High-precision measurement of the W boson mass at CMS

Higgs Hunting | 24 September 2024

A. Gilbert on behalf of the CMS Collaboration

The quest for EW precision

- Goal: test the self-consistency of the SM
  - Higgs boson discovery and precise m_H measurements

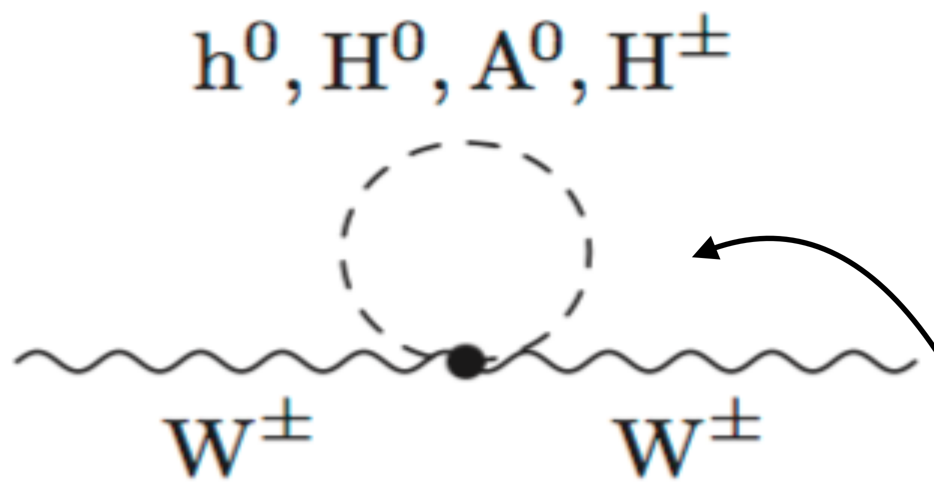
    ⇒ Electroweak sector over-constrained

    ⇒ Identify tension between direct & indirect constraints on observables
  - Deviations may be due to new physics in higher order virtual corrections

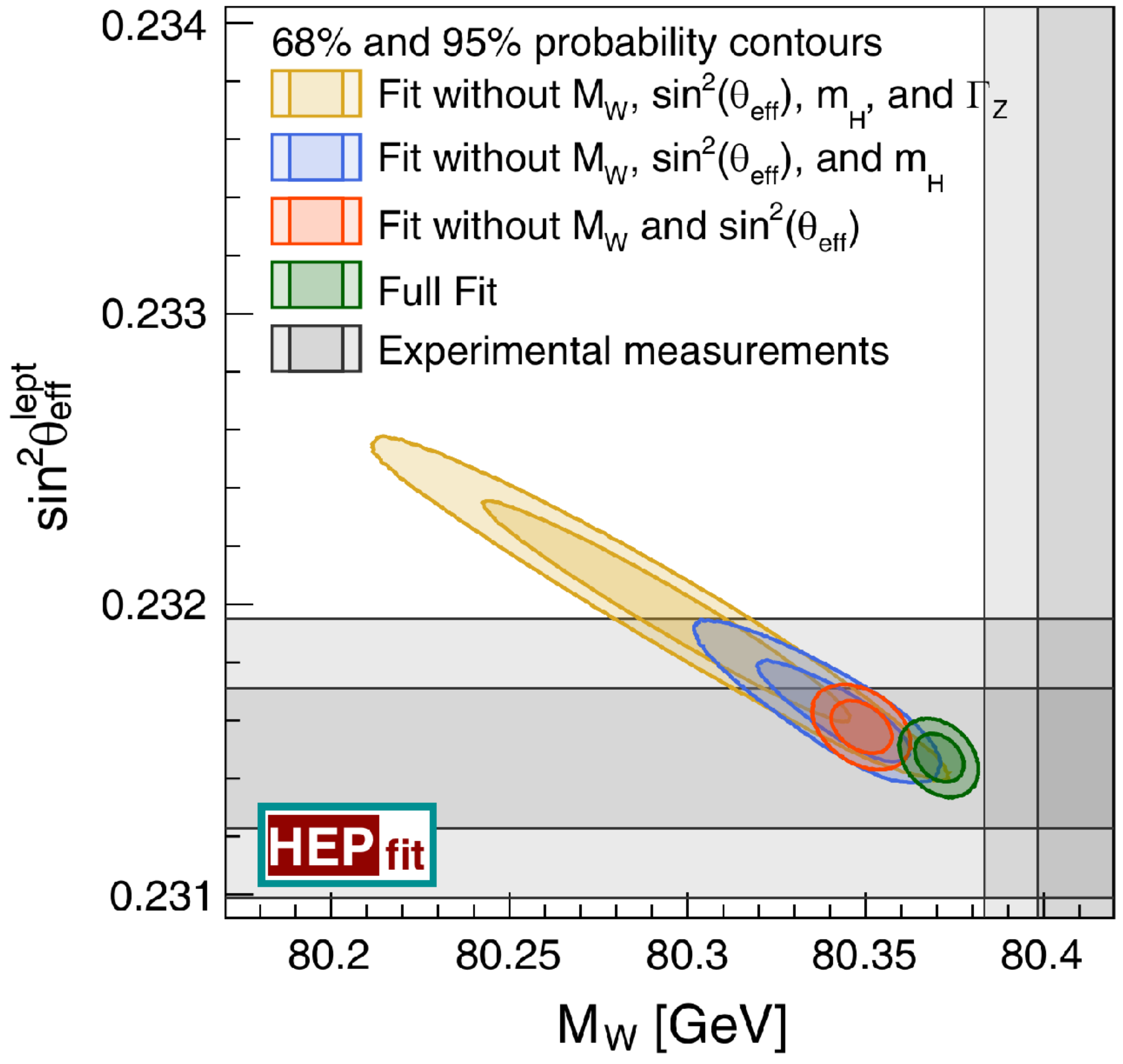
- Today: **the W boson mass**

- m_W predicted with a precision of 6 MeV, but measurement in data less sensitive (c.f. m_Z ~ 2 MeV uncertainty)
  - Neutrino forces us to use less direct observables to infer constraints on the mass ⇒ many systematic uncertainties to control

- Recently measured by CDF in 2022 was most precise to date (9.4 MeV uncertainty), but in significant tension with SM



$$M_W = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F M_Z^2}}\right)$$

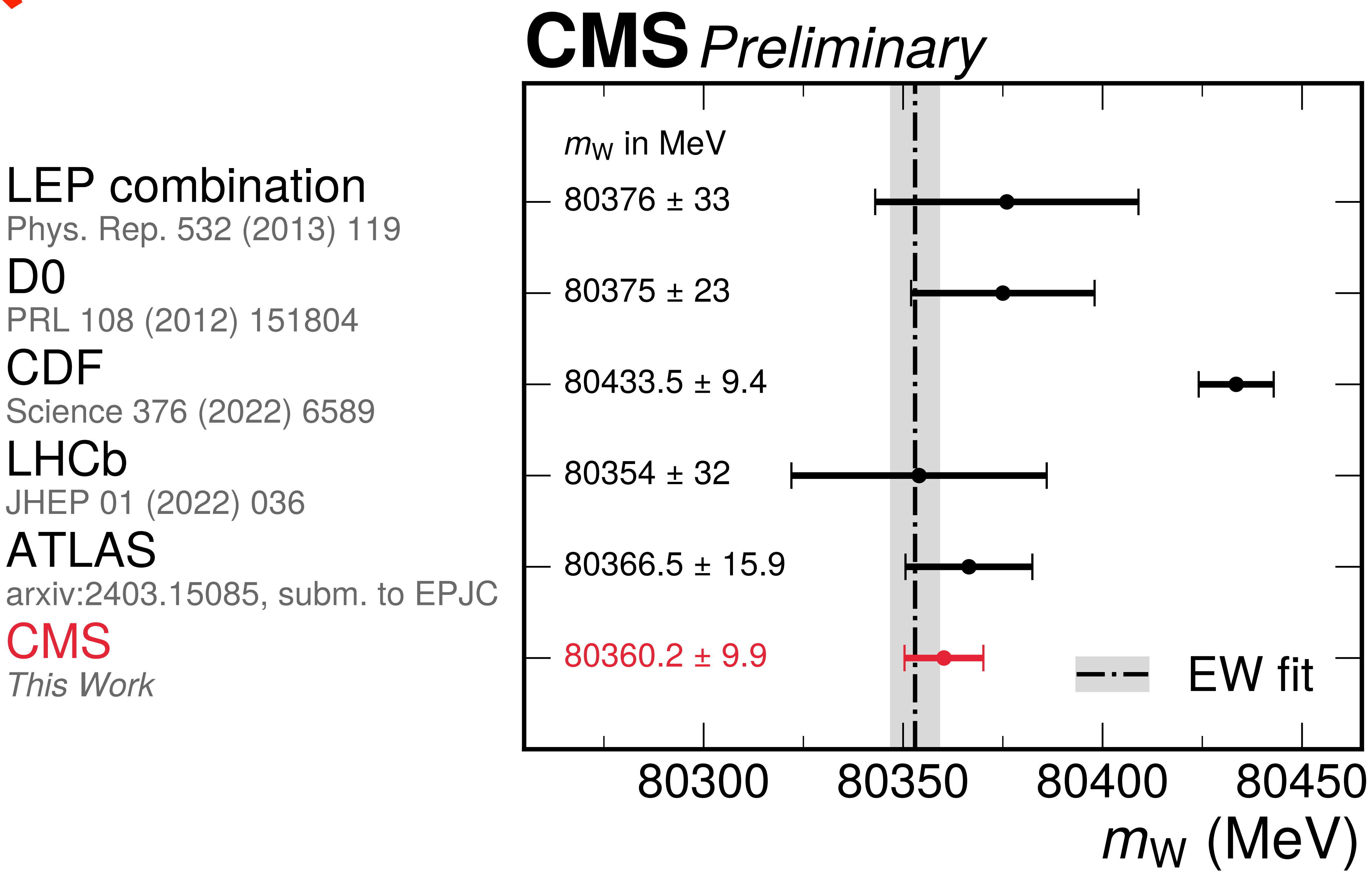


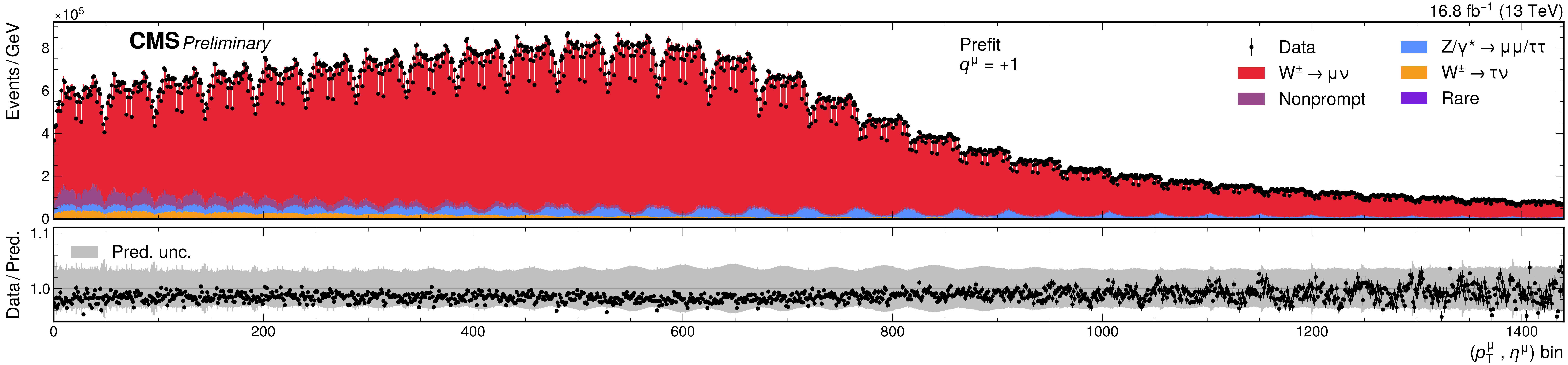
PRL 129 (2022), 27, 271801

The CMS W mass result

NEW

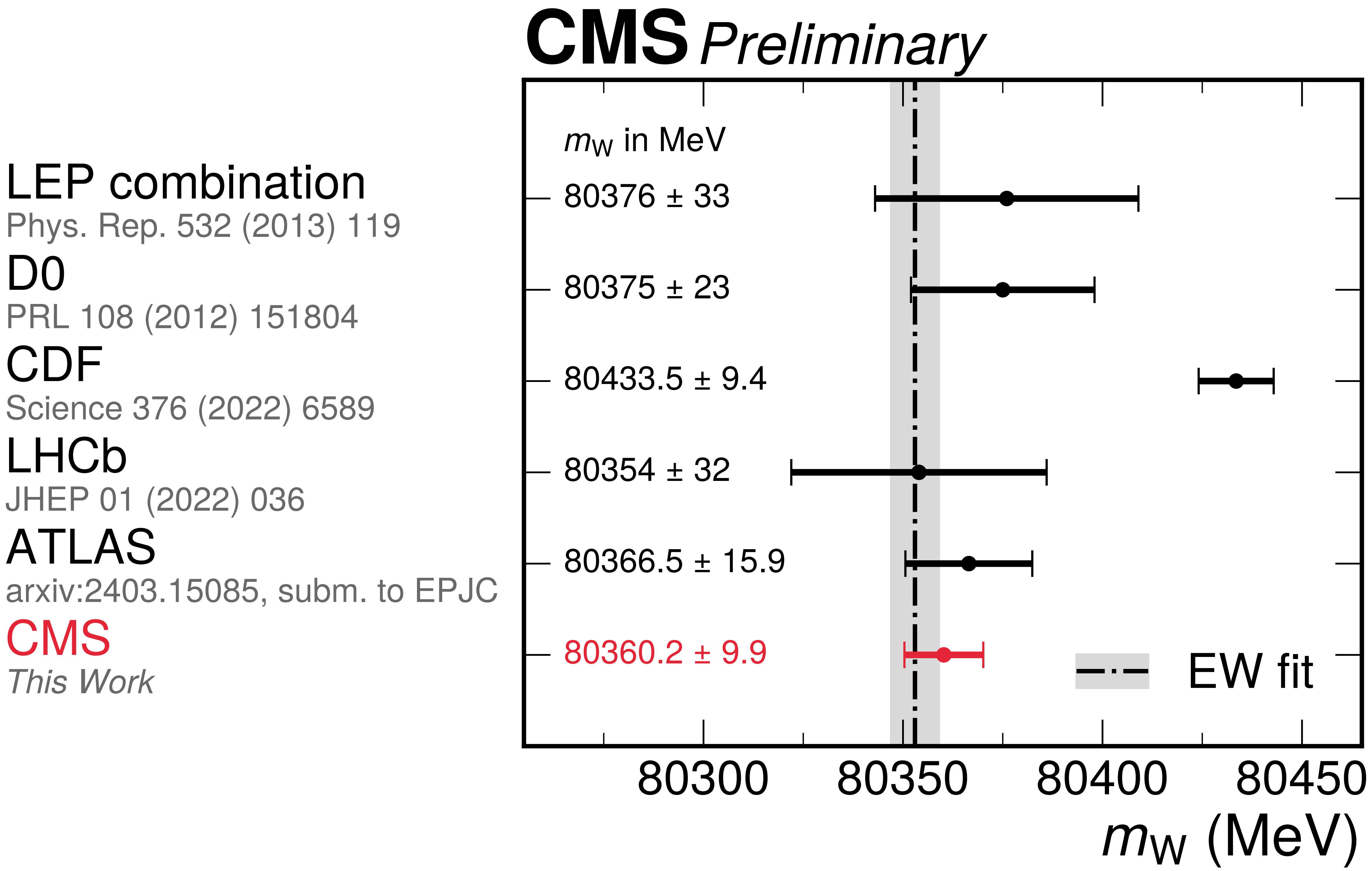
- Measured with uncertainty of **9.9 MeV**
  - Comparable to CDF precision, but consistent with SM
- This talk: summarise the key ingredients to reach this precision
- For a more detailed talk, recommend the CERN seminar of last week

