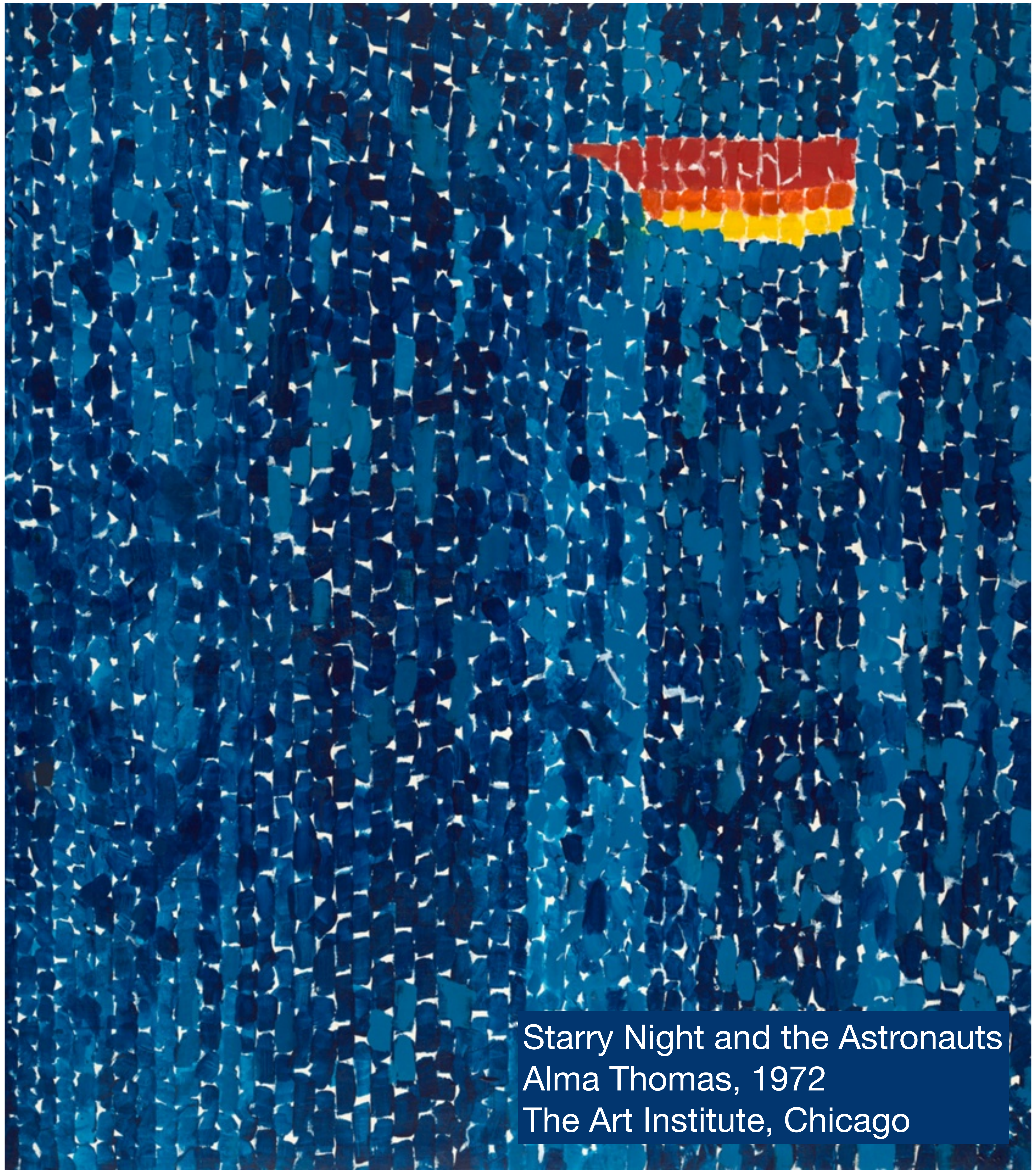
High-precision measurement of the W boson mass at CMS

Elisabetta Manca UCLA

Invited seminar @ EPFL

Dec 9th 2024

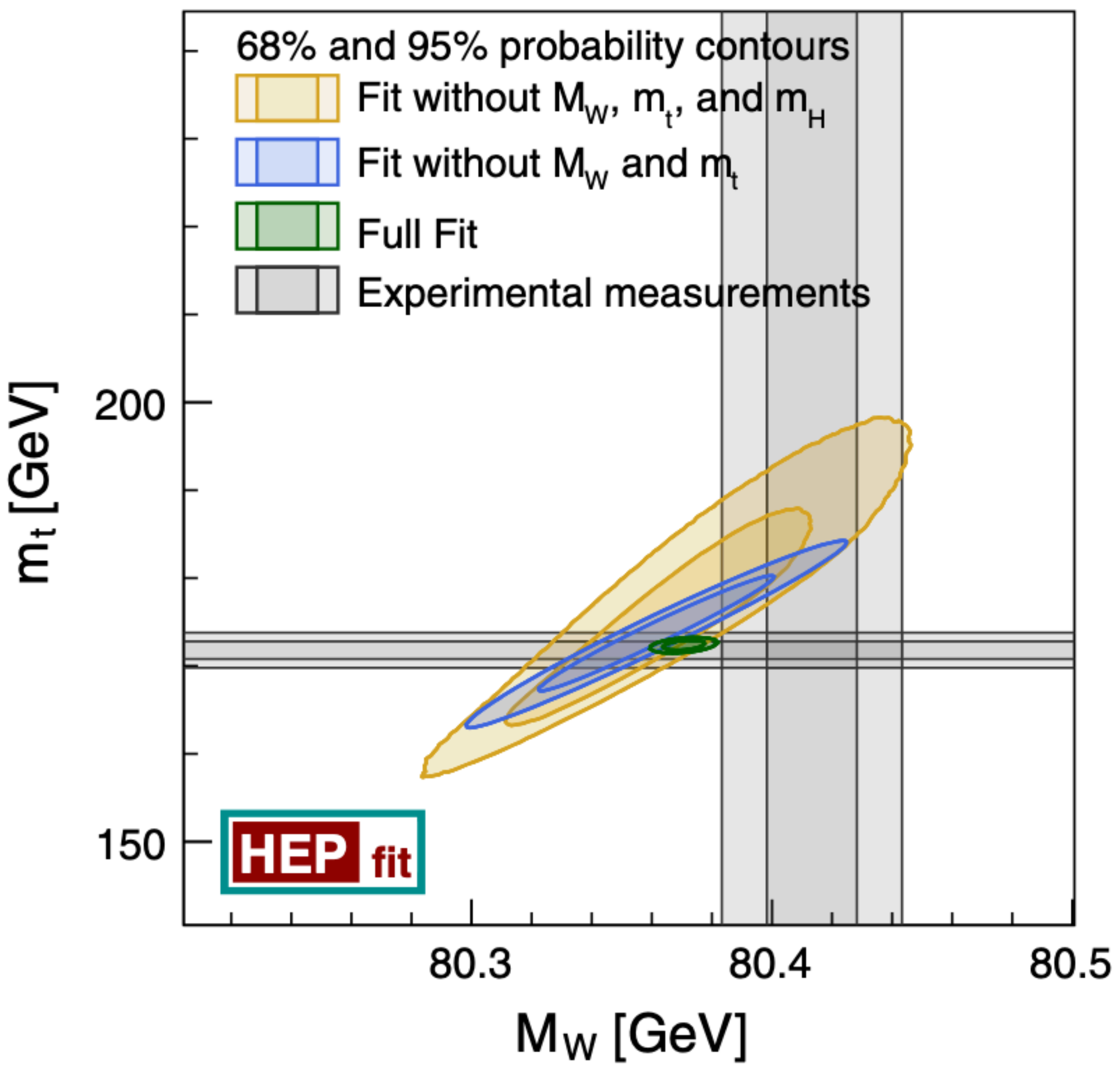


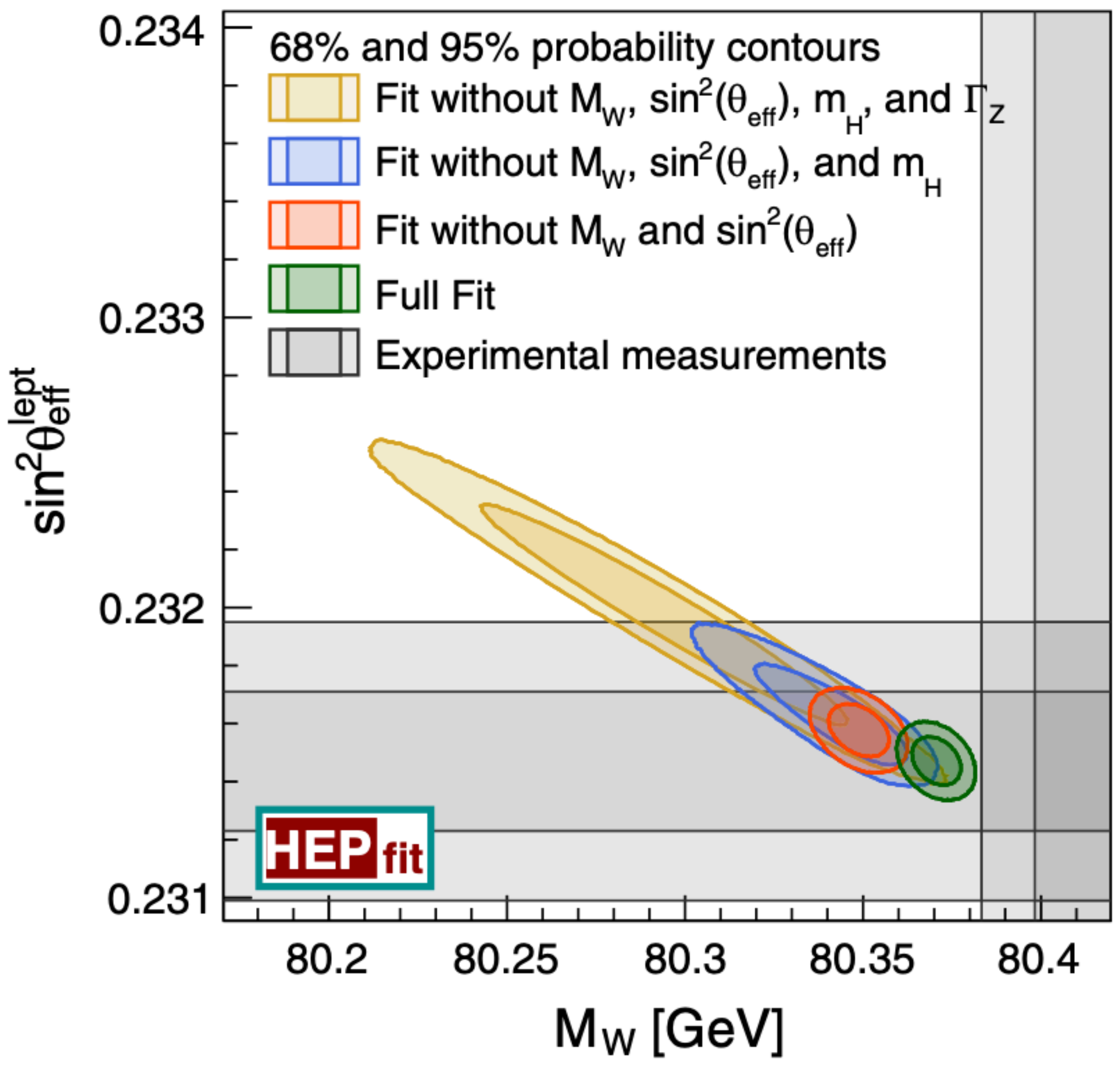
Starry Night and the Astronauts
Alma Thomas, 1972
The Art Institute, Chicago

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



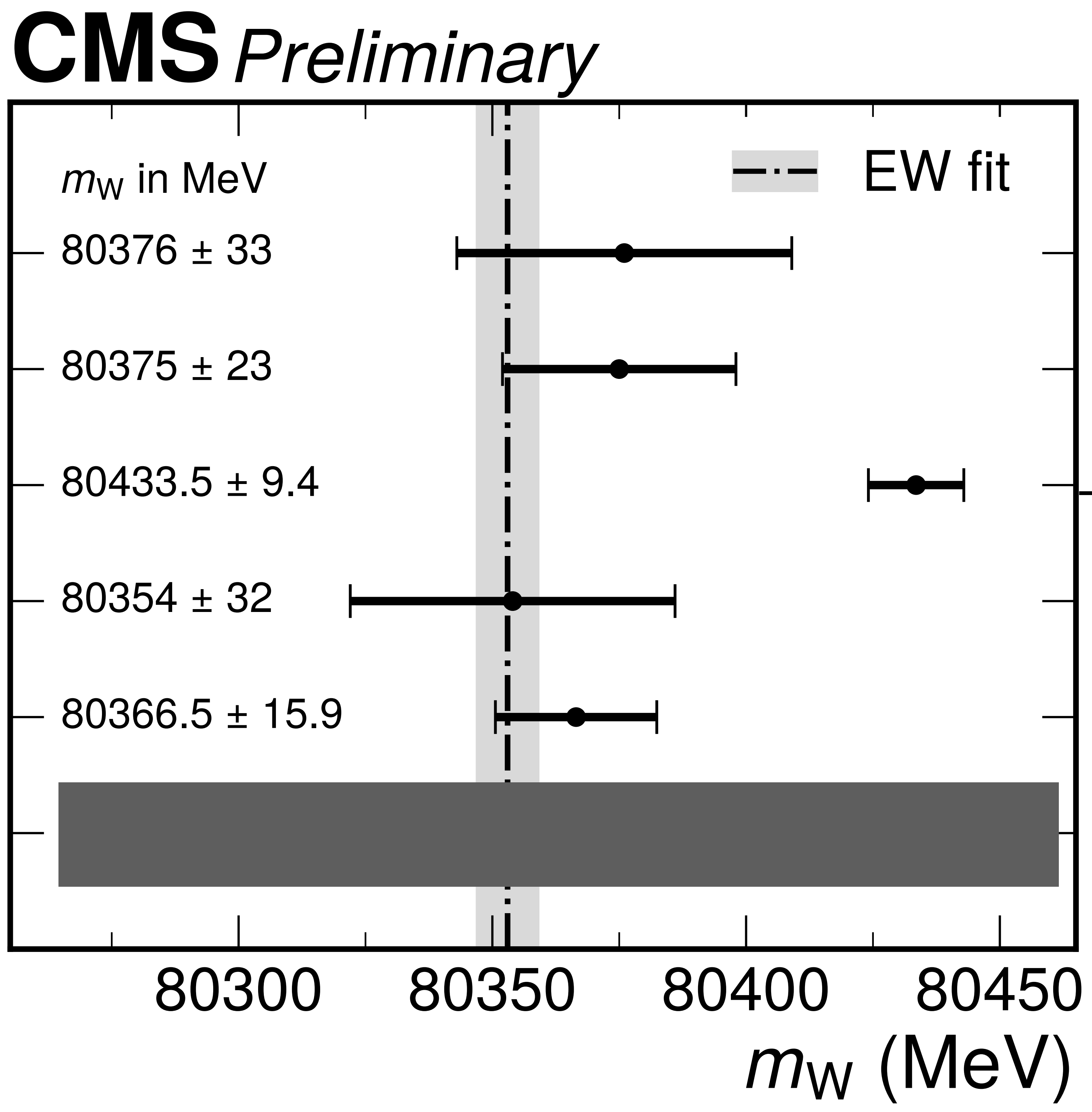


Phys.Rev.Lett. 129 (2022) 27, 271801

W boson mass scenario

Measurements from other LHC experiments agree with prediction and among each other

