W mass and related measurements

Elisabetta Manca (University of California, Los Angeles)

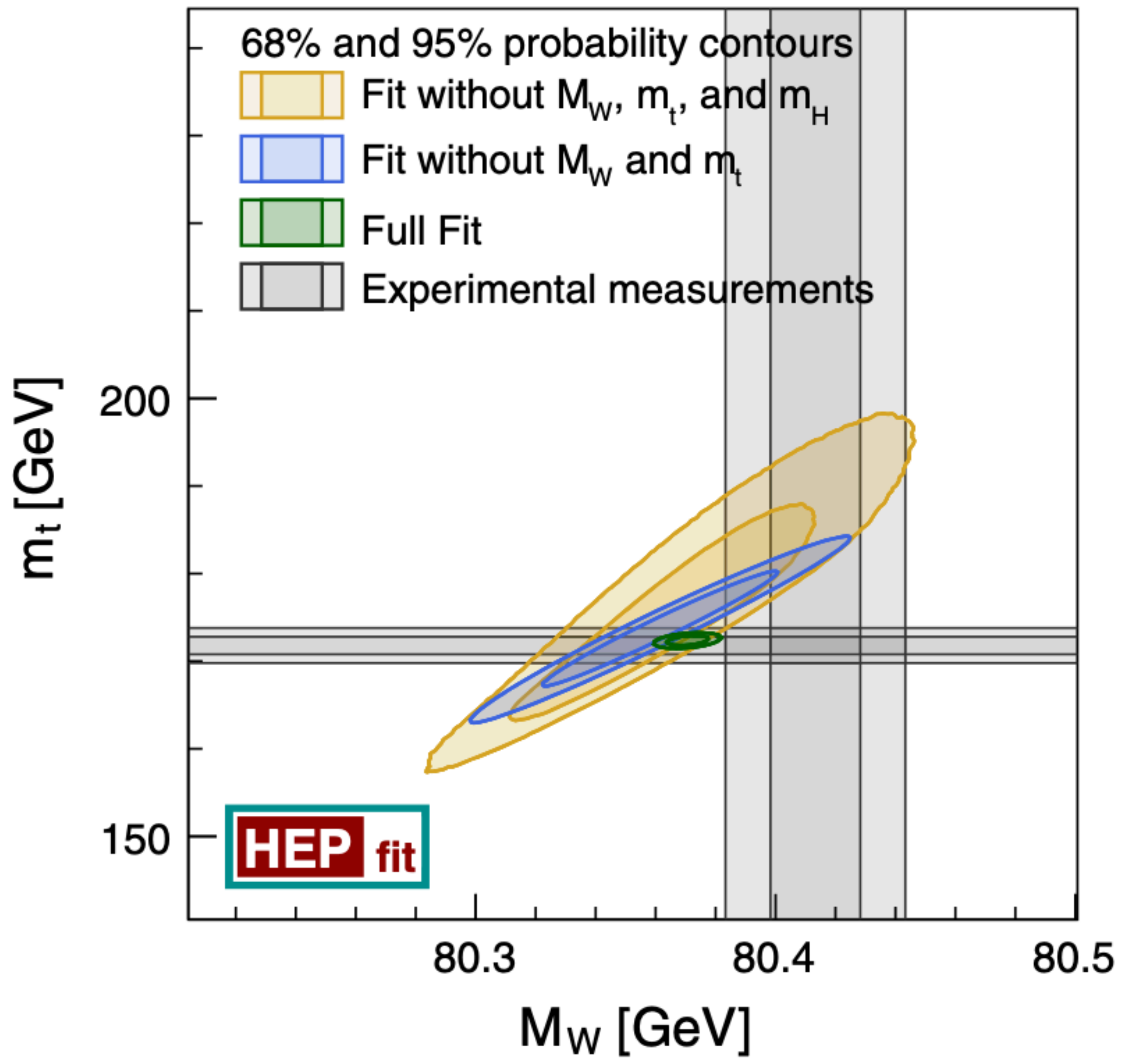
On behalf of ATLAS, CMS and LHCb collaborations

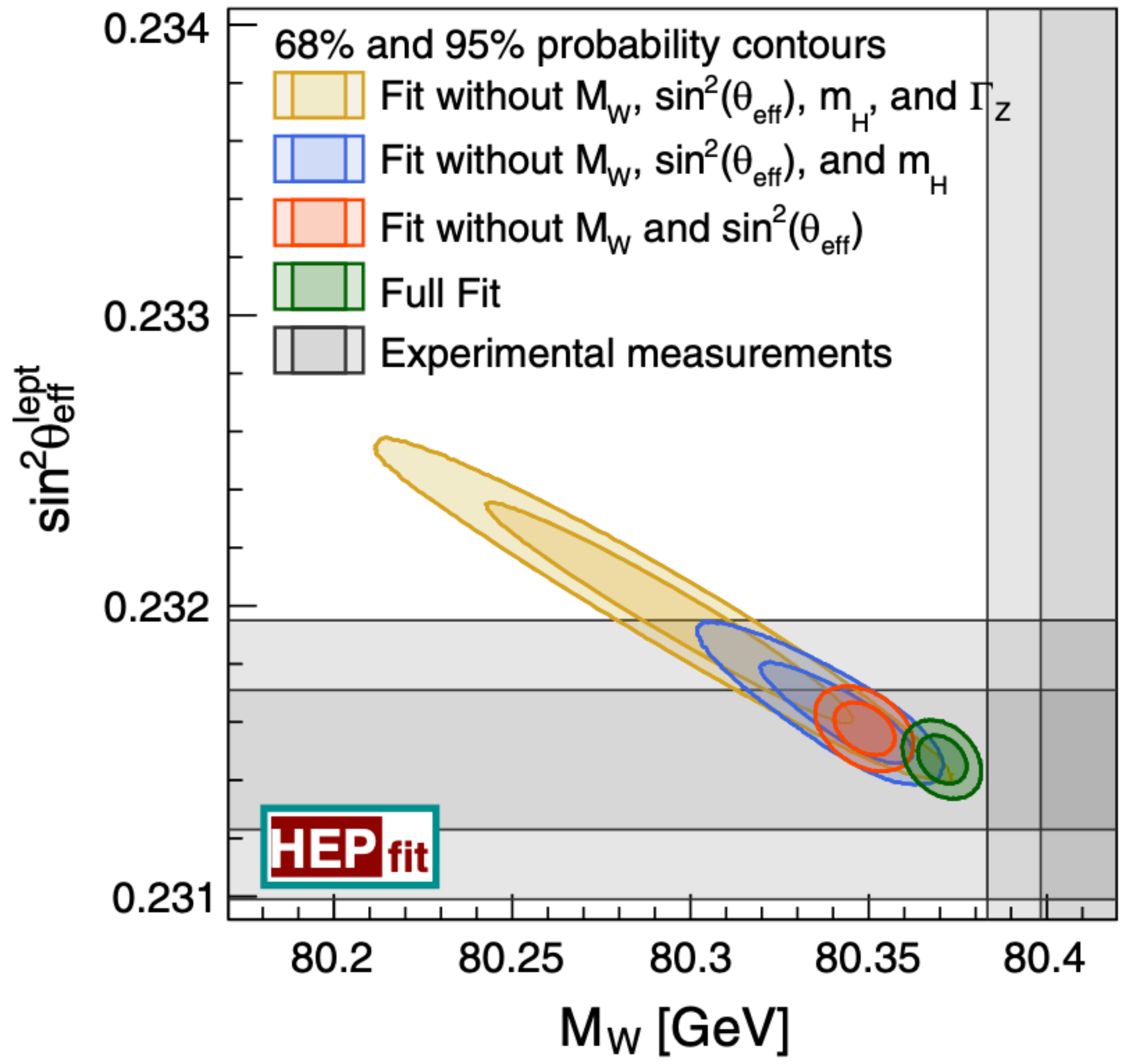
Rencontres de Moriond Electroweak 2025

Precision measurements in the Electroweak sector

Research program parallel to direct searches that could reveal precious signs of new physics

The Standard Model predicts relations among observables that we can check by providing precise measurements