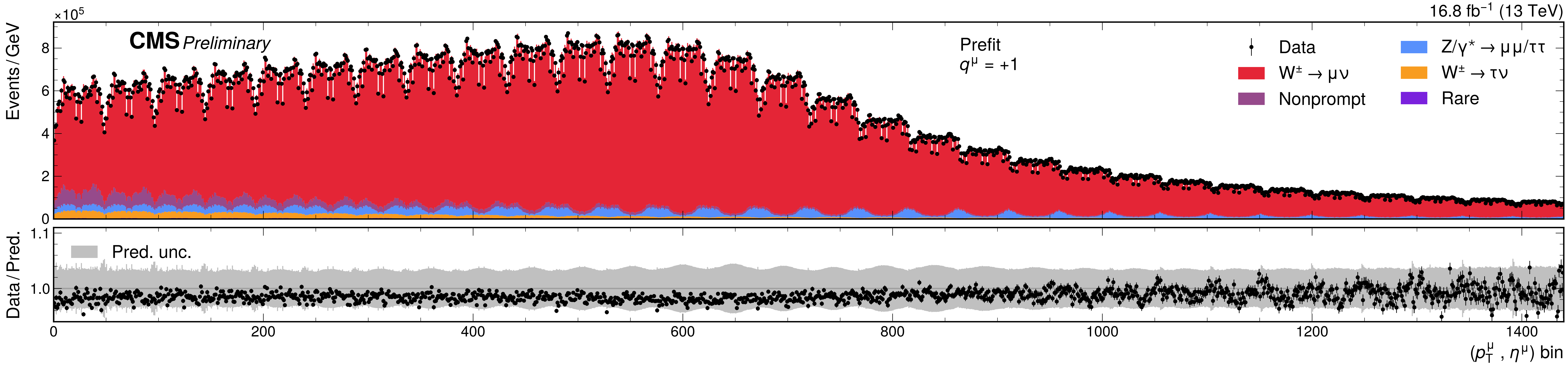




The CMS W mass strategy

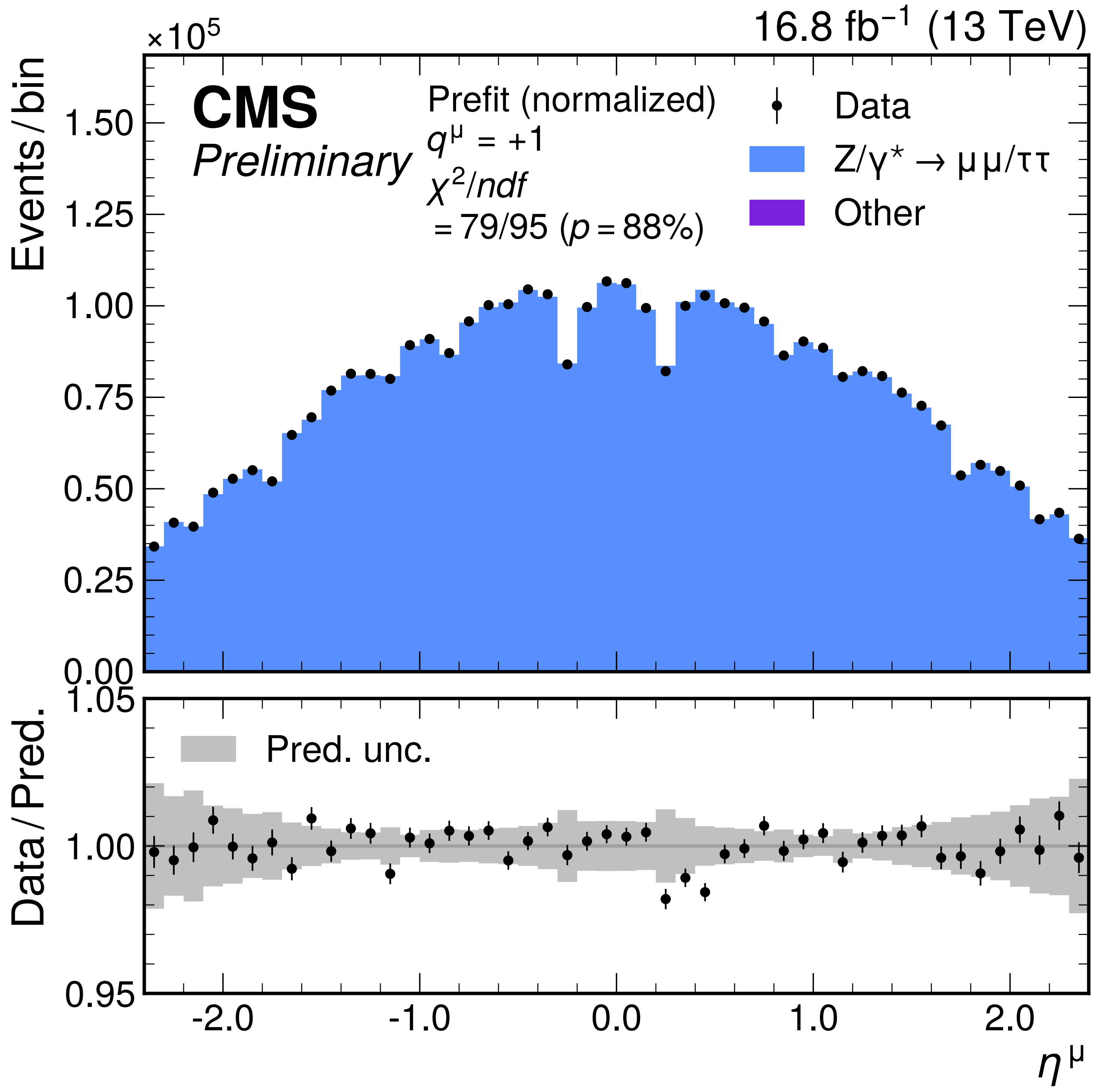
- Uses a well-understood portion of 13 TeV data
  - 16.8 fb^{-1} from 2016 run (~ 30 average pileup)
  - Large sample (>100M) of $W \to \mu\nu$ events
- Theoretical modelling
  - Use most accurate model & uncertainties available
  - Rely on in-situ constraints from the W data itself
- Muon calibration: from J/ψ, validated with the Z
- Fit to granular distribution of $\mathbf{p_T^\mu}$ x $\mathbf{\eta^\mu}$ x **charge**

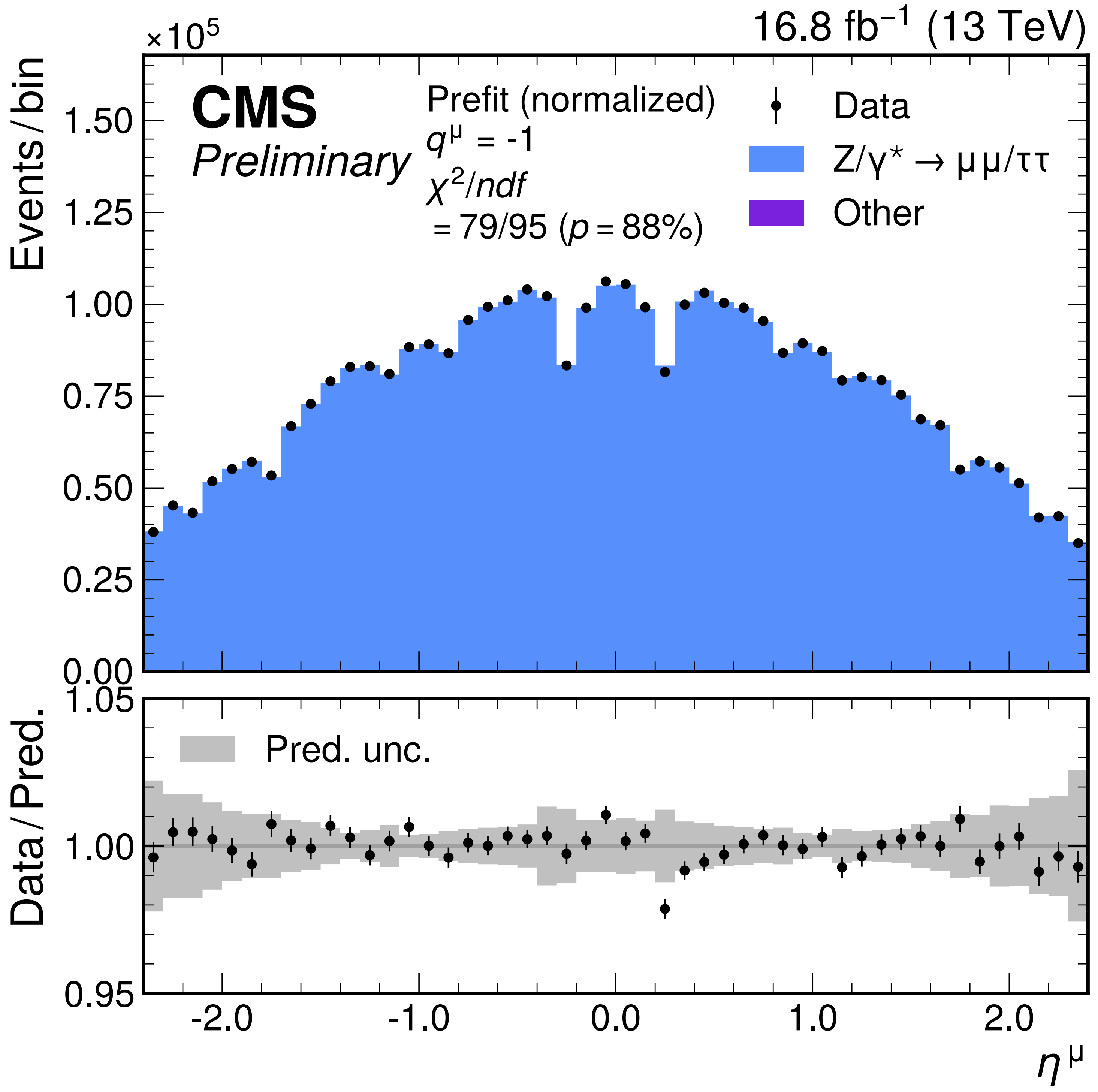


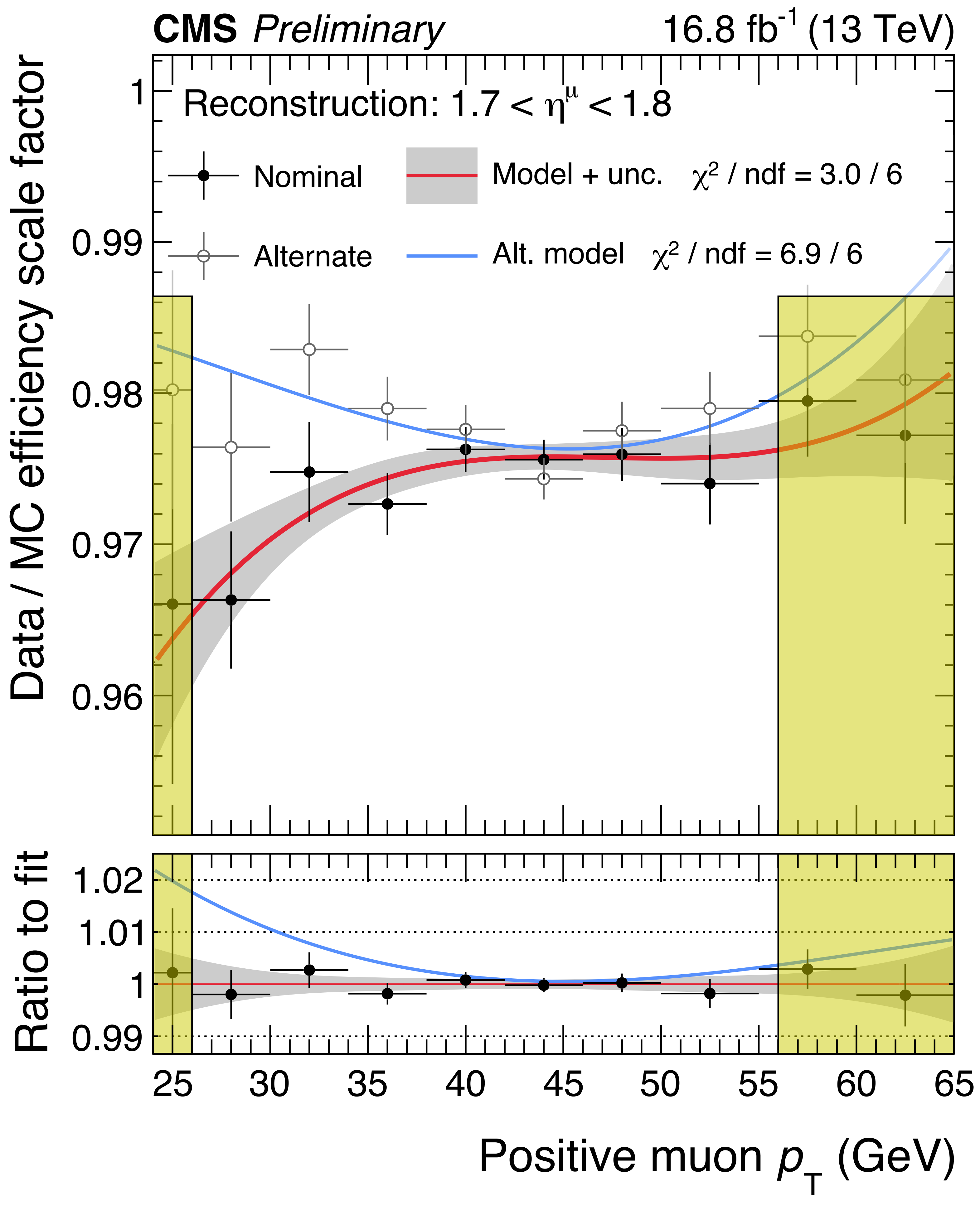


Muon efficiencies

- Granular corrections for tracking, reconstruction, identification, trigger, isolation efficiencies
  - Using Z→μμ tag and probe, vs. muon (η, p_T) and typically charge
- Isolation efficiencies account for measurement bis in Z vs W events
  - Muons produced in the vicinity of the hadronic recoil
- Smooth scale factors vs p_T to reduce overall statistical uncertainty