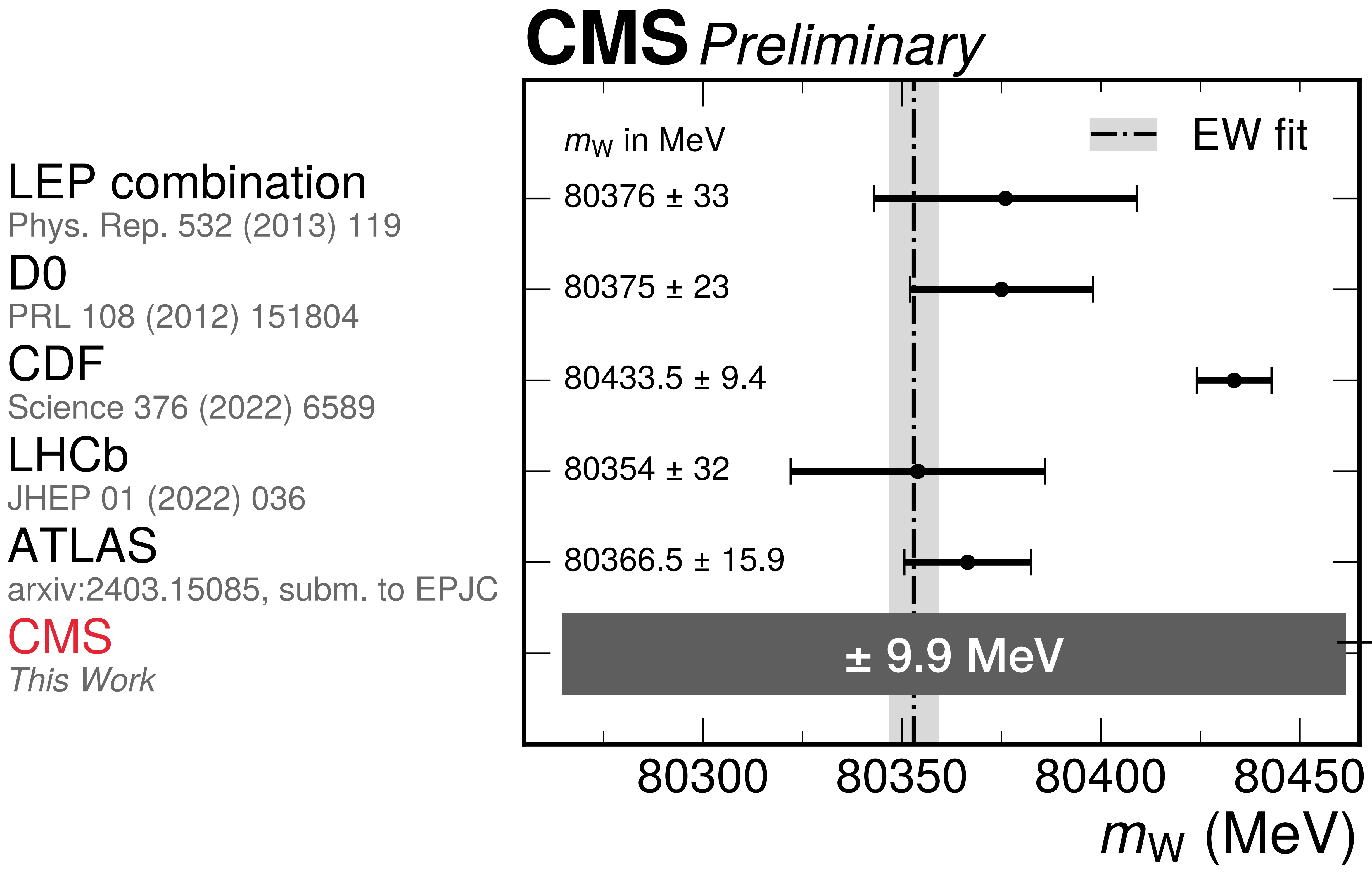
LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arxiv:2403.15085, subm. to EPJC
CMS
This Work



Measurement from CDF stands as outlier wrt prediction and other measurements

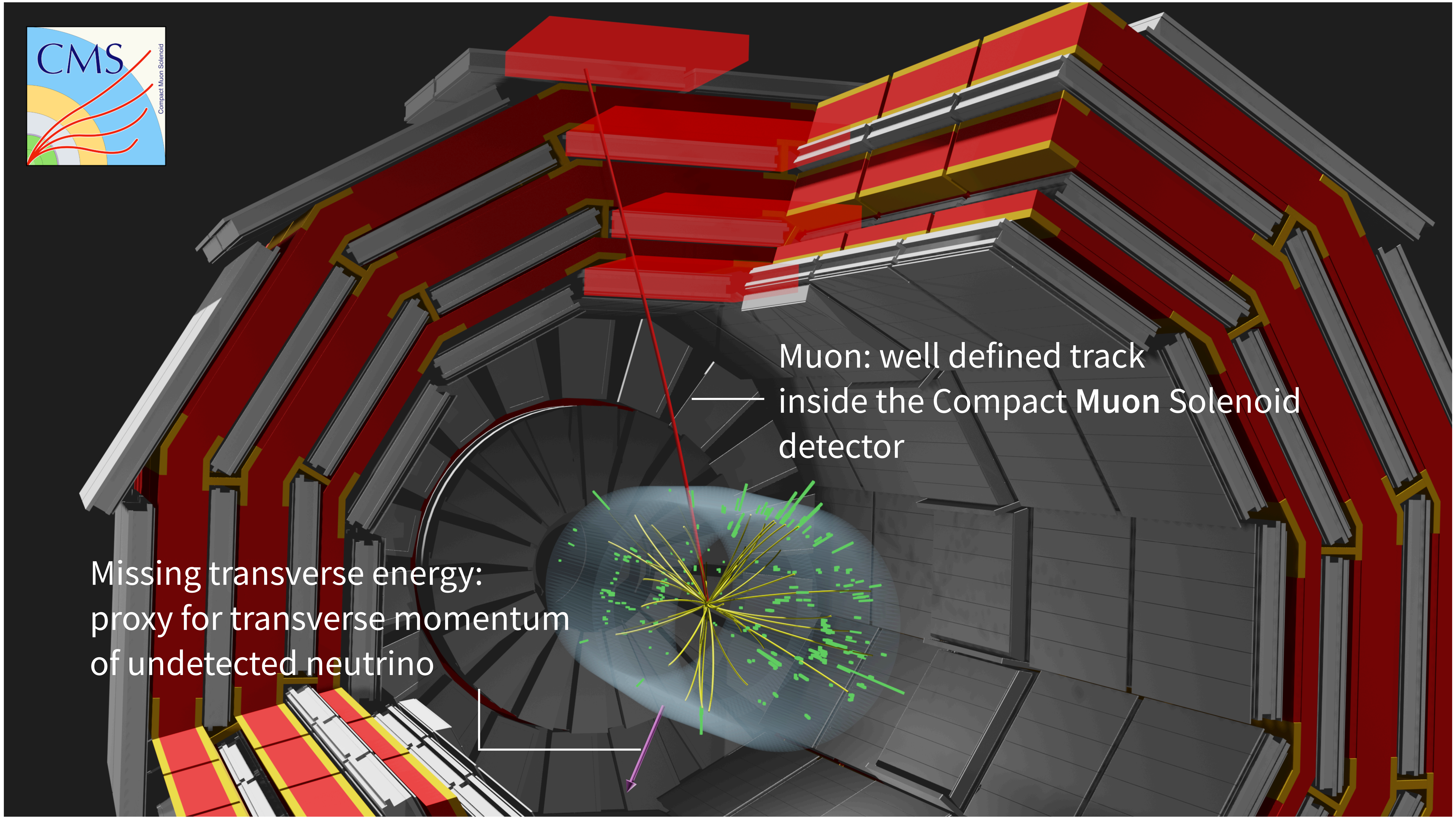
CMS can shed light on
the puzzle with a measurement with
comparable uncertainty as CDF

W boson mass: story of a number



Whatever the central value, its uncertainty is the real protagonist of this story: **How we measured the W mass in one year per MeV**

