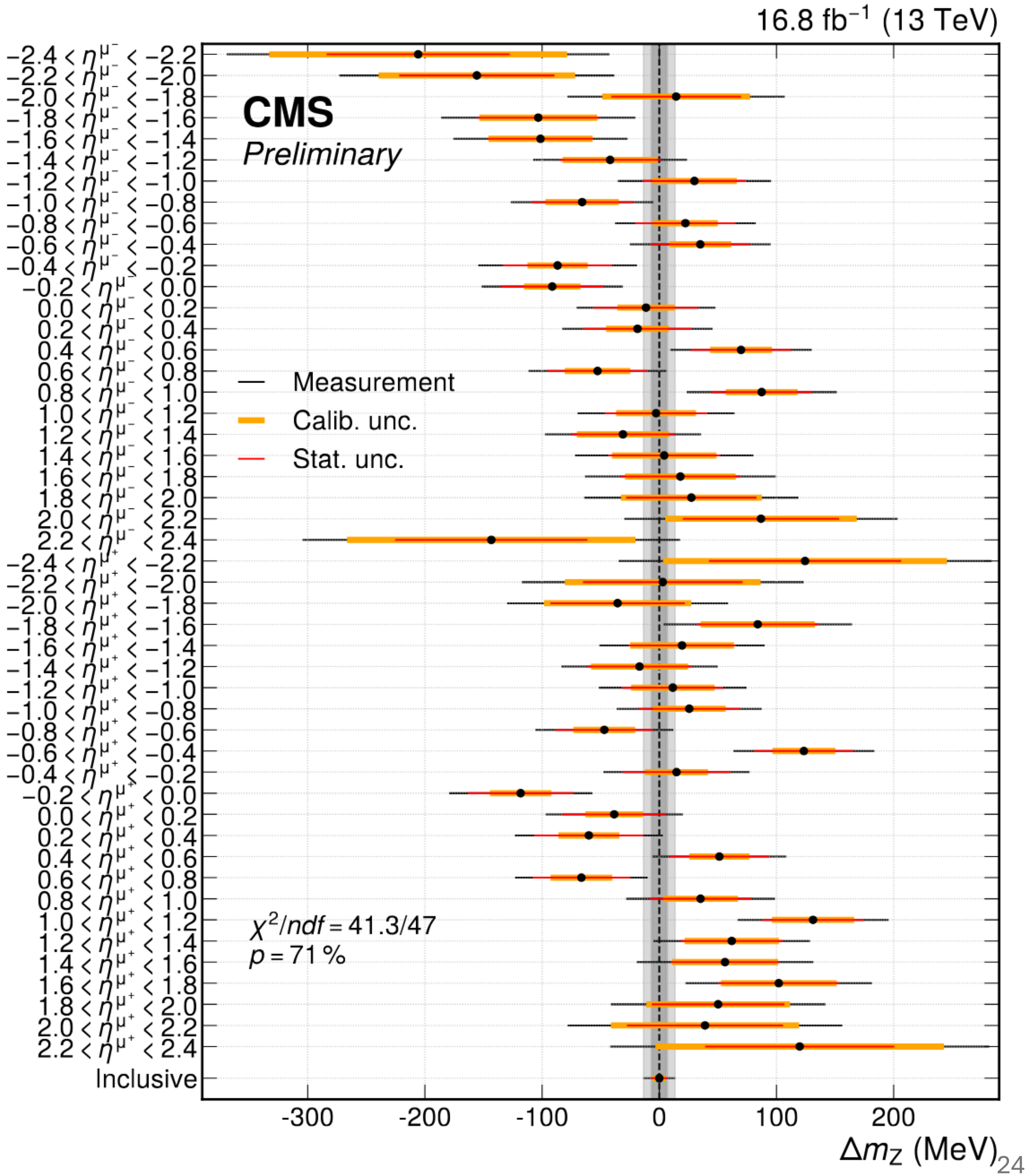
$$m_Z - m_Z^{\mathrm{PDG}} = 8 \pm 14\mathrm{MeV}$$



Good agreement !

Z mass crosschecks

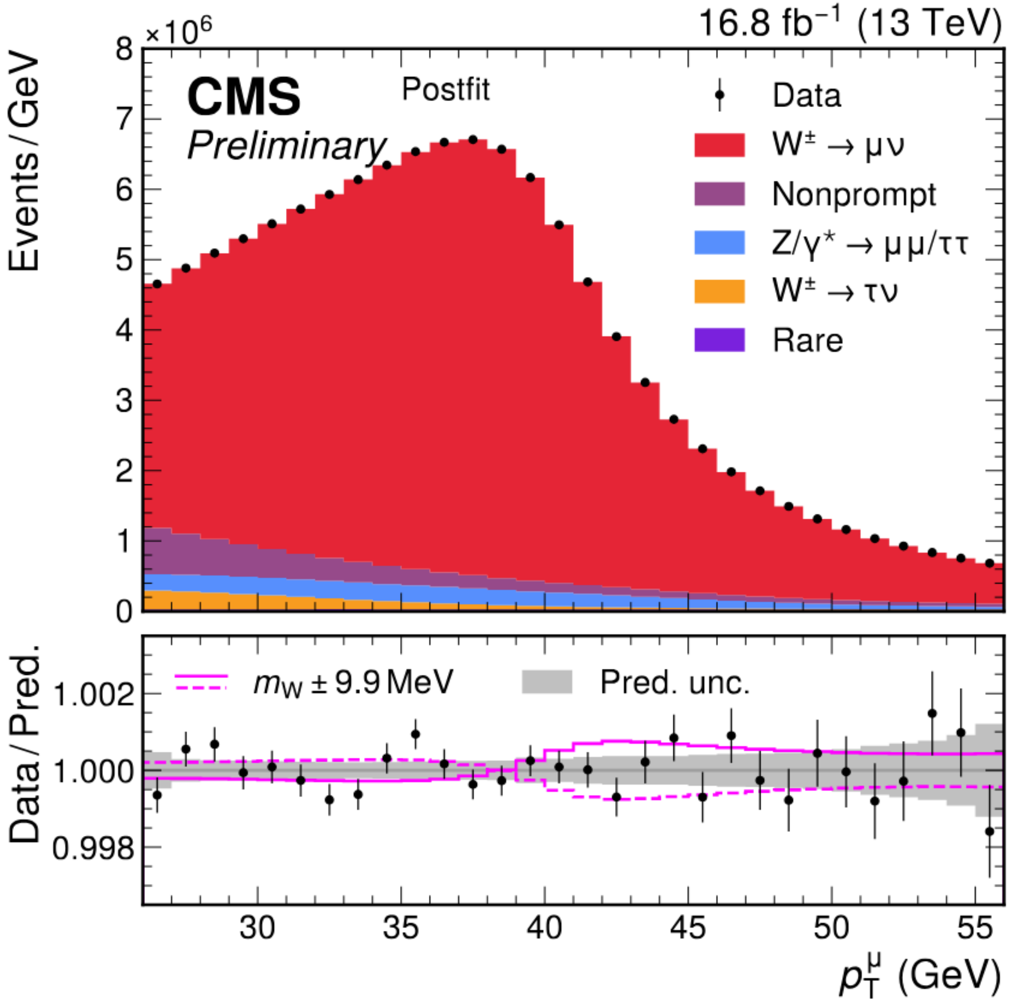
- Consistent results when extracting 48 independent m_Z values (+/–charge , 24 η bins)
- Pseudorapidity dependence:
  $M_Z^{\eta>0} - M_Z^{\eta<0}$ = 35 ± 20 MeV
- Charge dependence:
  $M_Z^{+} - M_Z^{-}$ = 31 ± 32 MeV
- Charge dependence with alternate selection:
  $M_Z^{+} - M_Z^{-}$ = 6 ± 32 MeV



W mass measurement

4859 fit parameters!
- 3658 muon efficiency
- 338 pT scale
- 390 background
- 458 theory related

$$m_W = 80\,360.2 \pm 2.4\,(\text{stat}) \pm 9.6\,(\text{syst}) = 80\,360.2 \pm 9.9\,\text{MeV}$$