Muon momentum calibration

- Calibrate with quarkonia → extrapolate to W/Z p_T range
- Approach:

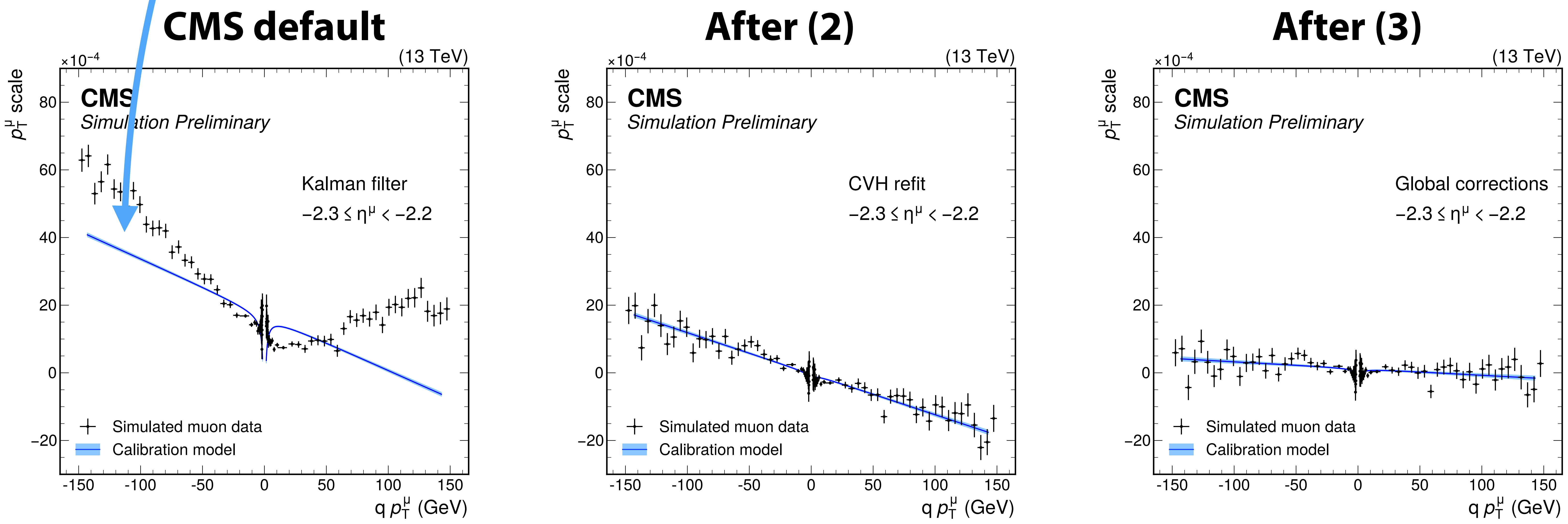
1. Tune simulation precision to remove small biases
2. Refit muon tracks w/ Continuous Variable Helix (CVH): improve accuracy + better B-field & material modelling
3. Correct for local B-field, material and alignment biases between data and reco. model w/ generalized global corrections (adding parameters for B-field + energy loss)
4. Derive final residual scale difference w/ J/ψ mass fits (fine bins in $\eta^+, p_T^+, \eta^-, p_T^-$)

magnetic field (A) **energy loss** (ε) **alignment** (M)

$$\frac{\delta k}{k} = A - \epsilon k + qM/k \qquad (k = 1/p_{\mathrm{T}})$$

Curvature bias vs charge & momentum

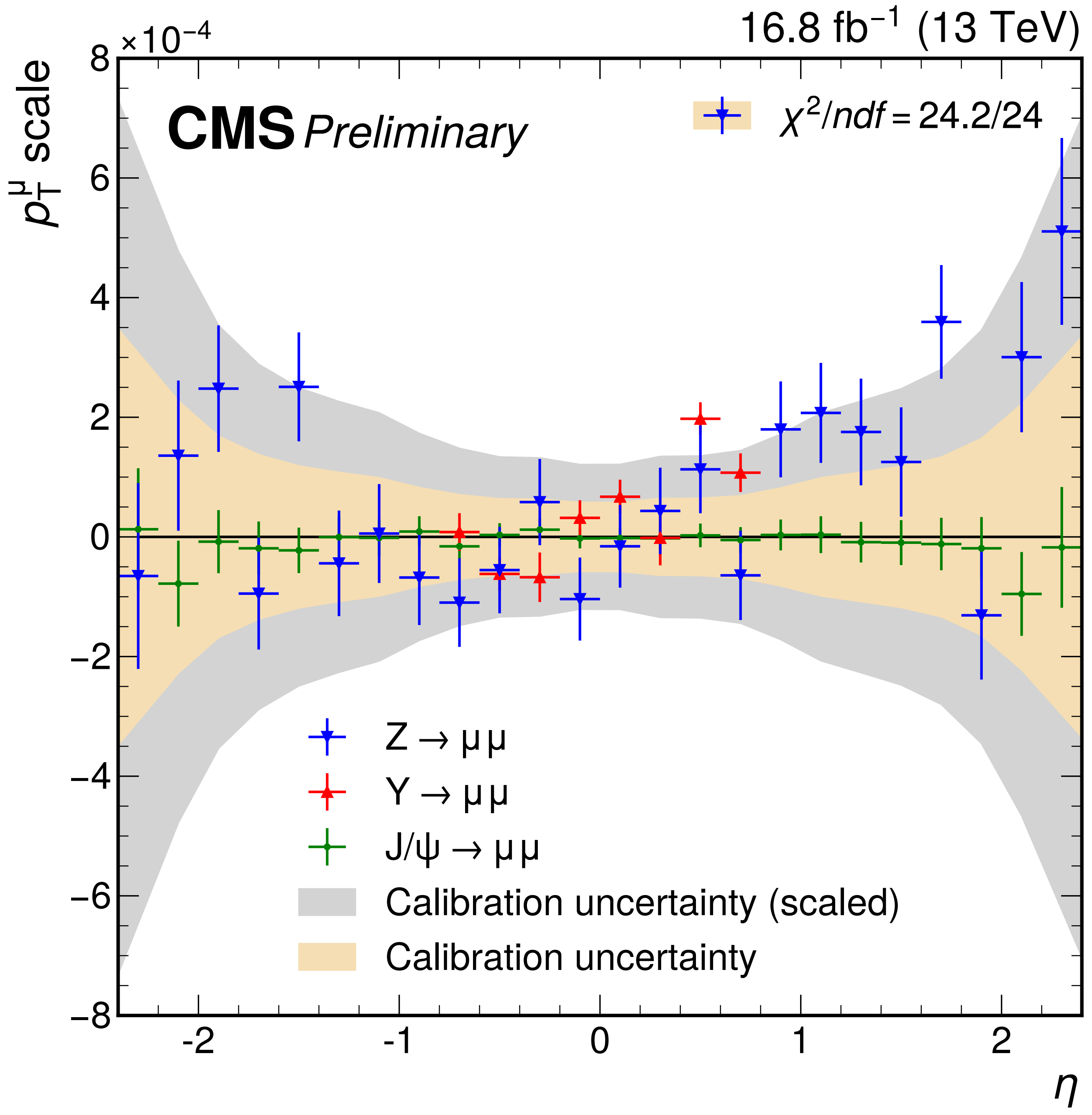
CVH refit and global corrections necessary to remove all local biases



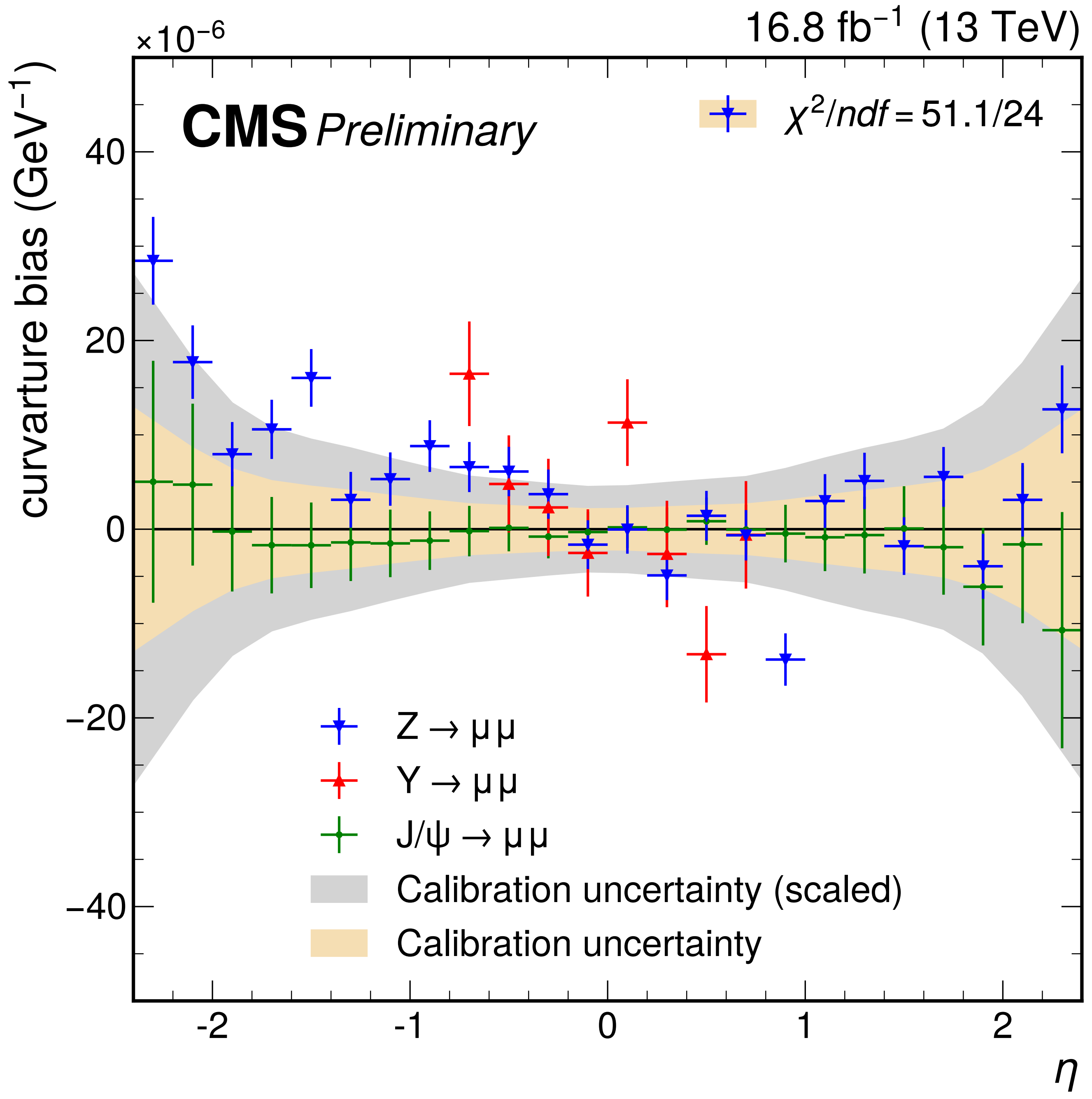
Muon momentum calibration

- Validated with $\Upsilon_{1S} \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ for remaining scale difference in terms of B-field and alignment-like parameters
- Statistical uncertainties on J/ψ calibration parameters scaled by 2.1
  - Cover all possible patterns of bias or missed systematic effects
- Z not used in final calibration, but uncertainties from J/ψ vs Z closure are included