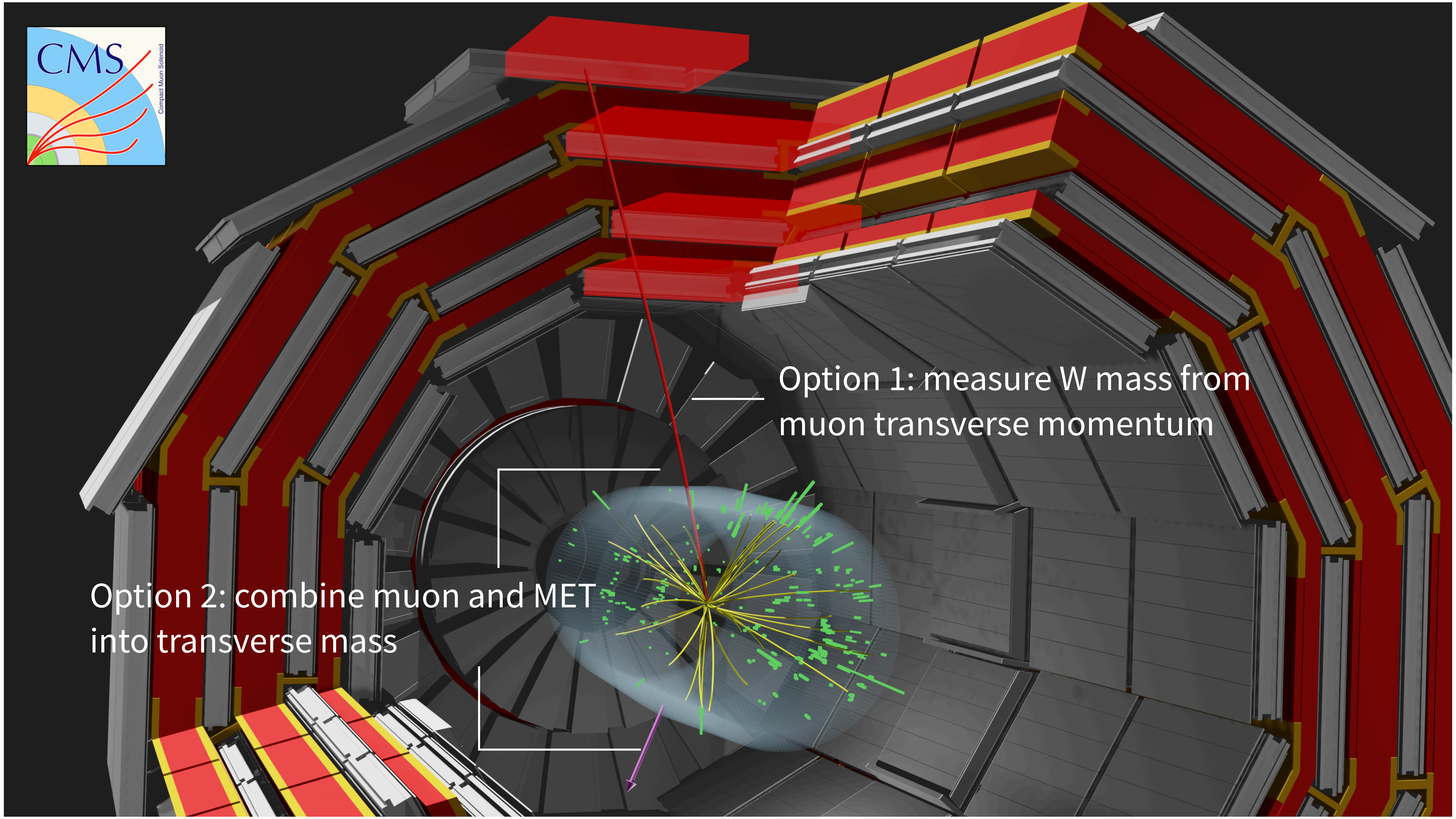
Detecting W bosons



Muon: well defined track inside the Compact **Muon** Solenoid detector

Missing transverse energy: proxy for transverse momentum of undetected neutrino

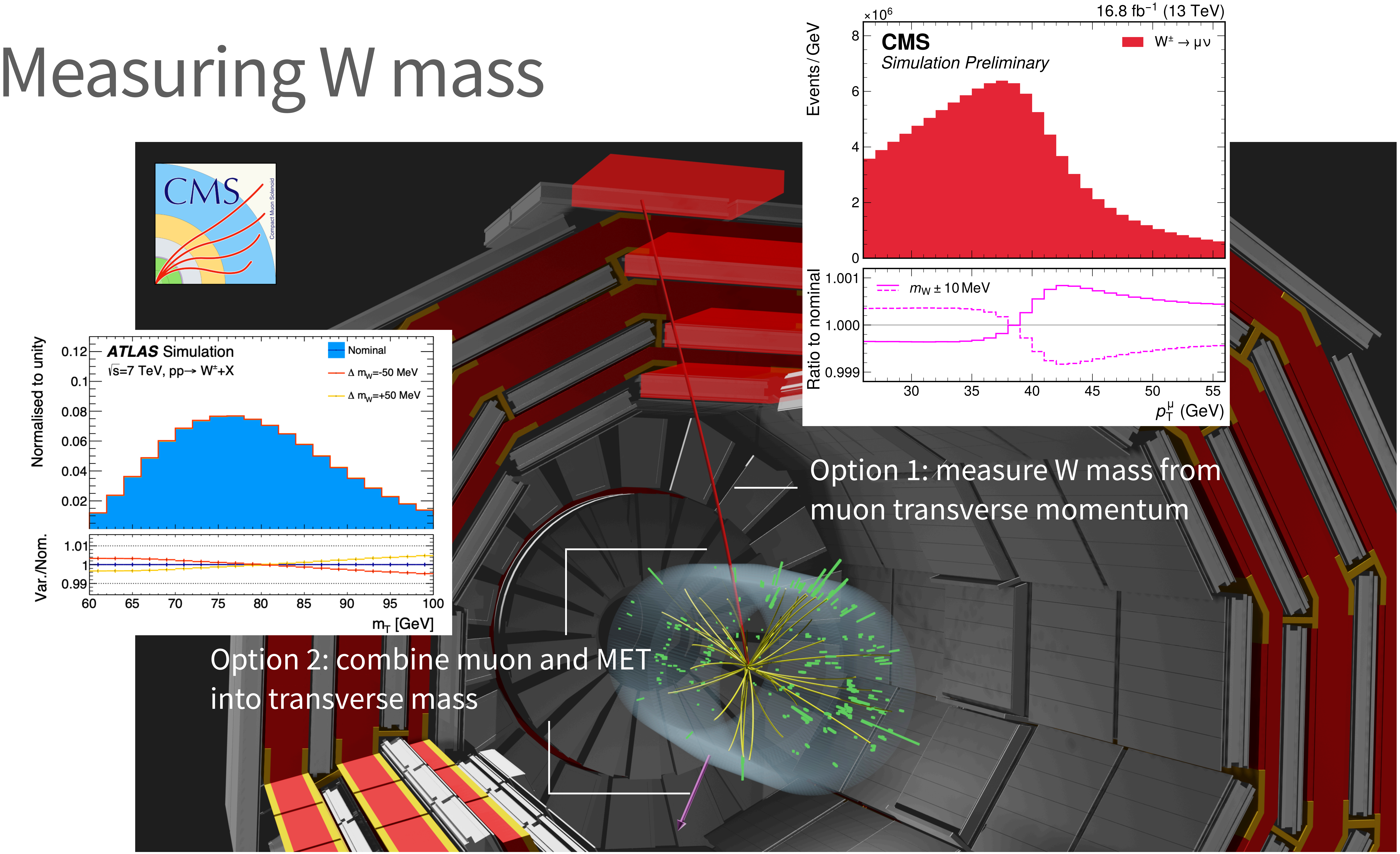
Measuring W mass



Option 1: measure W mass from muon transverse momentum

Option 2: combine muon and MET into transverse mass

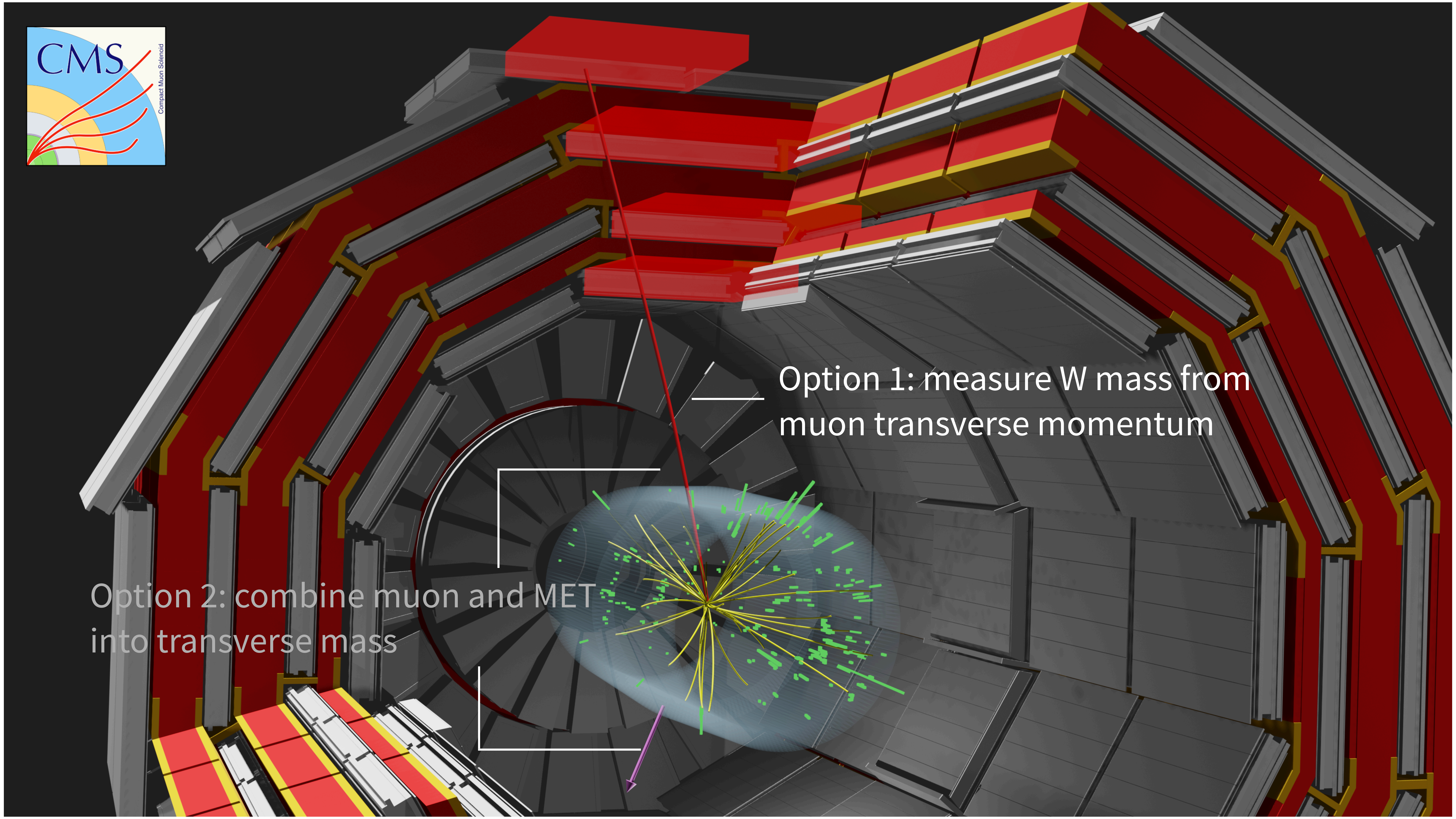
Measuring W mass



Option 1: measure W mass from muon transverse momentum

Option 2: combine muon and MET into transverse mass

Measuring W mass using a single muon



Option 1: measure W mass from muon transverse momentum

Option 2: combine muon and MET into transverse mass

Challenges

1. Measure the muon momentum scale with a precision of **0.01%**
   About one order of magnitude better than the typical analysis in CMS

2. Determine how the W boson was produced inside CMS in great detail
   Since none of the quantities that are available are Lorentz invariant

Challenges

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

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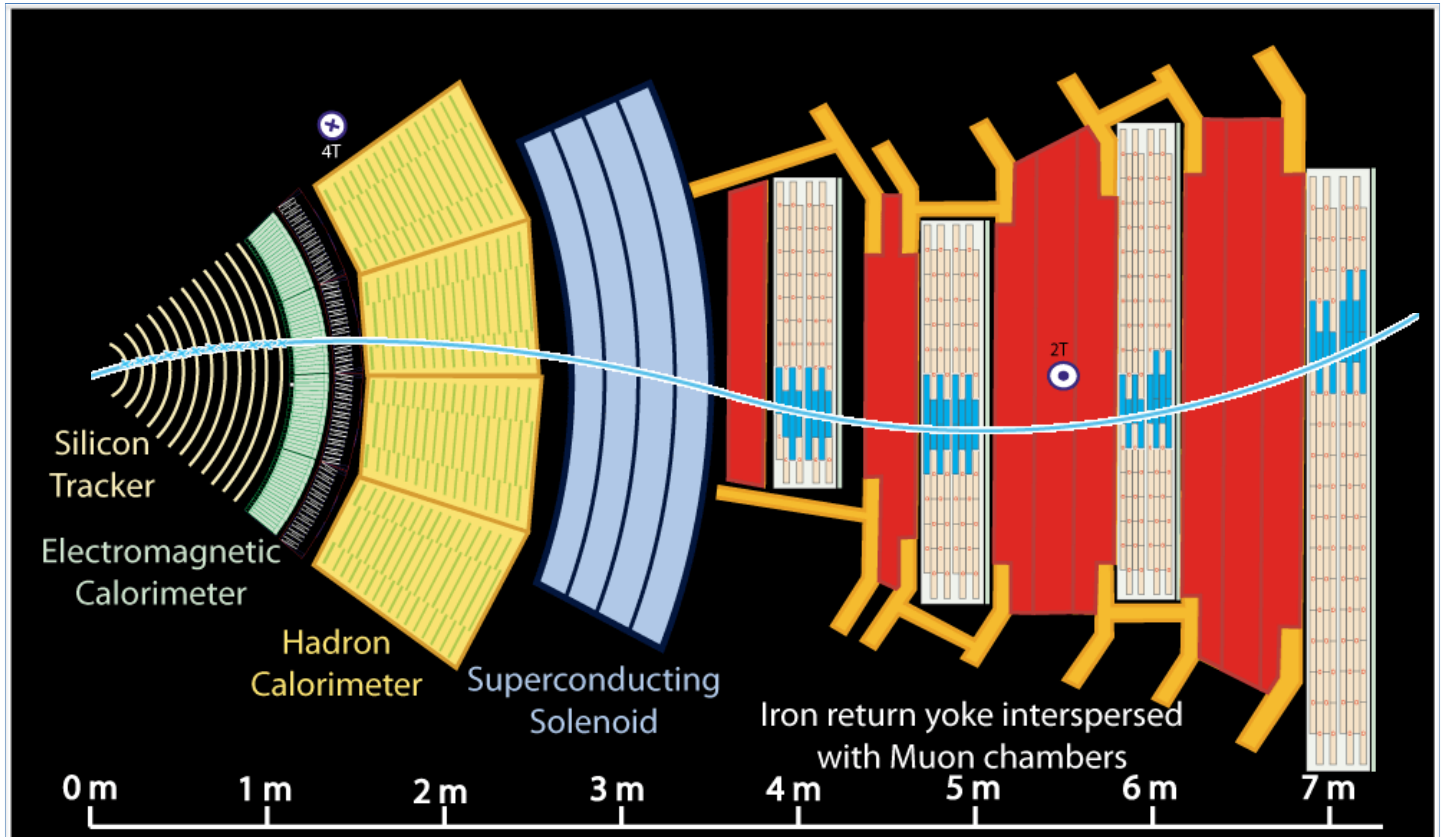
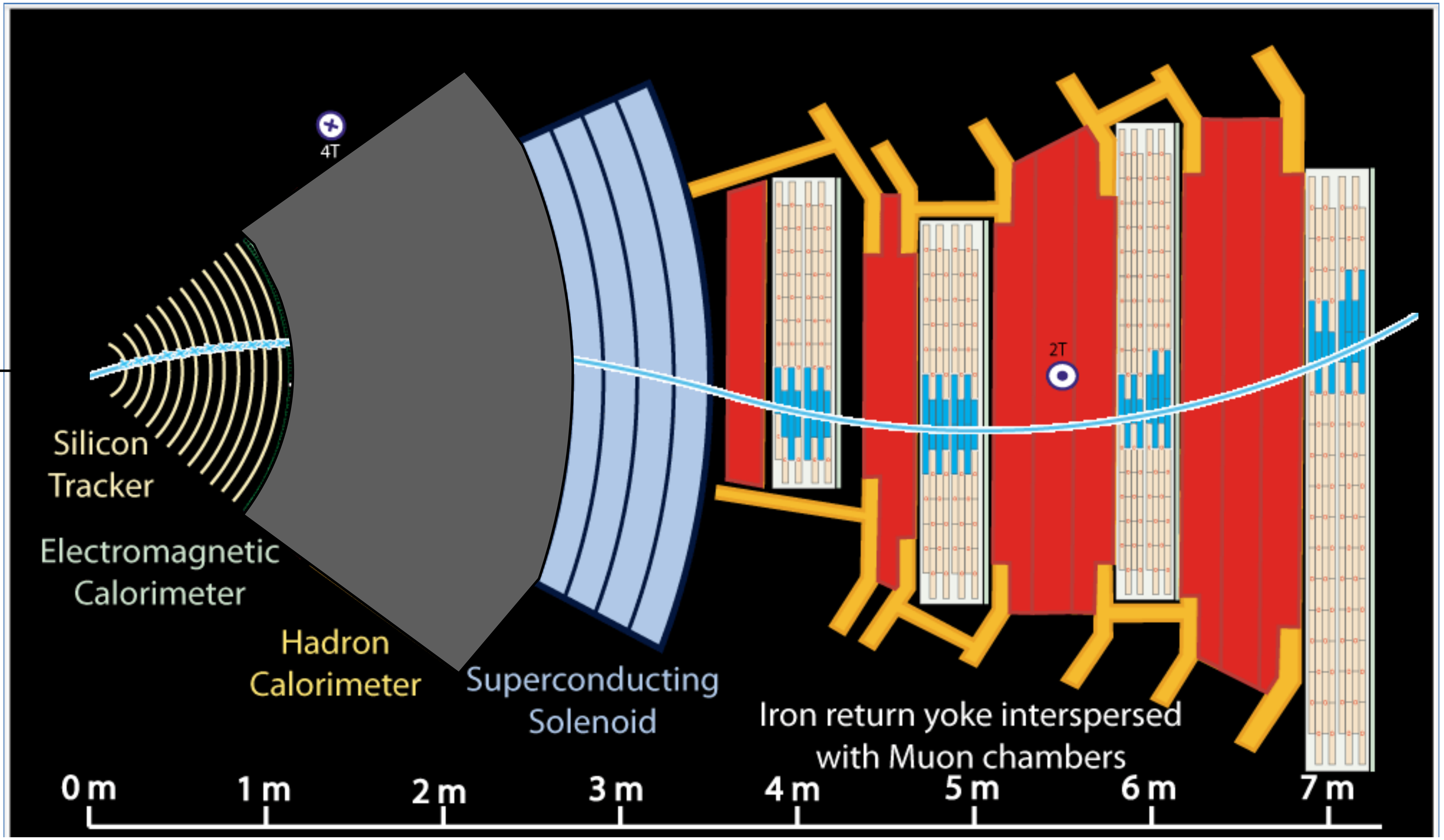
Detecting and measuring muons in CMS