Phys.Rev.Lett. 129 (2022) 27, 271801

W boson mass measurement results

Measurements from LHC experiments agree with prediction and among each other

Electroweak fit
Phys. Rev. D 110, 030001

LEP combination
Phys. Rep. 532 (2013) 119

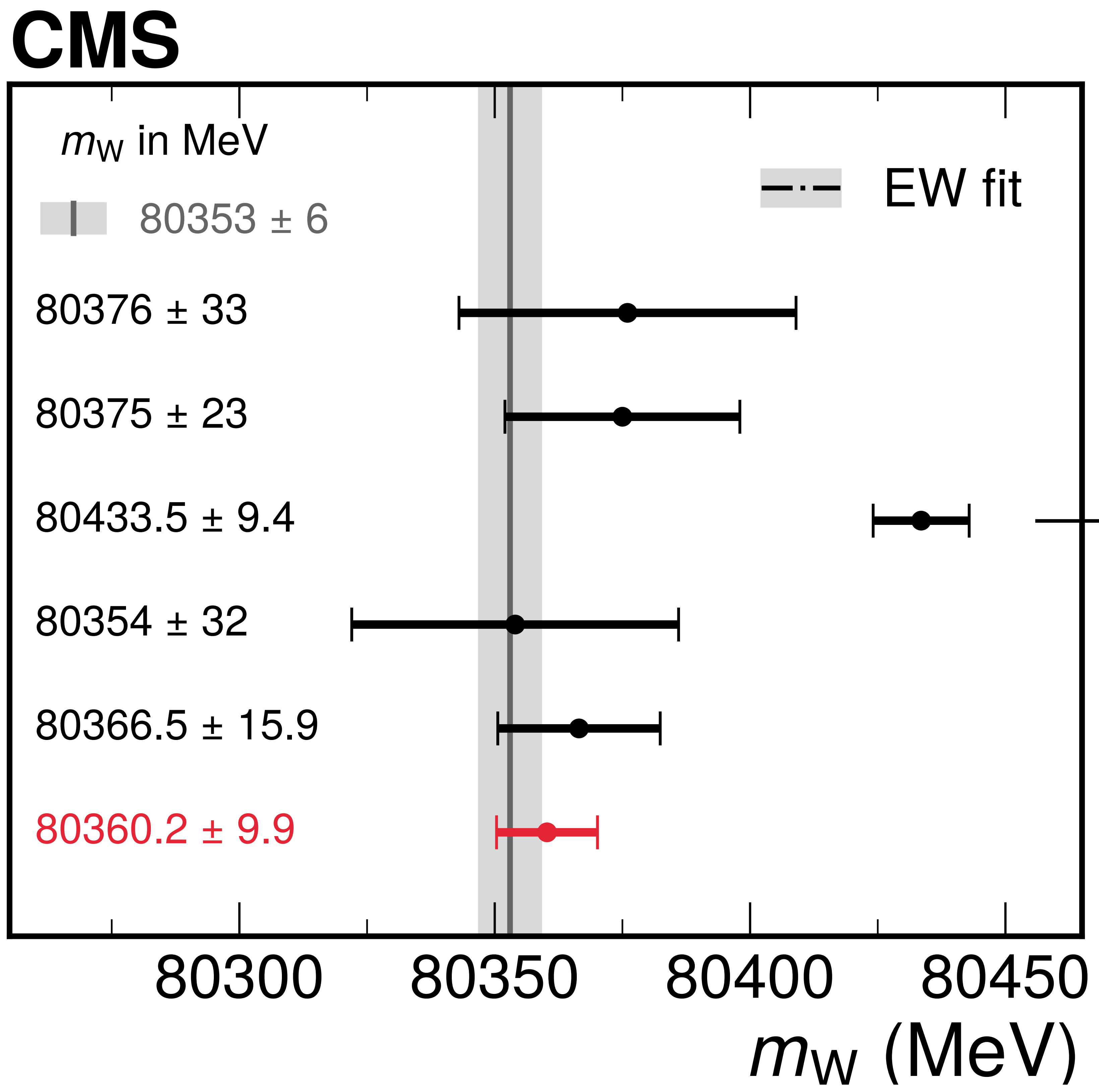
D0
PRL 108 (2012) 151804

CDF
Science 376 (2022) 6589

LHCb
JHEP 01 (2022) 036

ATLAS
Eur. Phys. J. C 84 (2024) 1309

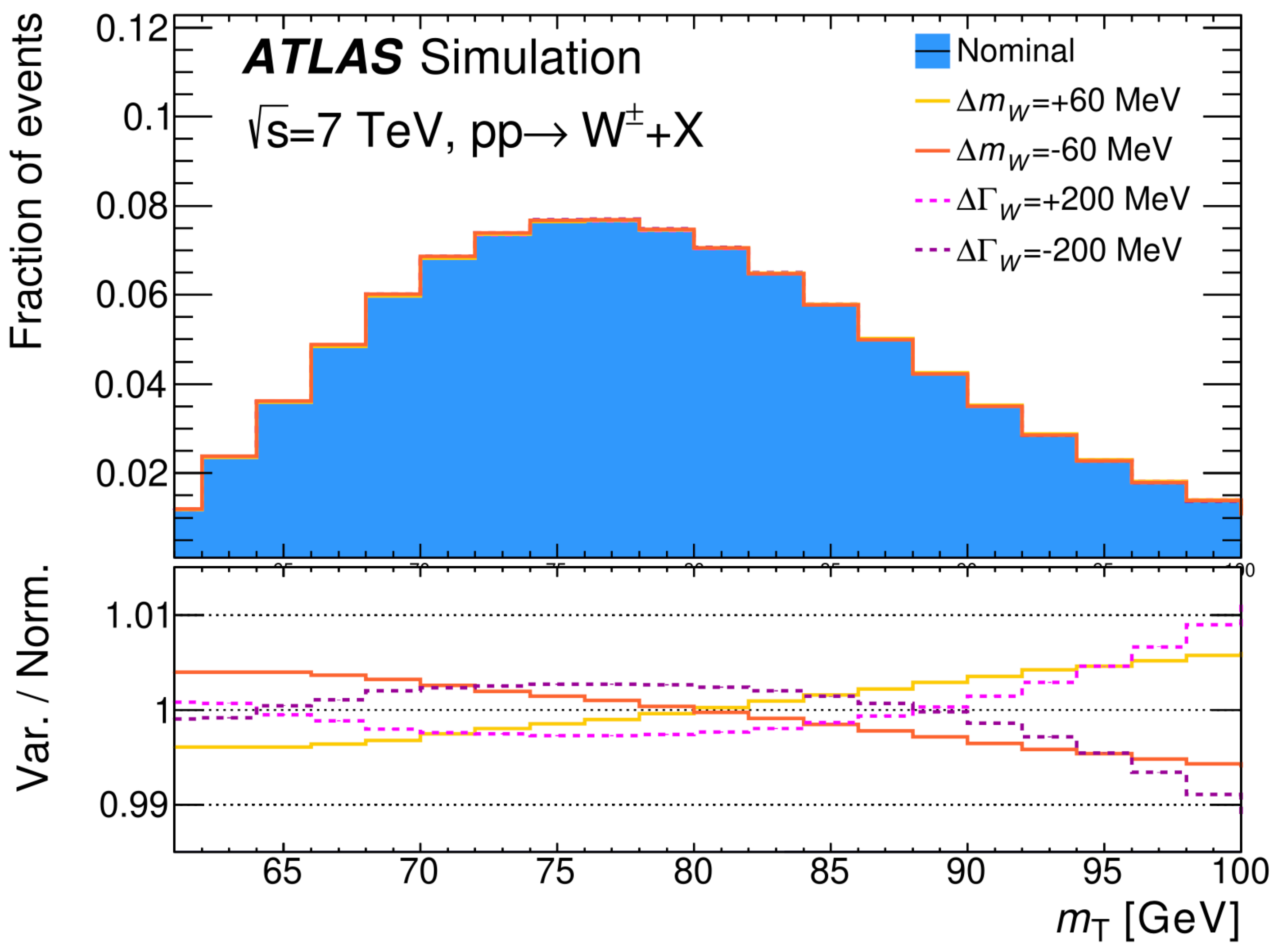
CMS
arXiv:2412.13872, subm. to Nature



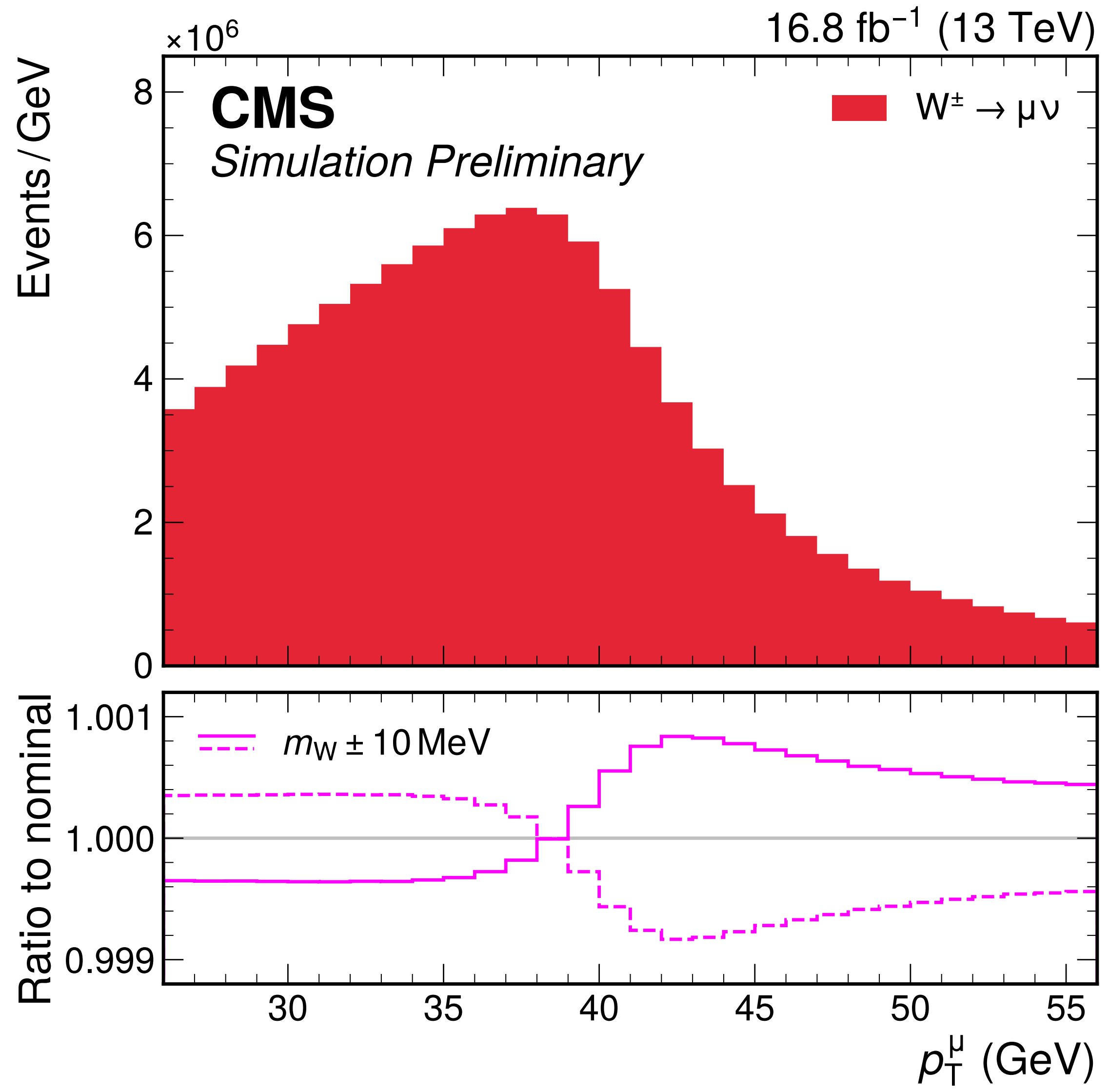
Measurement from CDF is the most precise so far but it stands as outlier wrt prediction and other measurements

How to measure m_W

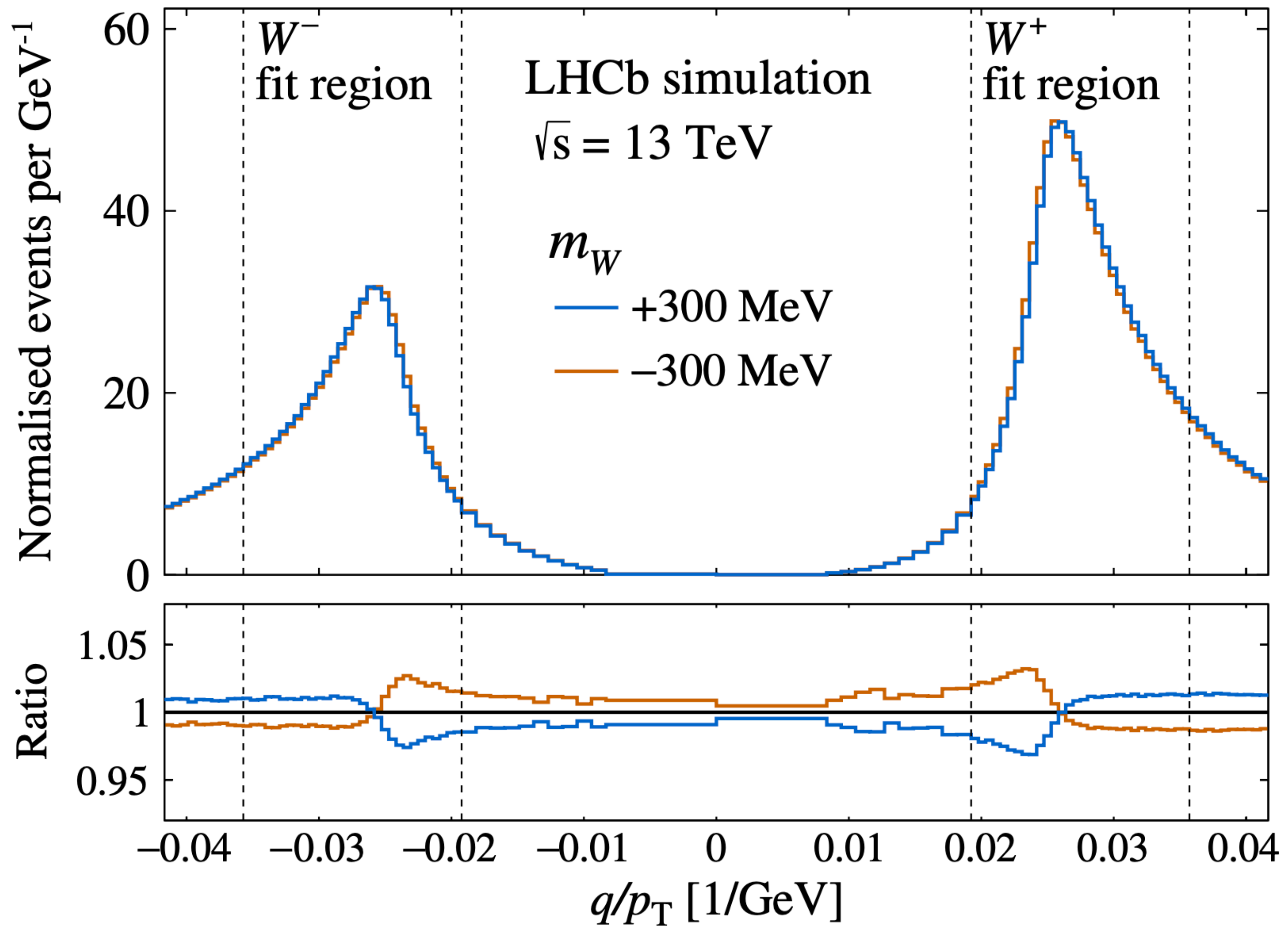
m_W is measured at hadron colliders from p_T^l or from a combination of p_T^l and MET — the transverse mass (m_T)



Eur. Phys. J. C (2024) 84 :1309



arXiv:2412.13872, subm. to Nature



JHEP01(2022)036

$\sqrt{s}$ = 7 TeV, 4.6 fb^{-1}
~8M $W^+_{\mu,e}$ and 5.7M $W^-_{\mu,e}$
from p_T^l and m_T split in bins of η^l and q^l

$\sqrt{s}$ = 13 TeV, 16.8 fb^{-1}
~117M $W^{+/-}_{\mu}$ from 3D η^μ-p_T^μ-q^μ

$\sqrt{s}$ = 13 TeV, 1.7 fb^{-1}
~2.4M $W^{+/-}_{\mu}$ from q/p_T^μ and Z ϕ^*

Challenges

One of the most complex measurements, requiring unprecedented control of the reconstructed objects

Today I will focus on two main common challenges and review the strategies that the various experiments adopted to tackle them

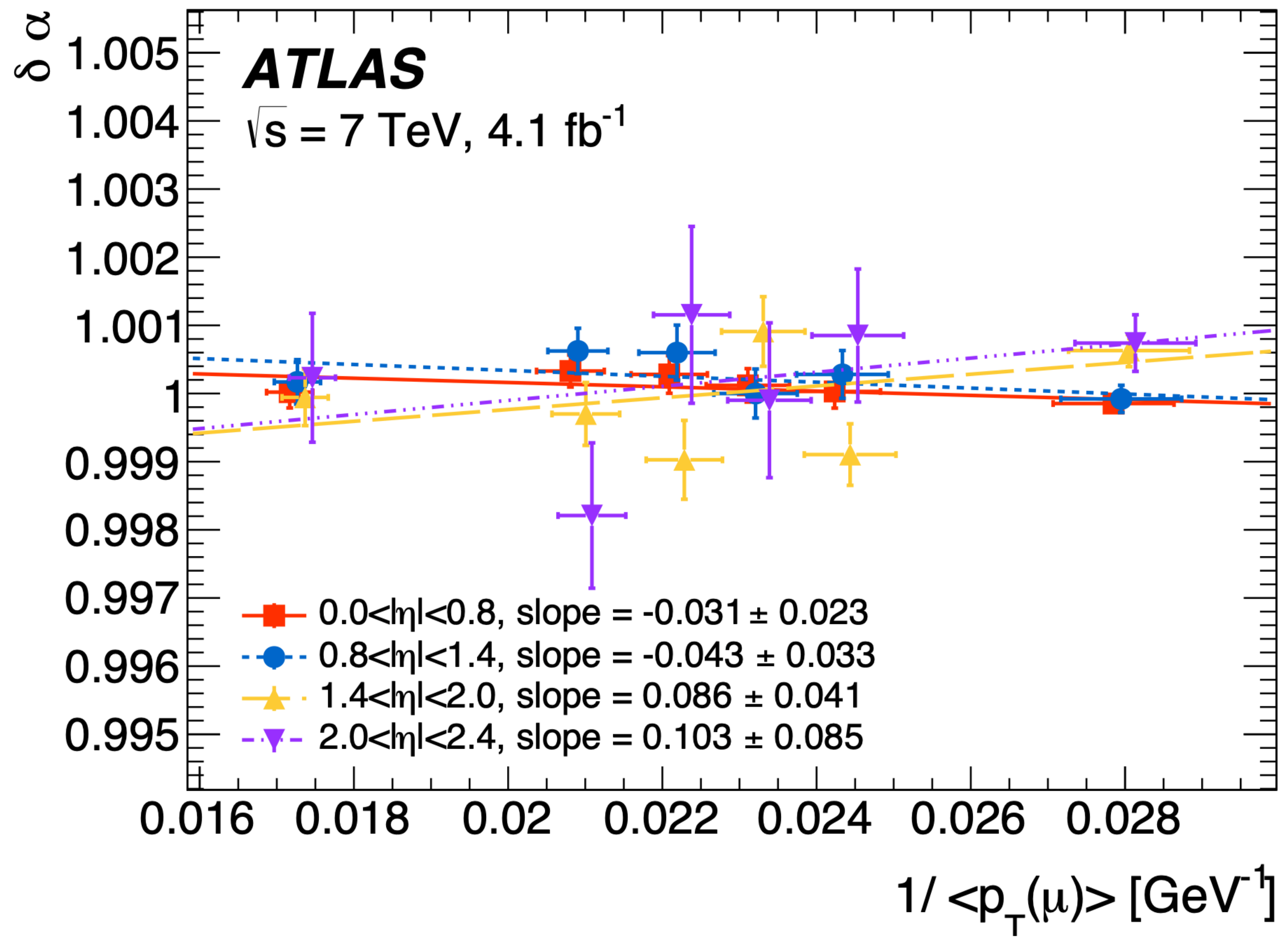
1. Measure the muon momentum scale with a precision of **0.01%**

2. Model the W production and its systematic uncertainties

Calibration of the muon momentum scale

ATLAS EXPERIMENT

Eur. Phys. J. C 78 (2018) 110



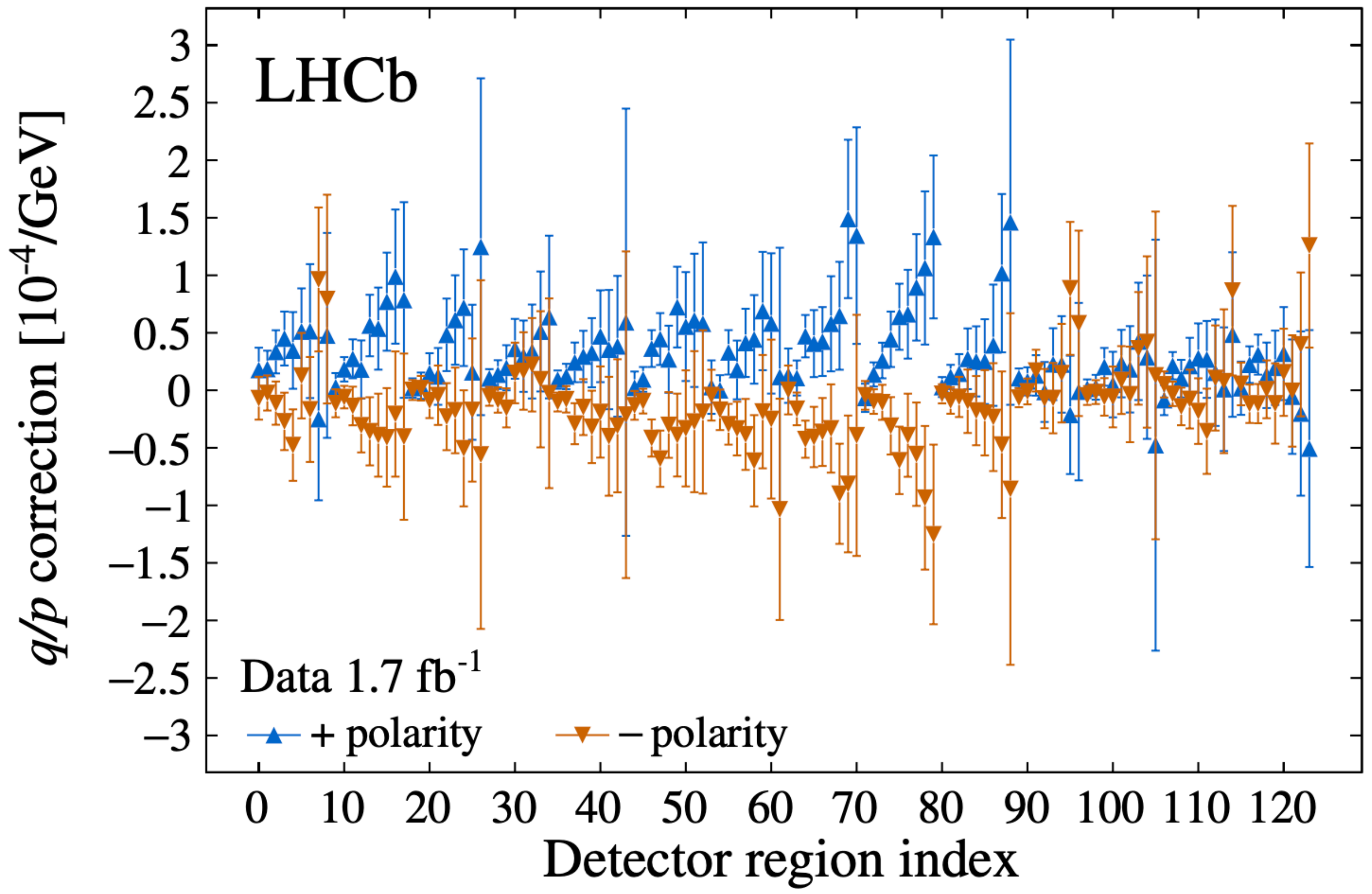
Calibrated using **Z dimuon events** and then extrapolated to W