charge-independent



charge-dependent

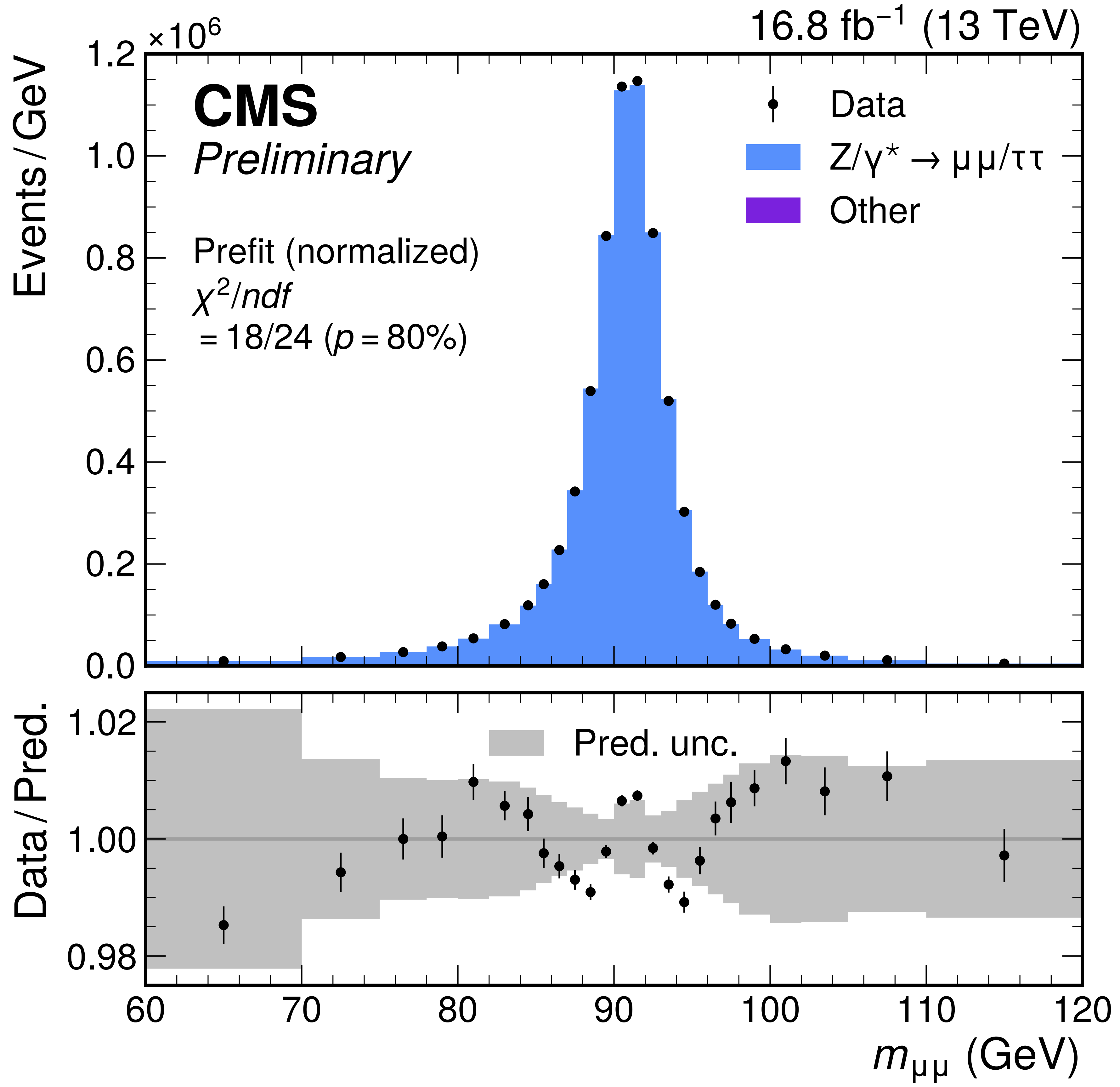


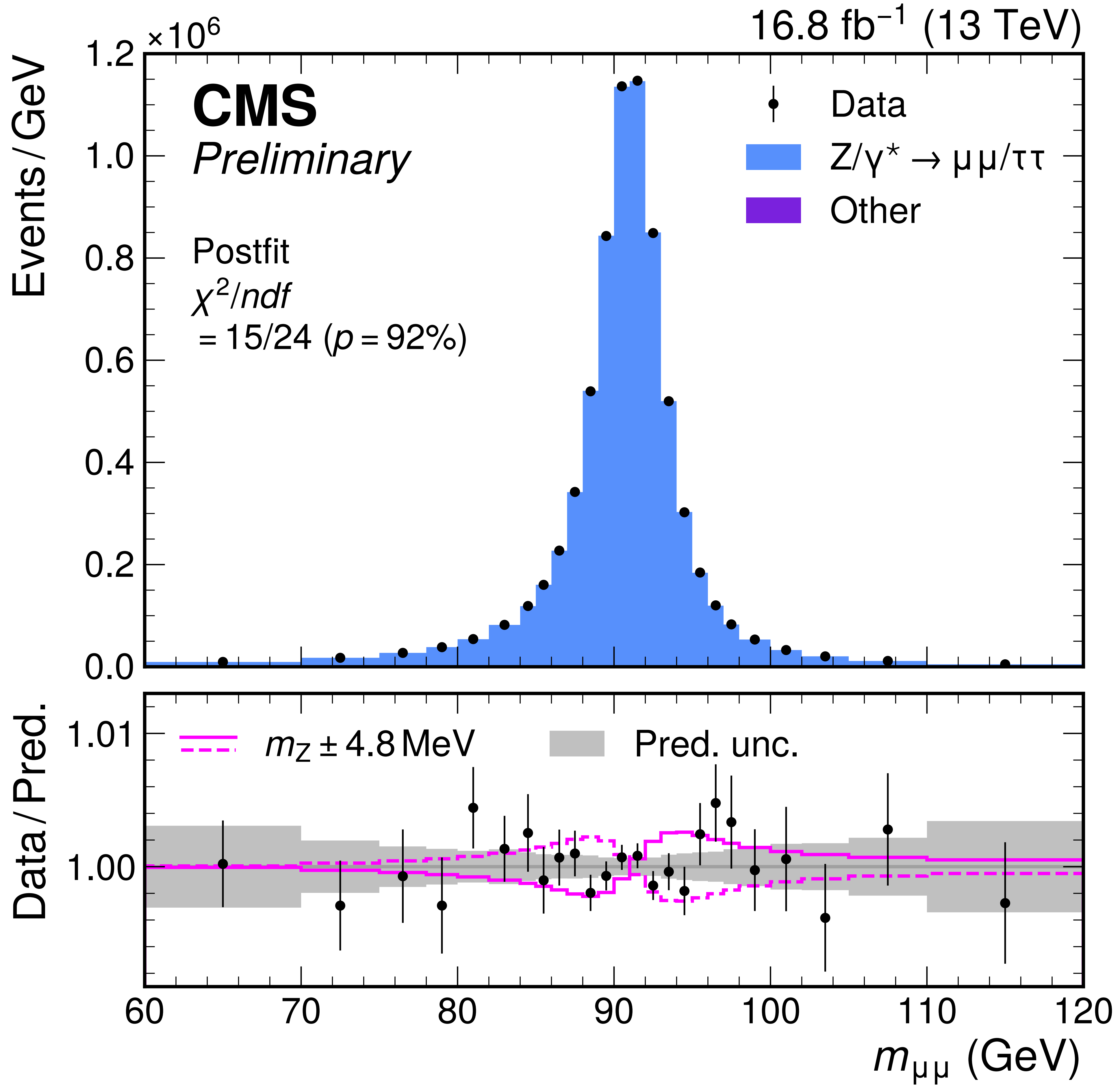
Source of uncertainty	Nuisance parameters	Uncertainty in m_W (MeV)
J/ψ calibration stat. (scaled $\times 2.1$)	144	3.7
Z closure stat.	48	1.0
Z closure (LEP measurement)	1	1.7
Resolution stat. (scaled $\times 10$)	72	1.4
Pixel multiplicity	49	0.7
Total	314	4.8

m_Z dilepton mass fit

- Validate calibration and uncertainty model by fitting for m_Z
  - Uncertainty dominated by calibration
- **NB: not yet an independent measurement of m_Z**

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



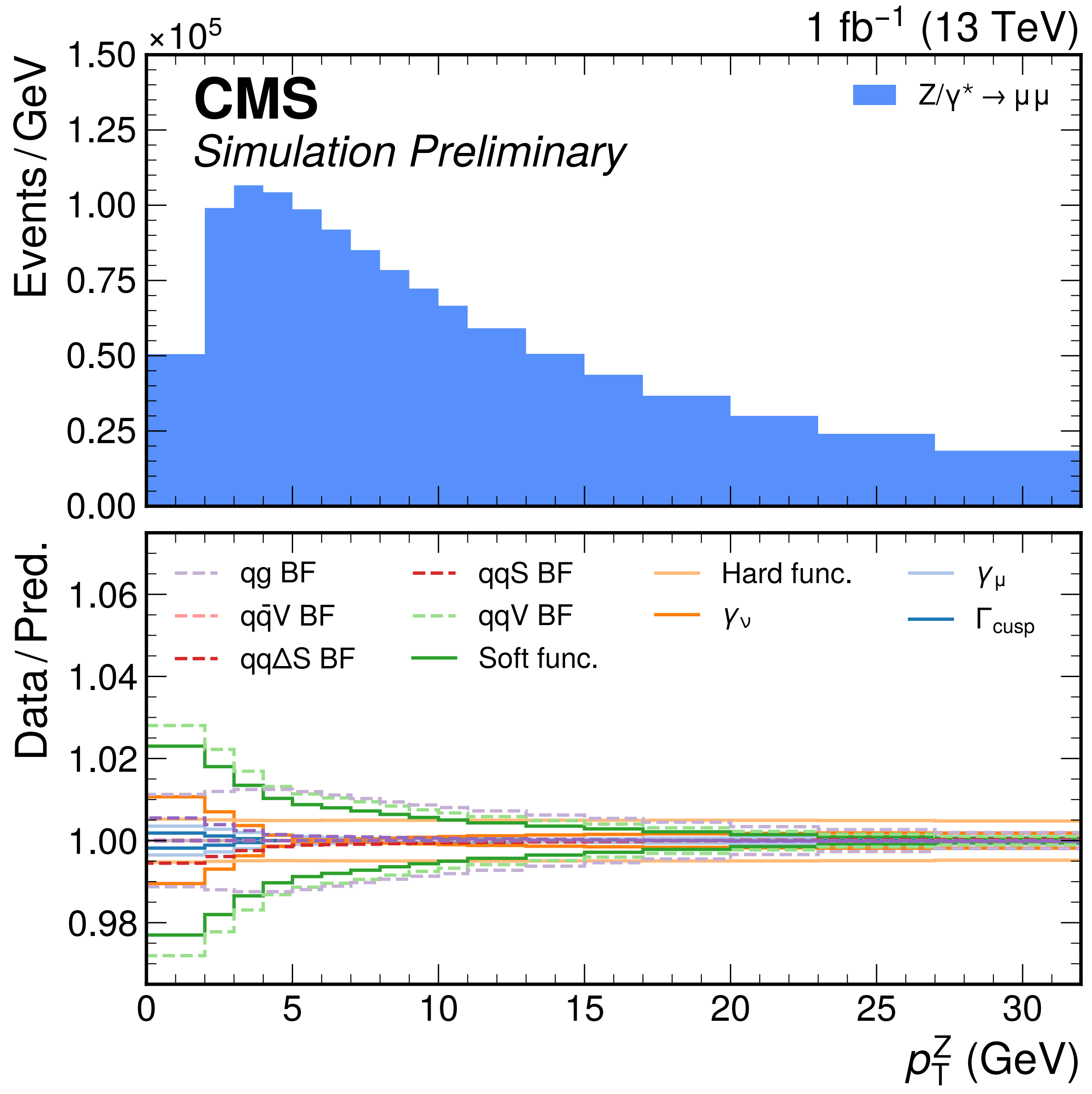


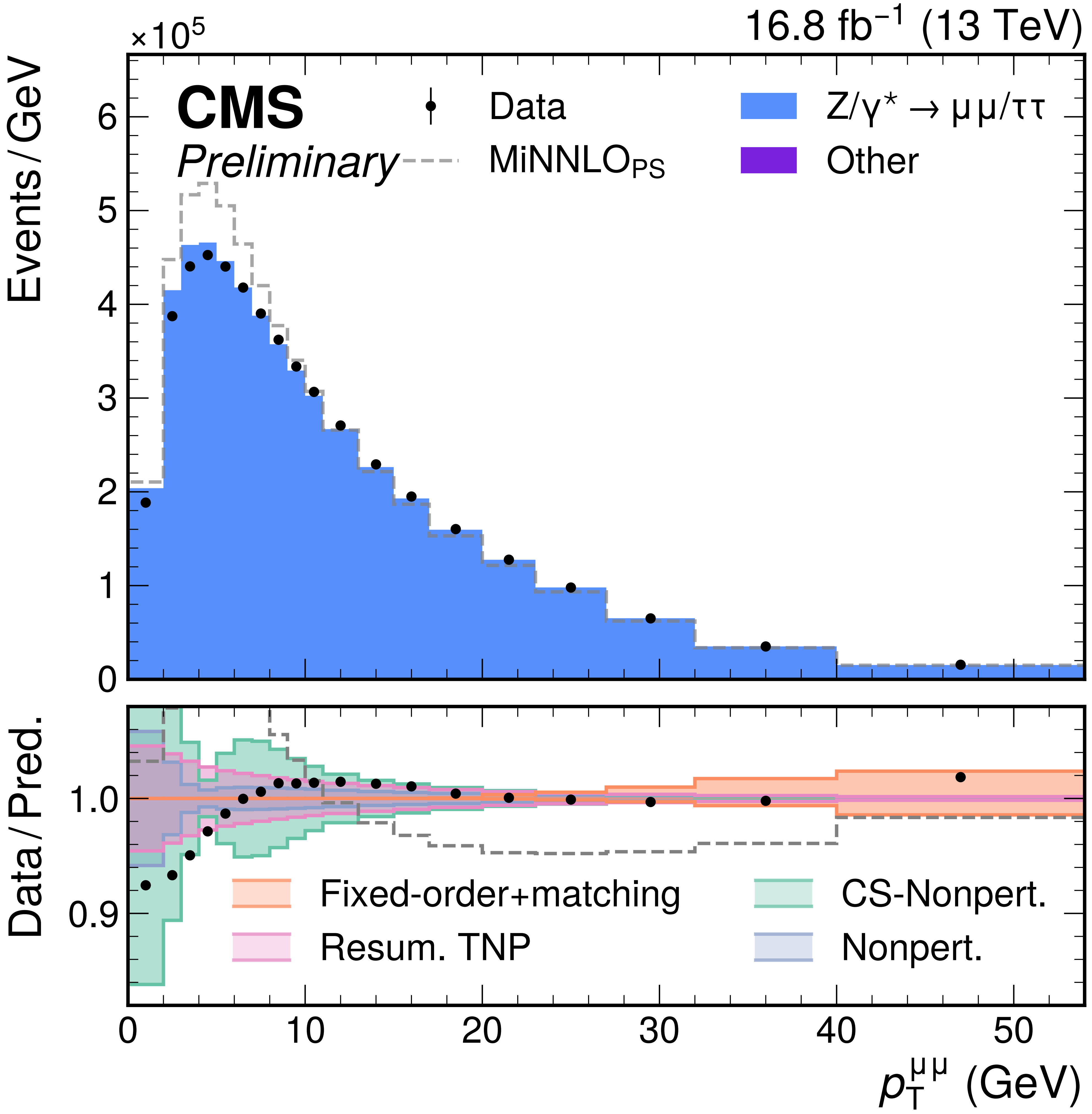
Theoretical model

$$\frac{d\sigma}{dp_T^2\, dm\, dy\, d\cos\theta^*\, d\phi^*} = \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T^2\, dm\, dy}\left[(1+\cos^2\theta^*) + \sum_{i=0}^{7} A_i(p_T, m, y) P_i(\cos\theta^*, \phi^*)\right],$$