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

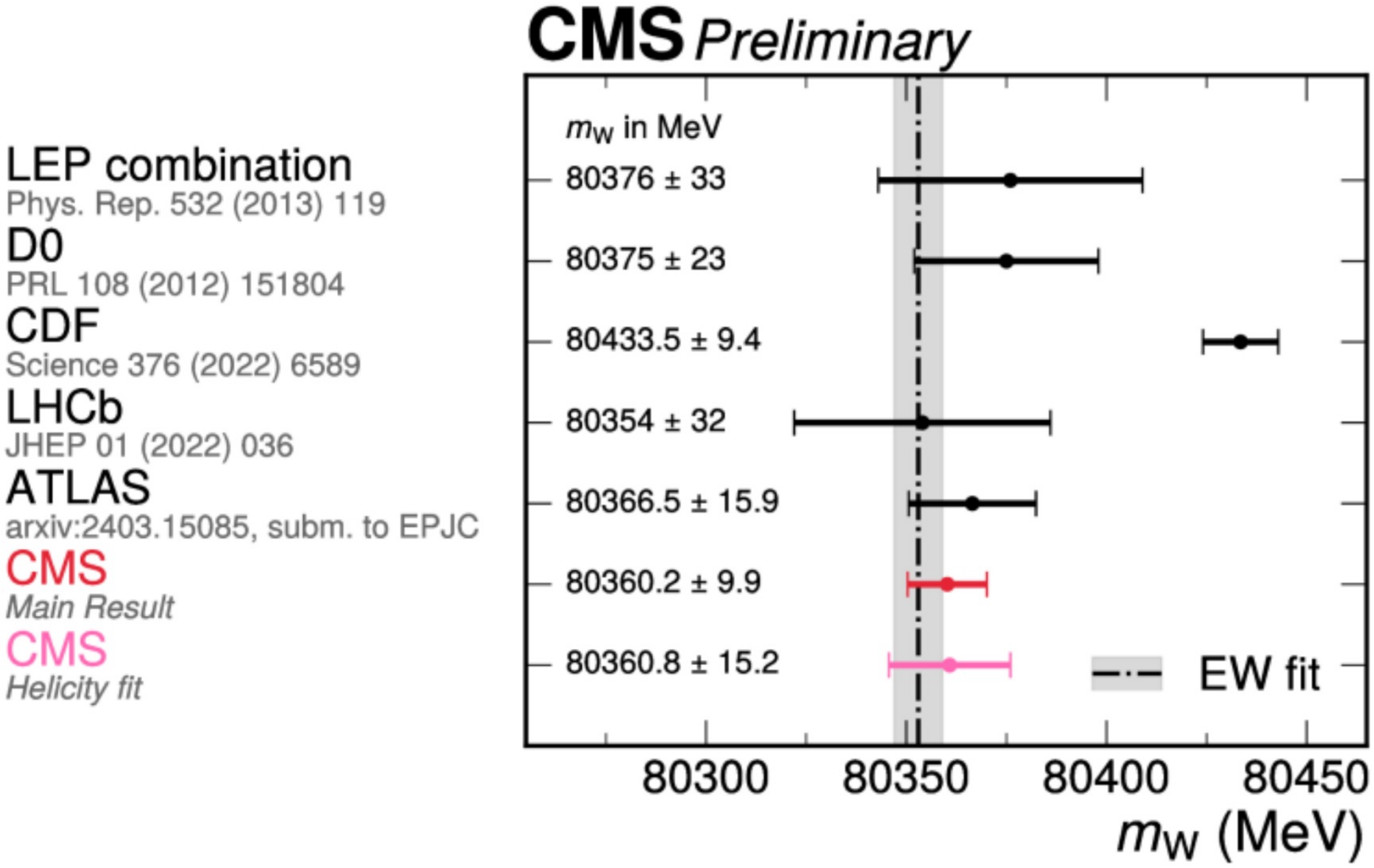
Similar contribution from exp and theory sources

Alternative helicity fit: $80\,360.8 \pm 15.2\,\text{MeV}$

Reduced theory, larger stat uncertainty

Global impact uses ATLAS definition of uncertainties for easier comparison

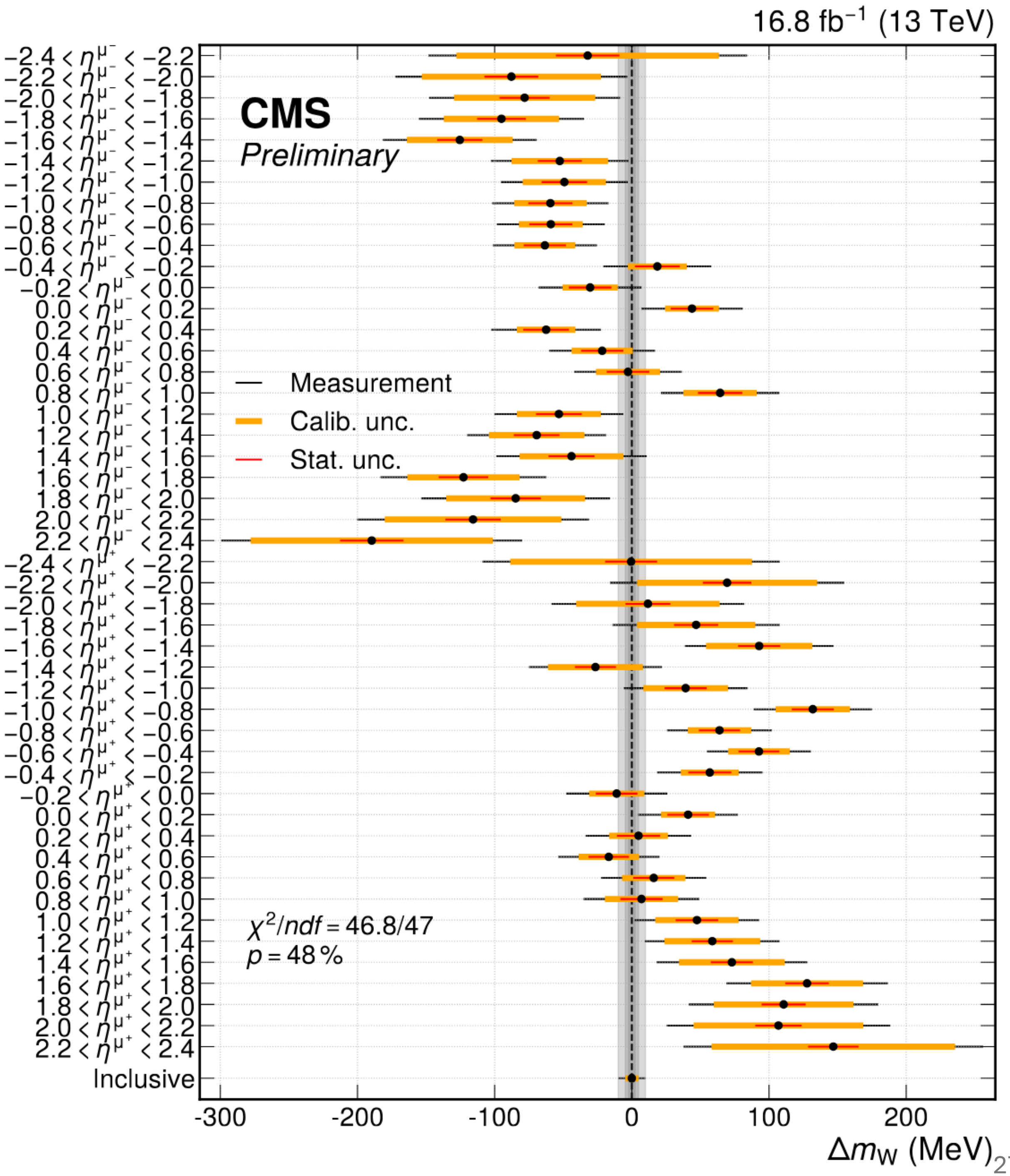
Standard Model triumphs again...