Residual corrections δα vs $1/\langle p_T^{\mu}\rangle$ are compatible with 1 within two standard deviations. (Sagitta bias subdominant)

9.8 MeV of 15.9 MeV

LHCb

JHEP01(2022)036



Calibrated using **Z dimuon events** using the **"pseudomass"** variable, independent of momentum

Pseudomass is fitted in bins of η^{μ} and ϕ and correction extracted

7 MeV of 32 MeV

Calibration of the muon momentum scale

Model that parametrizes the corrections as a function of $k = 1/p_T$

material

$$\frac{k_{true}}{k} = A - \epsilon k + \frac{qM}{k}$$

B field

misalignment

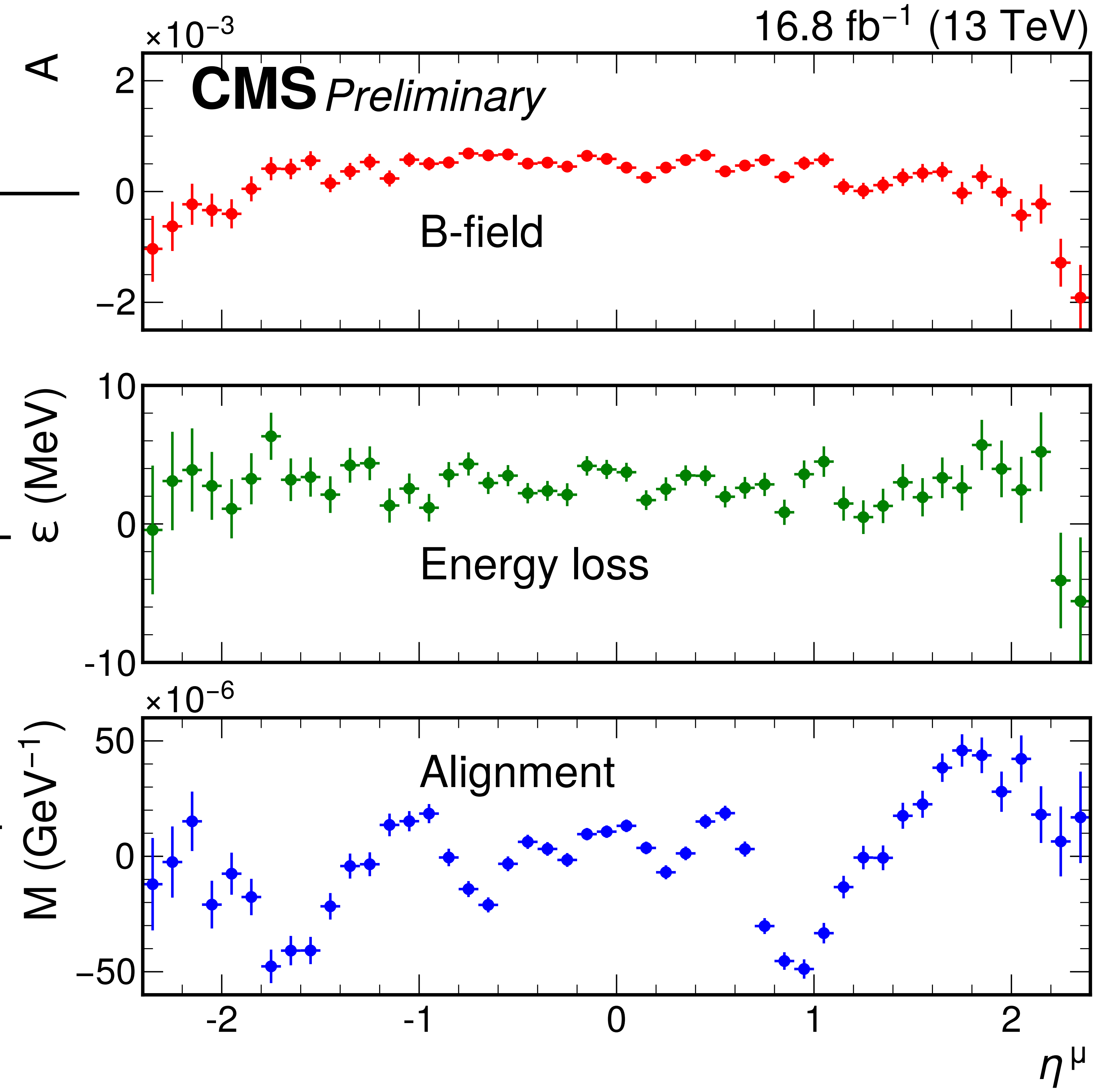
Extract corrections from thousands of fits of the **J/ψ mass** in all corners of the detector and **test the calibration on Υ(1S) and Z** before extrapolation to W events

Propagate **charge dependent and charge independent set of uncertainties**

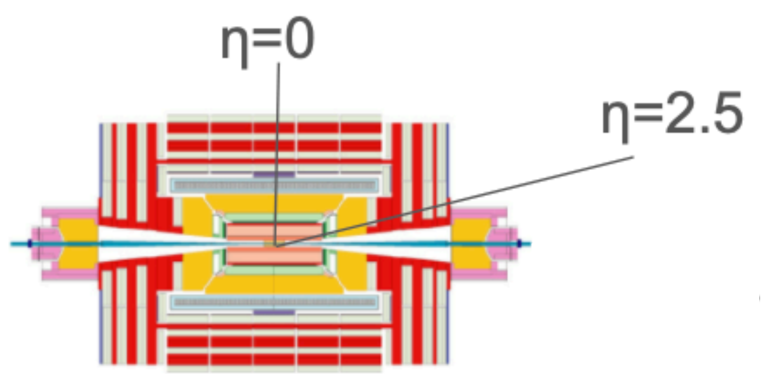
Magnetic field correction of ~40 gauss at the edge of the solenoid

Material correction equivalent to ~3.5 mm of iron

Silicon strip modules displacement of ~1-7 μm



4.4 MeV of 9.9 MeV



W production and decay

This formula describes how W rapidity and q_T are connected to charged lepton variables in W rest frame

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

W differential cross section in q_T and y

Decay angles of muons in W rest frame

Unpolarized cross section
Encodes W transverse momentum and rapidity

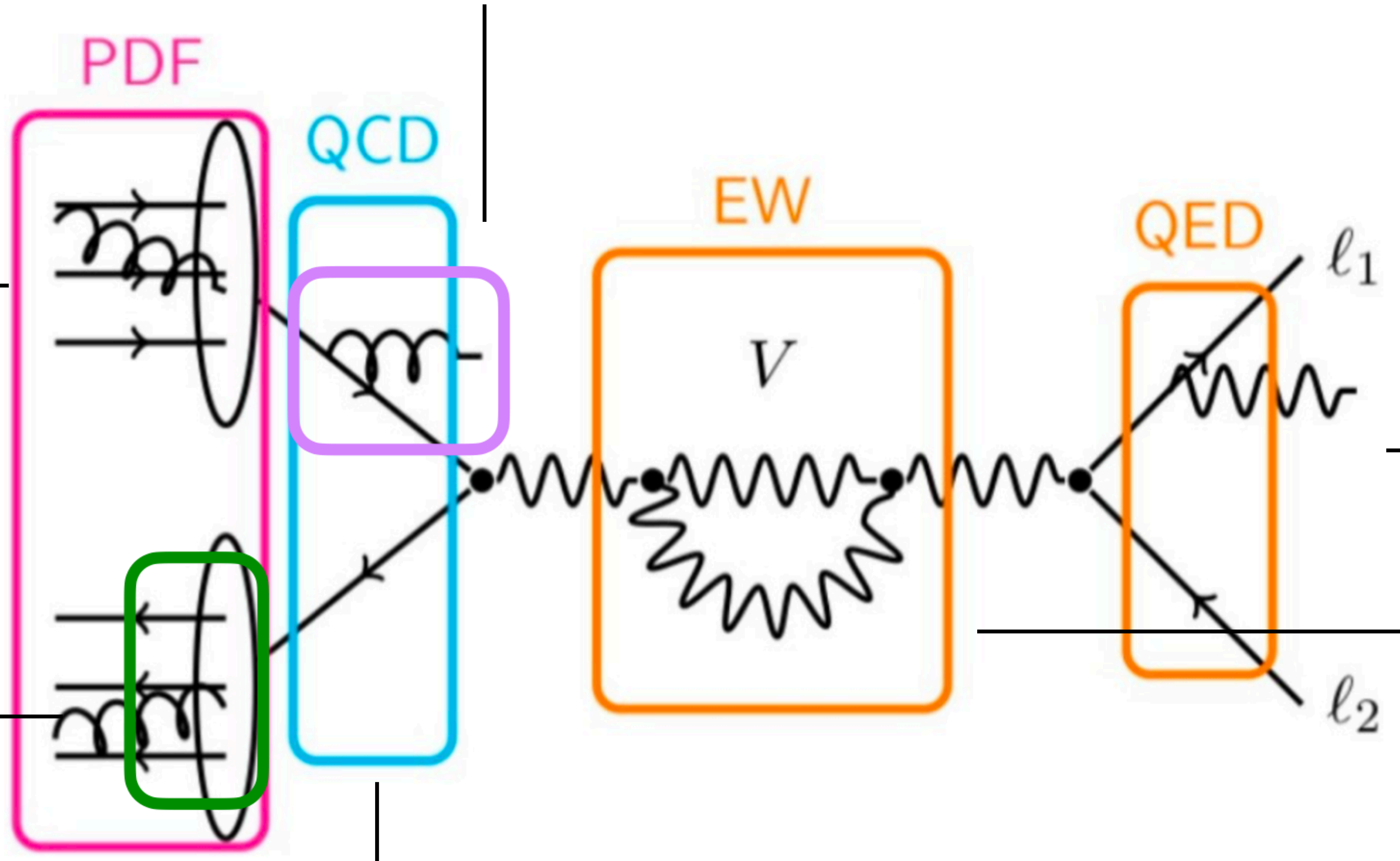
Angular coefficients
encode W polarization

Spherical harmonics
encode W decay

Modeling the W production

Resum soft gluons for low/
intermediate region

PDF determines quark
flavour and momentum



Electroweak corrections
small, but relevant impact

Non-perturbative motion of
quarks important at low q_T

perturbative QCD
describes high q_T

Uncertainty due to the Parton Distribution Functions

ATLAS and CMS: **profile likelihood fit.** Results shown in terms of **nominal and “scaled" uncertainties**

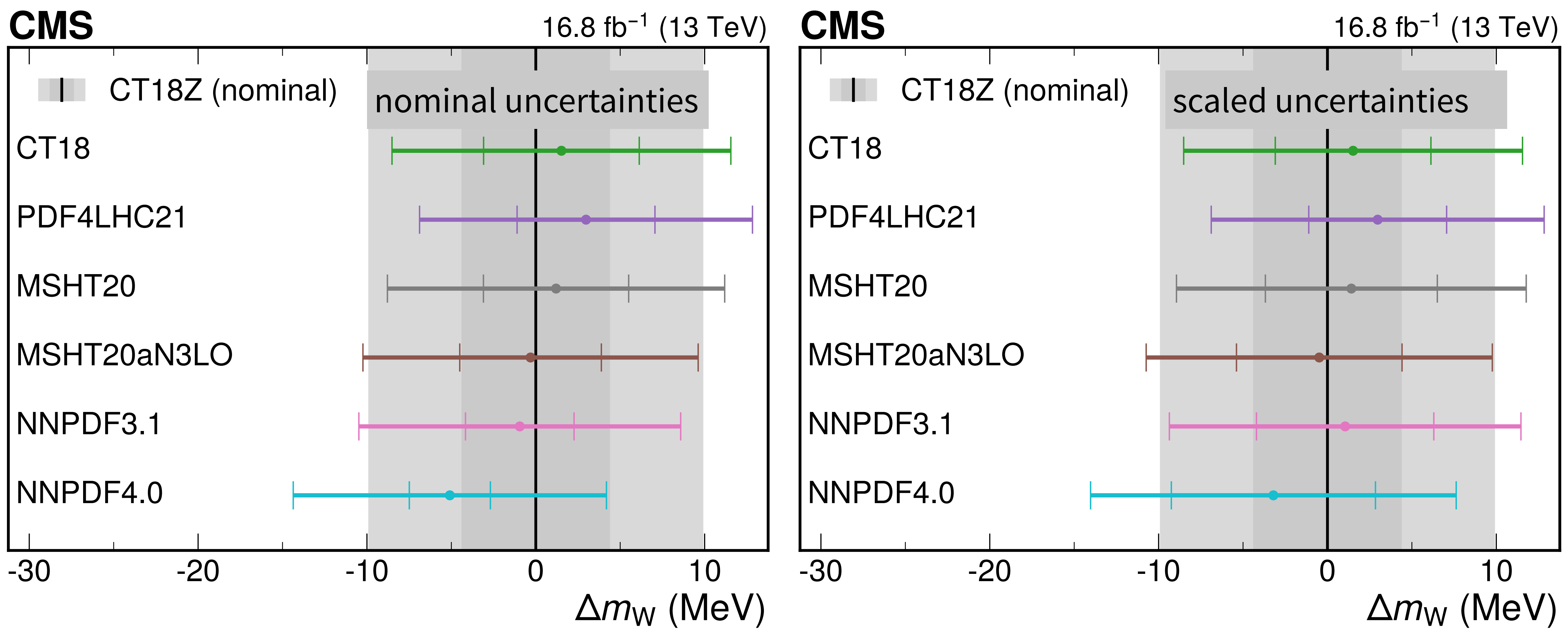
LHCb: **average** wrt three different sets of Parton Distribution Functions

Set	$\sigma_{\mathrm{PDF,base}}$ [MeV]	$\sigma_{\mathrm{PDF},\alpha_s}$ [MeV]	σ_{PDF} [MeV]
NNPDF3.1	8.3	2.4	8.6
CT18	11.5	1.4	11.6
MSHT20	6.5	2.1	6.8