- Simulation: MiNNLO$_{PS}$ + PY8 + Photos ⇒O(α_s^2), but limited logarithmic accuracy for W/Z p_T
- σ^{U+L} corrected to resummed SCETLIB + DYTurbo prediction (N3LL + NNLO)

Resummed calculation
"Theory nuisance parameters"
Well-defined correlation model across phase-space and between W and Z (F. Tackmann)

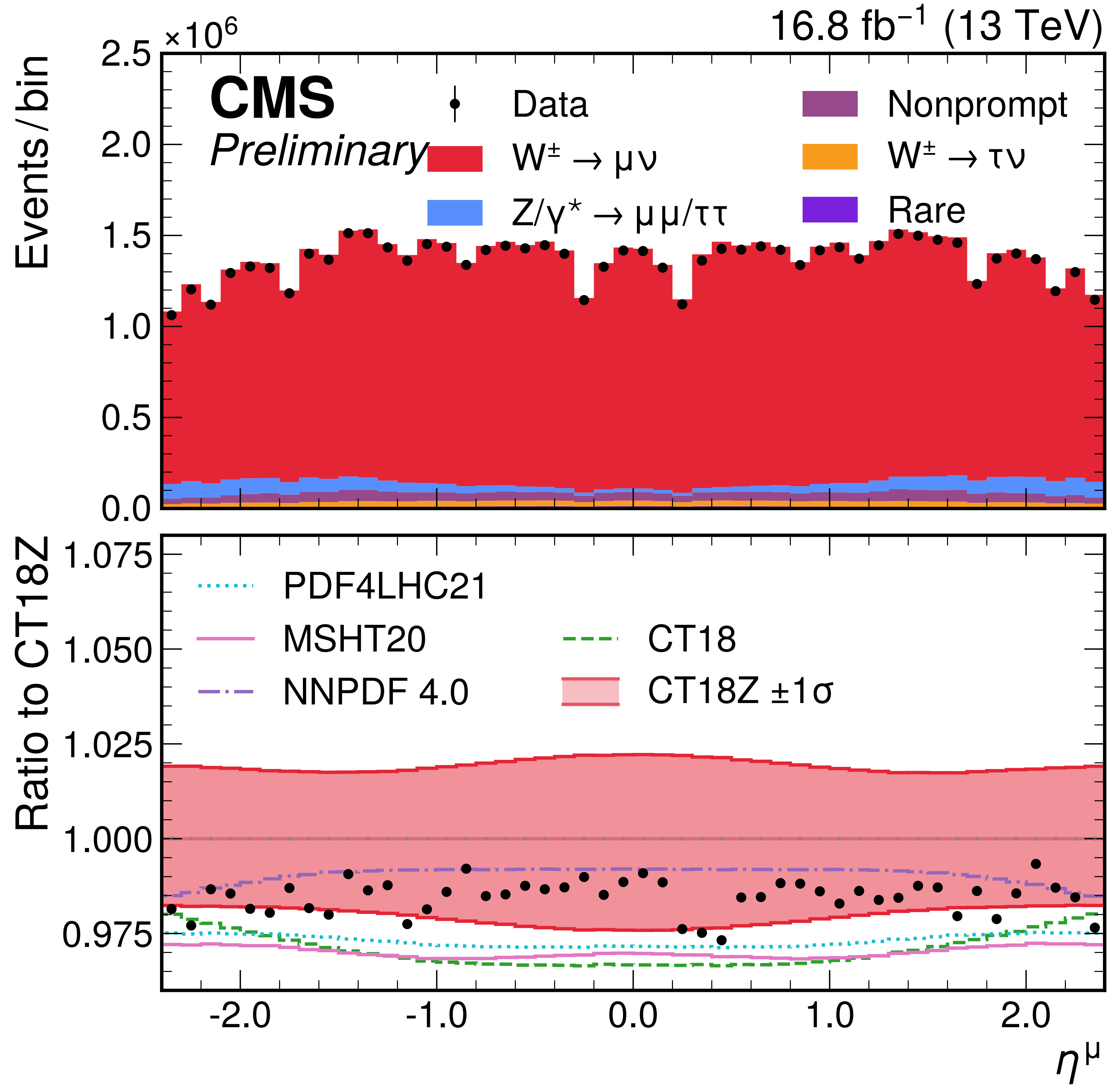




Non-perturbative
Related to intrinsic parton momentum: empirical model w/ Gaussian smearing of parton momenta - large a-priori unc.

Missing higher orders in α_s
μR, μF variations
+ variations in matching scale

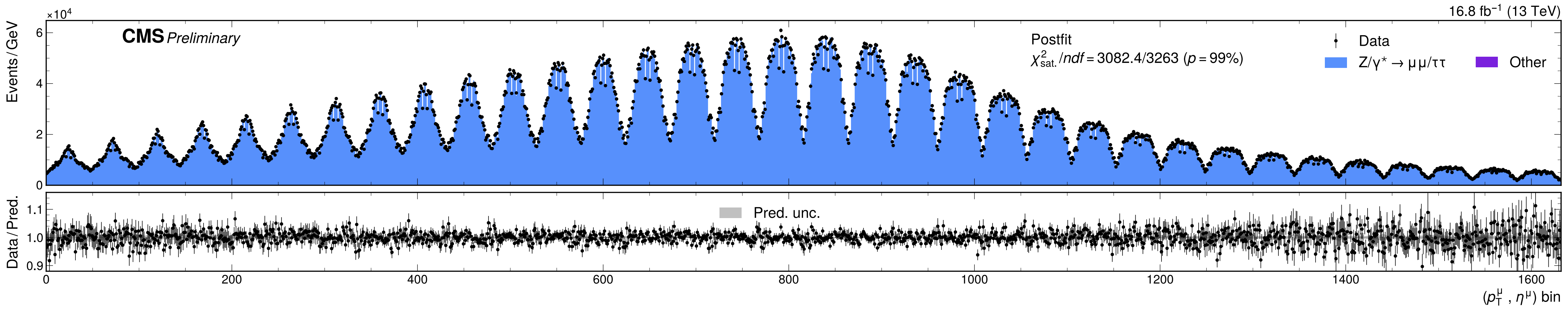
Theoretical model



- PDF sets give well-defined correlation structure in their uncertainties
- But do not always agree with each other within uncertainties
- ⇒ Scale pre-fit PDF uncertainties until expected m_W shift from other sets within uncertainties
  - Does not mean PDF are uncertainties are underestimated, only that they do not all cover wrt. other sets
- CT18Z chosen as nominal
  - Covers others without scaling
- **Other uncertainties** not discussed here (backup):
  - Uncertainties in angular coefficients + impact of PYTHIA intrinsic k_T
  - EW uncertainties

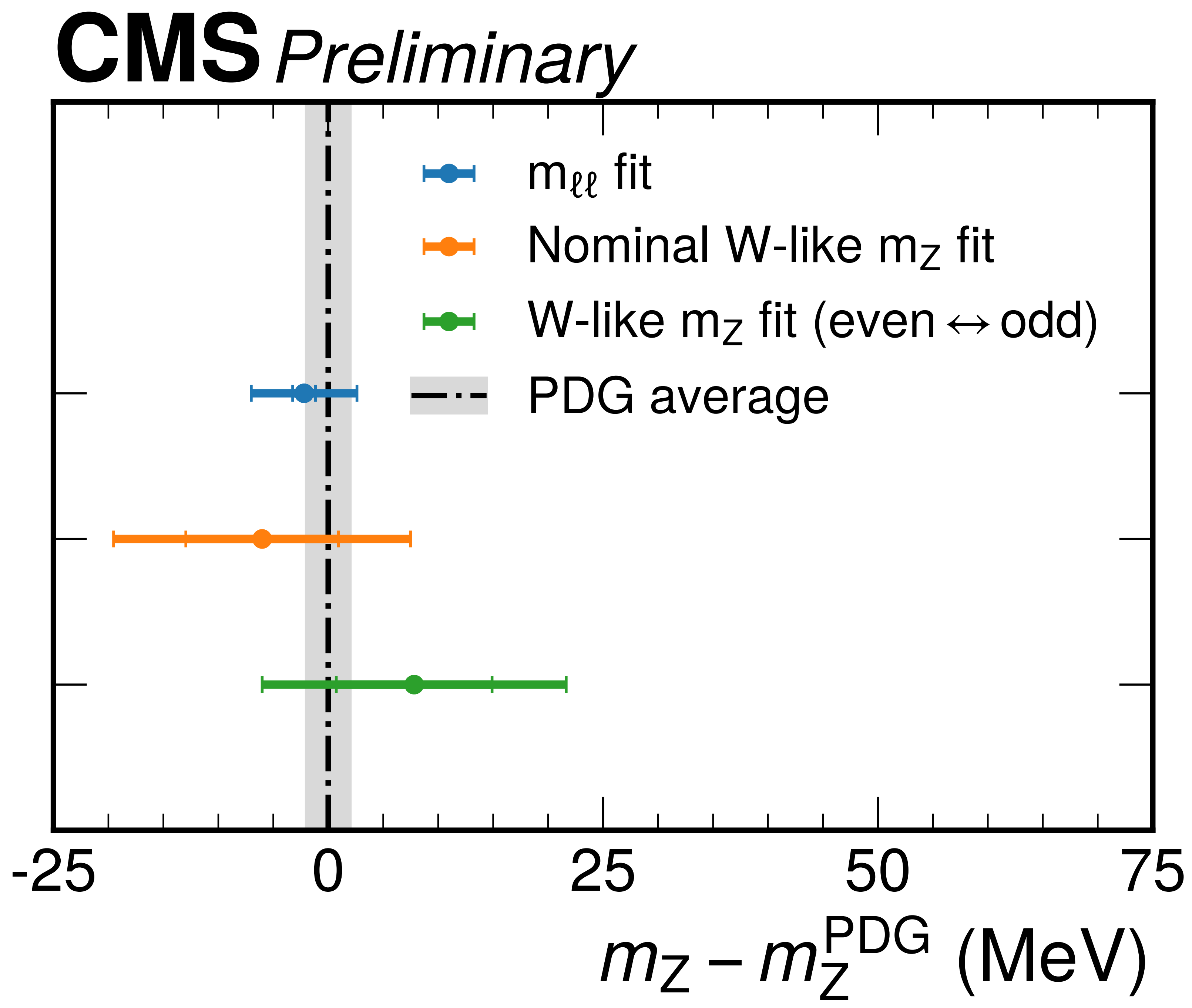
PDF set	Scale factor	Impact in m_W (MeV) Original σ_{PDF}	Impact in m_W (MeV) Scaled σ_{PDF}
CT18Z	–	4.4	
CT18	–	4.6	
PDF4LHC21	–	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0

W-like fit + p_T^Z validation

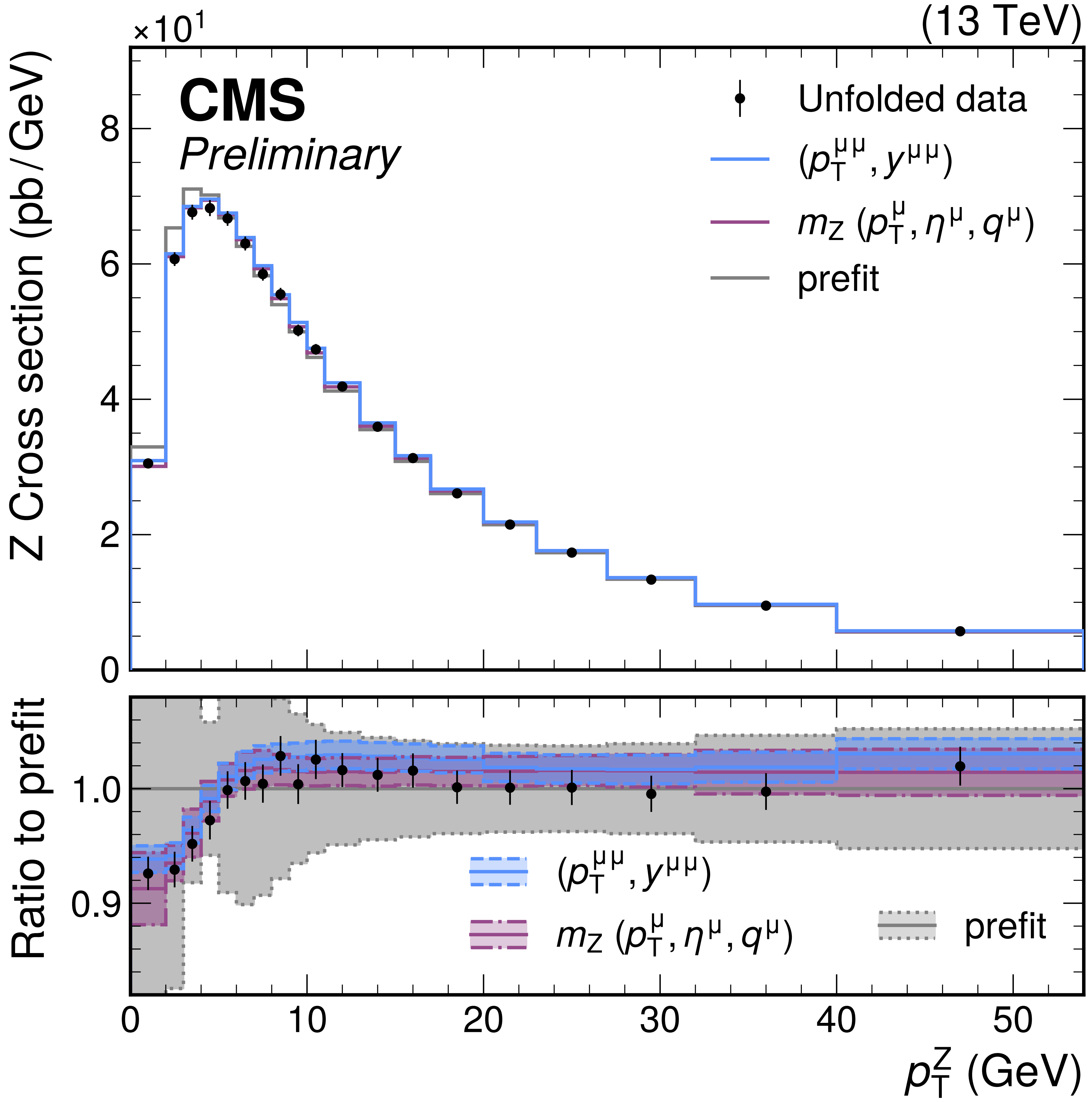


$$m_Z - m_Z^{\mathrm{PDG}} = -6 \pm 14\mathrm{MeV}$$

- Agreement with PDG value: main uncertainties statistics (6.9 MeV), calibration (5.6 MeV) and angular coefficients (4.9 MeV)
- Results compatible fitting different mZ in η regions, and with charge different