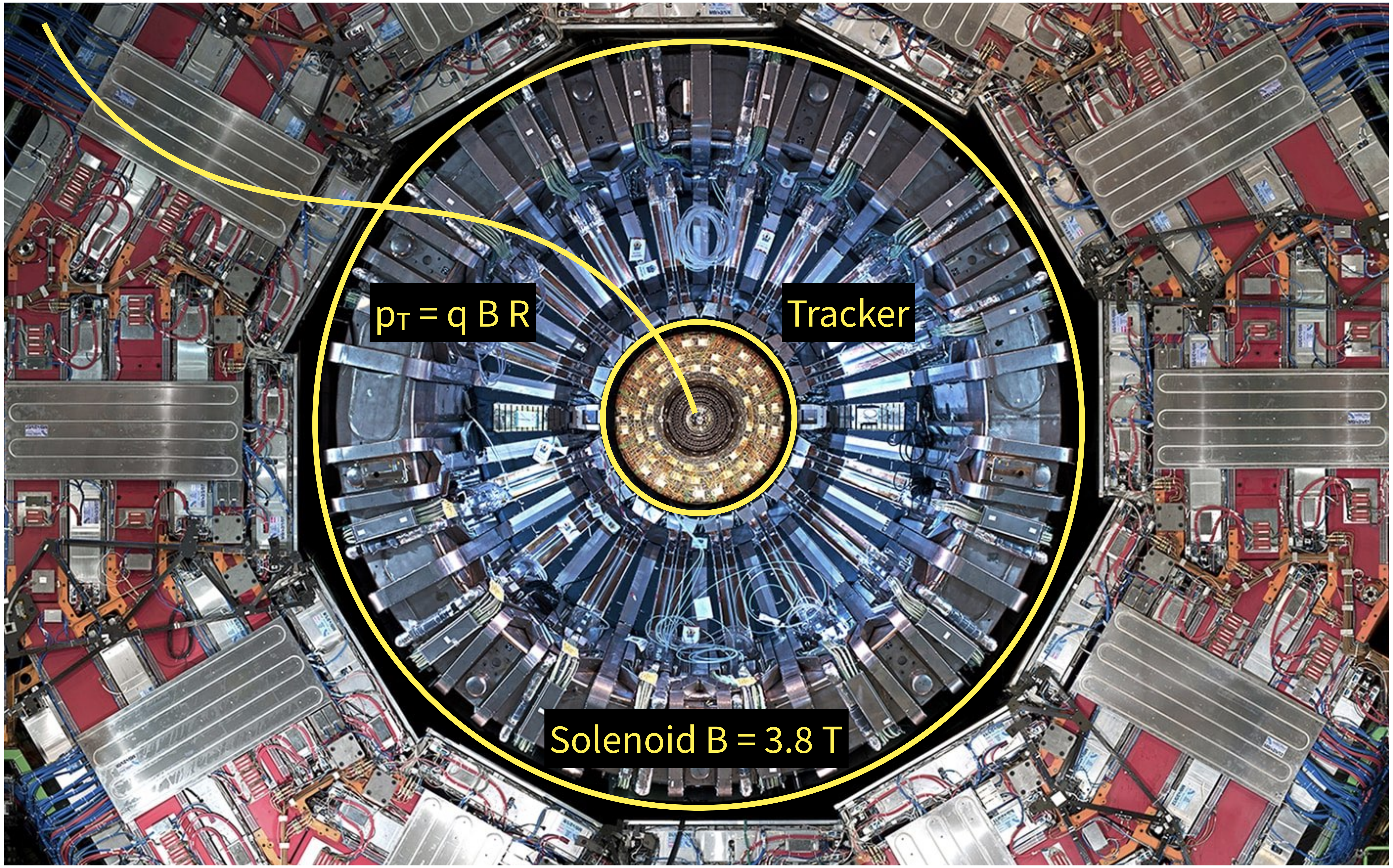
Detecting and measuring muons in CMS

Muons are **measured** in the Silicon Tracker

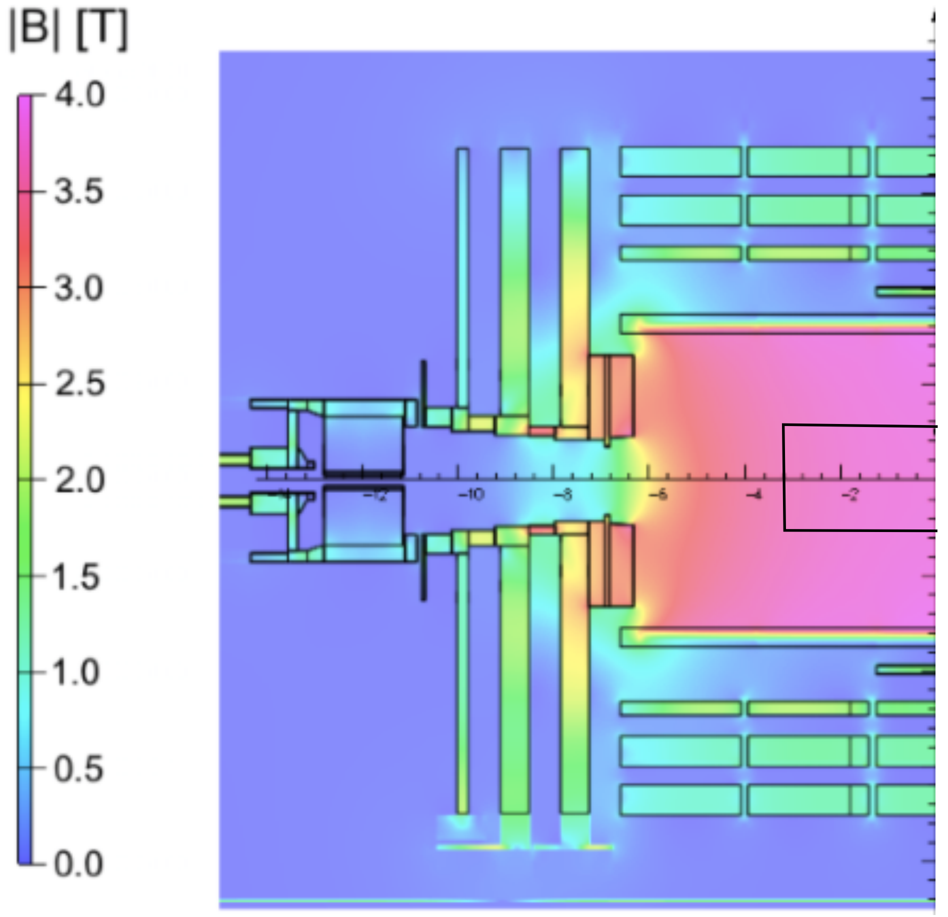


Muons are **identified** in the Silicon Tracker and in the Muon Chambers

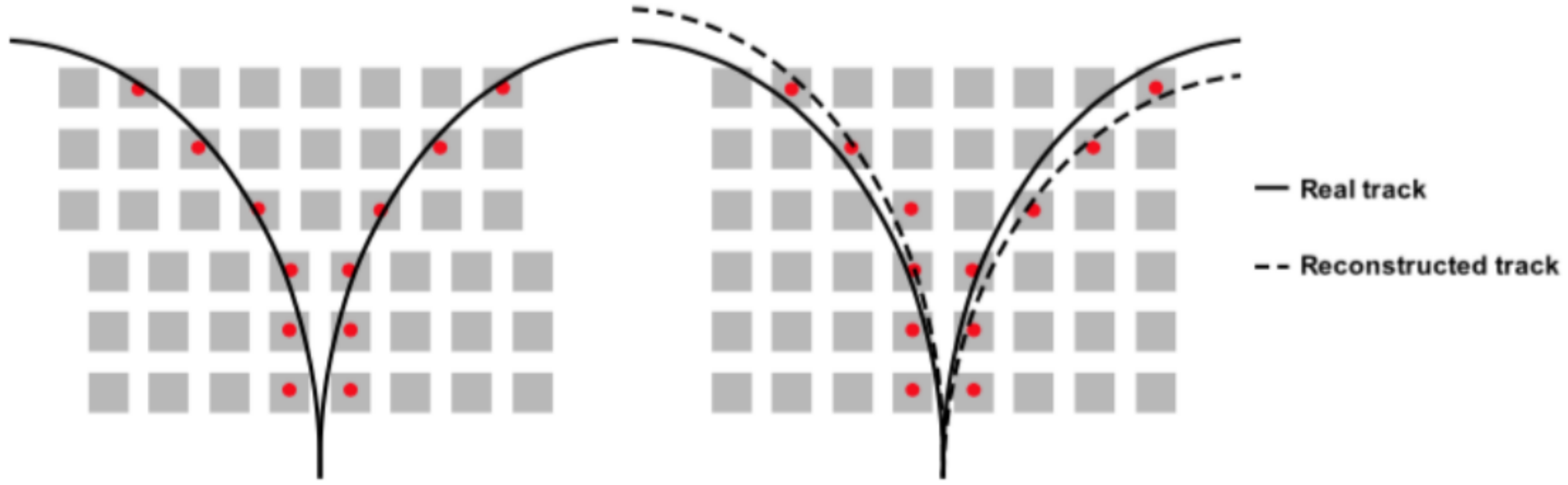
Measure transverse momentum from tracks



Imperfections propagating to muon momentum scale



$$p_T = q\,B\,R$$



1. Effect of mismodelling of magnetic field

Magnetic field mapped with Hall probes when the solenoid was empty and on the surface

Approximate magnetic field map is used by default as speed/performance compromise

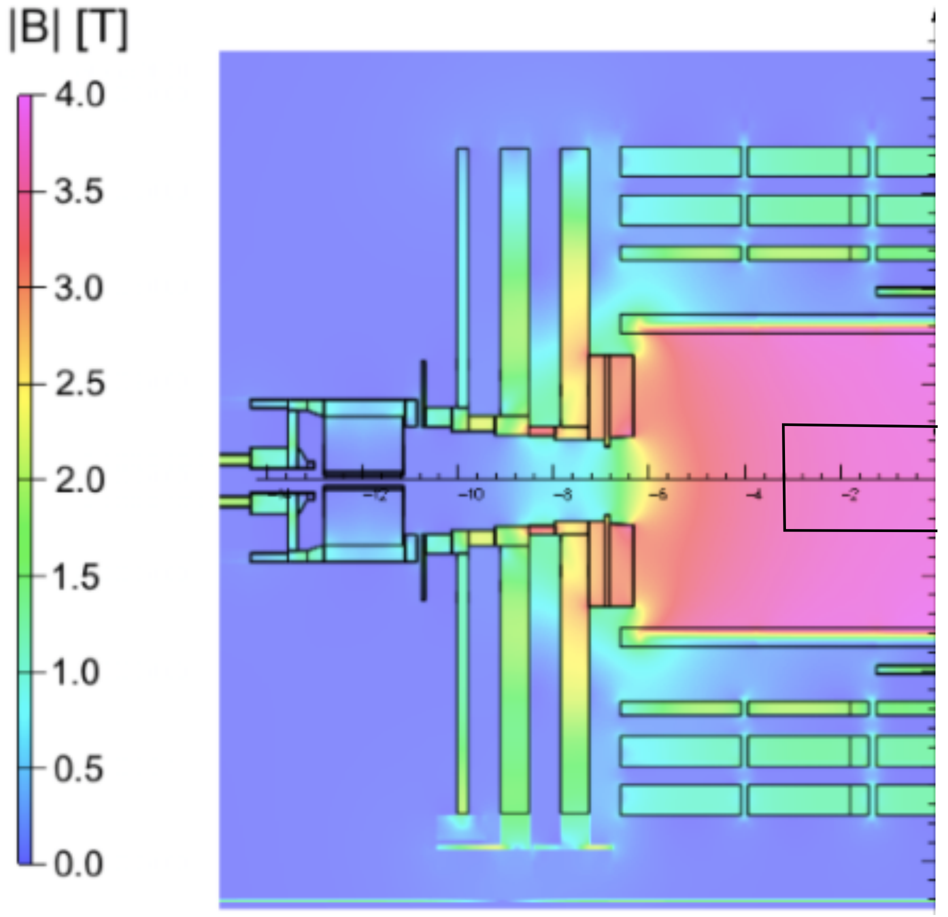
2. Effect of mismodelling of material budget

3. Effect of residual misalignment

Alignment has weak modes: geometry is prone to global scale deformations

Imperfections propagating to muon momentum scale

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

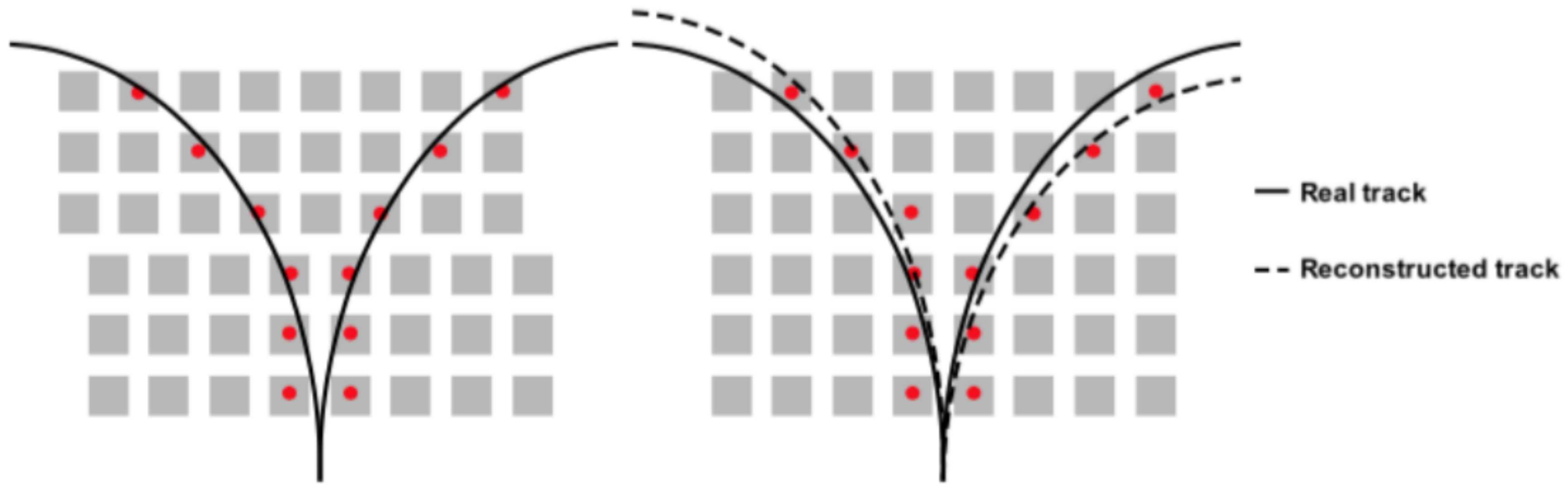


$$\frac{k_{true}}{k} = A - \epsilon k + \frac{qM}{k}$$

material

B field

misalignment



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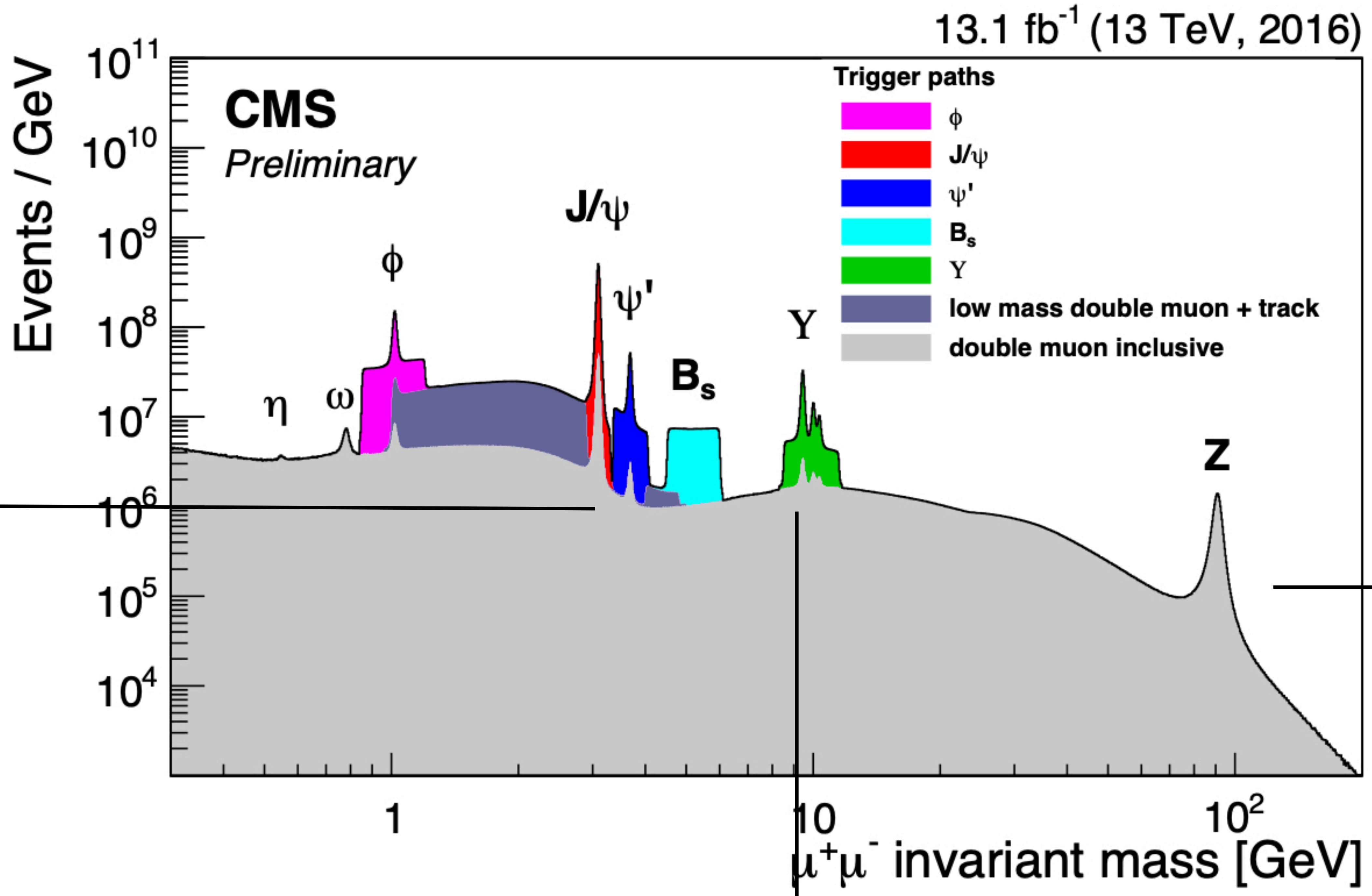
Alignment has weak modes: geometry is prone to global scale deformations

Strategy for momentum scale calibration

Plot of the invariant mass spectrum of the dimuon events



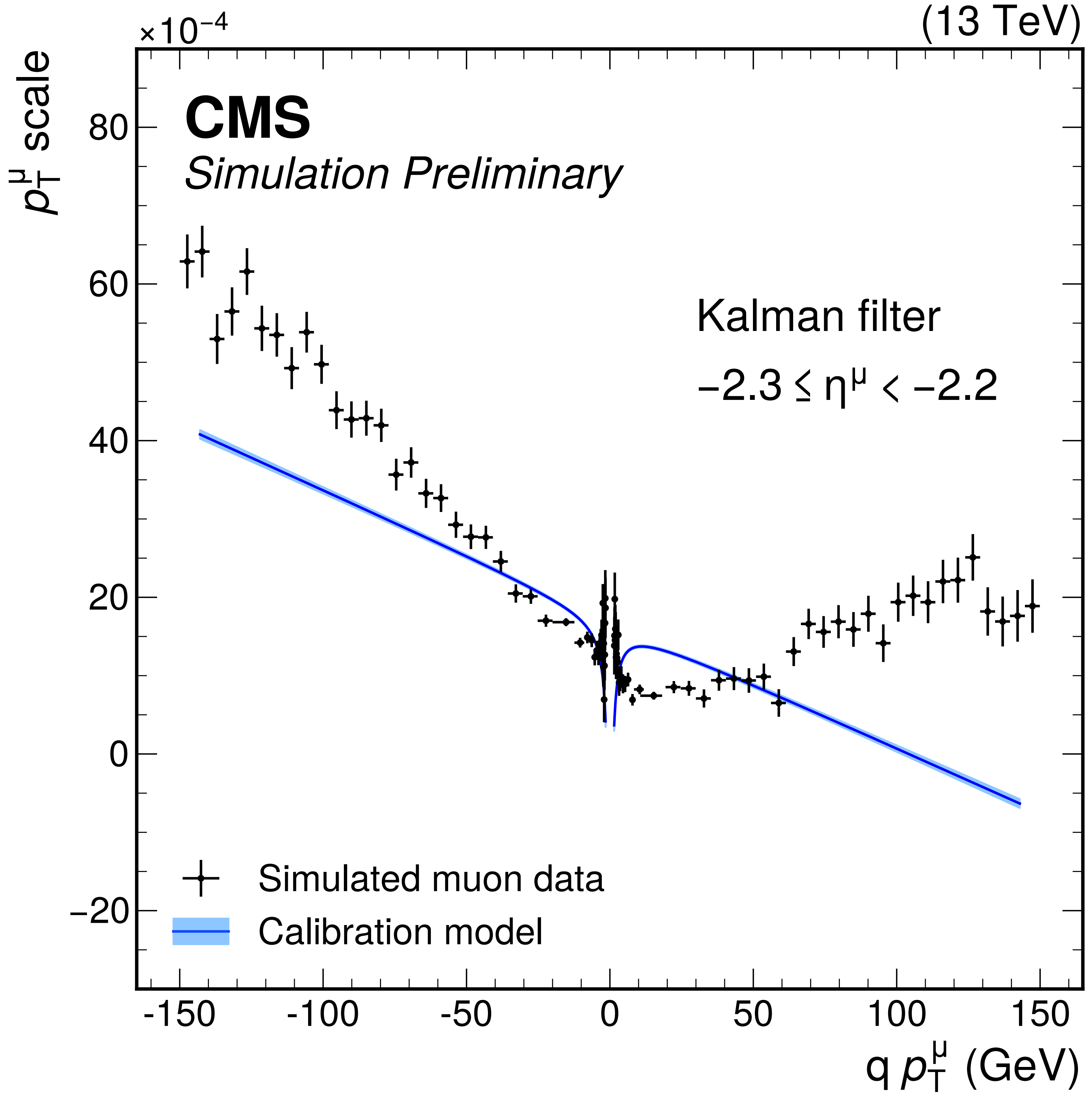
J/ψ dimuon events are used to extract corrections
using our model