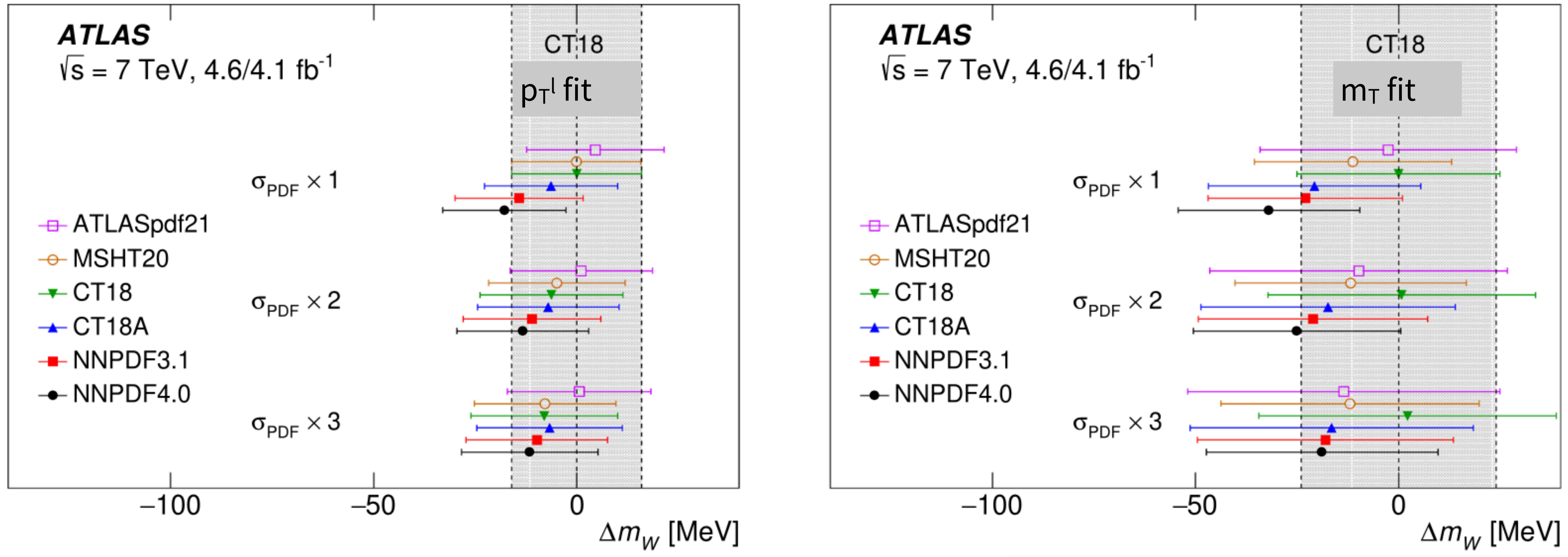
JHEP01(2022)036

9 MeV of 32 MeV

2.8 MeV of 9.9 MeV



5.7 MeV of 15.9 MeV



Eur. Phys. J. C (2024) 84 :1309

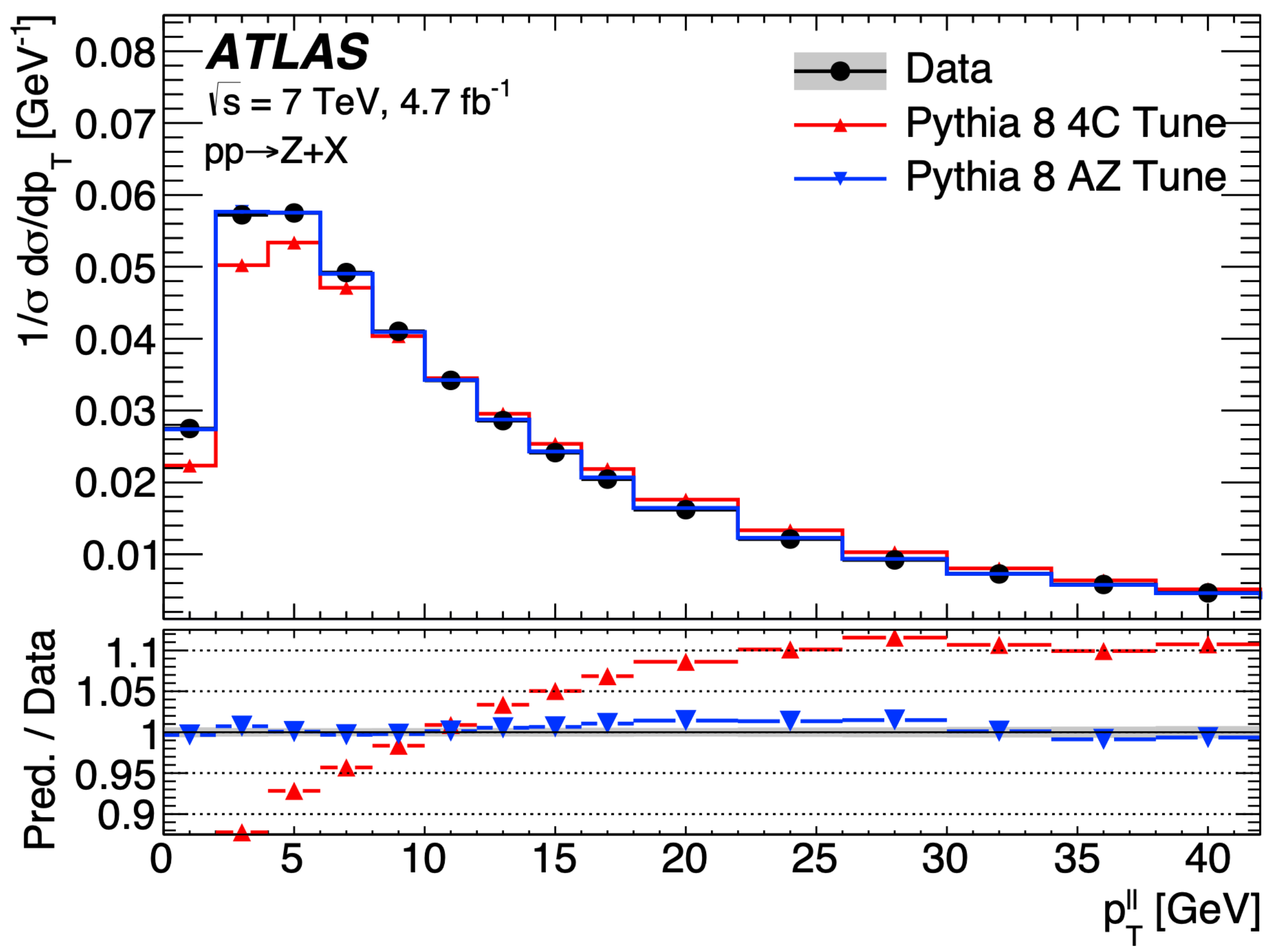
Modeling the W transverse momentum

ATLAS EXPERIMENT ~2-4MeV of 15.9 MeV

LHCb 11 MeV of 32 MeV

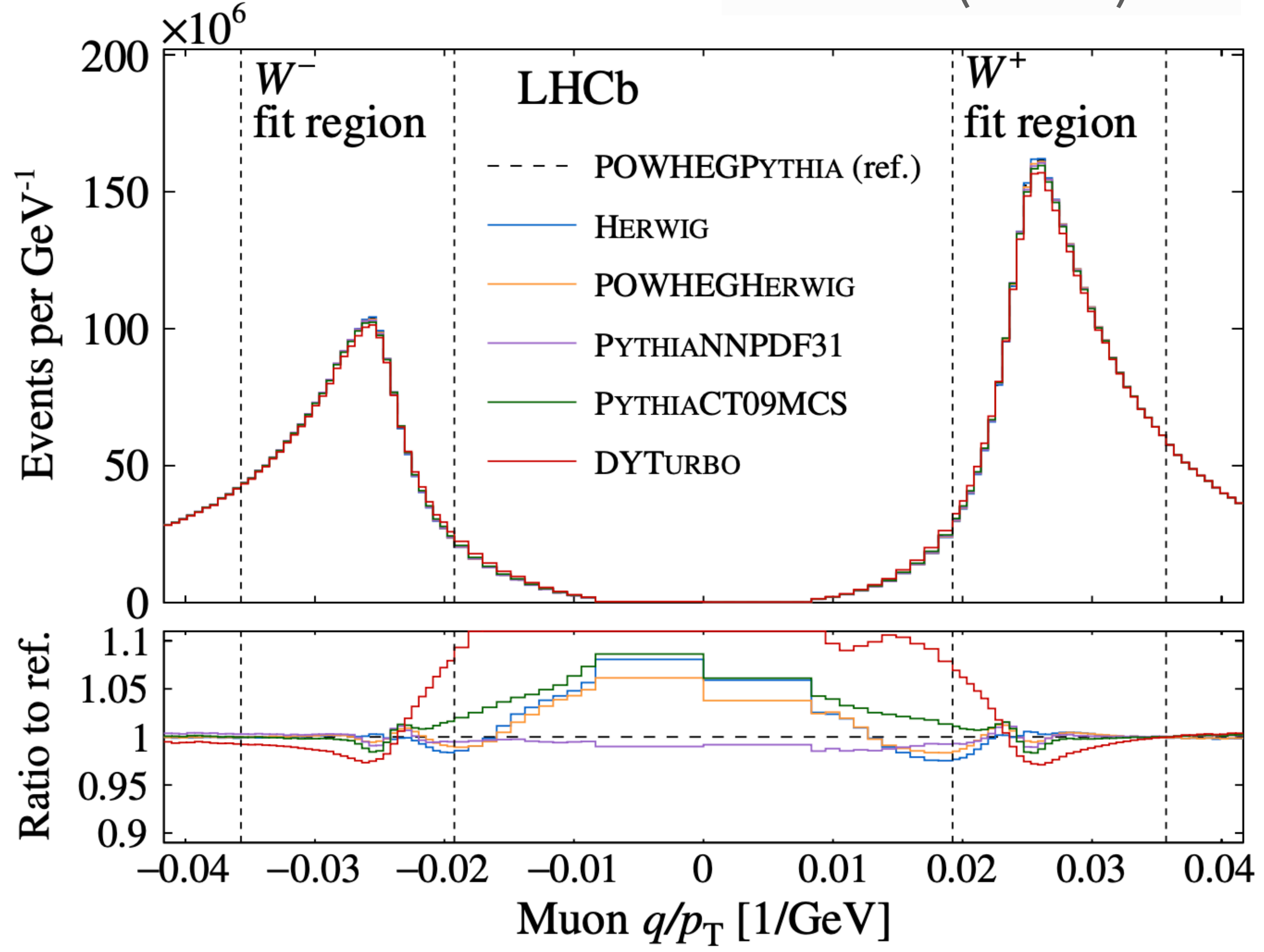
CMS 0.8 MeV of 9.9 MeV

Eur. Phys. J. C 78 (2018) 110



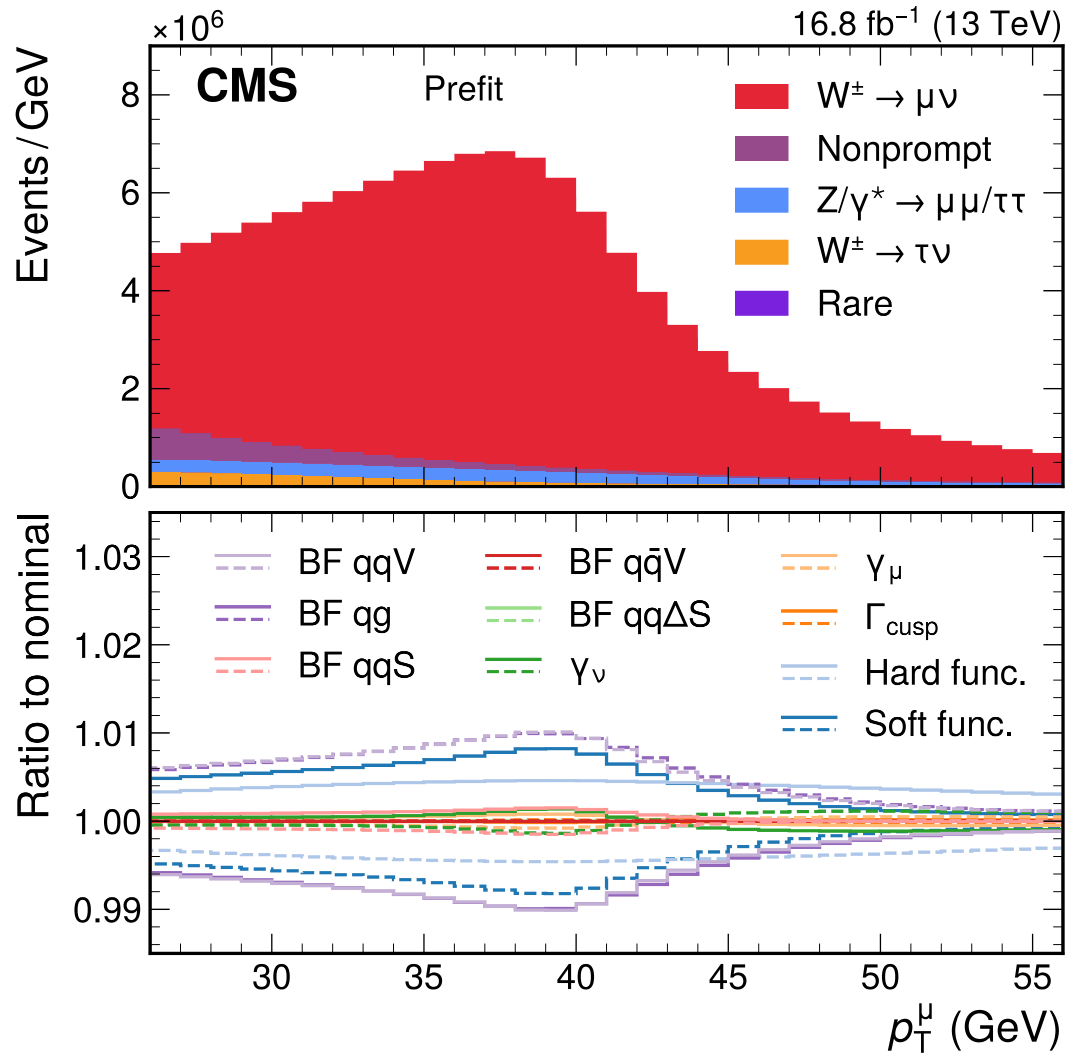
Pythia8 AZ Tune on Z dimuon p_T propagated to W events + extra profiled systematic variations

JHEP01(2022)036



POWHEGPYTHIA Tune on Z dimuon p_T propagated to W events + envelope of other 5 models.

Simultaneous fit with ϕ^* to constrain intrinsic k_T and α_S



Theoretical model with in-situ constraints aka "Theory Nuisance Parameters"†

Use constraining power of the data to adjust the value of the parameters of the model while fitting for the W mass

†arXiv:2411.18606.

Modeling the W polarization

ATLAS, CMS and LHCb model the angular coefficients using fixed order calculations at NNLO

ATLAS EXPERIMENT — 3.7MeV of 15.9 MeV

LHCb — 10 MeV of 32 MeV

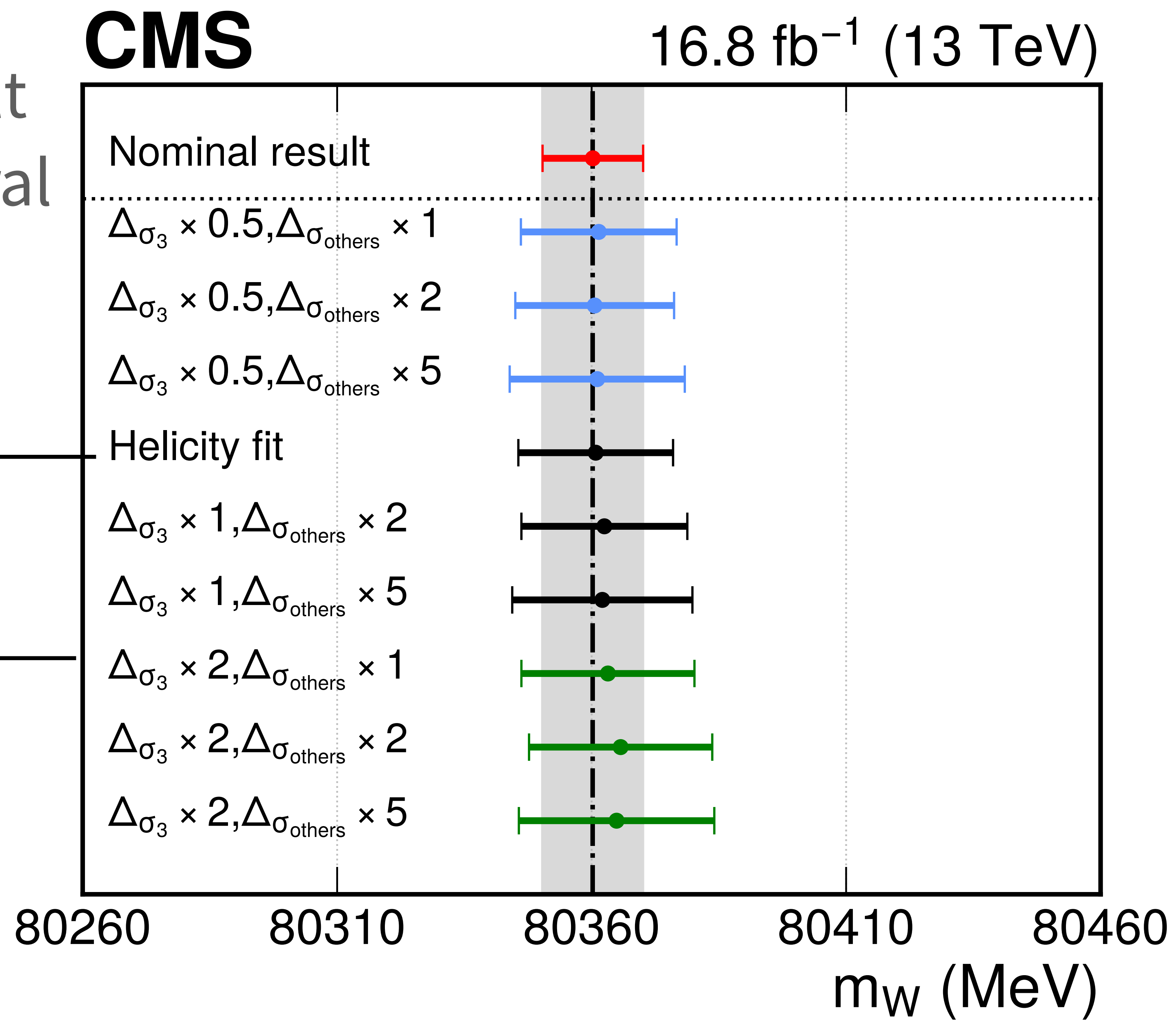
CMS — 3 MeV of 9.9 MeV

Complementary innovative approach by CMS: the **Helicity fit**
The unpolarized cross section and angular coefficients are extracted directly from the data, bounded to the prediction with large prefit uncertainties