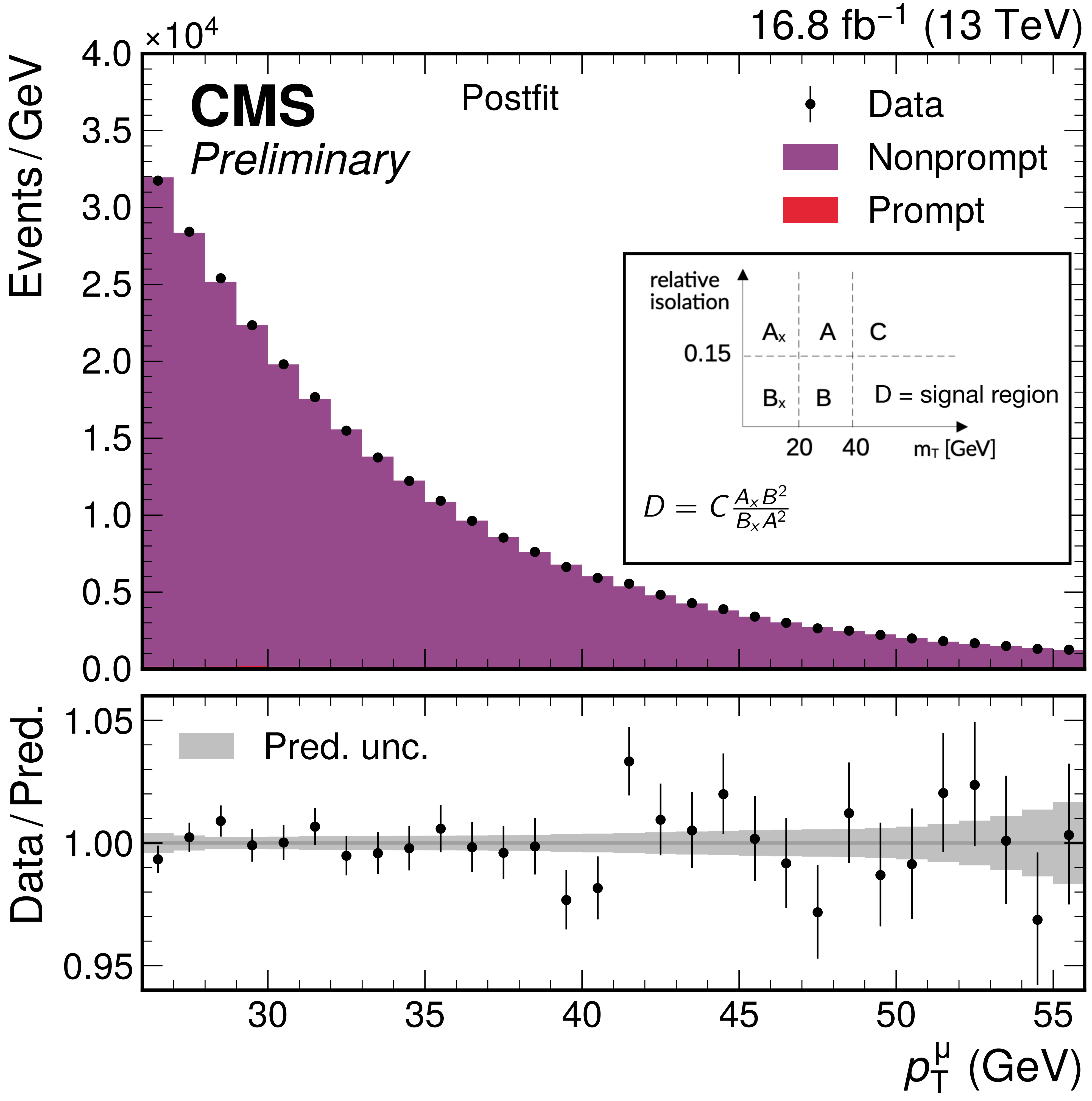
- Validation of p_T^Z modelling: propagate (p_T, η, charge) fit results to unfolded p_T^Z spectrum, compare to direct $p_T^{\mu\mu}$, $y^{\mu\mu}$ fit
- Direct fit gives stronger constraints, but both compatible



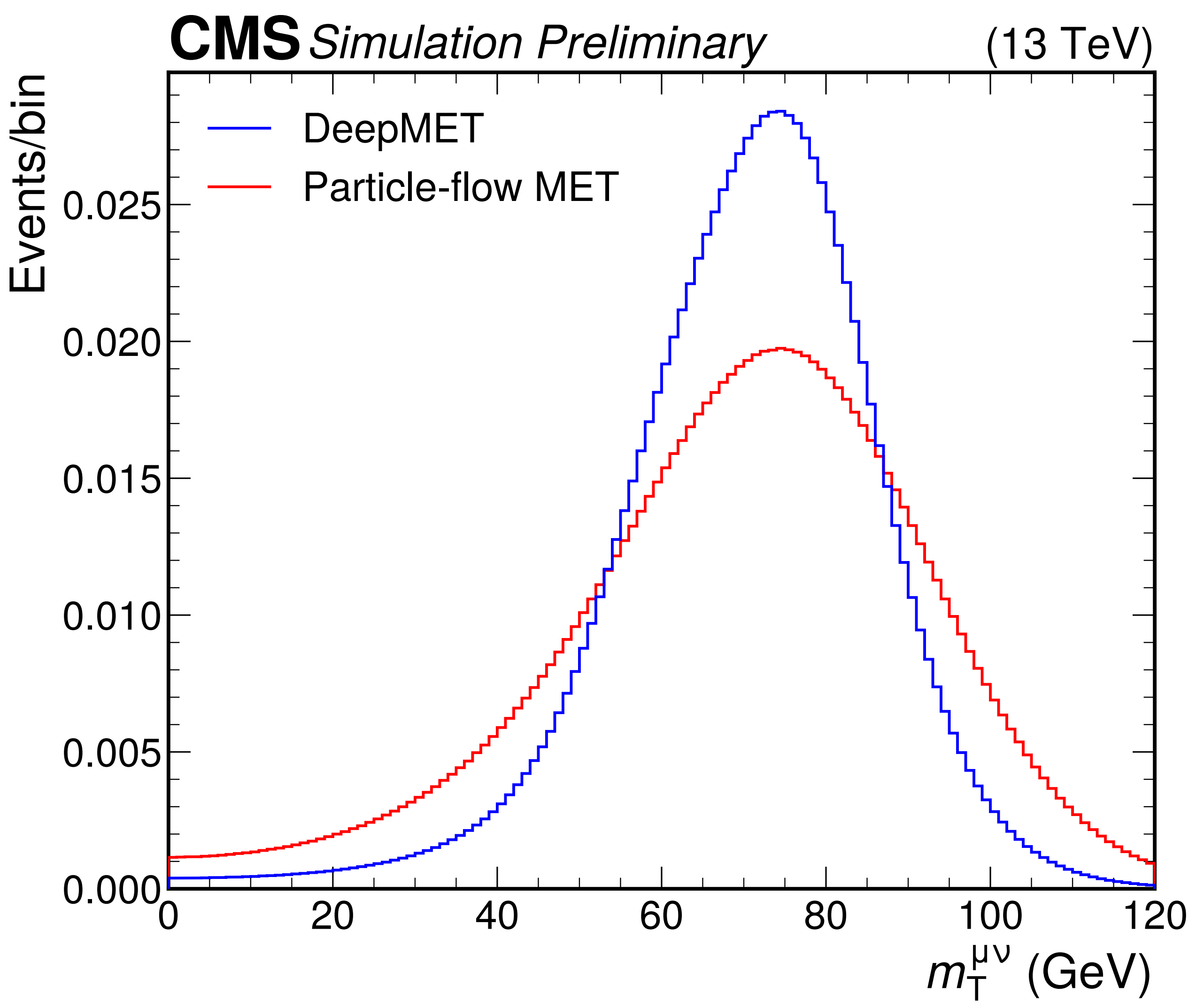
- Gives confidence m_W can be measured without tuning p_T^W via Z data

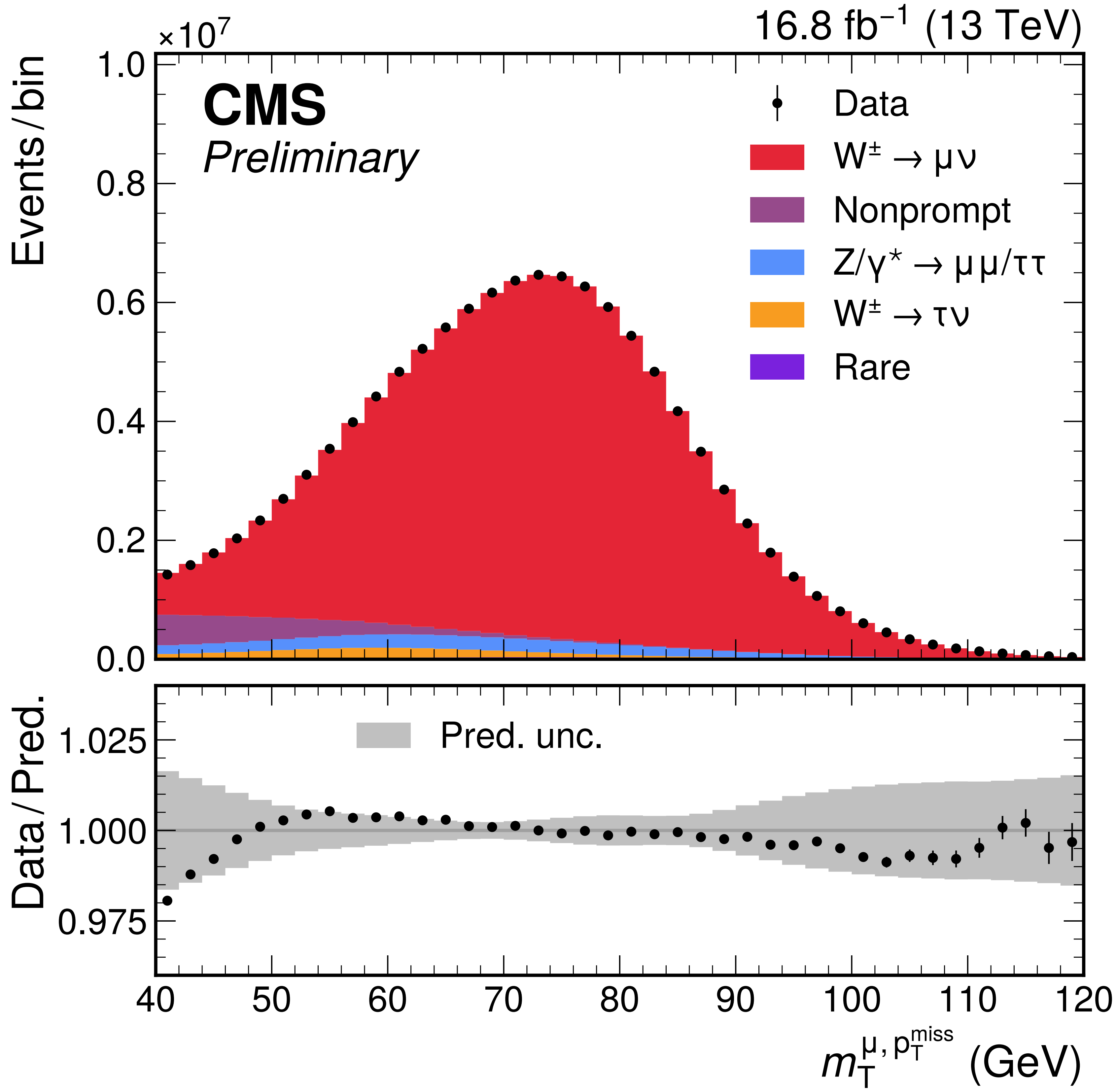
Other ingredients for fitting W events

- Non-prompt: extended ABCD method, validated in secondary vertex control region



- Hadronic recoil: do not fit m_T directly, but part of event selection and non-prompt estimate
- Use DNN-based "DeepMET", recoil response calibrated in $Z \rightarrow \mu\mu$ events