BUT...
tension between CDF II and other results still not understood...

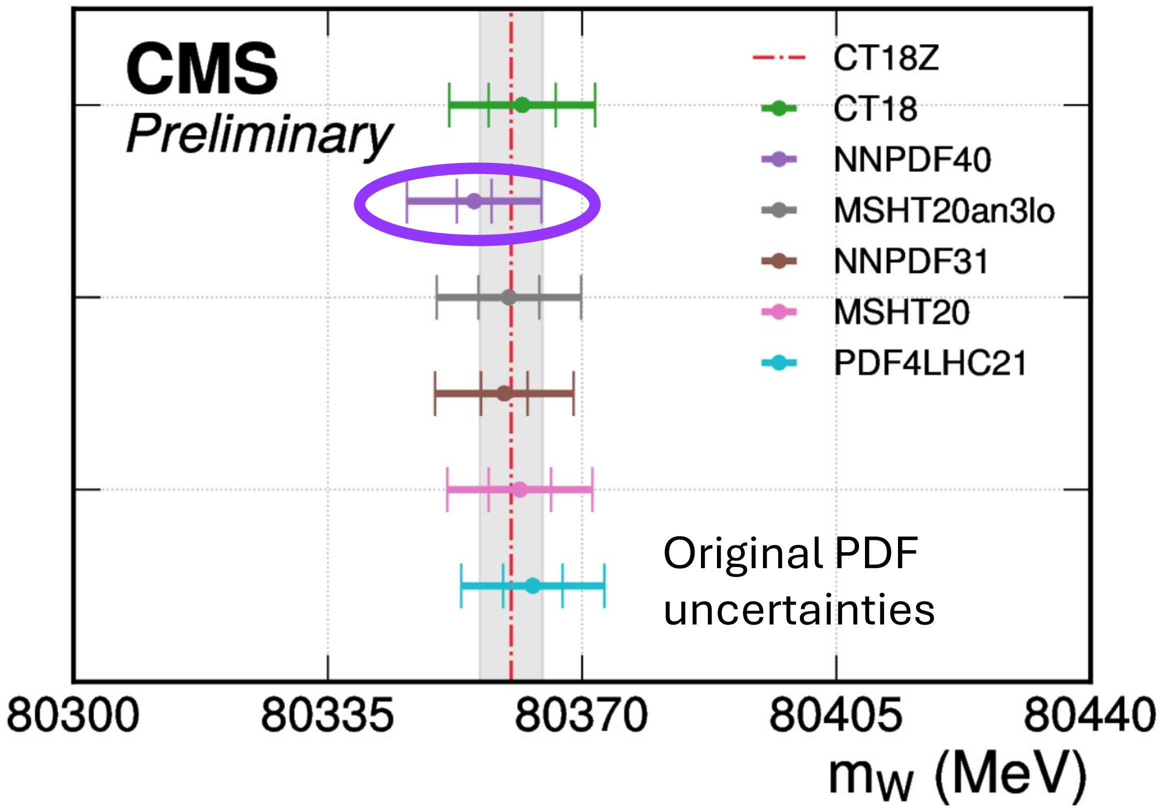
W mass crosschecks

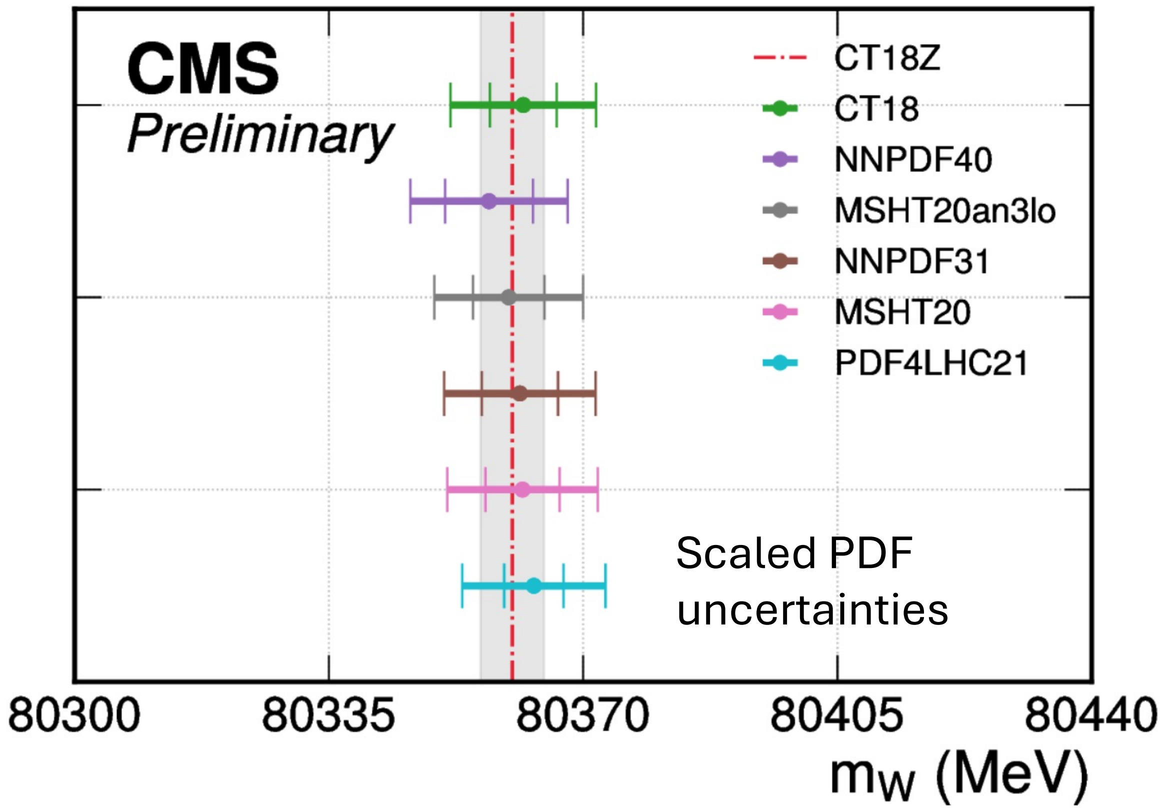
- Consistent results when extracting 48 independent m_W values (+/–charge , 24 η bins)
- Pseudorapidity dependence: $m_W^{\eta>0} - m_W^{\eta<0}$ = 5.8 ± 12.4 MeV
- Charge dependence: $m_W^{+} - m_W^{-}$ = 57 ± 30 MeV (p-value: 6.0%, within 2σ)
- Hint of residual mis-alignment issues?
- Strong anti-correlations between m_W^{+} and m_W^{-} due to experimental uncertainties (alignment) and theory uncertainties related to W polarization (opposite-parity coupling of W to μ^+ and μ^-)
- Correlation between charge difference and m_W only 2%
- Many crosschecks performed. No sign of anything suspicious