J/ψ are produced copiously
and their mass is known
at the level of 10^{-6}

Z dimuon events are used to test the calibration in the W phase space

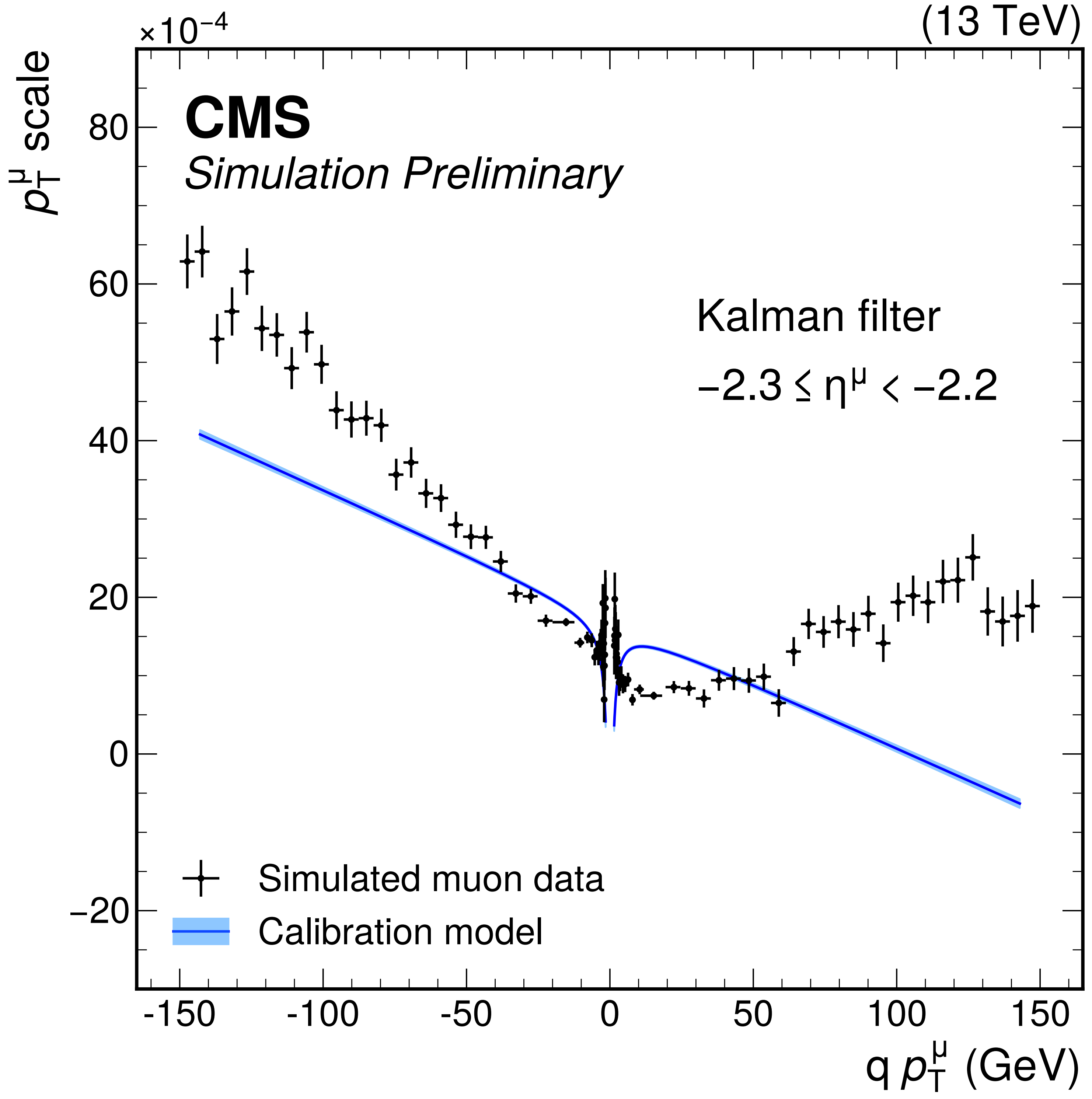
Υ dimuon events are used as a crosscheck

Testing our model on CMS simulation



Out of the box CMS reconstruction
not compatible with the model

Restoring the analytical model



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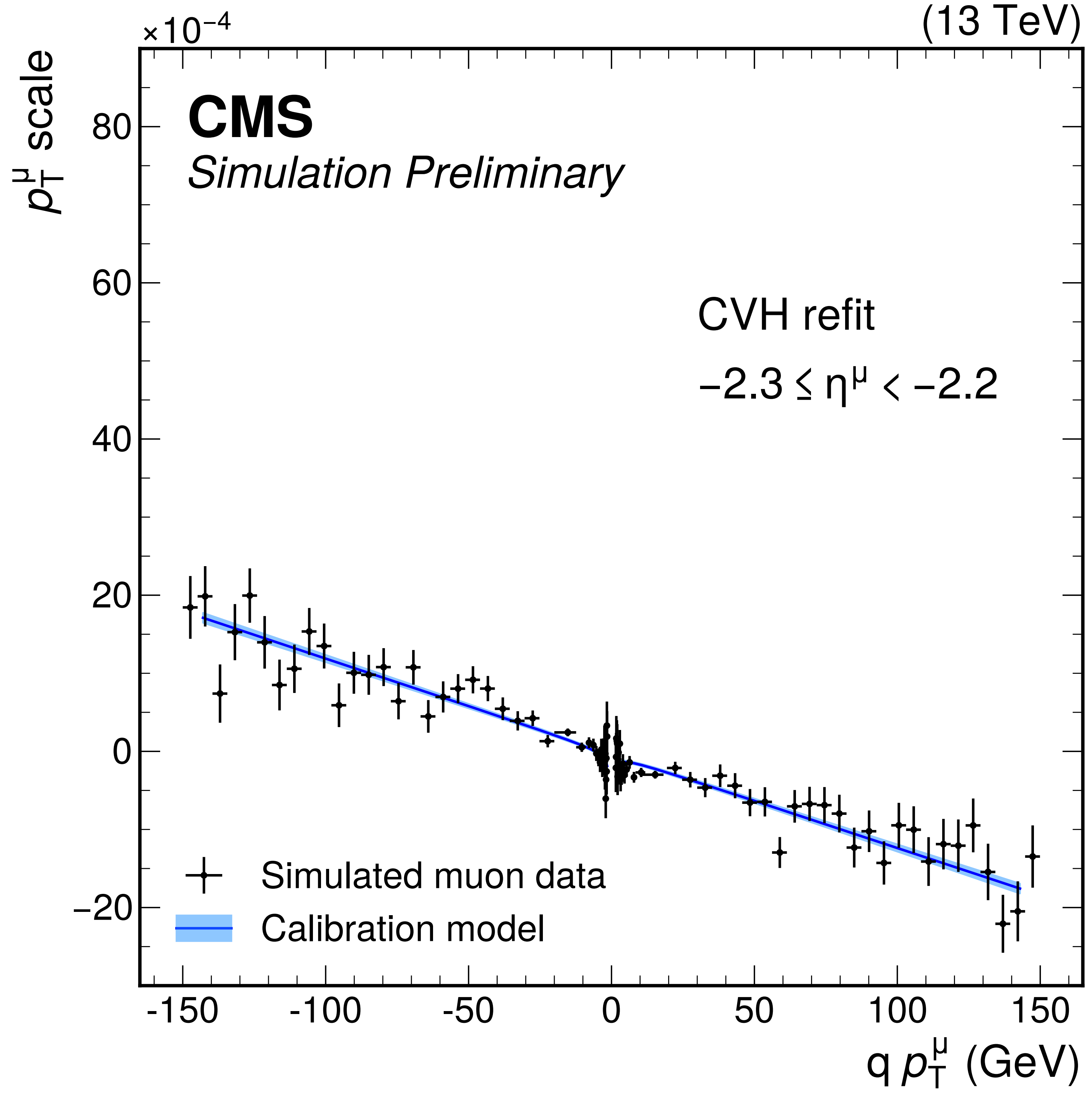
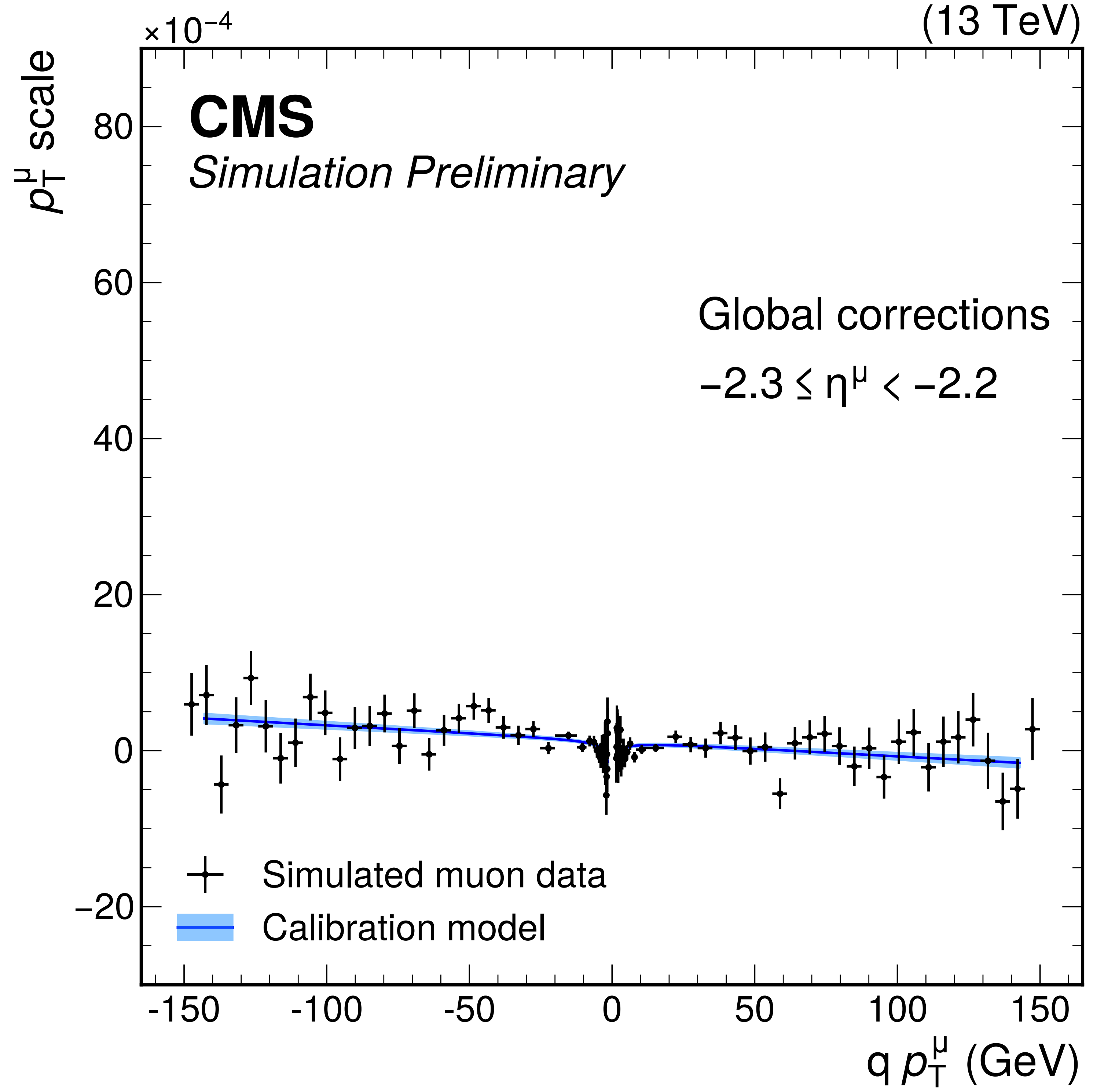
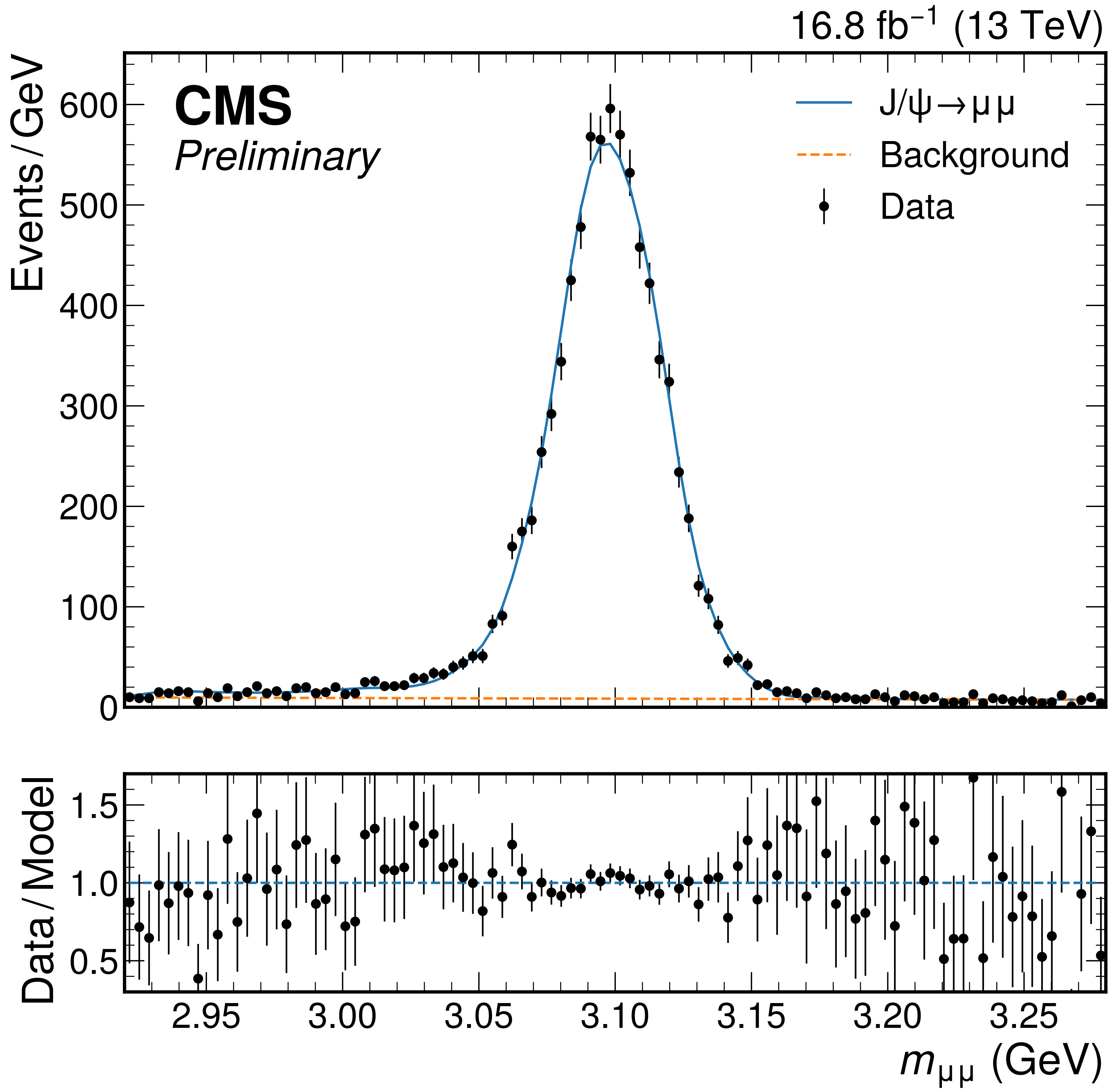


Add a new layer of track reconstruction on top of CMS reconstruction with refined treatment of magnetic field and material