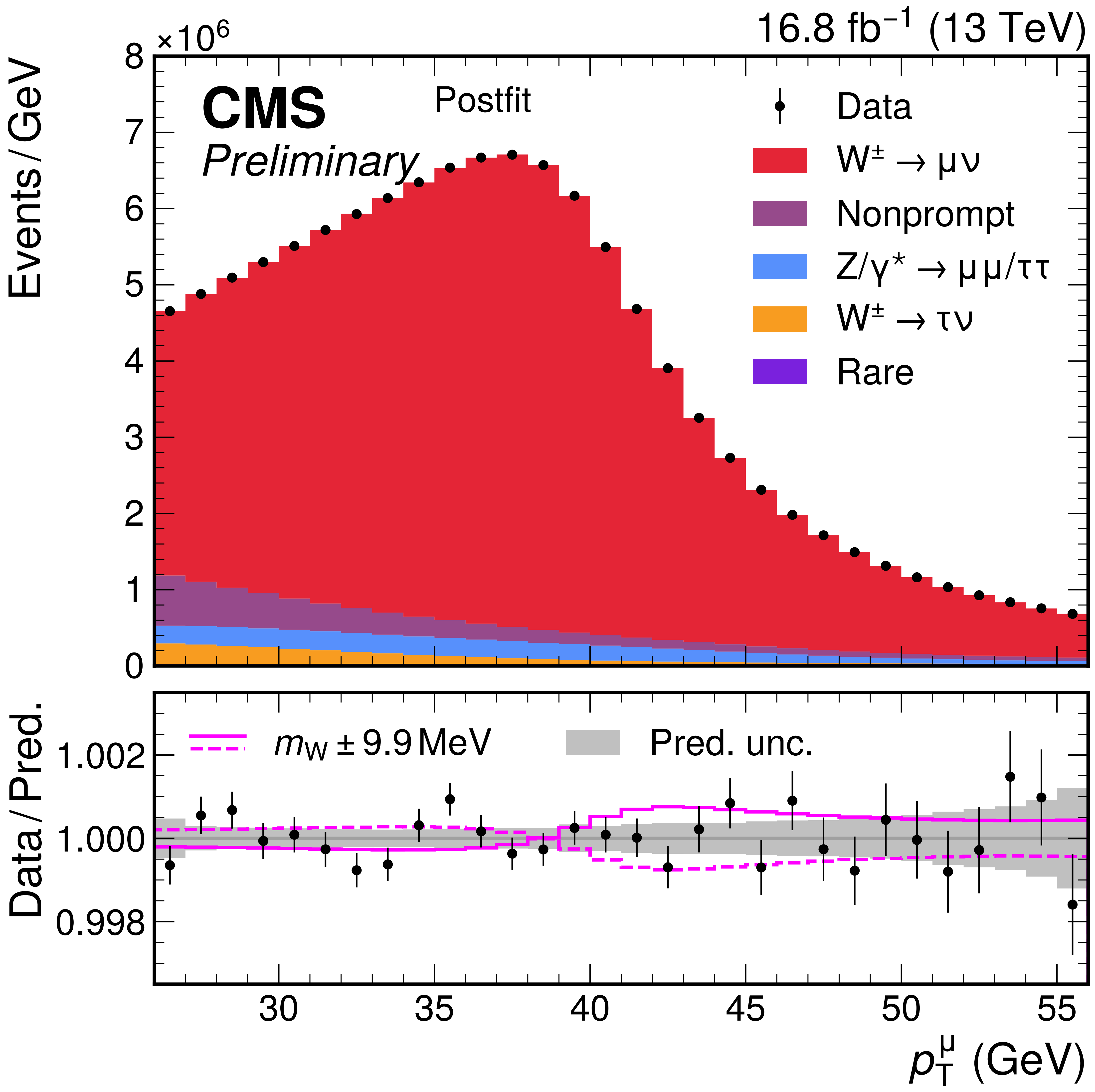


m_W measurement

m_W = 80360.2 ± 9.9 MeV

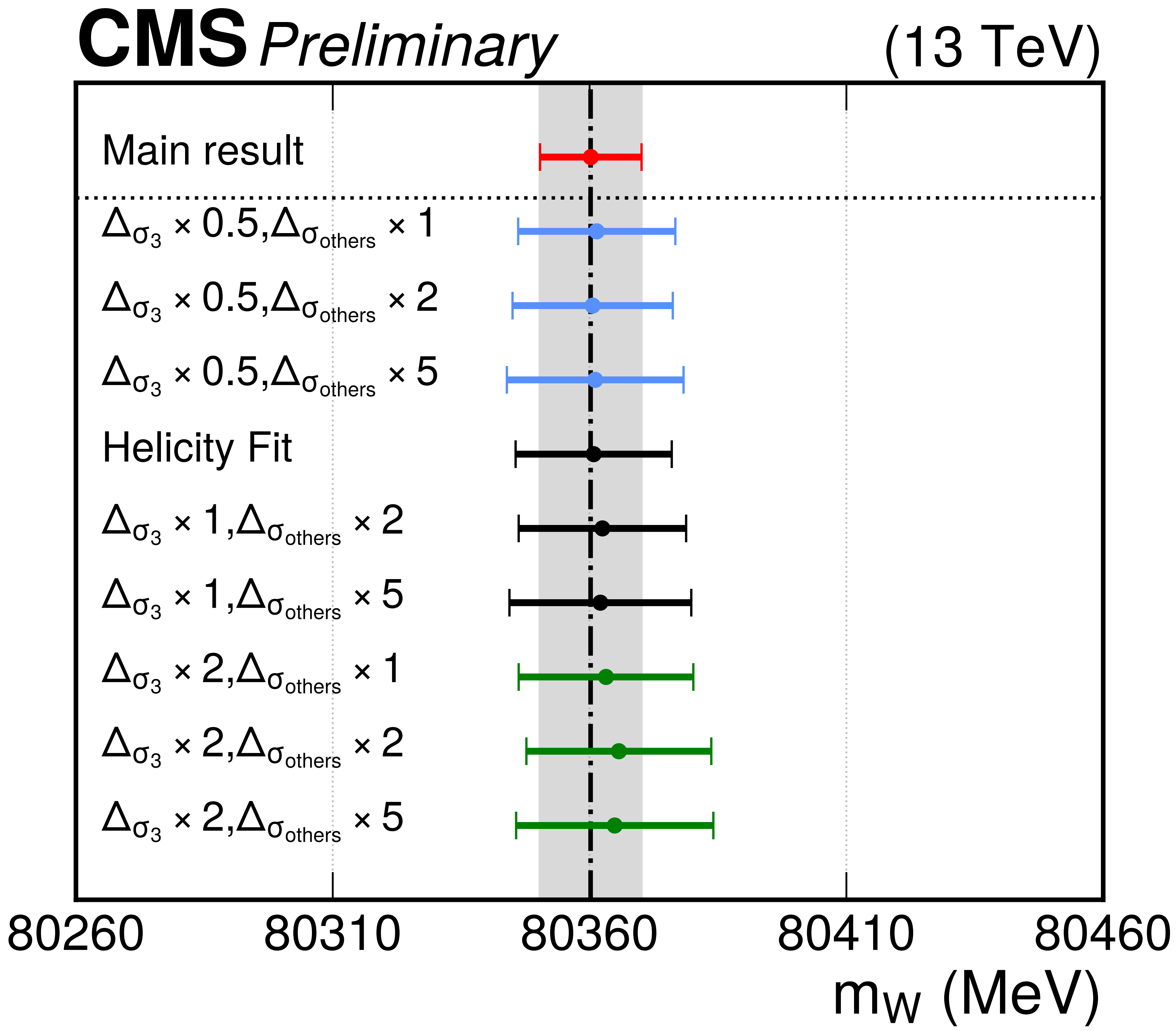
- Two approaches to breakdown of uncertainty
  - "Global" used in most recent ATLAS m_W results

Source of uncertainty	Impact (MeV) Nominal	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



Helicity cross section fit

- Fit in-situ helicity cross sections $\sigma_i = \sigma^{U+L} A_i$, double-differentially in y^W and $p_T^W \Rightarrow$ 144 x 6 = **864** additional degrees of freedom
- Theoretical uncertainties "traded" for larger stat. uncertainties
  - NB: current data set & strategy does not allow constraining all components simultaneously
  - Loose constraints to the nominal prediction are applied

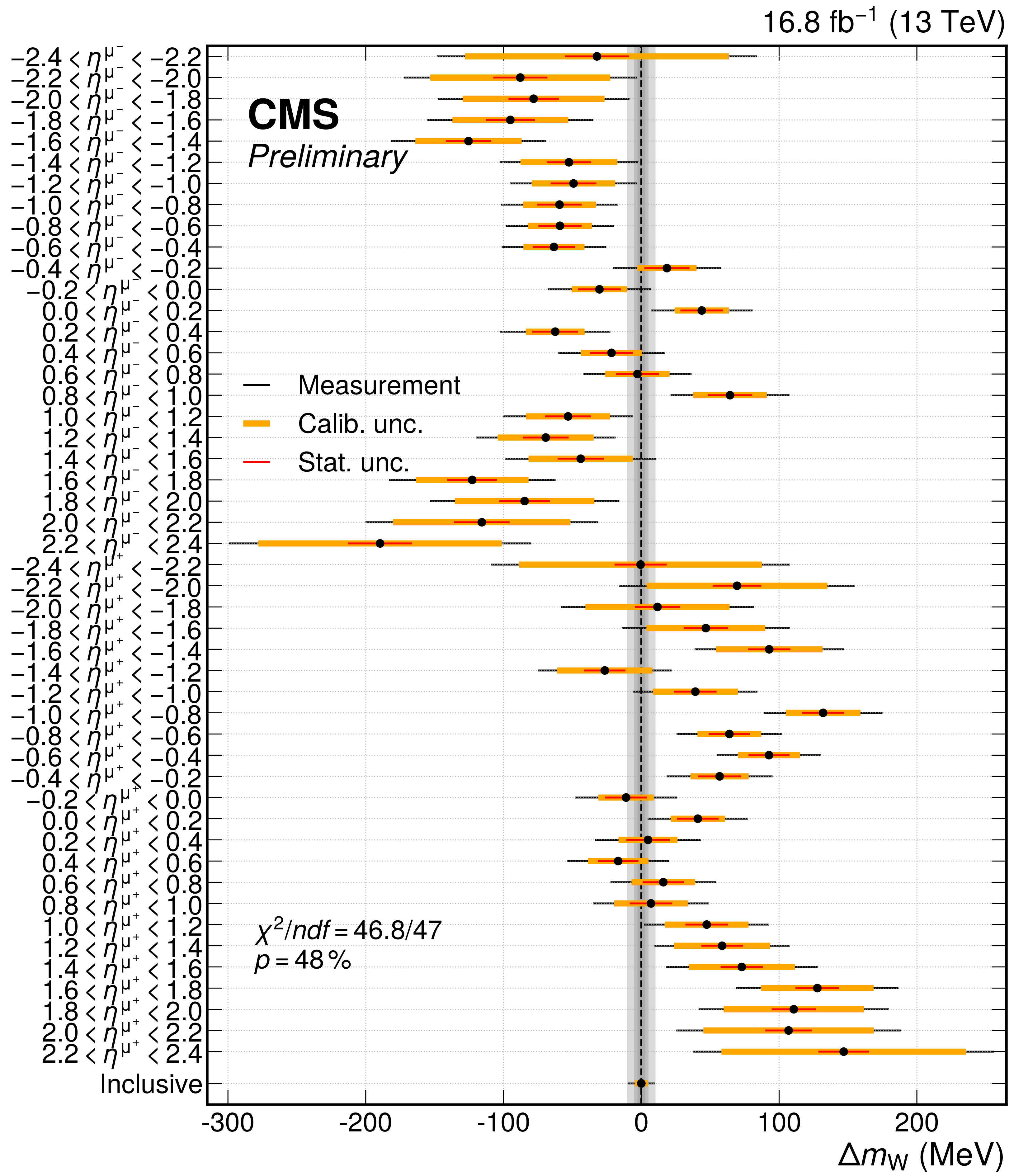


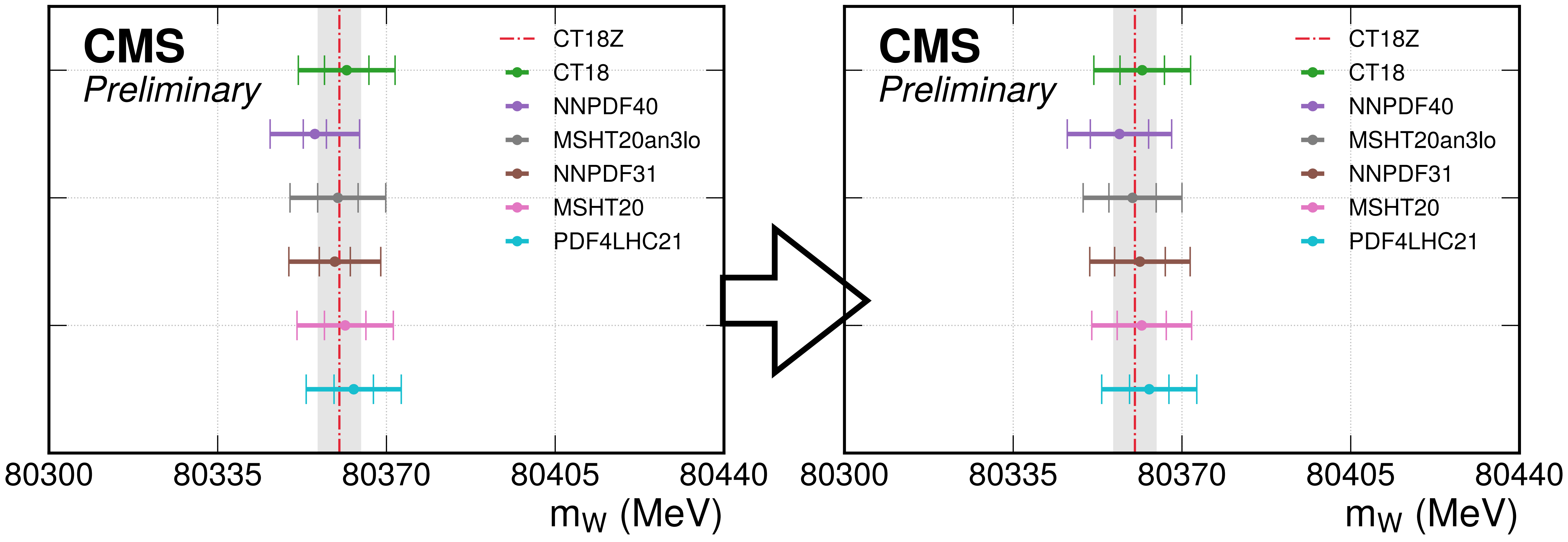
m_W = 80360.8 ± 15.2 MeV

- Compatible with nominal result
- Stable with looser or tighter initial constraints on the helicity cross sections
  - $\Rightarrow$ Data is not preferring some m_W value far from SM
  - σ_3 varied by independent factors: found to have stronger impact as distortion induced in p_T^μ very similar to shifts of m_W

Cross checks

- PDF set dependence reduced with application of pre-fit scaling ⇒ agreement within quoted uncs.