Increased uncertainty with respect to main result but fully compatible central value: 80360.8 ± 15.2 MeV

Result studied as a function of the magnitude of the prefit uncertainty

Correlation between m_W and A_3 observed and studied (also by LHCb)



Measurement of Γ_W by ATLAS

Measurement of Γ_W with m_W constrained: most precise from single experiment

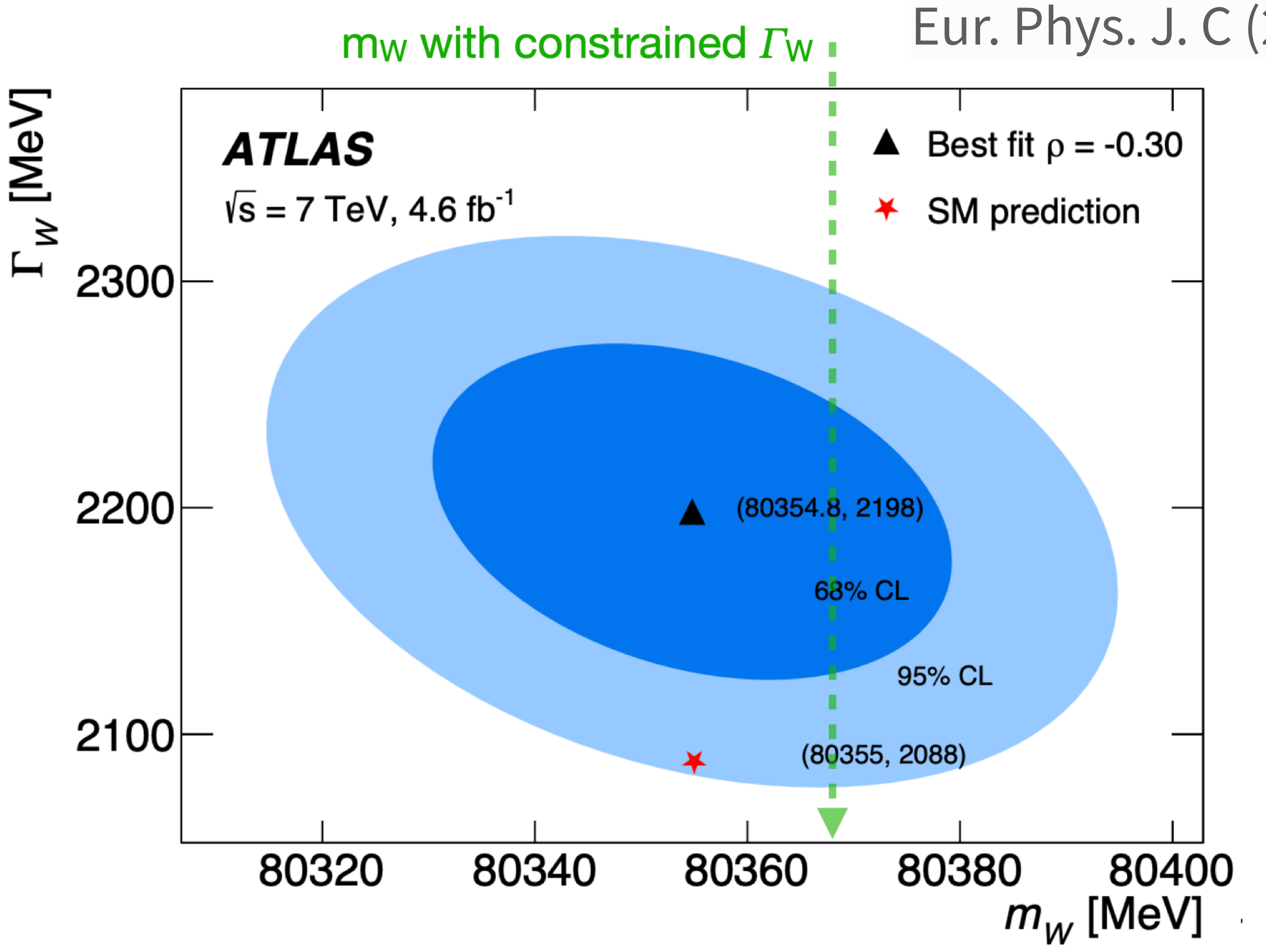
$$\Gamma_W = 2202 \pm 32(\text{stat}) \pm 34(\text{syst})\ \text{MeV} = 2202 \pm 47\text{MeV}$$

m_T is the most dominant channel (opposite of m_W)

Dominated by modeling (shower tune variations) and recoil uncertainty

Simultaneous measurement of Γ_W and m_W

Eur. Phys. J. C (2024) 84 :1309



Central value of m_W shifts by about 12 MeV wrt nominal but uncertainty increases by about 1%

Width uncertainty increases by about 4% in simultaneous measurement with very small shift in central value

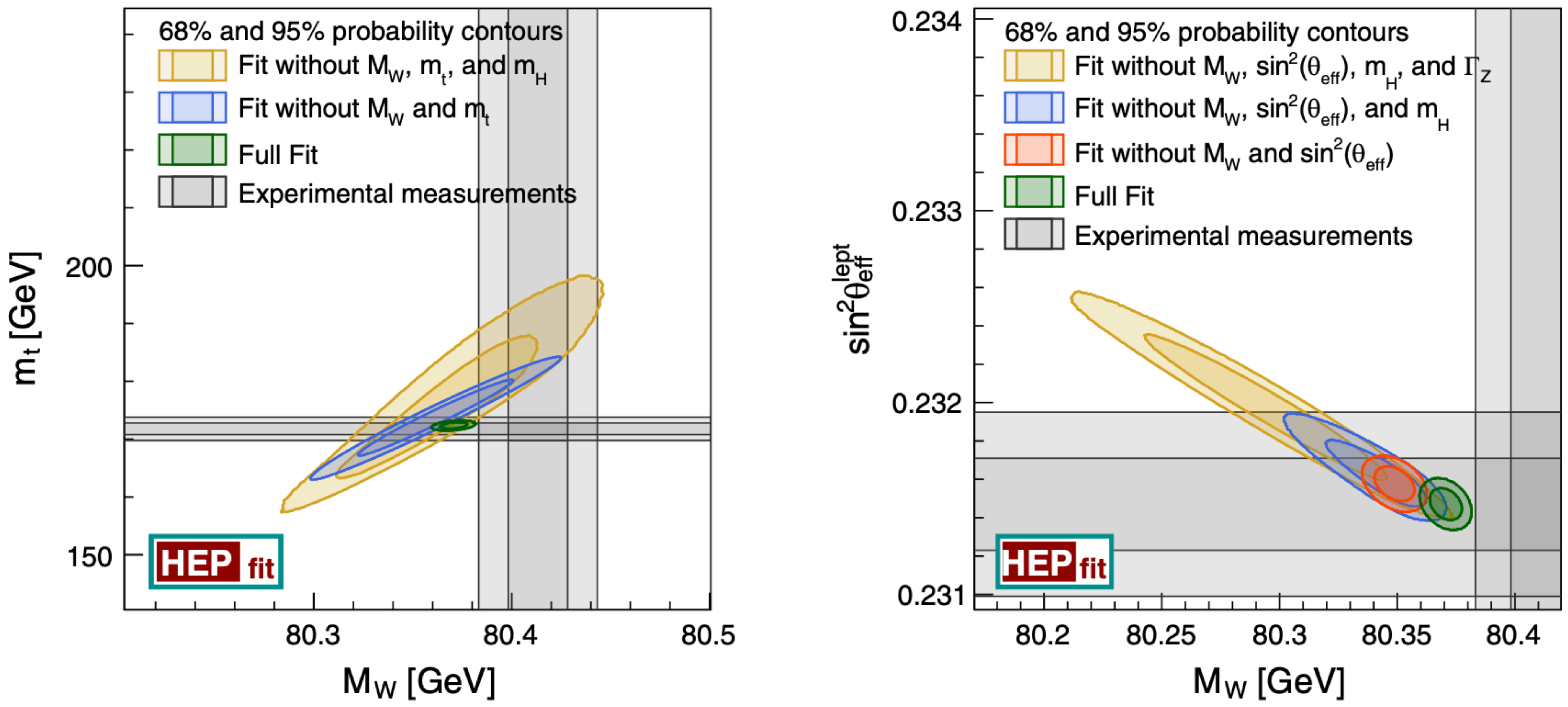
Conclusions

The measurement of m_W is one of the most challenging of our field

Today, I have reviewed the three measurements provided by ATLAS, CMS and LHCb, highlighting the main challenges and the adopted strategies to tackle them

This is just the start!

New tools, ideas, and unprecedented collected events will open the path to a new precision program at LHC



← To be updated with new results!

Phys.Rev.Lett. 129 (2022) 27, 271801

Extra material

Impacts on W mass measurement

CMS

Source of uncertainty	Impact (MeV) Nominal in m_Z	in m_W	Global in m_Z	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-muon 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

ATLAS EXPERIMENT

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

Eur. Phys. J. C (2024) 84 :1309

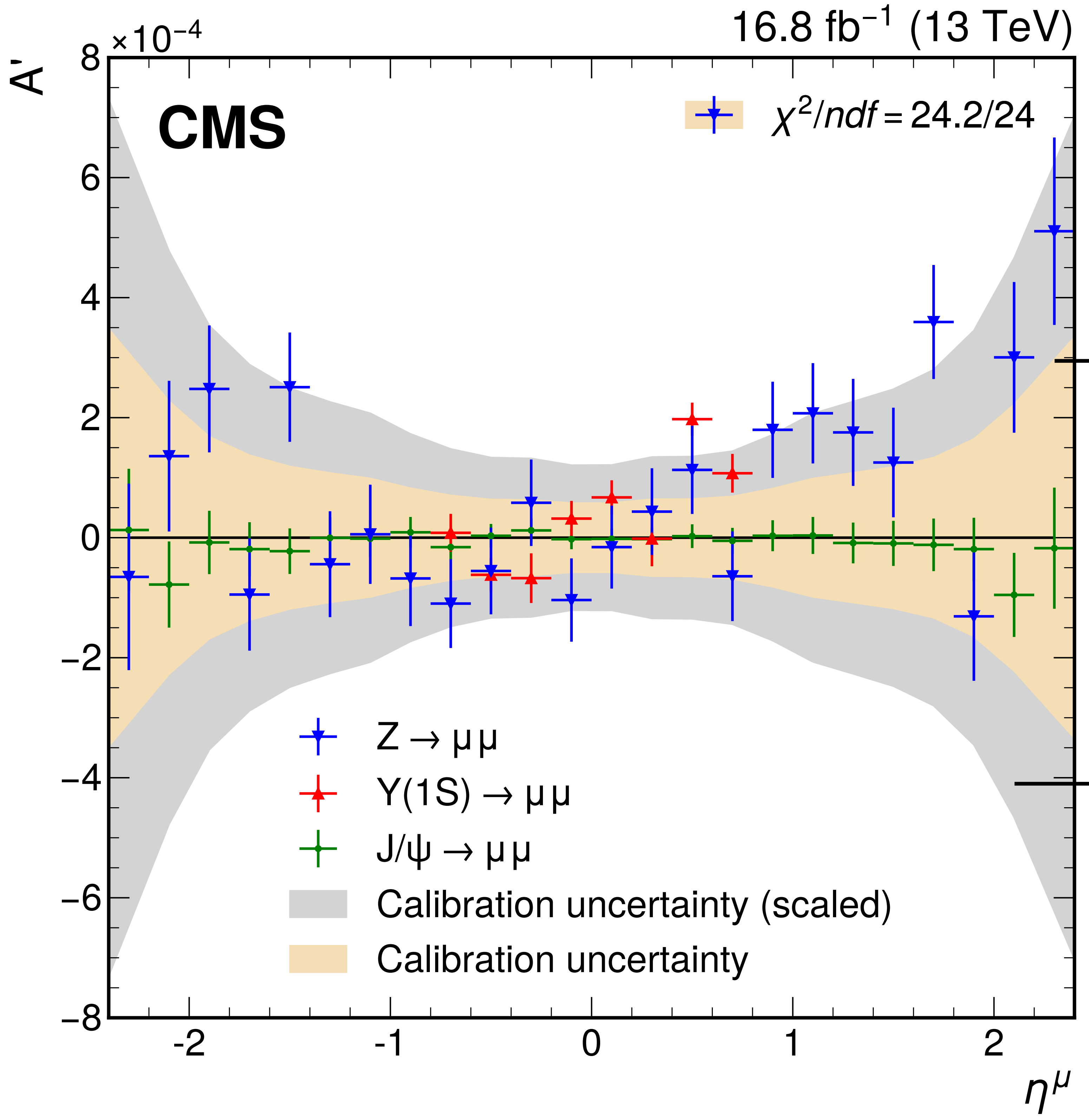
LHCb

Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

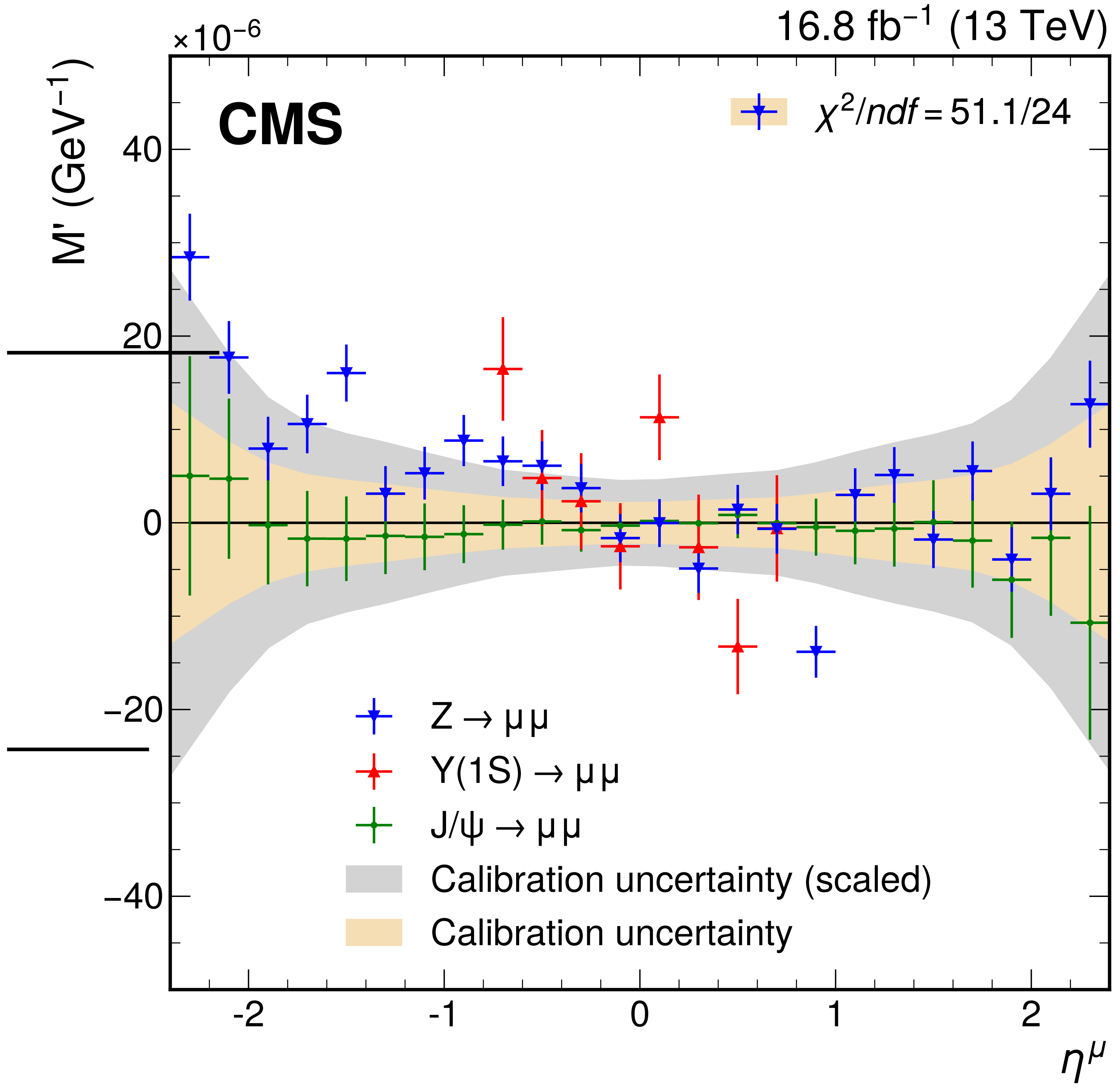
JHEP01(2022)036

Systematic uncertainty on muon momentum scale

Charge independent “B-field like”