m_W extracted with different PDF sets

Quoted uncertainty of m_W based on CT18Z



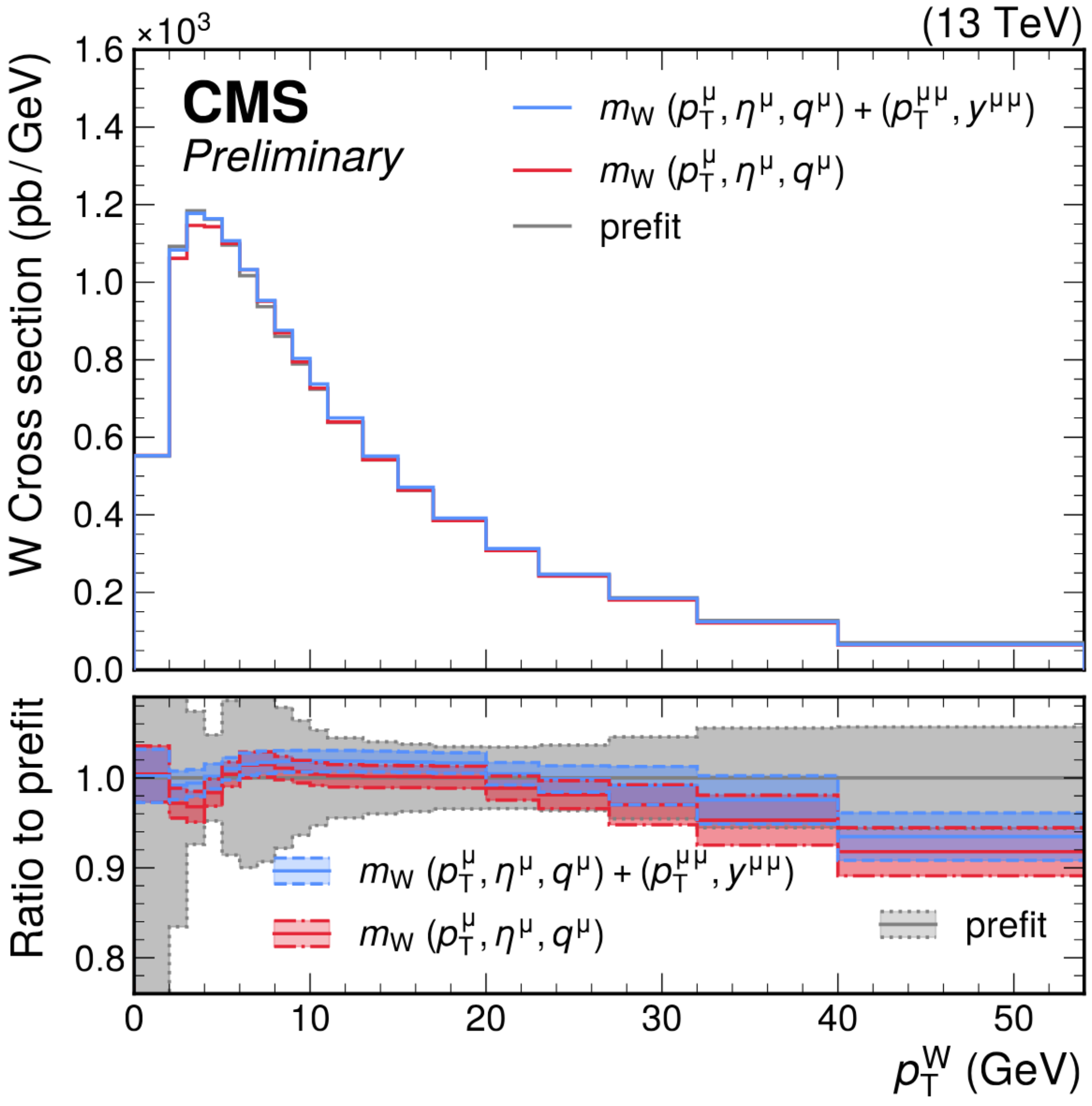


Inner bar: PDF uncertainty

Outer bar: total uncertainty

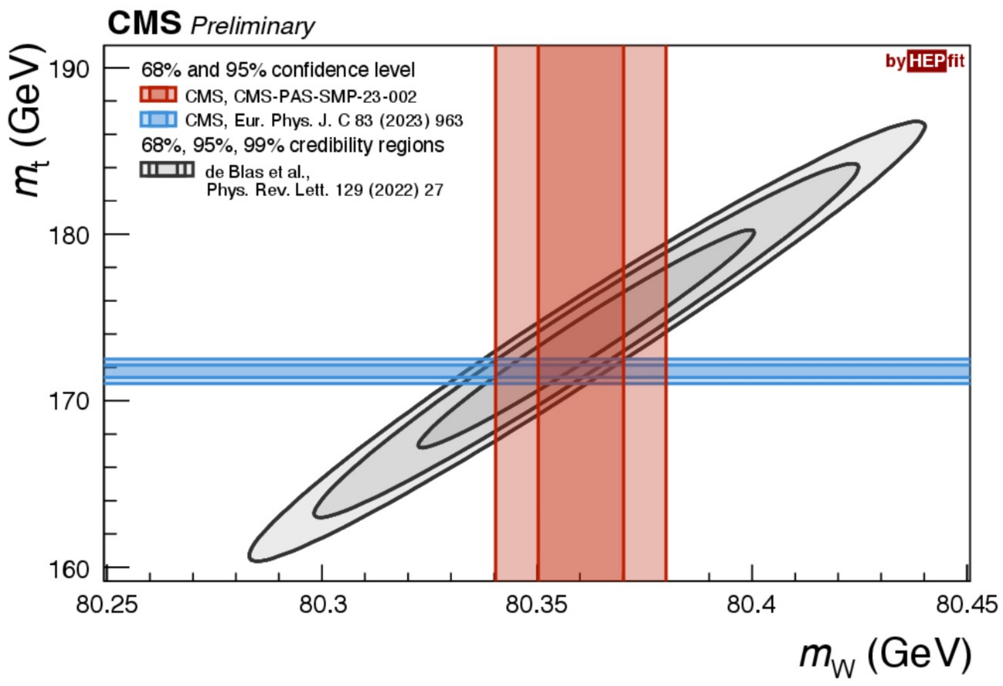
Combined fit to W and Z data

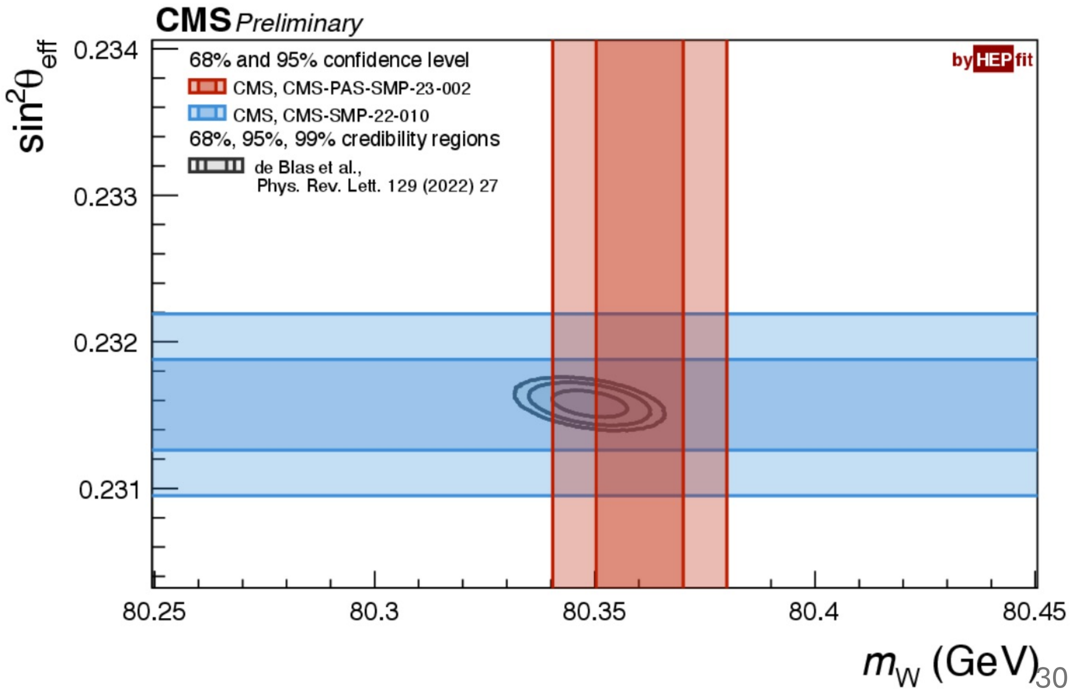
- Nominal result: fit to muon (η, pT , charge) for W candidates alone
- Compare with simultaneous fit to dimuon distribution from Z events
- Postfit W pT distributions consistent
- Strong constraints from data in both cases
- Δm_W = +0.6 MeV with respect to nominal
- Decreased uncertainty of 9.6 MeV
- Additional complications for W/Z correlations, so less robust result, not used as baseline