Correct for local biases in the reconstruction

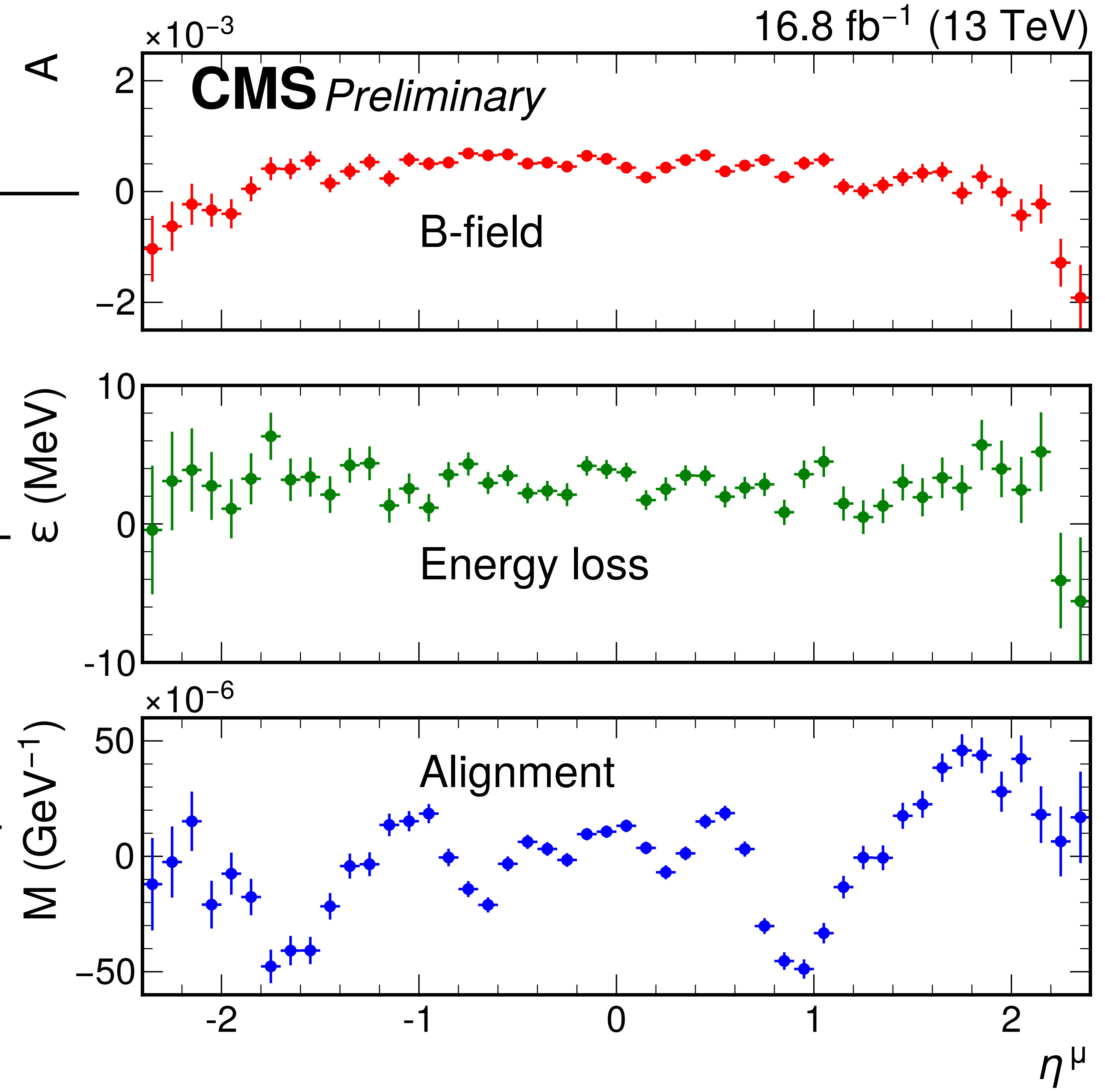
Extraction of calibration parameters



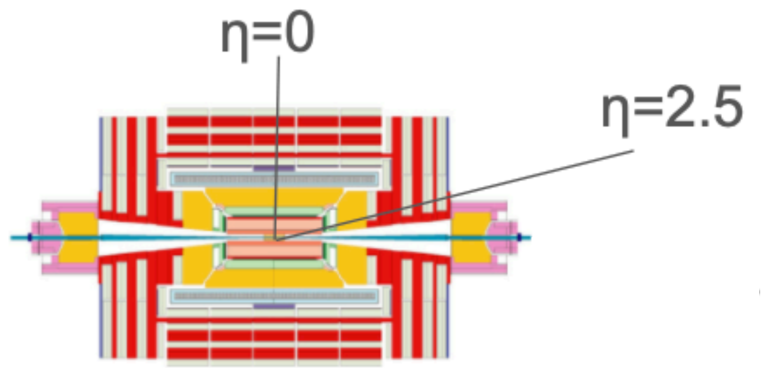
Magnetic field correction of ~40 gauss at the edge of the solenoid

Material correction of ~3.5 mm of iron

Silicon strip modules displacement of ~1-7 μm

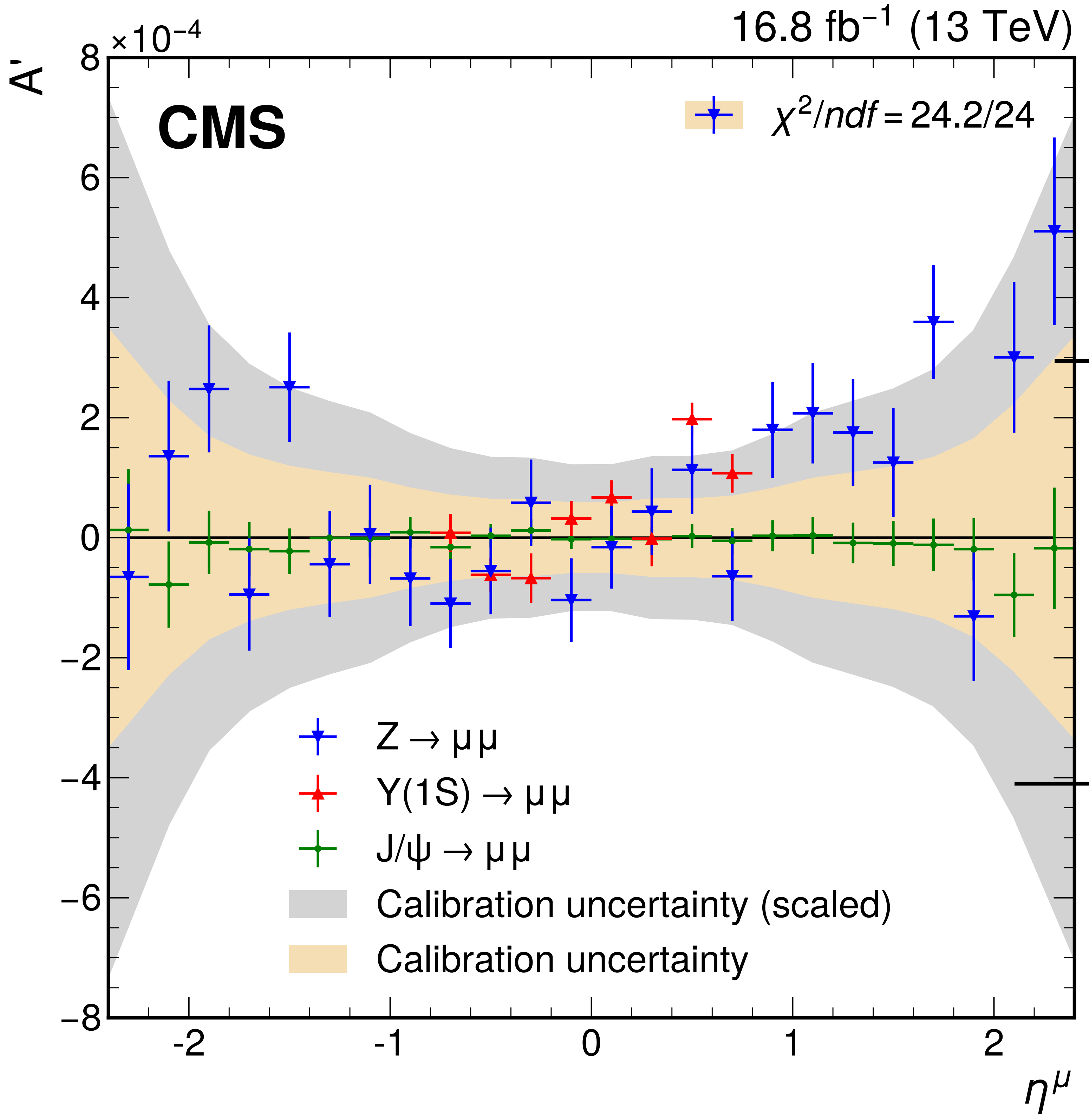


Extract corrections from thousands of fits of the J/ψ mass in all corners of the detector

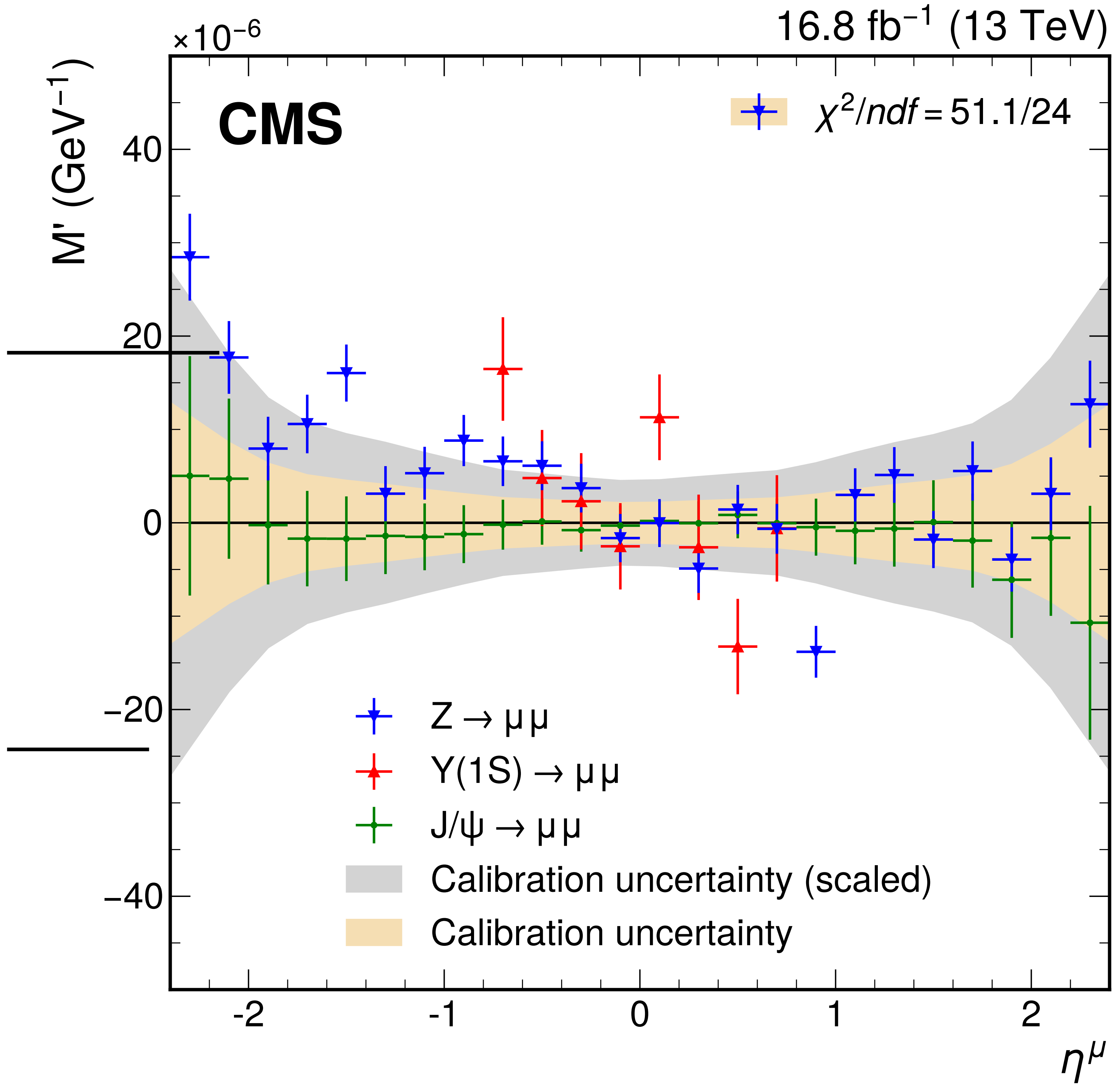


Assign systematic uncertainty

Charge independent “B-field like”



Charge dependent “alignment like”



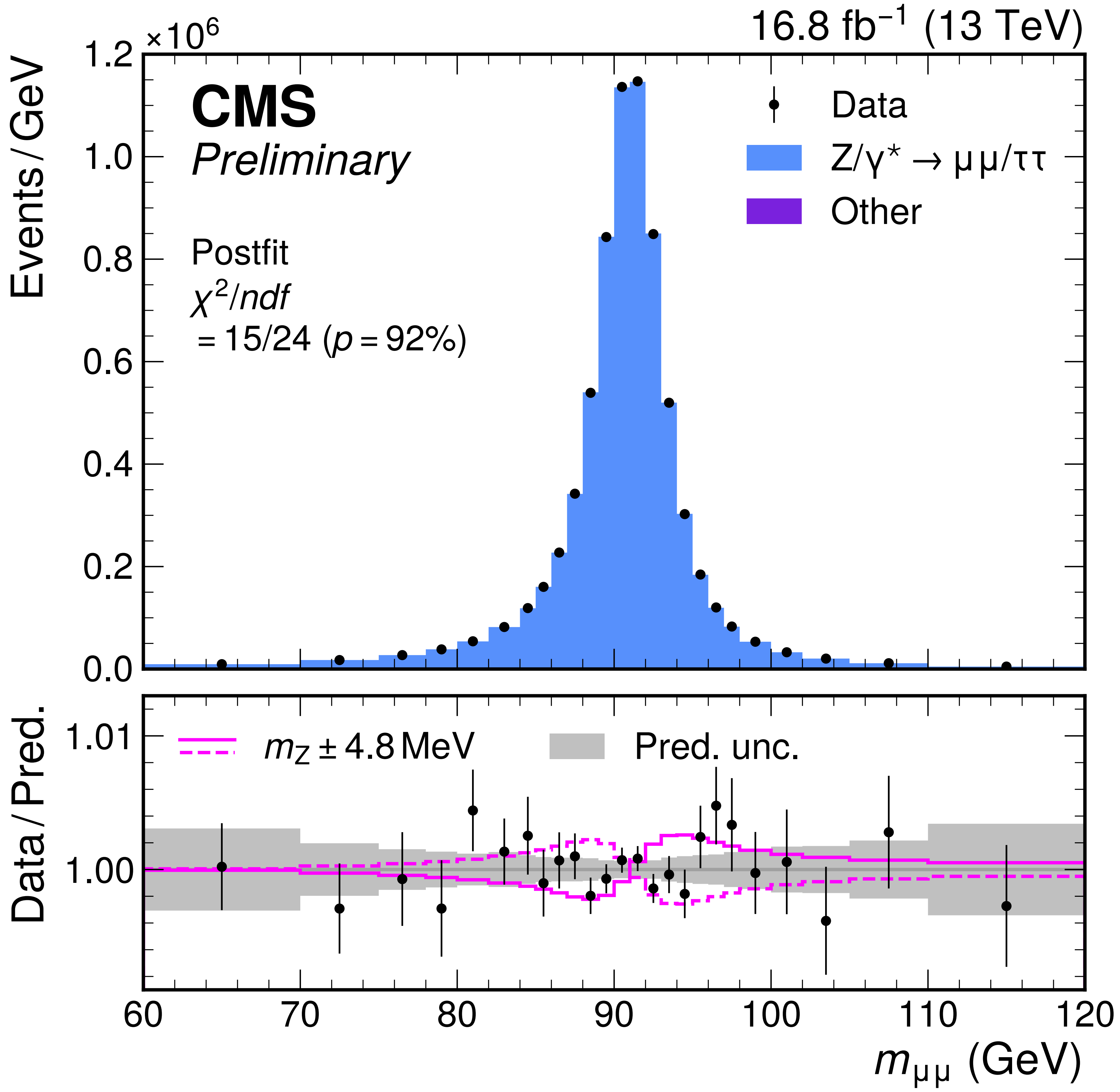
B-field-like term for Z is consistent with zero within statistical uncertainties, alignment-like almost so