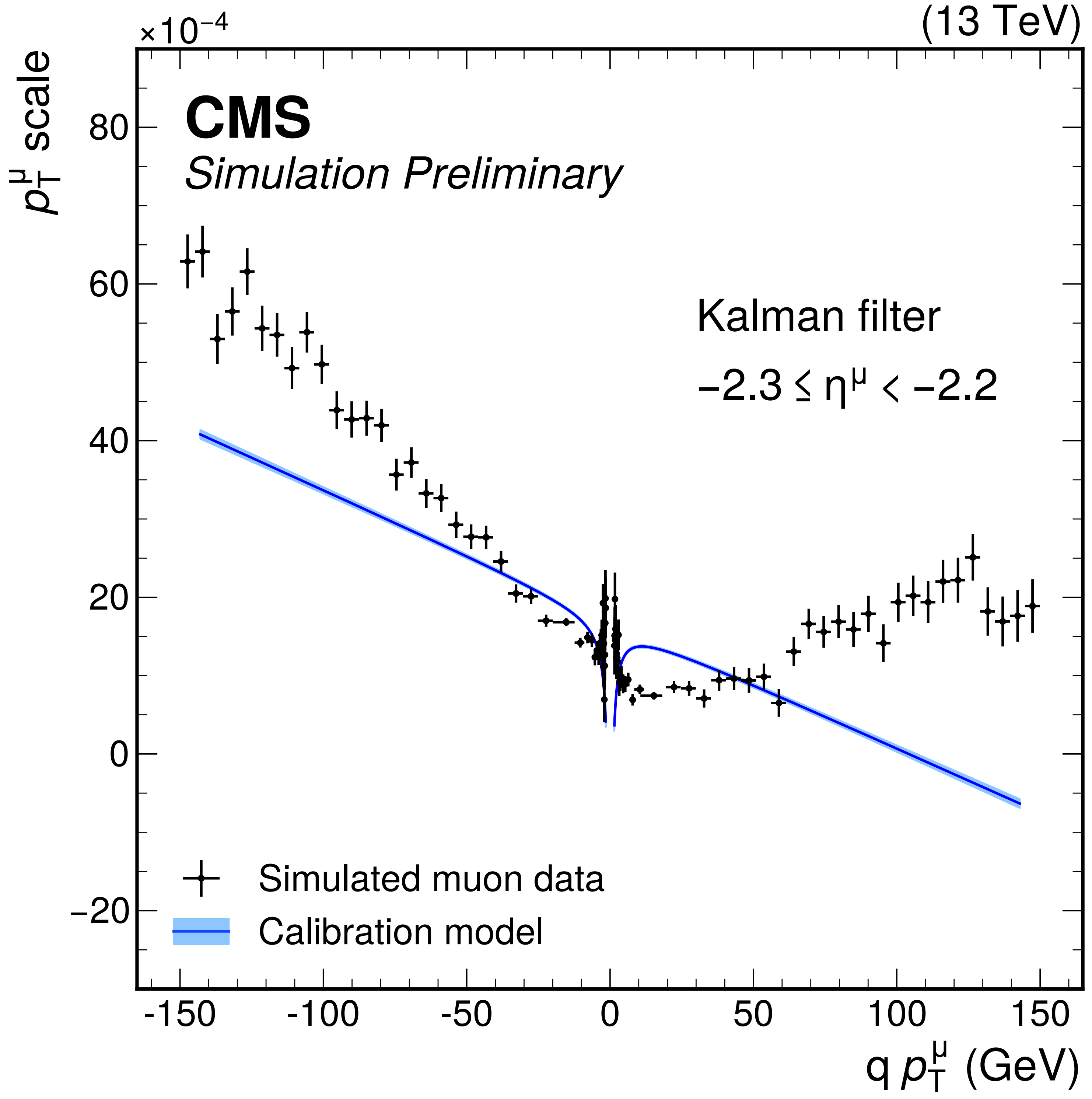
Charge dependent “alignment like”



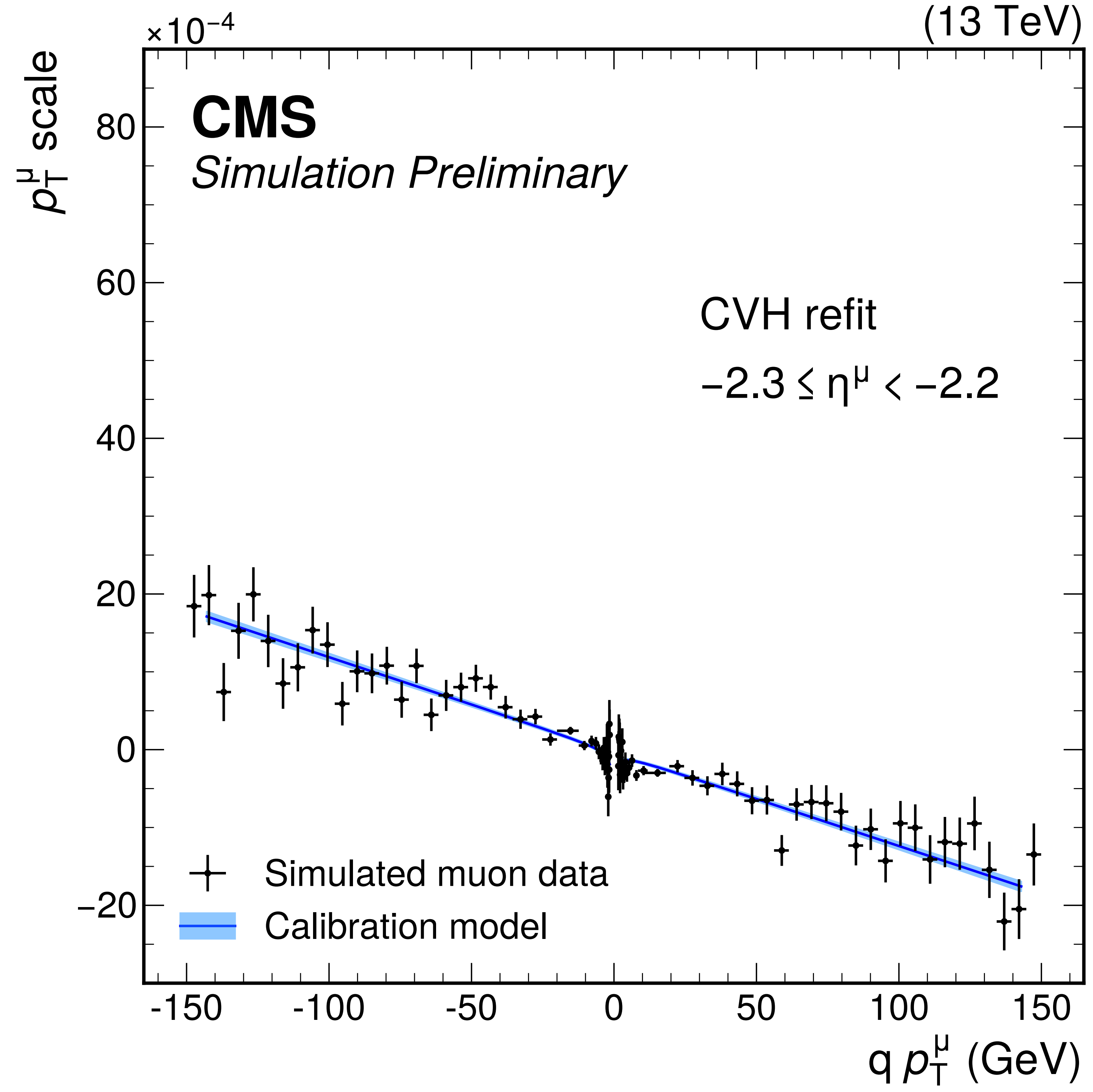
B-field-like term for Z is consistent with zero within statistical uncertainties, alignment-like almost so

Statistical uncertainty from on calibration parameters from J/ψ scaled by 2.1 to account for any not-explicitly-accounted-for systematic effects

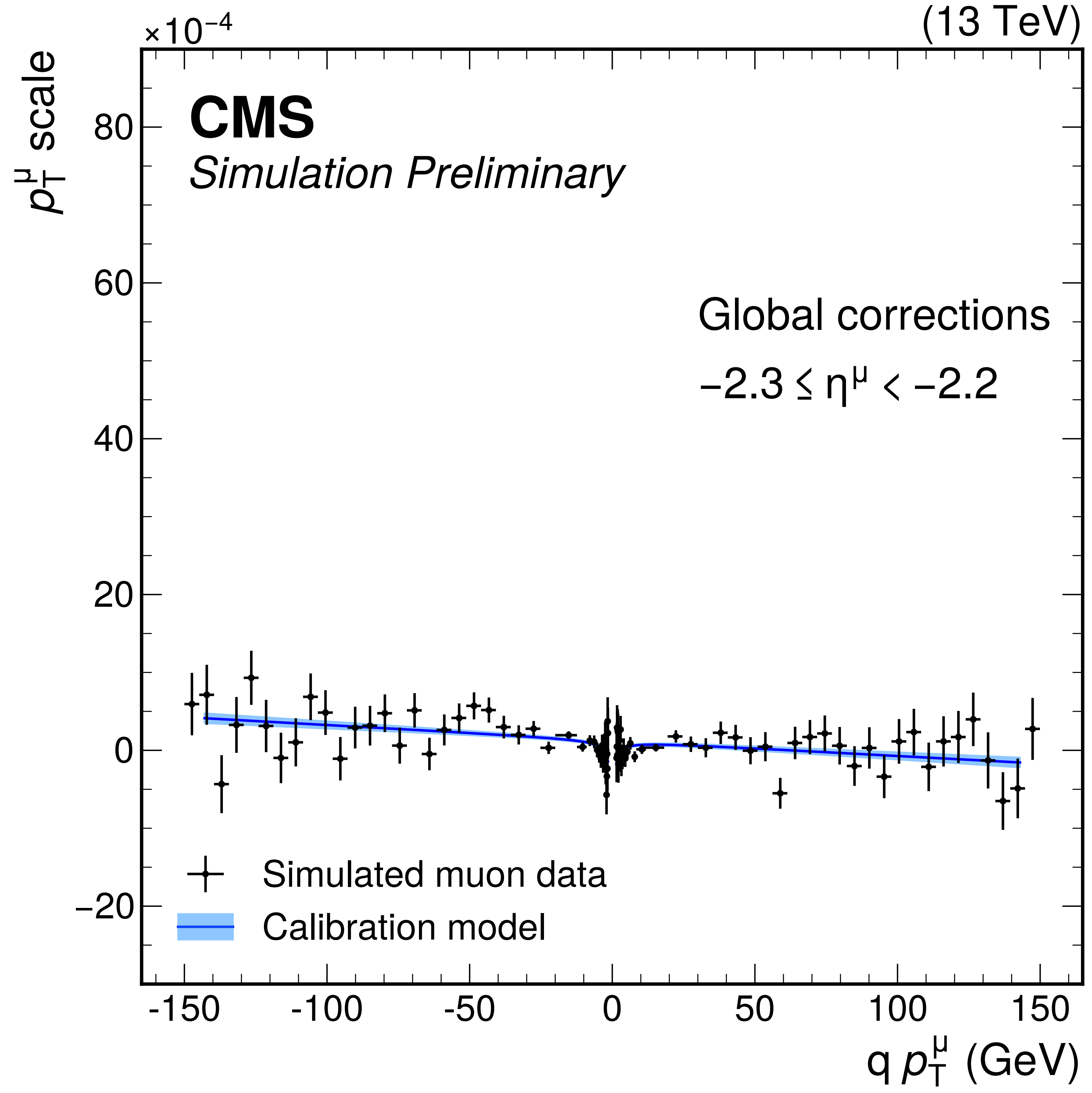
Calibration model tested on simulation



Out of the box CMS reconstruction not compatible with the model



Add a new layer of track reconstruction on top of CMS reconstruction with refined treatment of magnetic field and material