Summary: SM is alive ☺

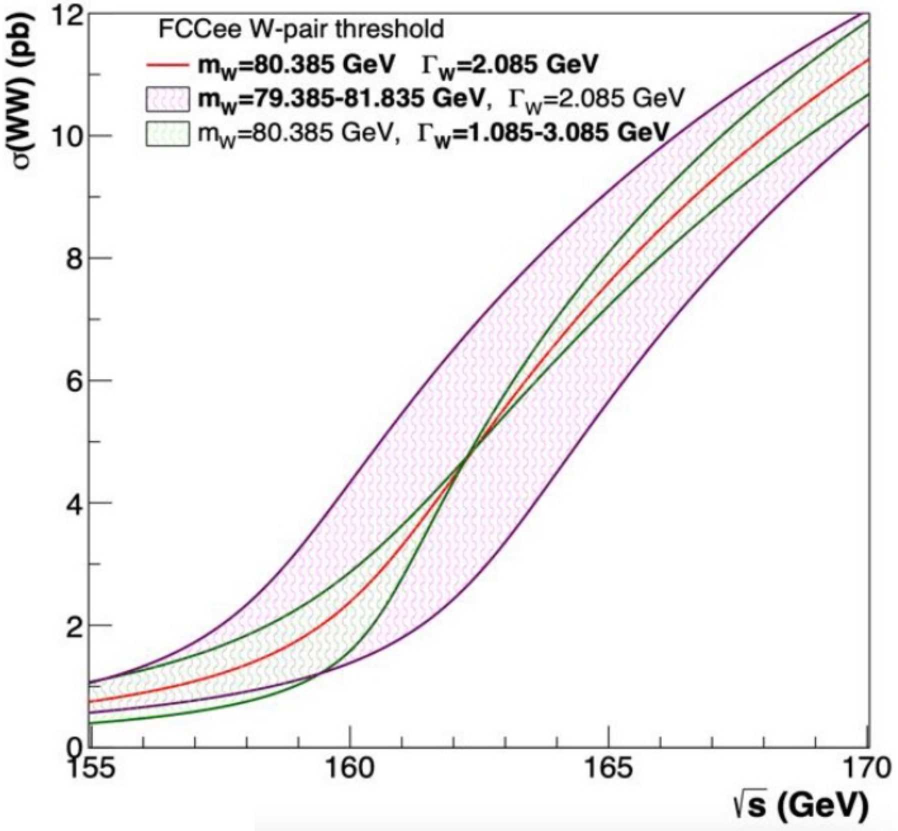
- CMS (and LHC in general) became a ”precision” experiment
- Very high accuracy determination of experimental effects
- 3D max LH fit constrains in-situ the theoretical inputs and their uncertainties
  - Requires high accuracy of theoretical predictions
  - Novel techniques to model their uncertainties and correlations across phase-space using theory nuisance parameters
  - Large data statistics
- 80360.2 ± 9.9MeV result breaks the “psychological” barrier of 10 MeV
- Comparable precision with CDF II but excellent agreement with SM





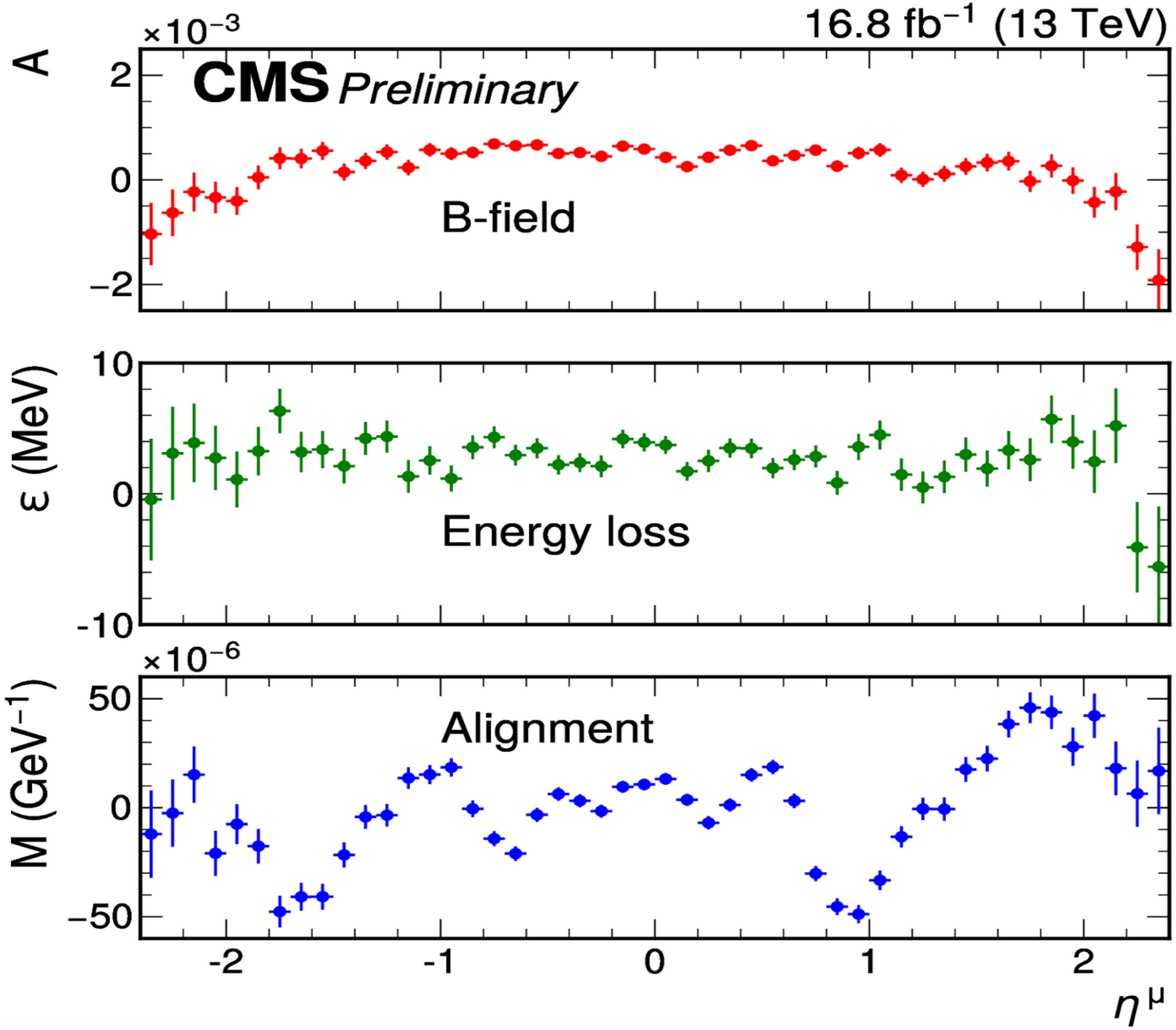
Future improvements?

- Much more CMS data to include
  - takes long time as very careful re-reconstruction of data needed
- Include m_T in extraction – more info, better constraints on theory
  - Improve hadronic recoil, missing transverse momentum reconstruction
- Use low PU runs with better control of m_T
- Combine experiments
- Next electron – positron collider from WW cross section threshold scan (<1 MeV)
  - Rather far in future



Extra

Muon calibration factors (48 bins)