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

Direct assessment of Z mass

Ultimate test of calibration and associated uncertainty

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



Challenges

2

Determine how the W boson was produced inside CMS in great detail

Since none of the quantities that are available are Lorentz invariant

W production and decay

This formula describes how W rapidity and q_T are connected to muon 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

Angular coefficients
encode W polarization

Spherical harmonics
encode W decay

Unpolarized cross section
Encodes W transverse momentum and rapidity

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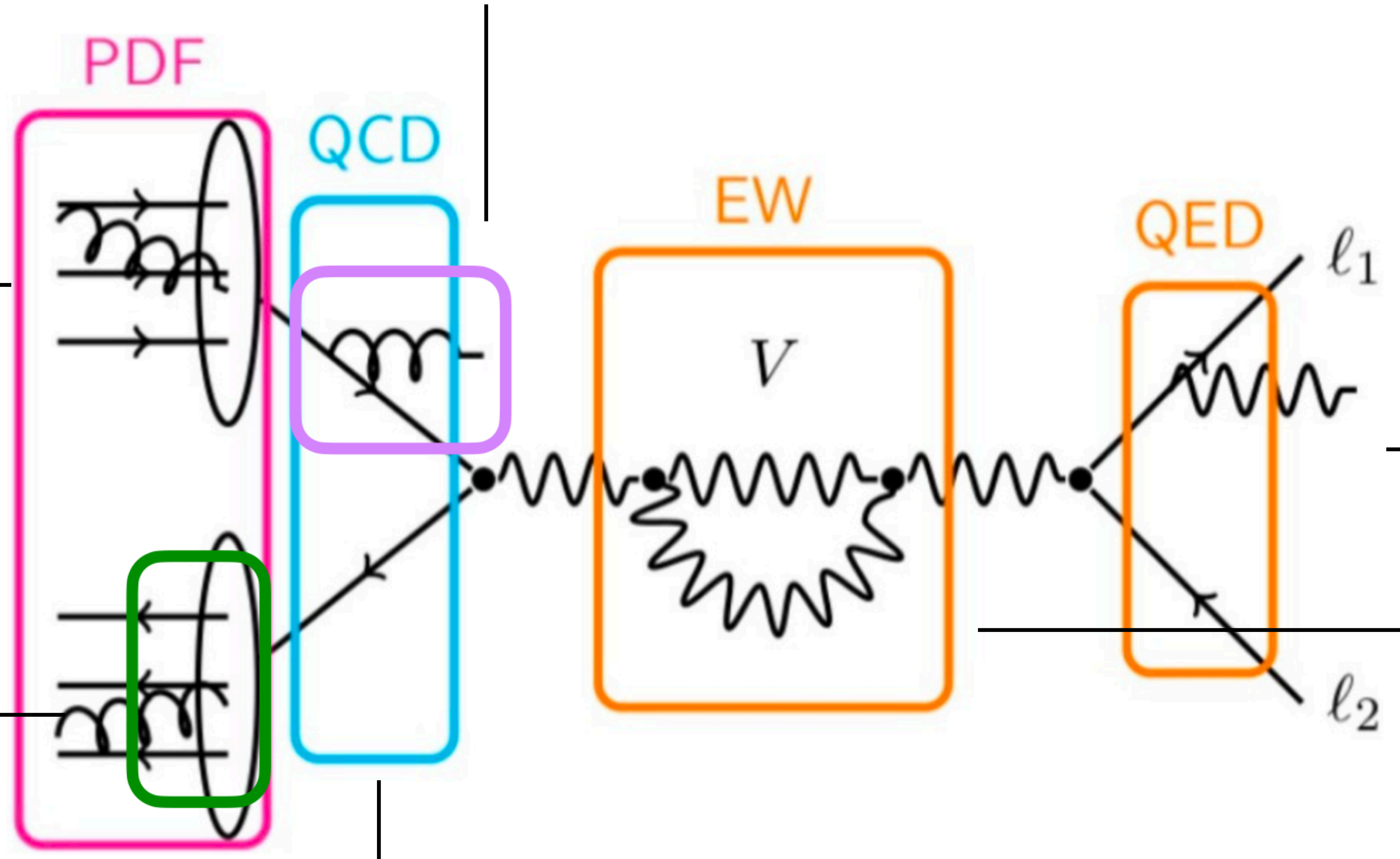
Modeling the W production



Resum soft gluons for low/ intermediate region

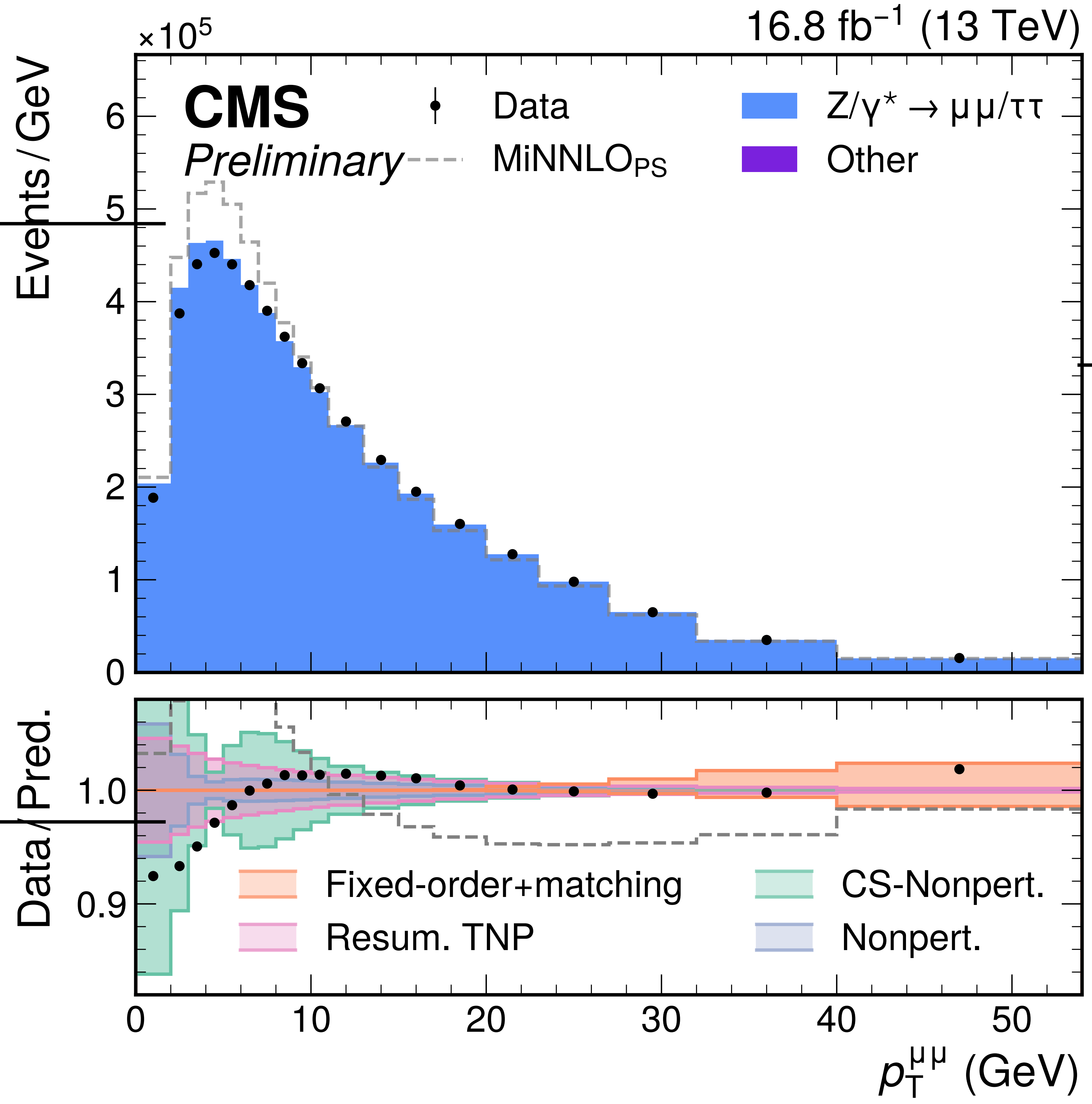
PDF determines quark flavour and momentum

Electroweak corrections small, but relevant impact

Non-perturbative motion of quarks important at low q_T

perturbative QCD describes high q_T

How well we model the W transverse momentum



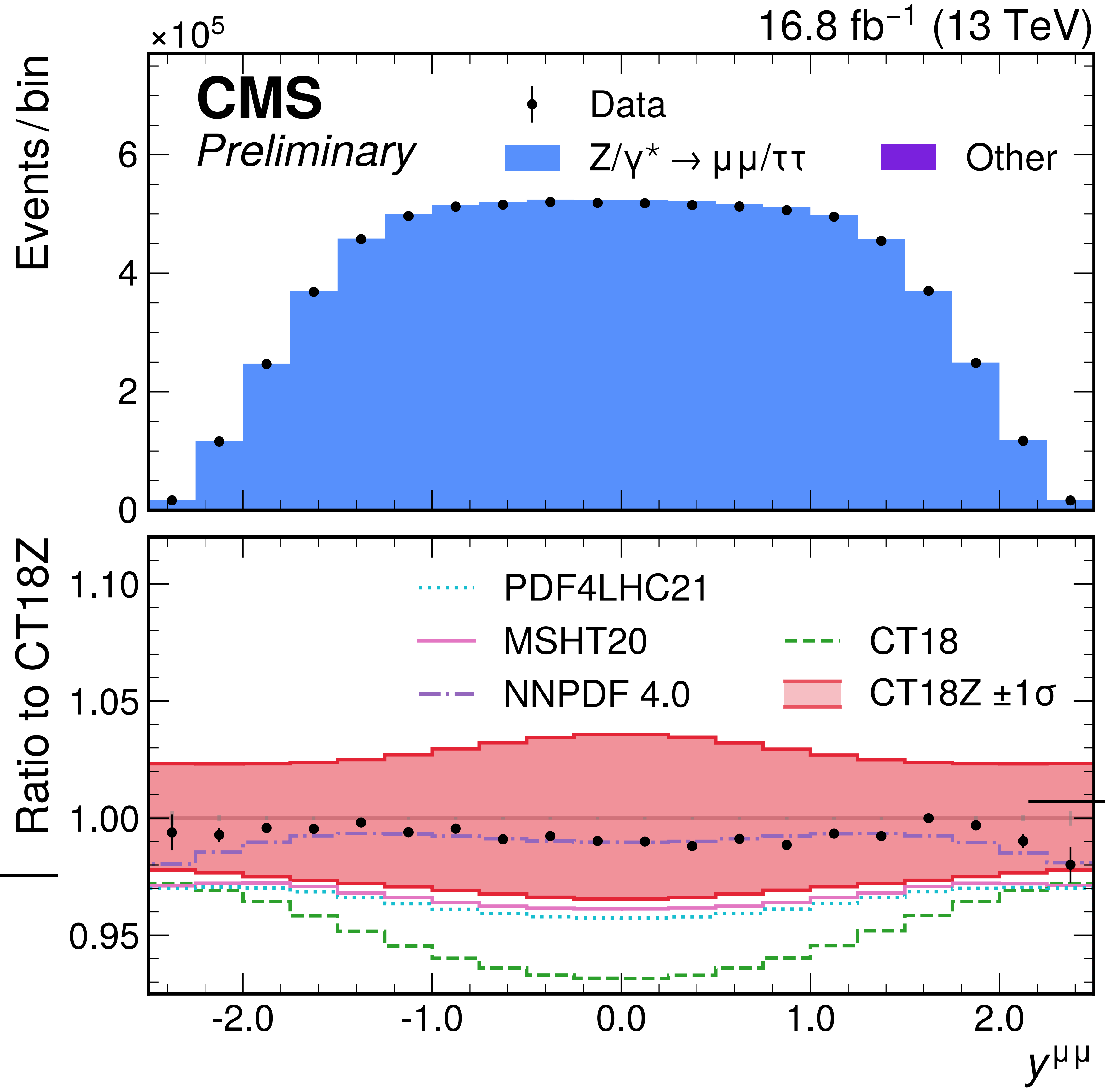
Huge Monte Carlo samples with full detector simulation (4B events) from MiNNLO$_{PS}$+Pythia+Photos is validated using Z events

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

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

How well we model the W longitudinal momentum

Z rapidity events in data and simulation using different PDF sets



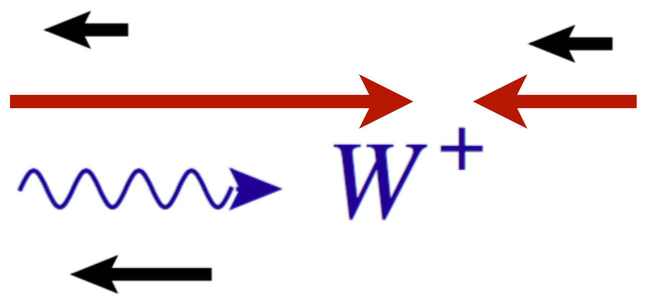
Different PDFs not necessarily agree among themselves

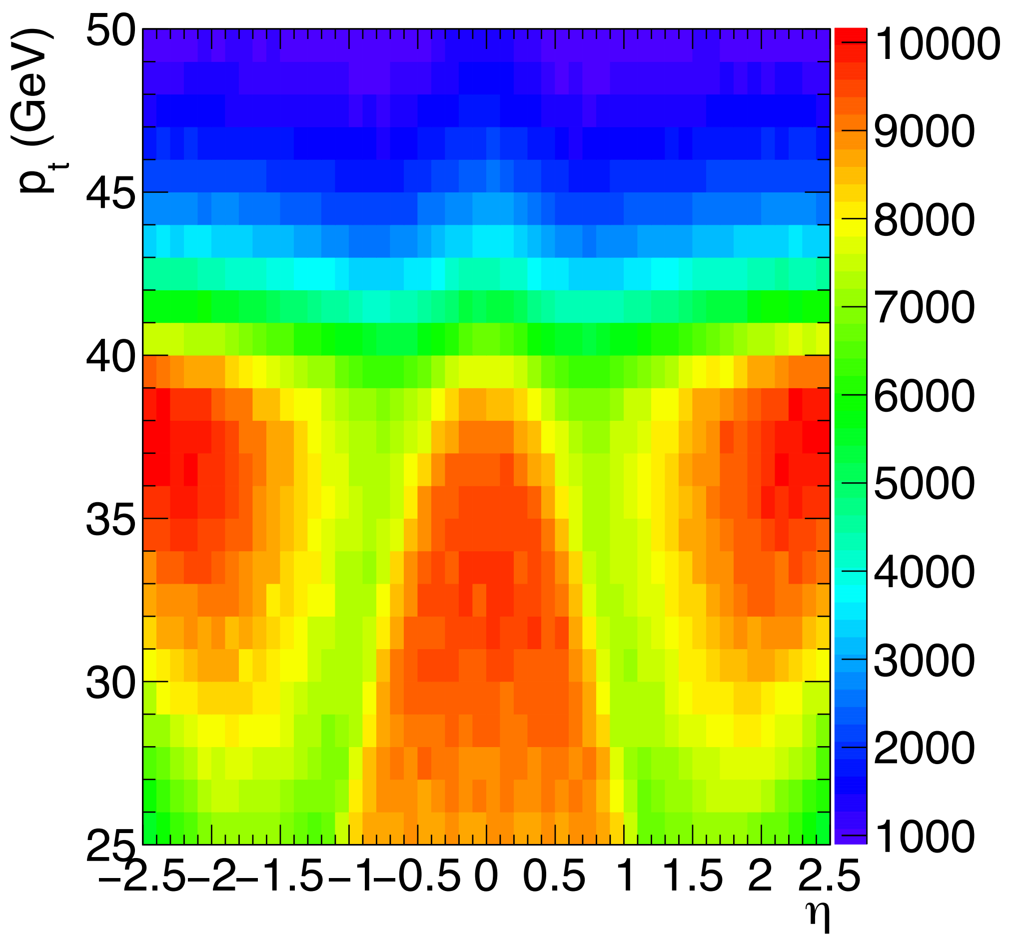
CT18Z is the PDF set chosen as central with its uncertainties because it has the flexibility to cover for all the others when measuring the W mass