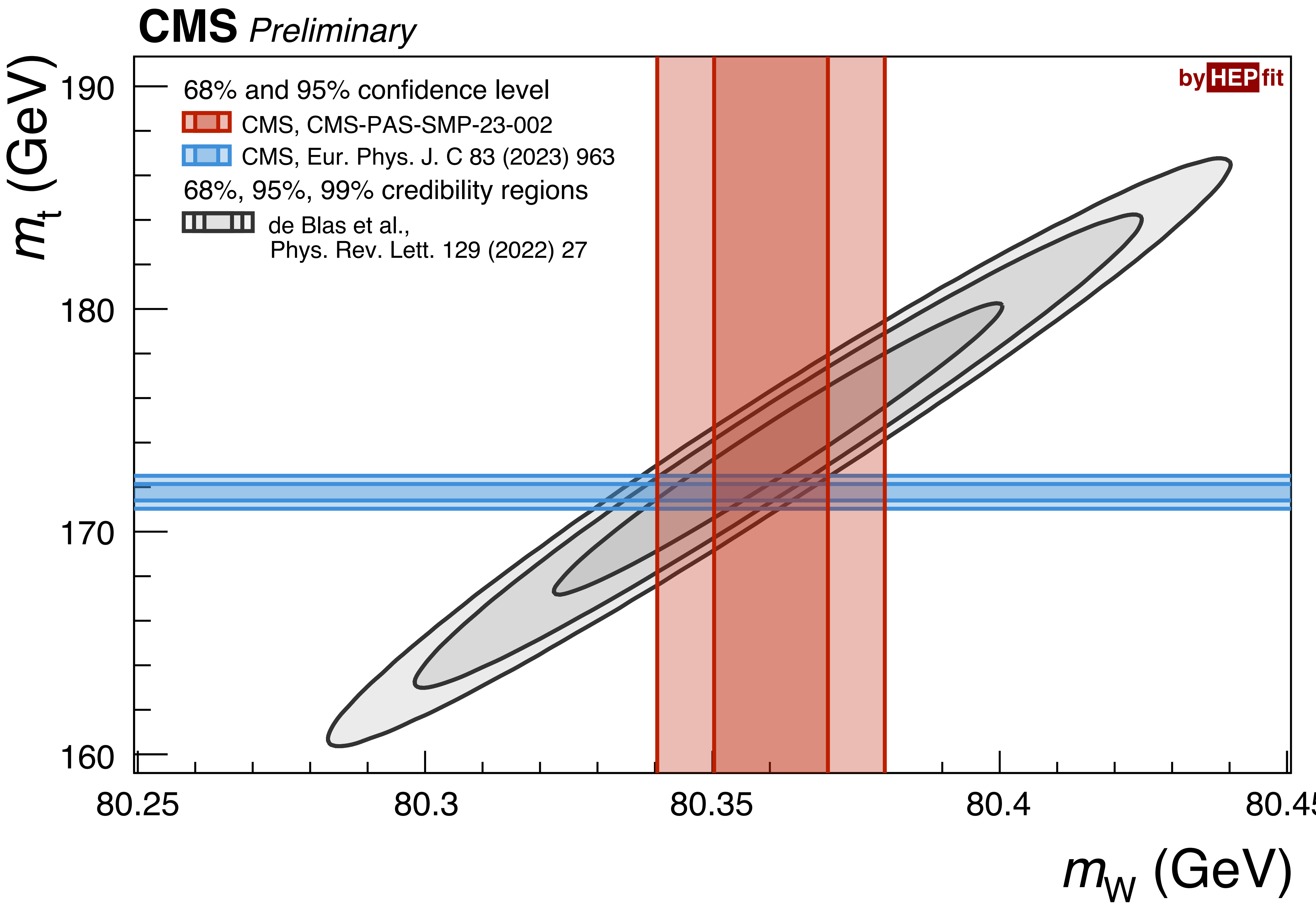


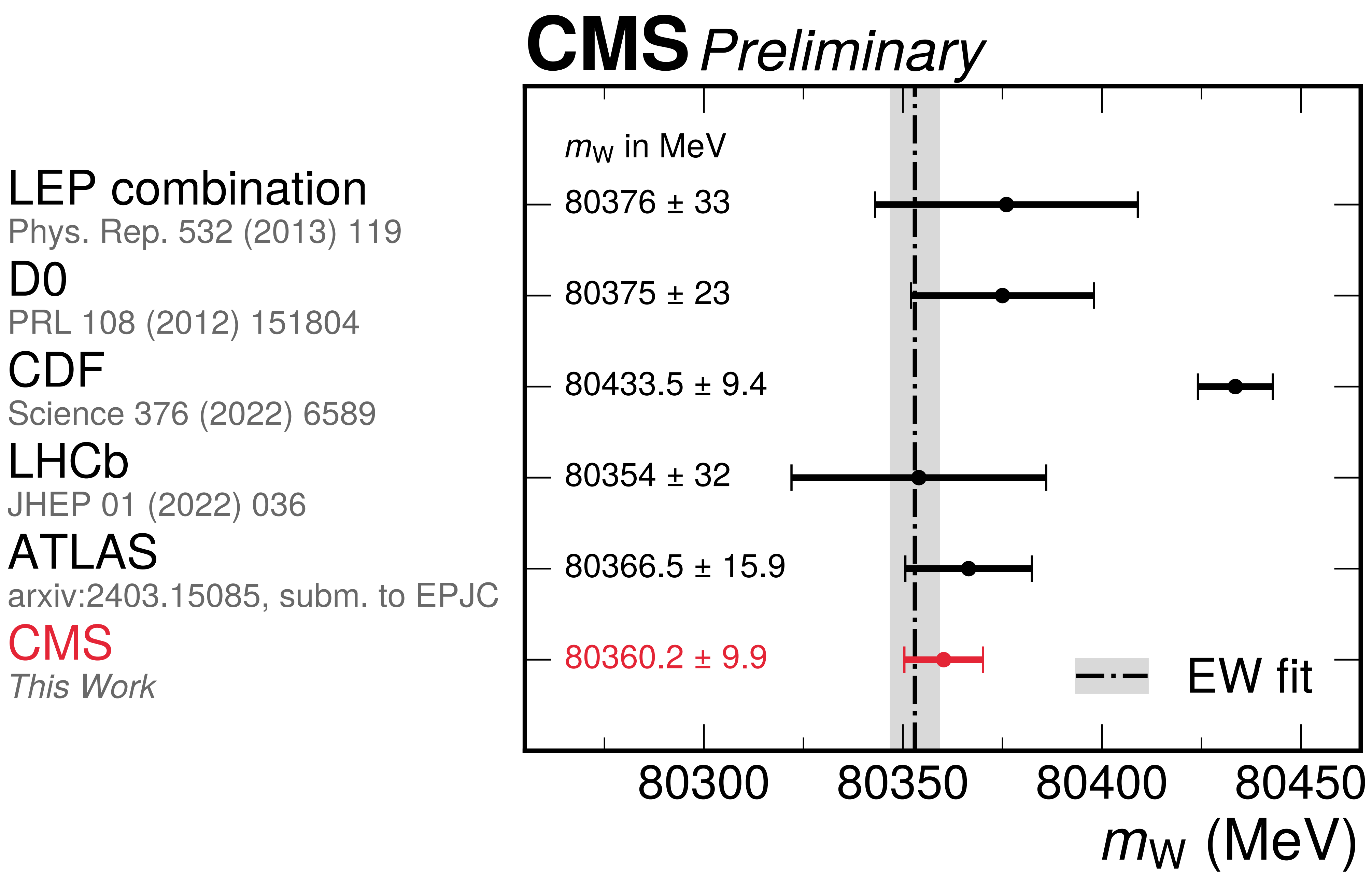


- Extract 48 independent mW values in η and charge slices
  - η sign difference: $\Delta m_W = 5.8 \pm 12.4$ MeV
  - Charge difference: $\Delta m_W = 57 \pm 30$ MeV
    - p-value 6% - anti-correlations due to alignment and W polarization uncertainties
    - **Correlation between charge difference and m_W only 2%**

Summary

- First m_W measurement from CMS
- Innovative strategy based on unprecedented calibration of detector effects and theoretical modelling, in a challenging PU environment
- Extensive validation using m_{ll} and the W-like m_Z fits
- Consistent helicity cross section fit with relaxed constraint
- The SM appears to win, for now

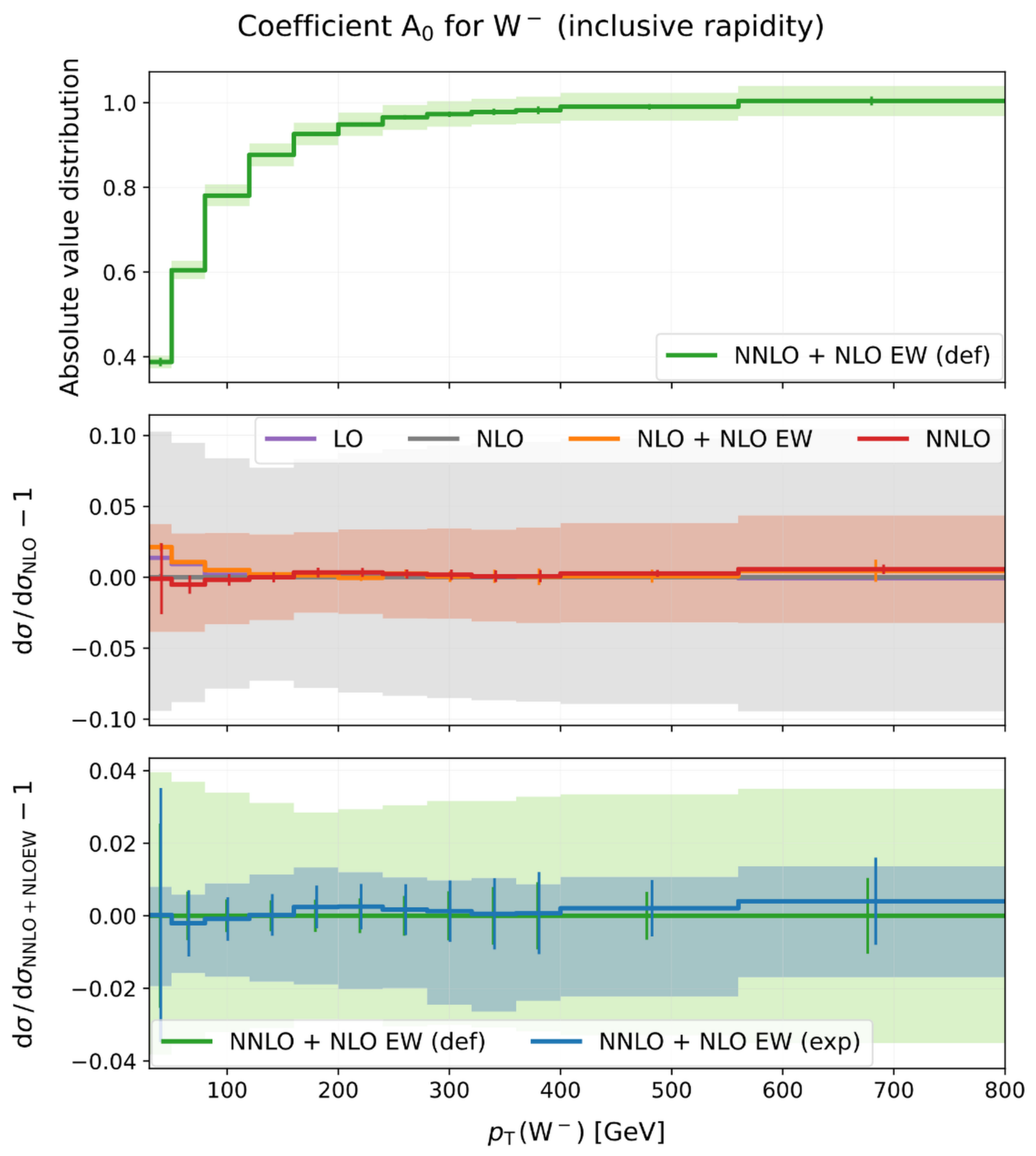




Backup

Angular distributions

- Missing higher order uncertainties propagated to angular coefficients through variations of μ_r and μ_f in MiNNLOPS
- While MiNNLOPS predicts angular coefficients consistent with fixed order calculations, Pythia intrinsic k_T treatment actually modifies them somewhat
  - In particular A_1 and A_3 at low boson p_T due to isotropic smearing
- This effect may or may not be physical → propagate the full difference as an additional uncertainty



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Charge difference

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

Goodness-of-fit for PDF sets

PDF set	Nominal fit		Without PDF+α_s unc.		Without theory unc.	
	χ^2/ndf	p-val. (%)	χ^2/ndf	p-val. (%)	χ^2/ndf	p-val. (%)
CT18Z	100.7/116	84	125.3/116	26	103.8/116	78
CT18	100.7/116	84	153.2/116	1.0	105.7/116	74
PDF4LHC21	97.7/116	89	105.5/116	75	104.1/116	78
MSHT20	97.0/116	90	107.4/116	70	98.8/116	87
MSHT20aN3LO	99.0/116	87	122.8/116	31	101.9/116	82
NNPDF3.1	99.1/116	87	105.5/116	75	115.0/116	51
NNPDF4.0	99.7/116	86	104.3/116	77	116.7/116	46

Goodness-of-fit test statistics for different PDF sets when fitting simultaneously the η^{μ} distributions for selected W^+ (W^-) events and the $y^{\mu\mu}$ distribution for $Z \to \mu\mu$ events. The fit is performed in the nominal configuration with all uncertainties (left column), nominal configuration without PDF and α_s uncertainties (middle column), and nominal configuration without theory uncertainties (right column). The p-value denotes the probability for the observed data to agree with a given configuration as well as, or worse than, it does.