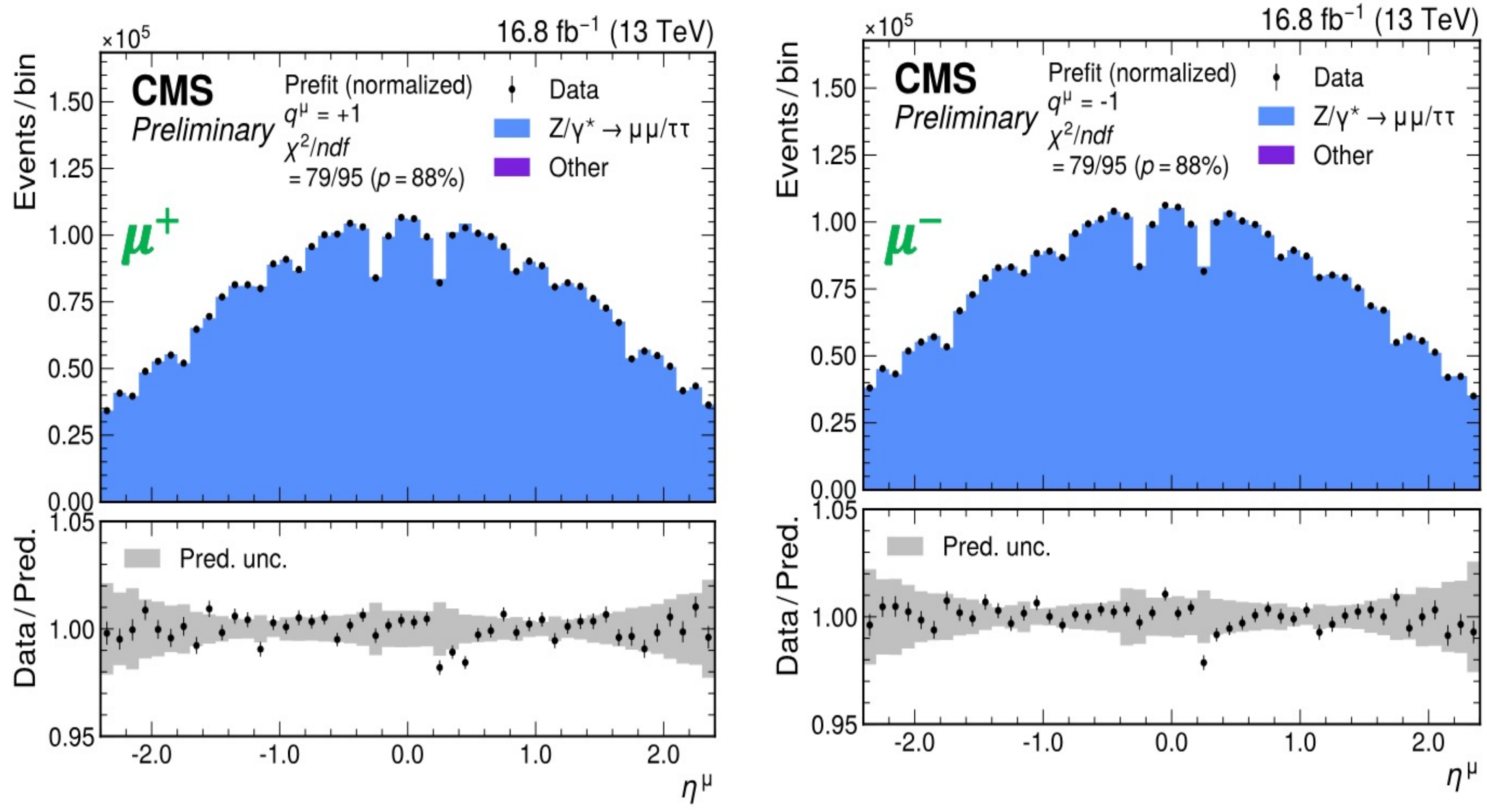


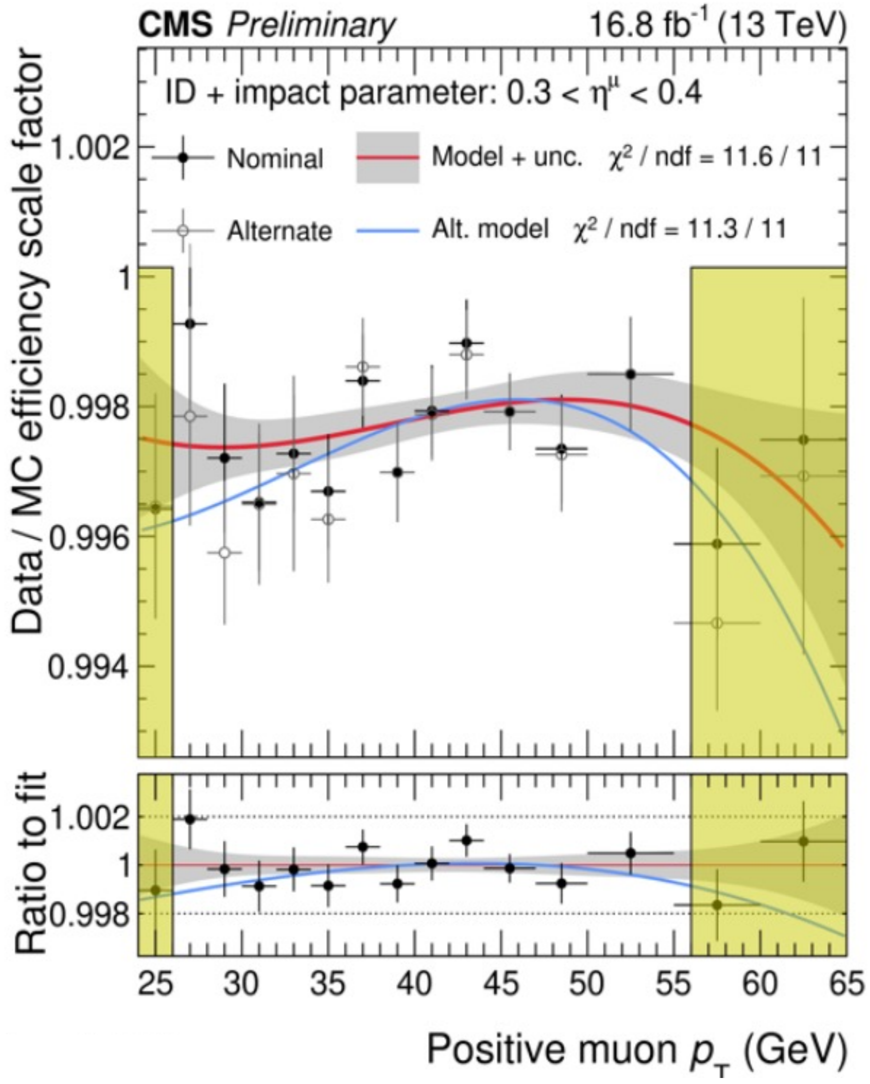
Muon efficiency

- Measured from data using the tag-and-probe method using Z events binned in (p_T^μ, η^μ), and for most steps in charge
- Factorized to tracking, reconstruction, identification, isolation, trigger efficiencies
- For isolation (and trigger), contribution from hadronic recoil to isolation sum also to be taken into account
  - measure in bins of (p_T^μ, η^μ, u_T), with u_T being hadronic recoil projection into muon probe: $\dfrac{\vec{p_T^{\mu}} \cdot \vec{p_T^{Z}}}{|\vec{p_T^{\mu}}|}$
- Correction factors calculated wrt Z simulation, and applied for all samples
- Smooth in p_T^μ and u_T to improves correlation model and reduce statistical uncertainty
- Impact ~3 MeV on W mass

Muon efficiency

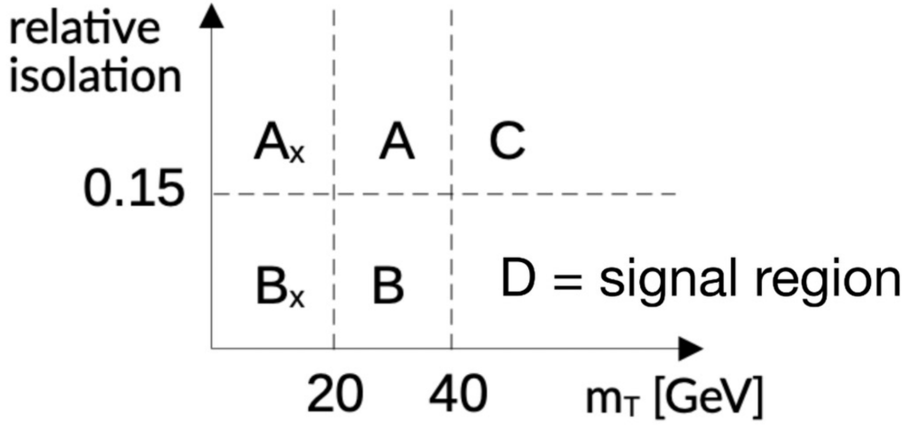
Pre-fit data-MC comparison of η^{μ} in $Z \to \mu\mu$ selection