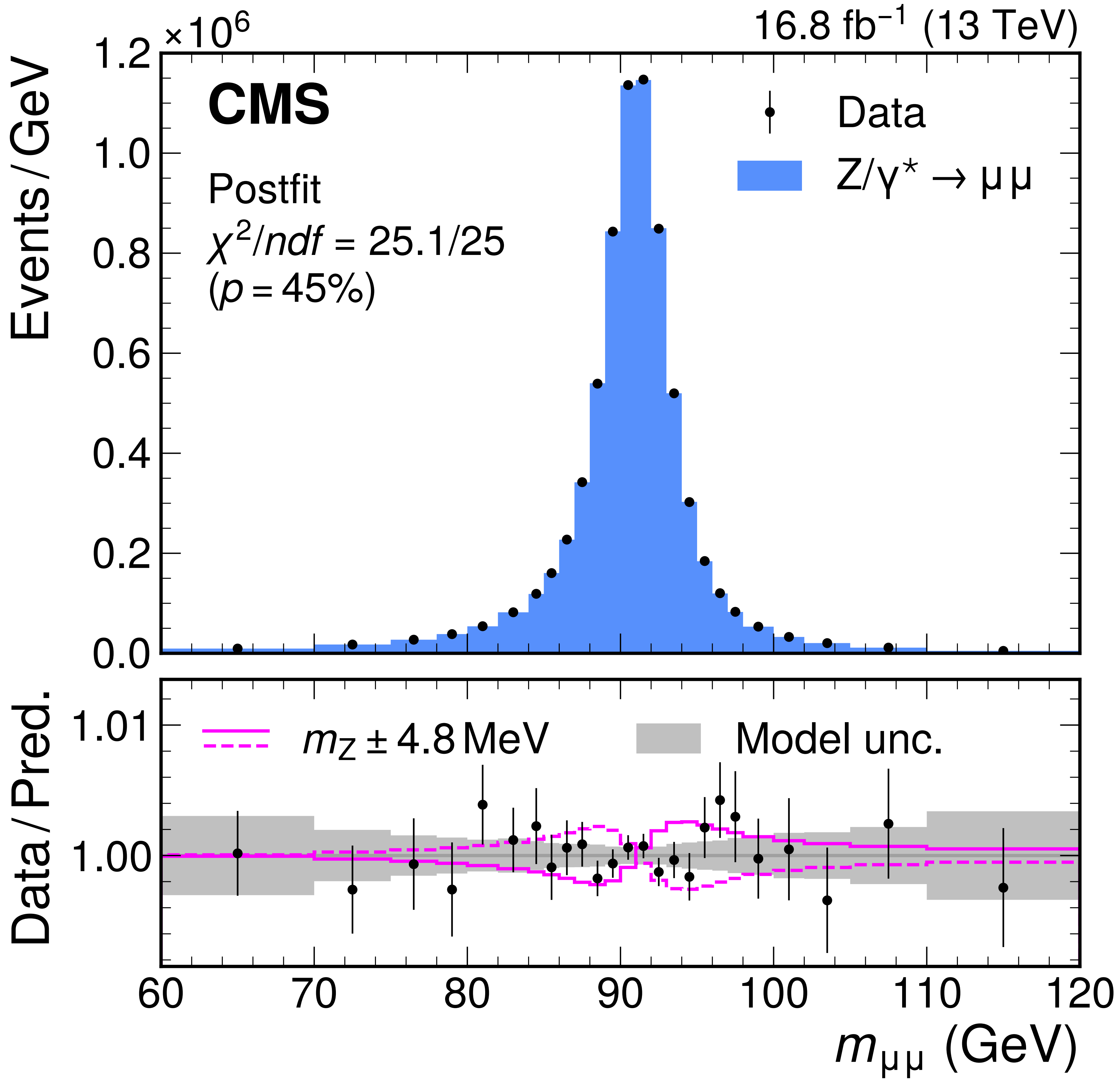


Correct for local biases in the reconstruction

Direct assessment of Z mass

Ultimate test of calibration and associated uncertainty

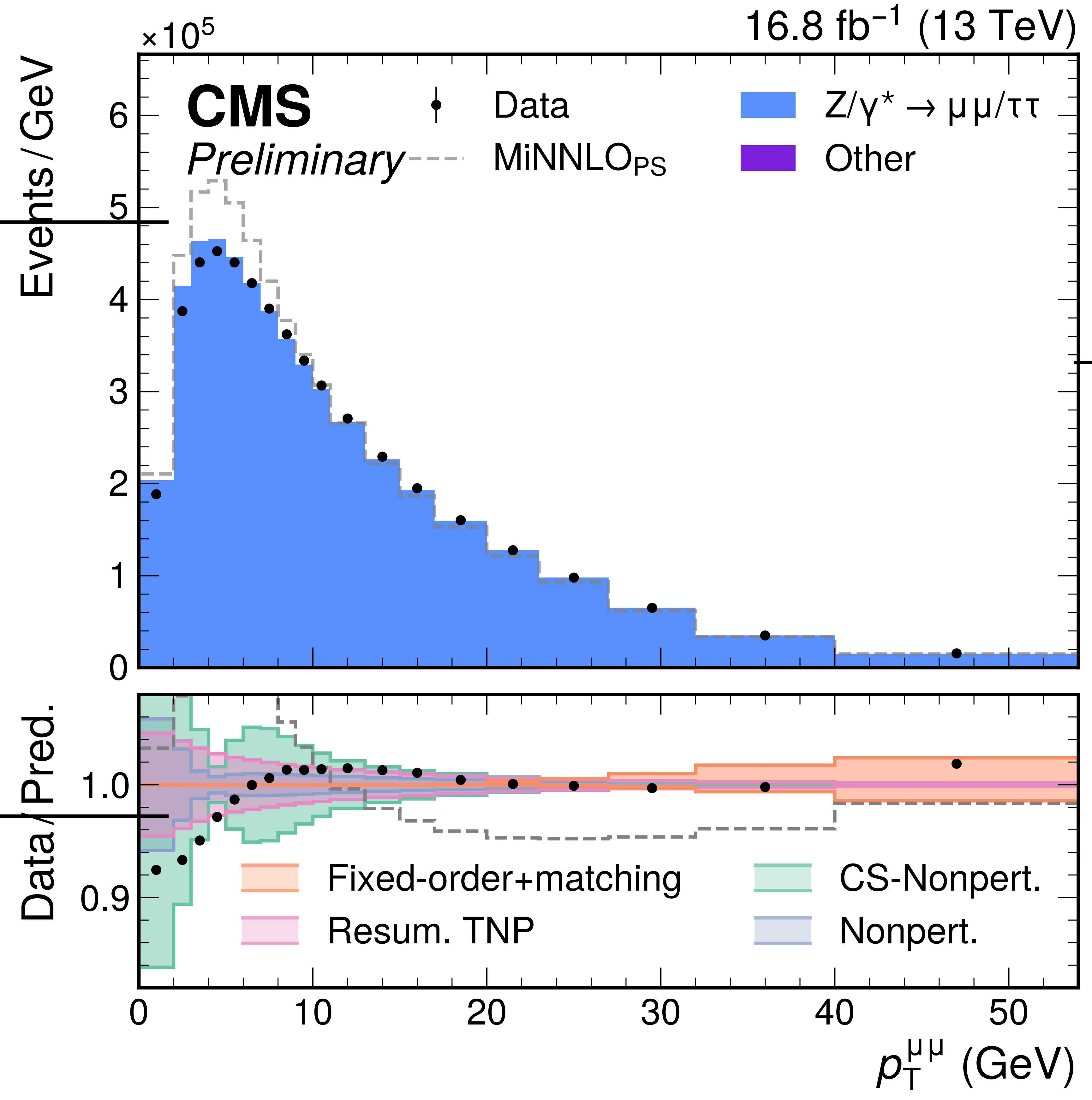
m_Z - m^{PDG}_Z = -2.2 ± 4.8 MeV = −2.2 ±1.0 (stat) ±4.7 (syst) MeV



How well we model the W transverse momentum

MiNNLO gets further corrections from SCETlib (N^3LL+NNLO)

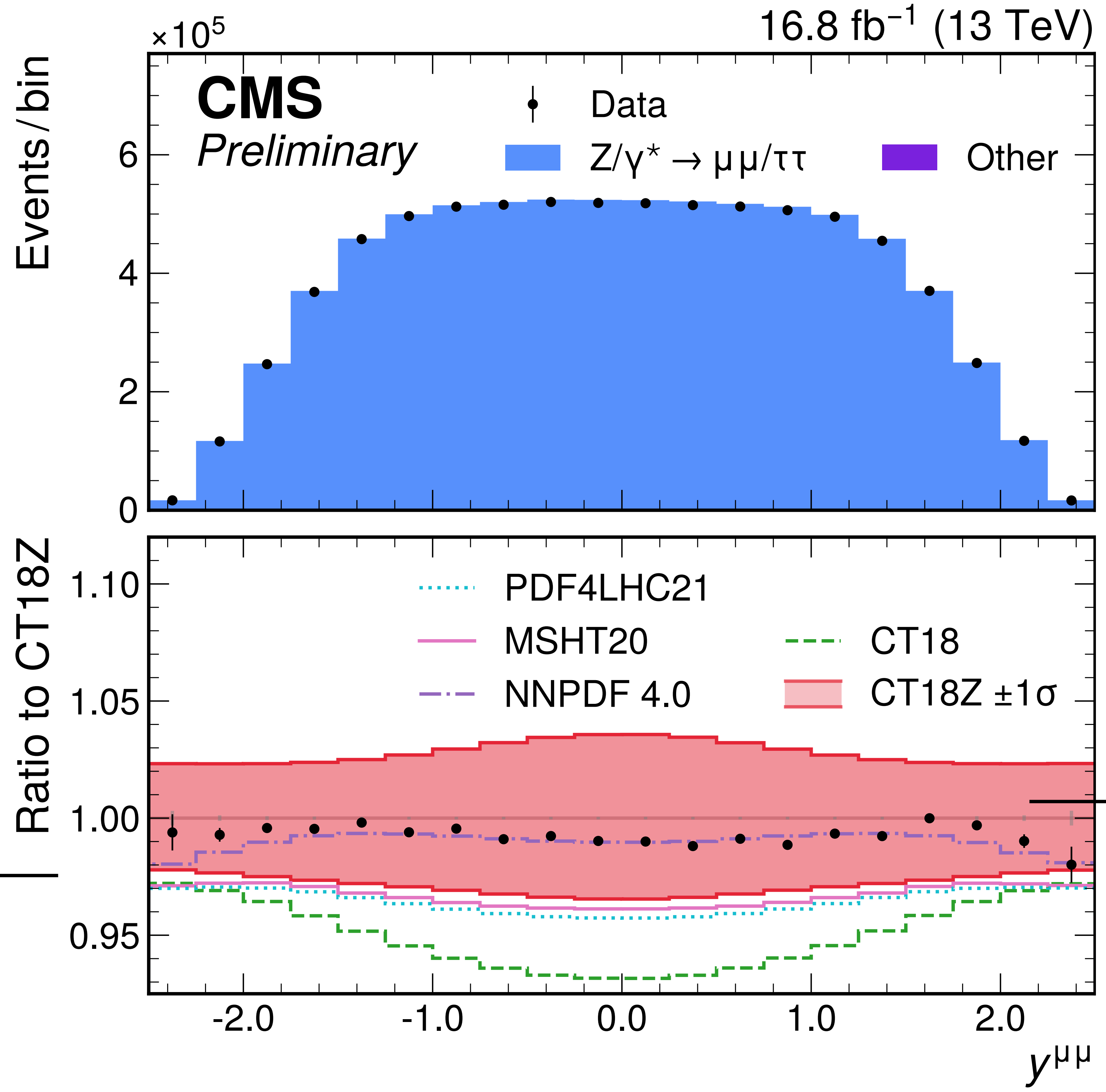
About 10% discrepancy between data and simulation at low Z p_T



Huge Monte Carlo samples with full detector simulation (4B events) from $MiNNLO_{PS}$+Pythia+Photos is validated using Z events

How well we model the W longitudinal momentum

Z rapidity events in data and simulation using different PDF sets

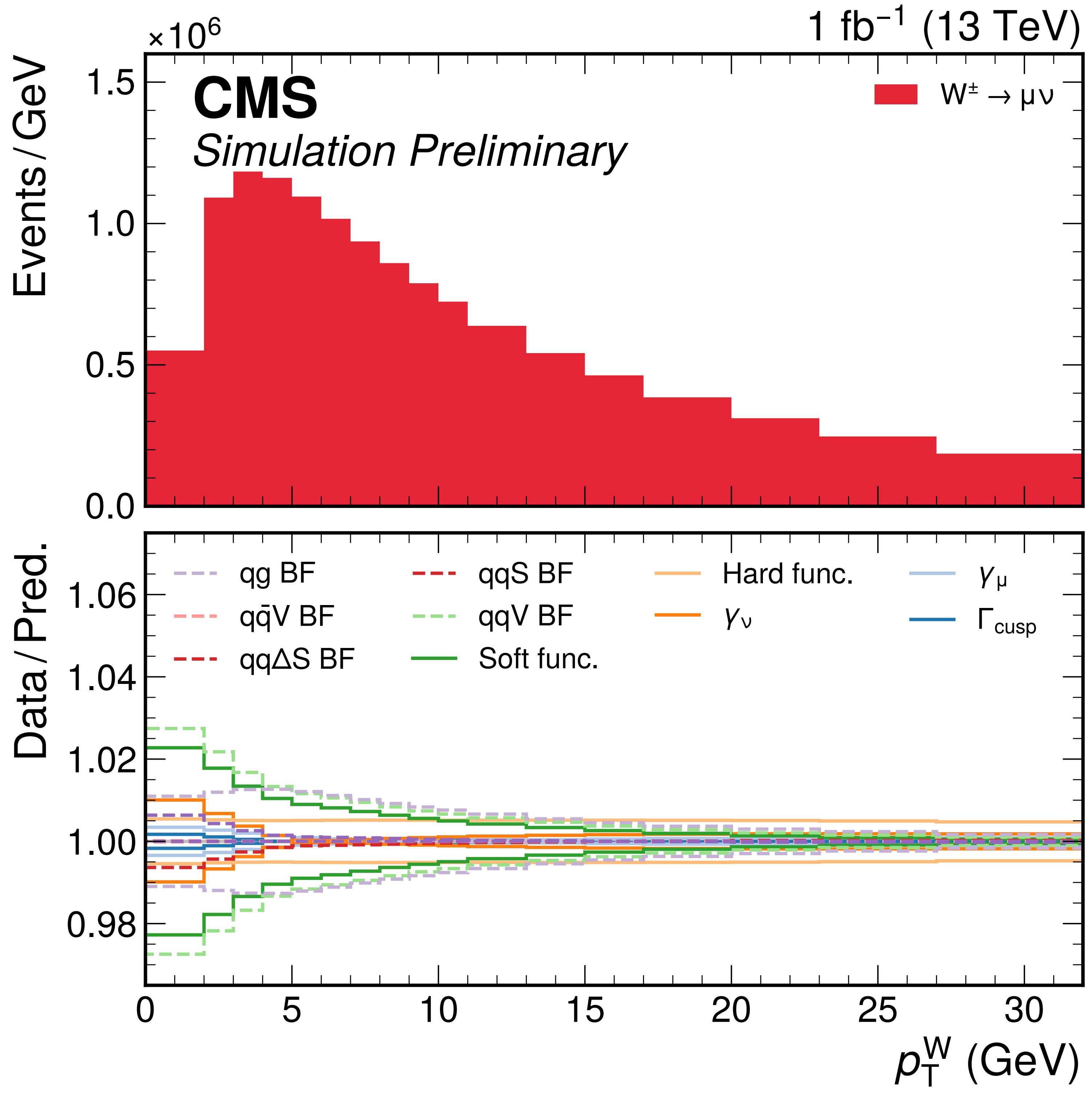


Different PDFs not necessarily agree among themselves

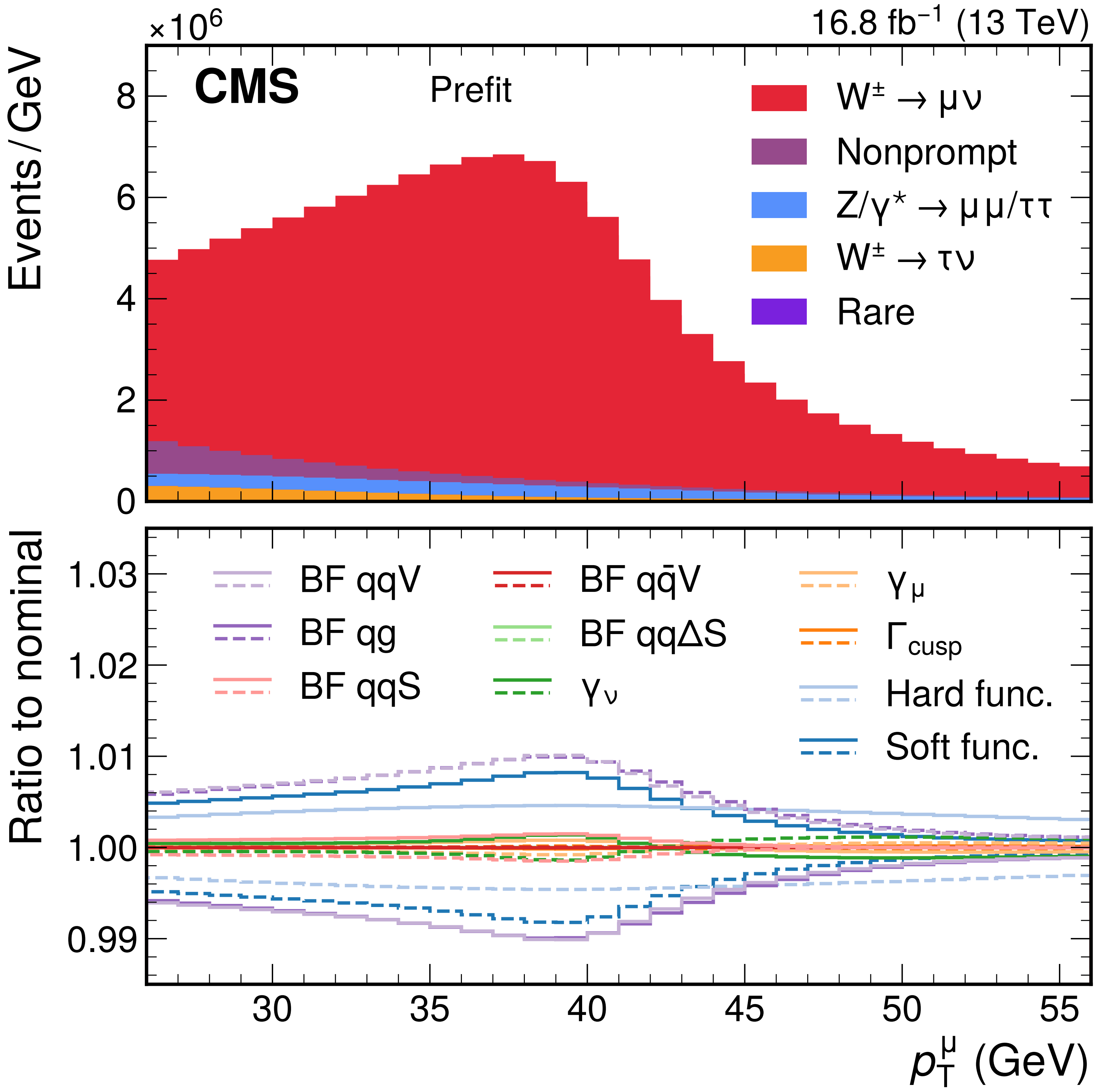
CT18Z is the PDF set chosen as central with its uncertainties because it has the flexibility to cover for all the others when measuring the W mass

Theoretical model with in-situ constraints

Theory nuisance parameters calculated from SCETlib at N³LL
are able to change the transverse momentum of the W and therefore of the muon*



Parametrize the elements of the resummation series since the structure of the resummation is known to all orders



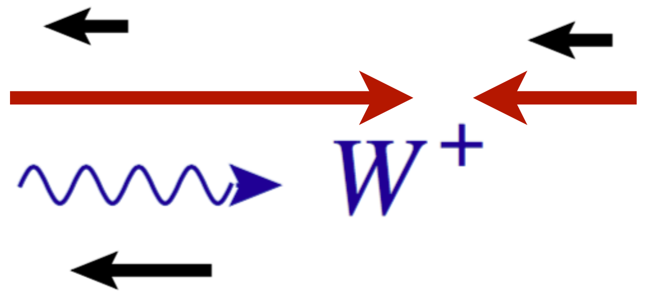
Let data choose the preferred curve

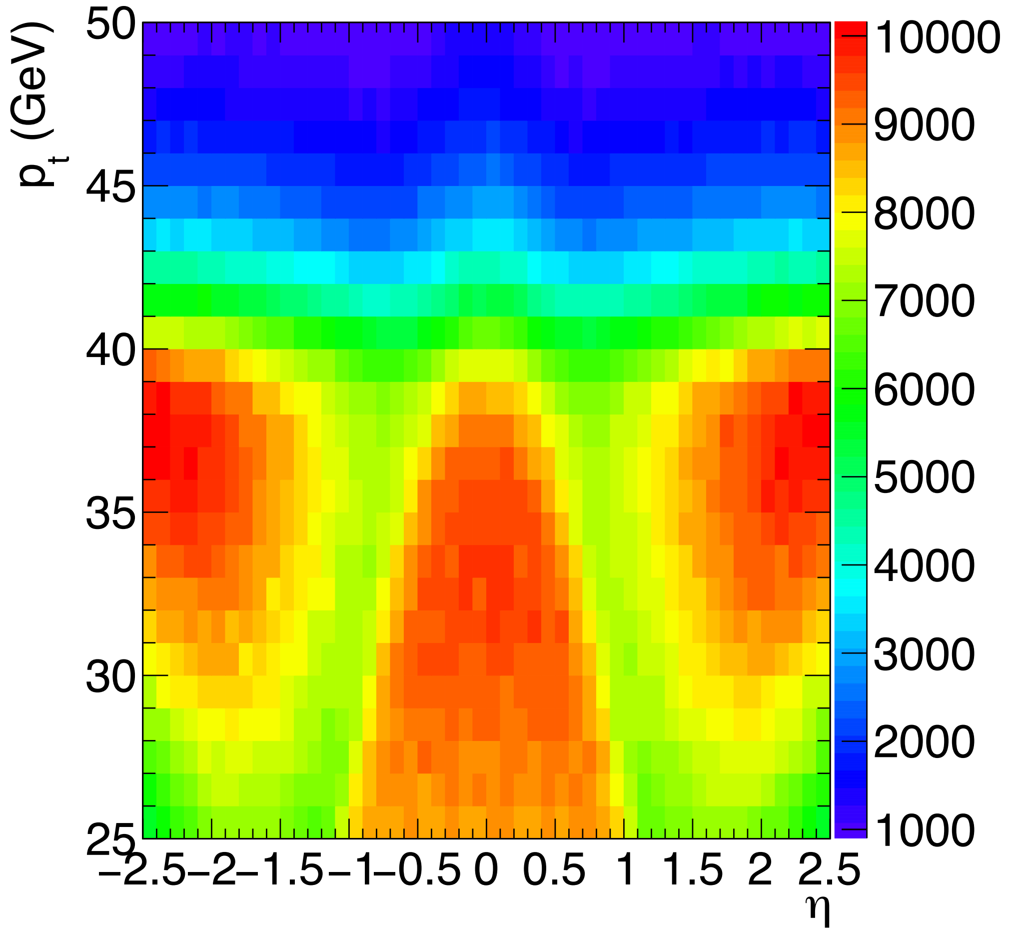
*arXiv:2411.18606.

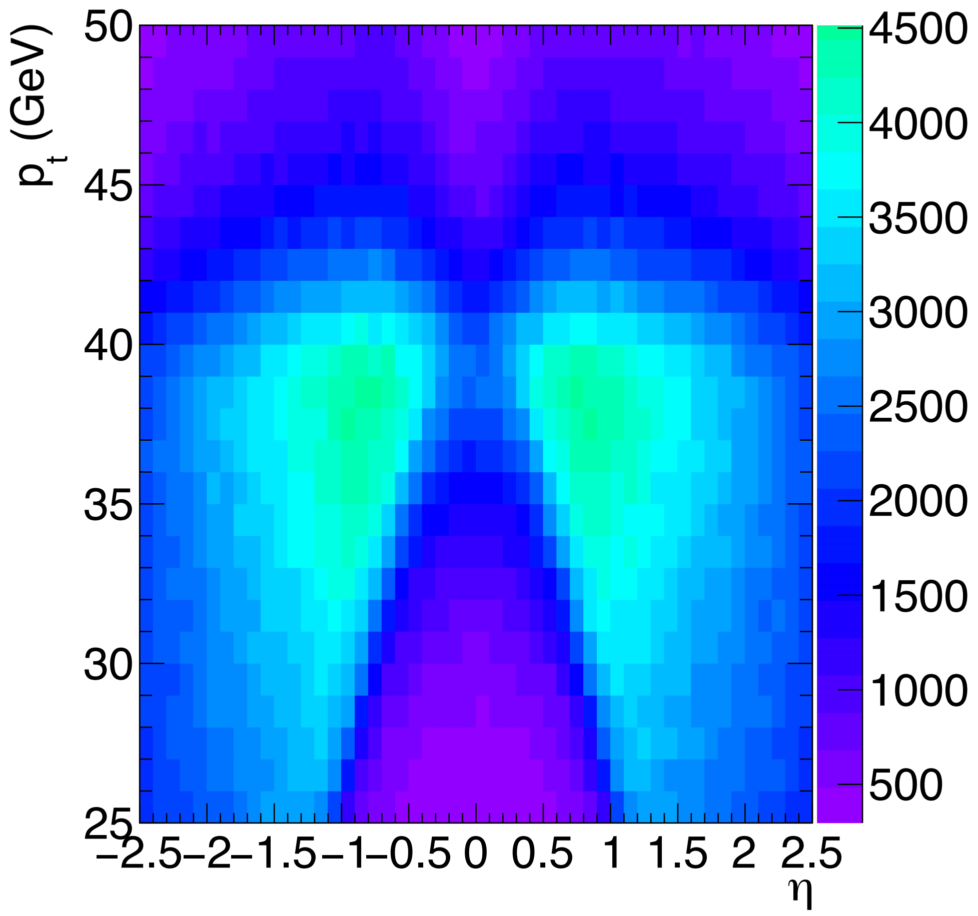
Sensitivity to the W polarization

While the muon transverse momentum alone carries information about the value of the W mass, its correlation with η is very sensitive to the W polarization and longitudinal motion

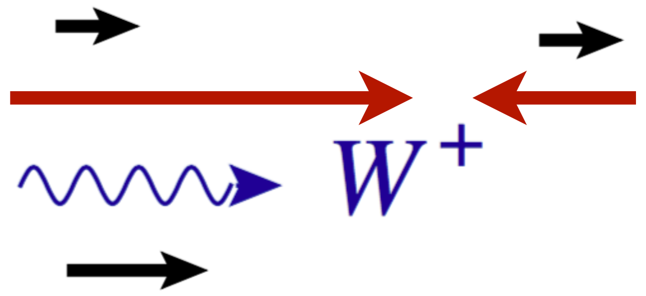
a left-handed W+

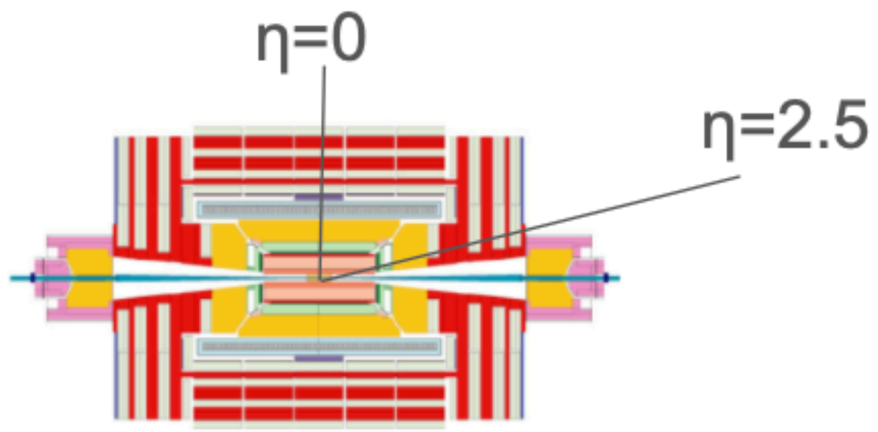






a right-handed W+





E.M. et al. J. High Energ. Phys. (2017) 2017: 130.

E.M. CERN-THESIS-2021-271

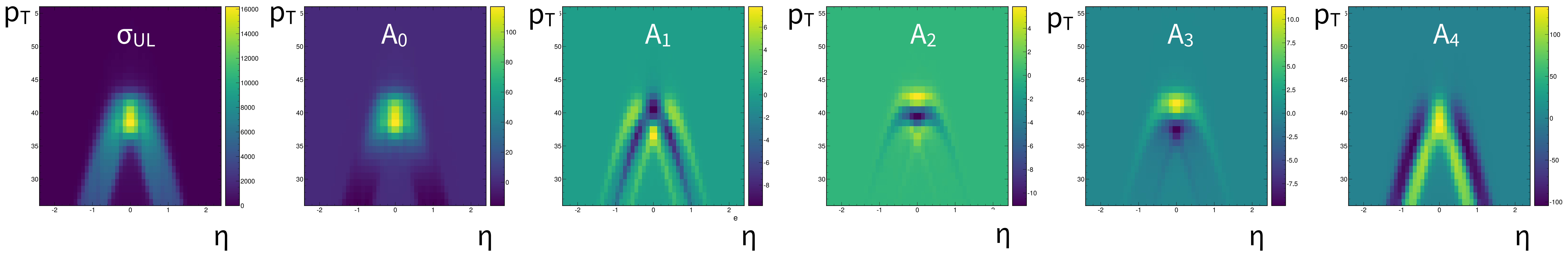
Phys. Rev. D 102 (2020) 092012

A complementary approach: the Helicity Fit

Exploit the full constraining power of the data to measure the W production directly from data

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

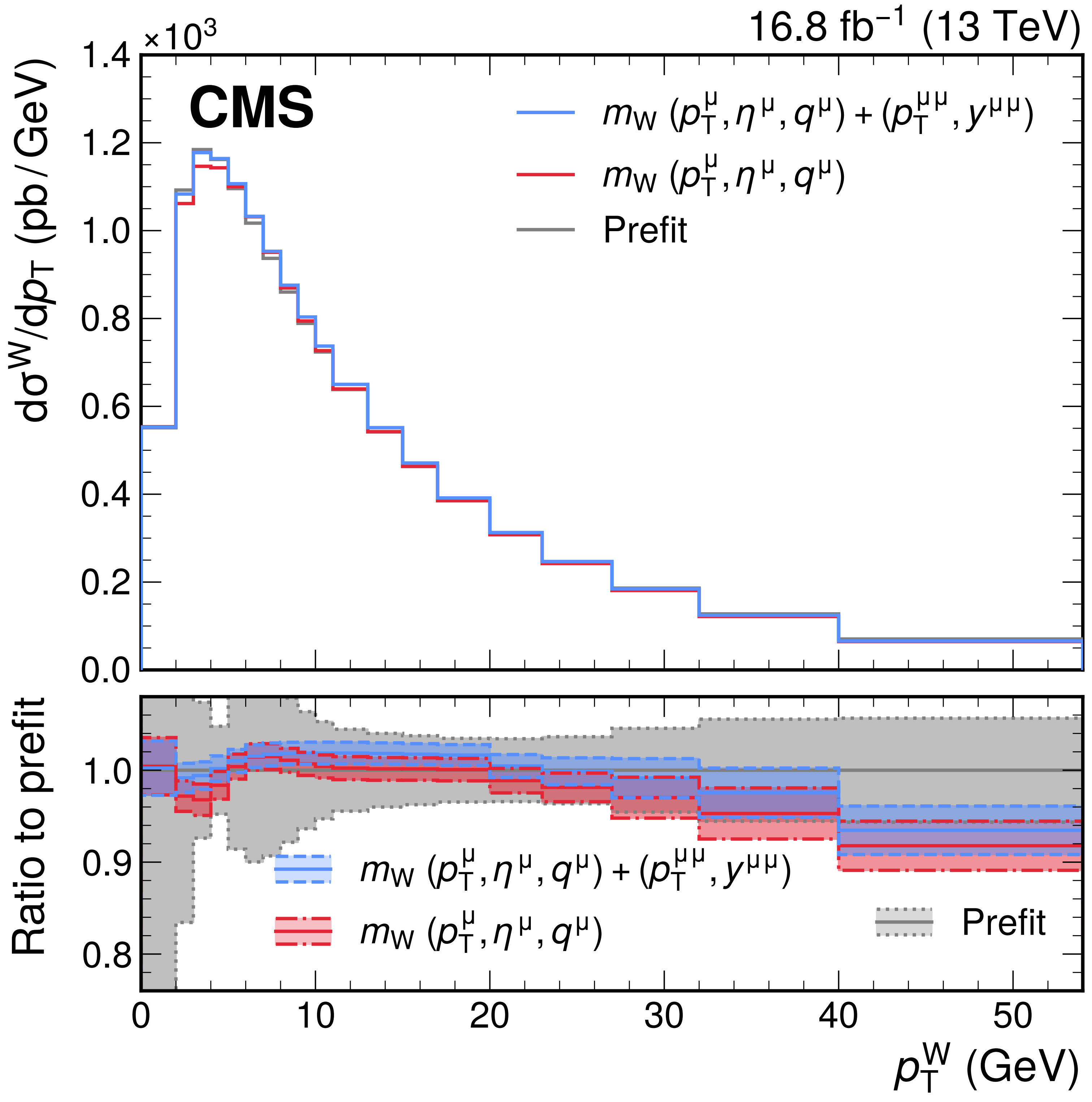
Each component can be discriminated in the plane of muon transverse momentum and η



E.M. CERN-THESIS-2021-271

Extraction of W transverse momentum

"Theory Nuisance Parameters" approach



Helicity fit