Non-prompt background estimation

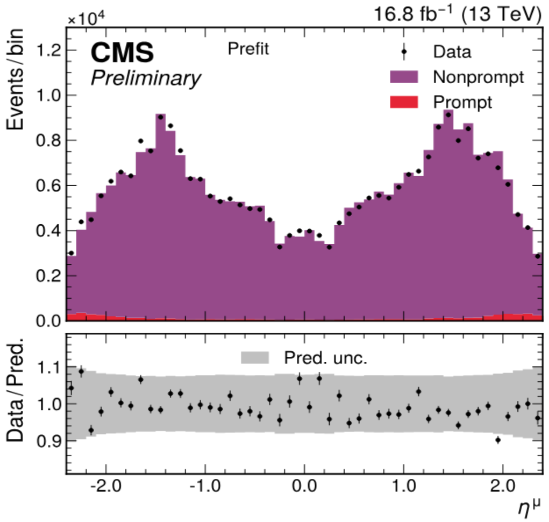
- Non-prompt background from QCD multijet event, mostly heavy flavour
- Estimated using data driven fake extended ABCD method
- Prompt contamination in sideband regions dominated by W and Z events, estimated from simulation with all corrections and uncertainties
- Procedure validated using QCD simulation and secondary-vertex control region in data
- Negligible for dilepton and W-like Z measurements, important for W measurement



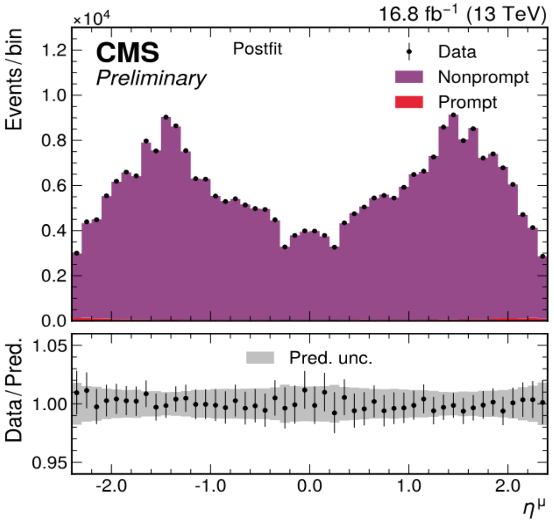
$$D = C\frac{A_x B^2}{B_x A^2}$$

Comparison between the estimation and the data in a non prompt enriched phase space, sepected requiring that the muon is not compatible to originate from the primary vertex

Pre-fit



Post-fit



Monte Carlo simulations

- 4B fully simulated Monte Carlo events using detailed GEANT4 model of CMS
- W and Z boson production at NNLO in QCD using MINNLOPS in POWHEG-BOX-V2 interfaced with PYTHIA 8 for the parton shower and hadronization, and with PHOTOS++ for the final-state photon radiation
- To get most accurate modeling of the W and Z pT, MINNLOPS predictions corrected bin-by-bin using SCETLIB matched to fixed-order from DYTURBO, thereby achieving NNLO+N3LL accuracy
- CT18Z PDF set for the nominal analysis
- Pile-up and z vertex position reweighting
- Correction of efficiencies of trigger, muon reconstruction and identification
- p_T^{miss} and m_T corrected for hadronic recoil mismodelling

Number of fit parameters

<table>
<tr><th>Systematic uncertainties</th><th>W-like m_Z</th><th>m_W</th></tr>
<tr><td>Muon efficiency</td><td>3127</td><td>3658</td></tr>
<tr><td>Muon eff. veto</td><td>–</td><td>531</td></tr>
<tr><td>Muon eff. syst.</td><td colspan="2">343</td></tr>
<tr><td>Muon eff. stat.</td><td colspan="2">2784</td></tr>
<tr><td>Nonprompt background</td><td>–</td><td>387</td></tr>
<tr><td>Prompt background</td><td>2</td><td>3</td></tr>
<tr><td>Muon momentum scale</td><td colspan="2">338</td></tr>
<tr><td>L1 prefire</td><td colspan="2">14</td></tr>
<tr><td>Luminosity</td><td colspan="2">1</td></tr>
<tr><td>PDF (CT18Z)</td><td colspan="2">60</td></tr>
<tr><td>Angular coefficients</td><td>177</td><td>353</td></tr>
<tr><td>W MiNNLO$_{PS}$ μ_F, μ_R</td><td>–</td><td>176</td></tr>
<tr><td>Z MiNNLO$_{PS}$ μ_F, μ_R</td><td colspan="2">176</td></tr>
<tr><td>PYTHIA shower k_T</td><td colspan="2">1</td></tr>
<tr><td>p_T^V modeling</td><td>22</td><td>32</td></tr>
<tr><td>Nonperturbative</td><td>4</td><td>10</td></tr>
<tr><td>Perturbative</td><td>4</td><td>8</td></tr>
<tr><td>Theory nuisance parameters</td><td colspan="2">10</td></tr>
<tr><td>c, b quark mass</td><td colspan="2">4</td></tr>
<tr><td>Higher-order EW</td><td>6</td><td>7</td></tr>
<tr><td>Z width</td><td colspan="2">1</td></tr>
<tr><td>Z mass</td><td colspan="2">1</td></tr>
<tr><td>W width</td><td>–</td><td>1</td></tr>
<tr><td>W mass</td><td>–</td><td>1</td></tr>
<tr><td>$\sin^2 \theta_W$</td><td colspan="2">1</td></tr>
<tr><td>Total</td><td>3750</td><td>4859</td></tr>
</table>

Uncertainties in W-like m_Z and m_W measurements

Source of uncertainty	Impact (MeV) Nominal in m_Z	Nominal in m_W	Global in m_Z	Global in m_W
Muon momentum scale	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt background	–	3.2	–	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

Summary of extraction uncertainties

Source of uncertainty	Global impact (MeV) in $m_{Z^+} - m_{Z^-}$	in m_Z	in $m_{W^+} - m_{W^-}$	in m_W
Muon momentum scale	21.2	5.3	20.0	4.4
Muon reco. efficiency	6.5	3.0	5.8	2.3
W and Z angular coeffs.	13.9	4.5	13.7	3.0
Higher-order EW	0.2	2.2	1.5	1.9
p_T^V modeling	0.4	1.0	2.7	0.8
PDF	0.7	1.9	4.2	2.8
Nonprompt background	–	–	4.8	1.7
Integrated luminosity	< 0.1	0.2	0.1	0.1
MC sample size	6.4	3.6	8.4	3.8
Data sample size	18.1	10.1	13.4	6.0
Total uncertainty	32.5	13.5	30.3	9.9

Summary of extraction uncertainties

Source of uncertainty	Nominal impact (MeV)			
	in $m_{Z^+} - m_{Z^-}$	in m_Z	in $m_{W^+} - m_{W^-}$	in m_W
Muon momentum scale	23.1	5.6	21.6	4.8
Muon reco. efficiency	7.1	3.8	7.2	3.0
W and Z angular coeffs.	14.5	4.9	18.7	3.3
Higher-order EW	0.2	2.2	1.5	2.0
p_T^V modeling	0.6	1.7	7.4	2.0
PDF	0.9	2.4	11.8	4.4
Nonprompt background	–	–	7.5	3.2
Integrated luminosity	< 0.1	0.3	0.1	0.1
MC sample size	4.9	2.5	3.0	1.5
Data sample size	13.9	6.9	4.7	2.4
Total uncertainty	32.5	13.5	30.3	9.9

m_W result: Closer look at charge difference

Configuration	$m_W^+ - m_W^-$ (MeV)	Δm_W (MeV)
nominal	57 ± 30	0
Alignment $\sim$1 sigma up	38 ± 30	< 0.1
LHE A_i as nominal	48 ± 30	-0.5
A_3 one sigma down	49 ± 30	0.4
Alignment and A_i shifted as above	21 ± 30	0.1
Alignment $\sim$ 3 sigma up	-5 ± 30	0.6

- Reminder: For W-like m_Z fit:
  $m_Z^+ - m_Z^- = 31 \pm 32$ MeV (nominal)
  $m_Z^+ - m_Z^- = 6 \pm 32$ MeV (reversed even-odd event selection)
- No conclusive evidence for a systematic problem ($< 2\sigma$)
- Statistical fluctuations from finite data and MC samples at the level of 16 MeV for $m_W^+ - m_W^-$
- Even extreme variations of the related systematics lead to small variations in m_W (< 1MeV), within associated uncertainties
- Possible/plausible scenario: $\sim 1\sigma$ off on alignment and A_i's plus ~ 1 σ statistical fluctuation corresponds to totally negligible effect on m_W (0.1MeV)

Different p_T^W modelling

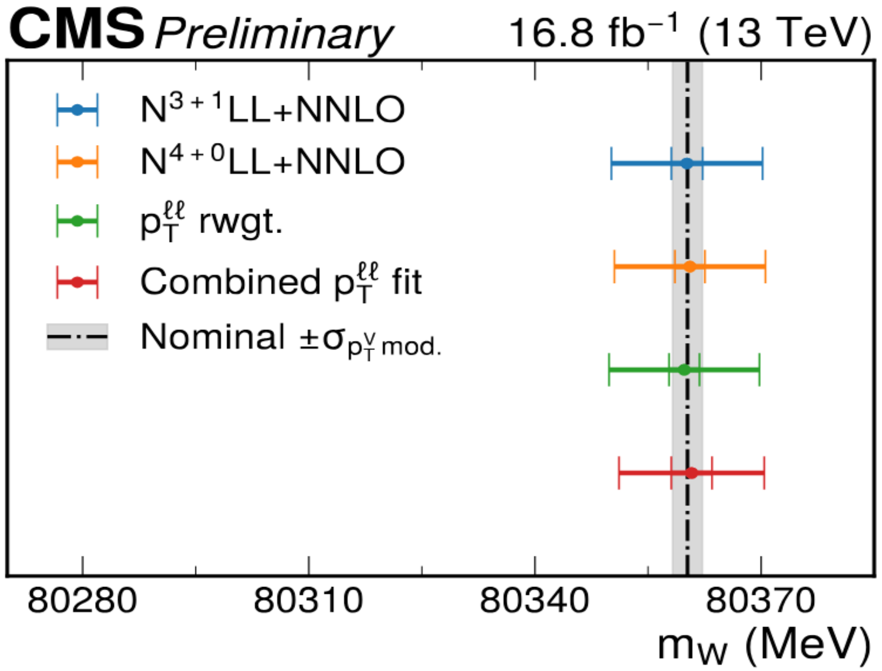
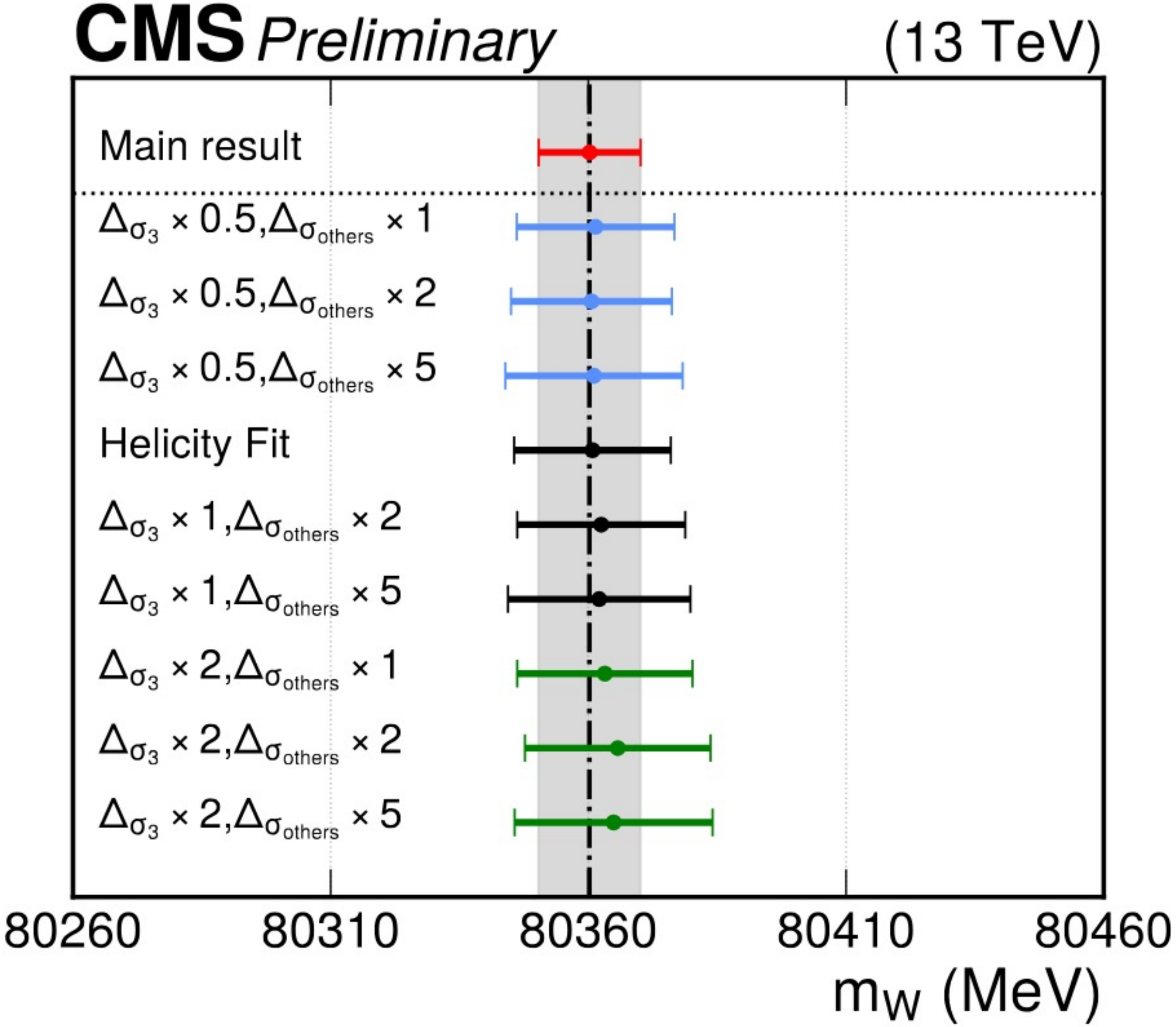


Figure A.16: Comparison of the nominal result and its theory uncertainty, using SCETLIB+DYTURBO at $N^3LL + NNLO$, with the value of m_W measured when using alternative approaches to the p_T^W modeling and its uncertainty. The impact of correcting the p_T^W distribution with the $p_T^{\mu\mu}$ data, both via bin-by-bin reweighting corrections and via a simultaneous maximum likelihood fit, is also shown. The dash-dotted black line represents the nominal result, while the shaded gray band shows the p_T^W-modeling uncertainty. The results from alternative approaches to the p_T^W-modeling and uncertainty are shown as points. The p_T^W-modeling uncertainties are shown as the inner bars, while the outer bars denote the total uncertainty.

Helicity fit

- Angular coefficients sensitive to beyond SM contributions
- Simultaneous extraction of helicity cross section components with m_W allows more freedom in theoretical description
- Larger uncertainty as expected (more free parameters!)
    - Trading theory to stat uncertainty
- Check stability of helicity fit: inflate or shrink prefit helicity cross section uncertainties
- Observed shifts within uncertainty of baseline method
- Theory description seems adequate!

$$\sigma_i = \sigma^{U+L} A_i$$



No sensitivity to i > 4
Loose priors on unpolarised xsec and i=0..4 components