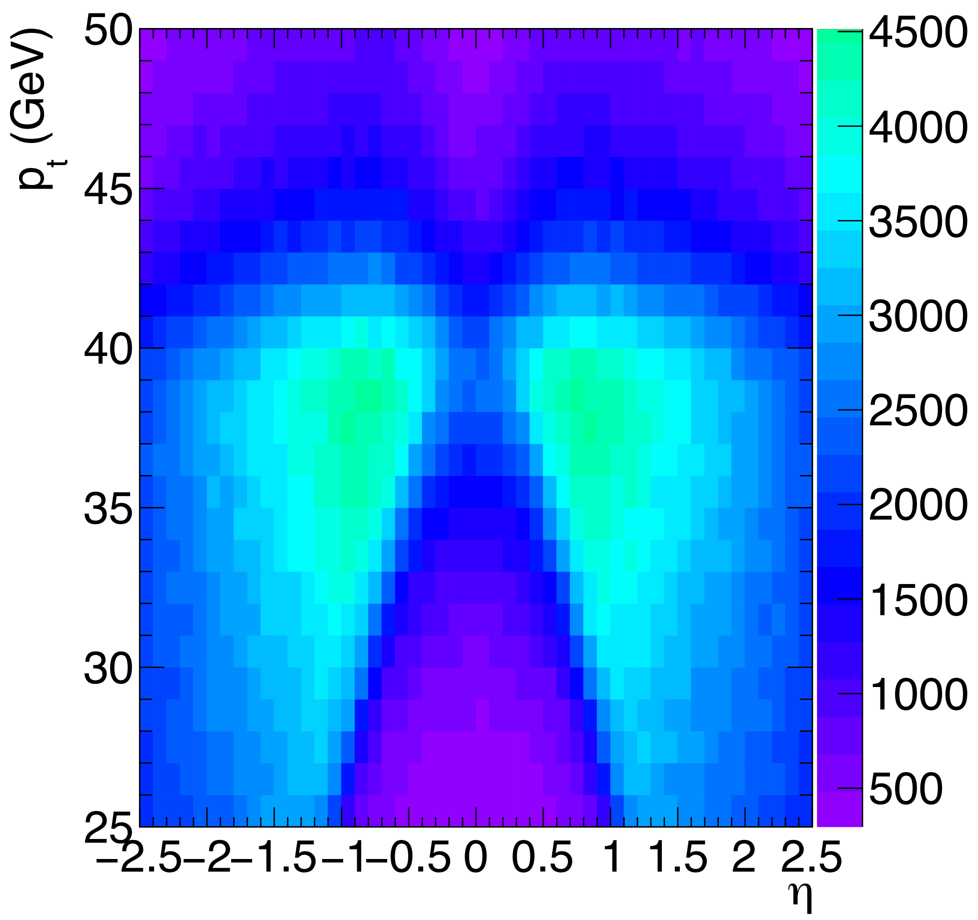
Sensitivity to the W polarization

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

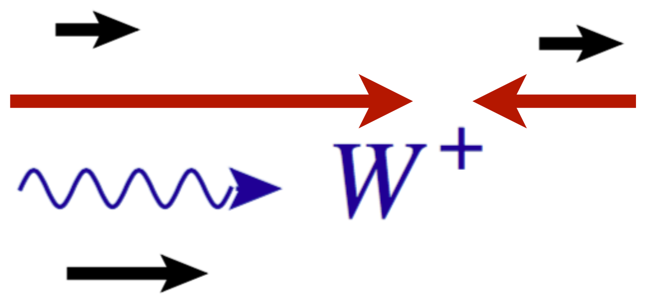
a left-handed W+

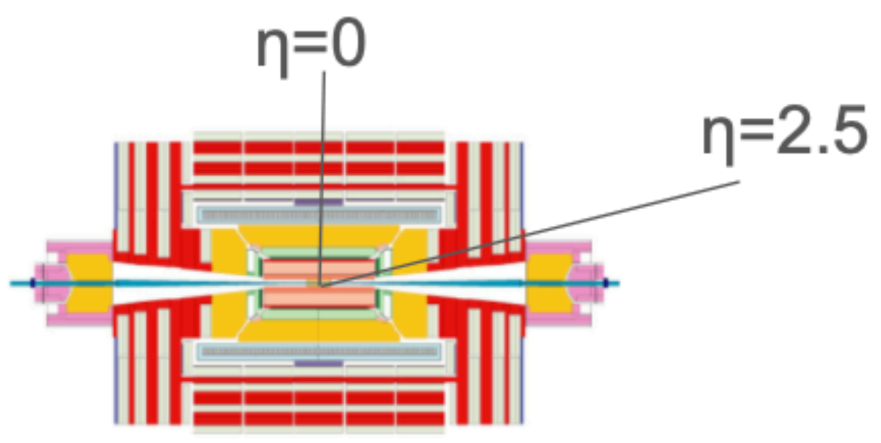






a right-handed W+





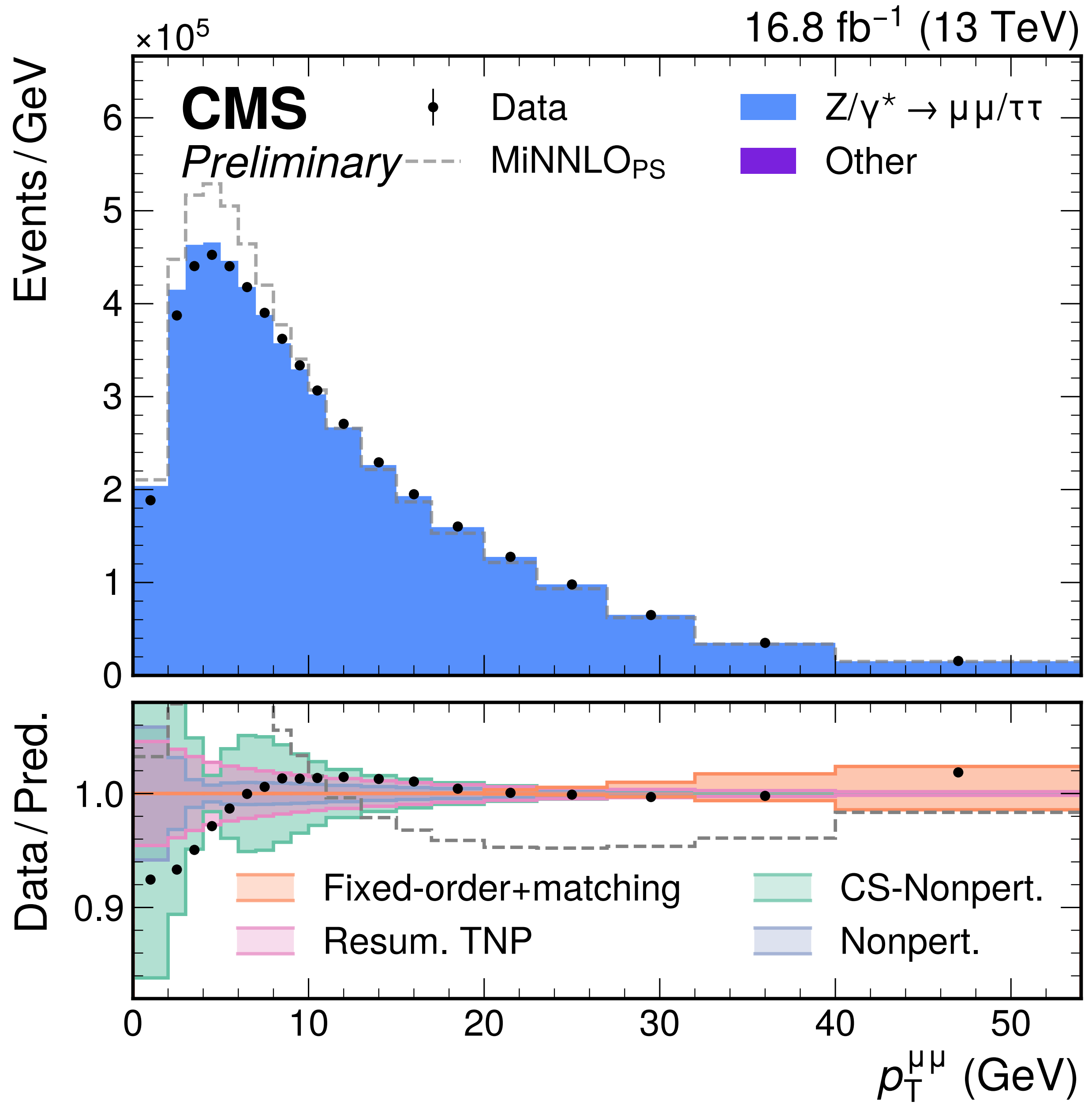
E.M. et al. J. High Energ. Phys. (2017) 2017: 130.

E.M. CERN-THESIS-2021-271

Phys. Rev. D 102 (2020) 092012

How to determine the W transverse momentum

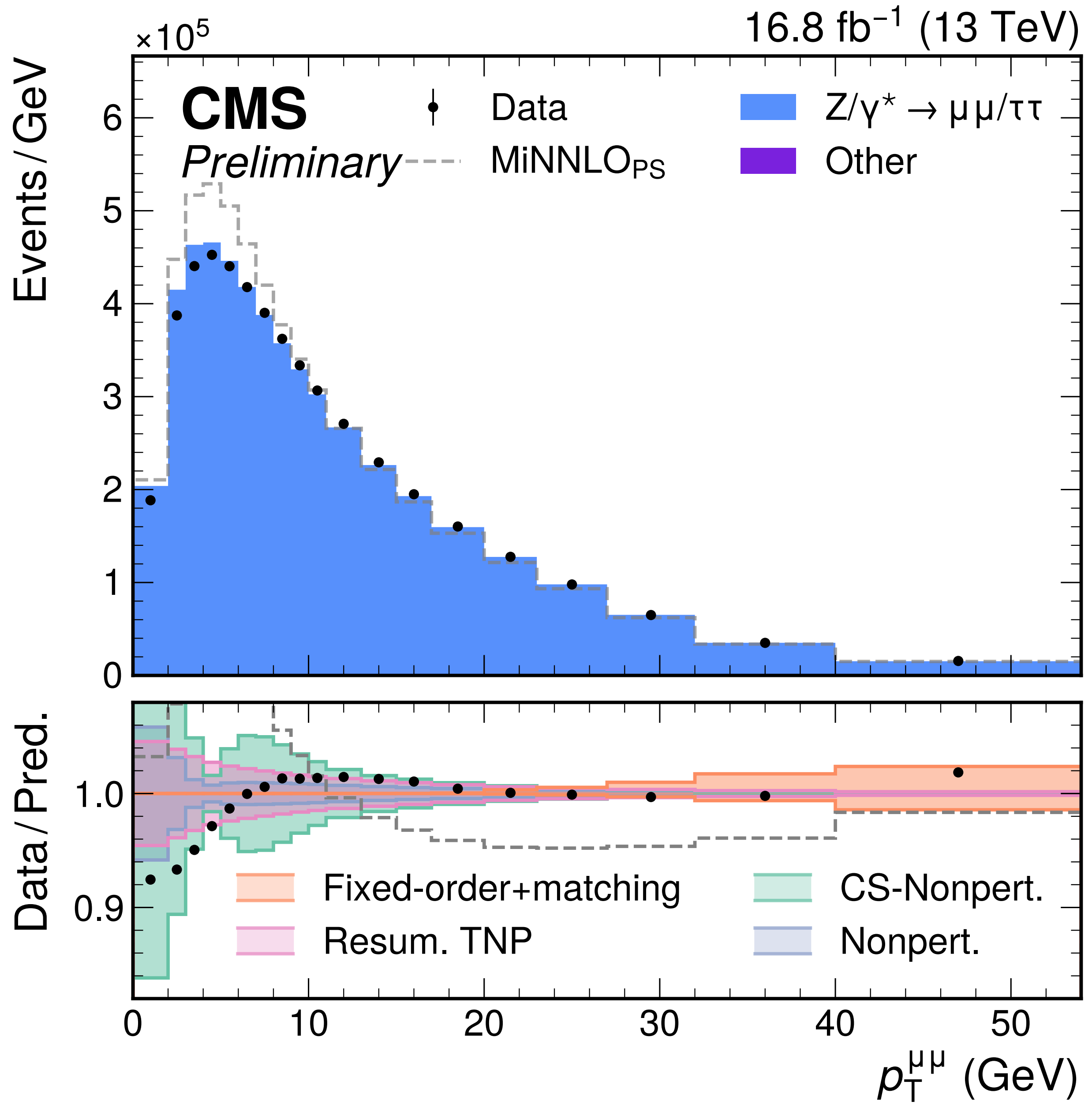
“Traditional”



Use the parameters of the model to maximize the agreement on Z and use the same value of the parameters on W simulation

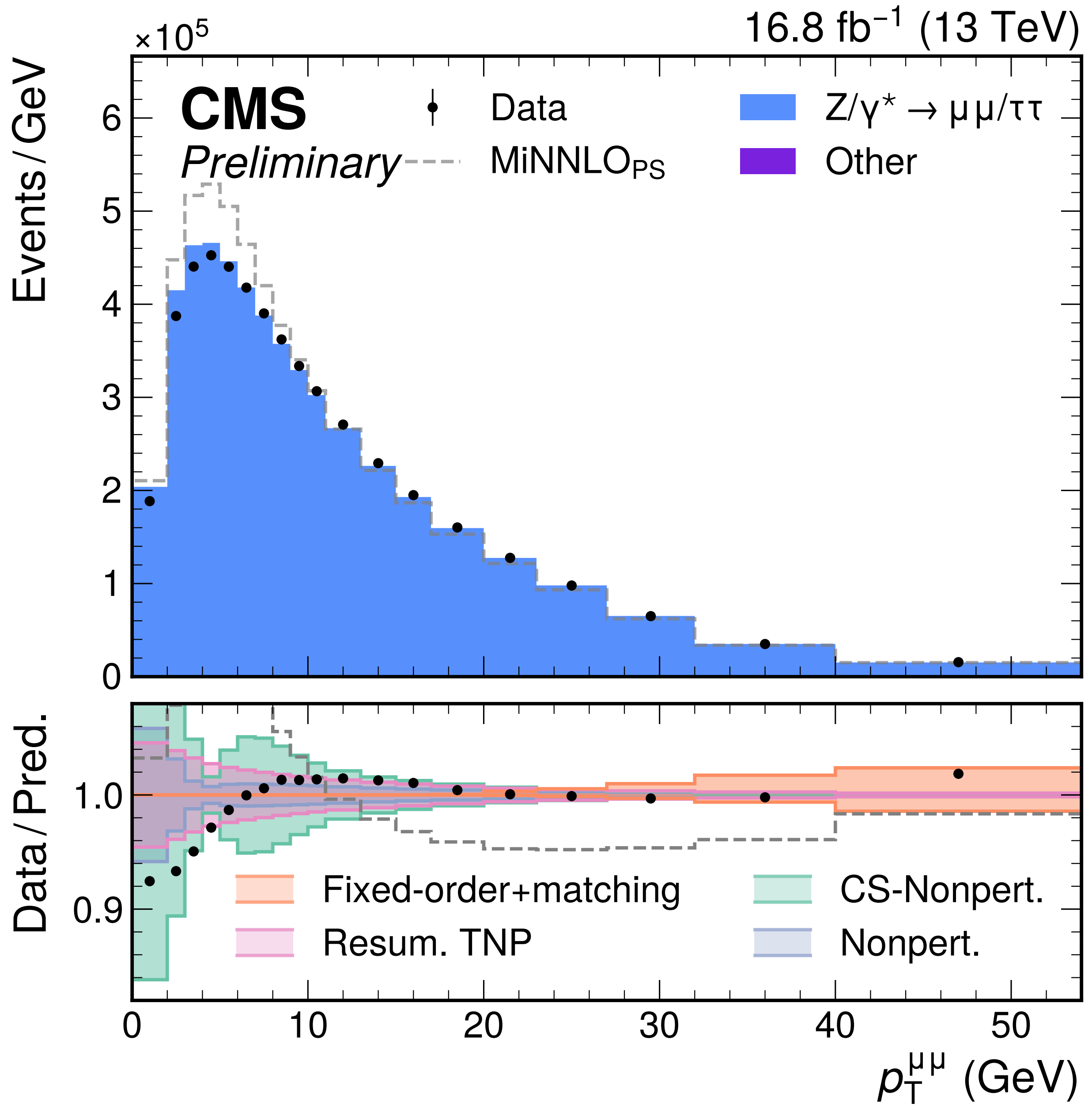
How to determine the W transverse momentum

“Traditional”



Use the parameters of the model to maximize the agreement on Z and use the same value of the parameters on W simulation

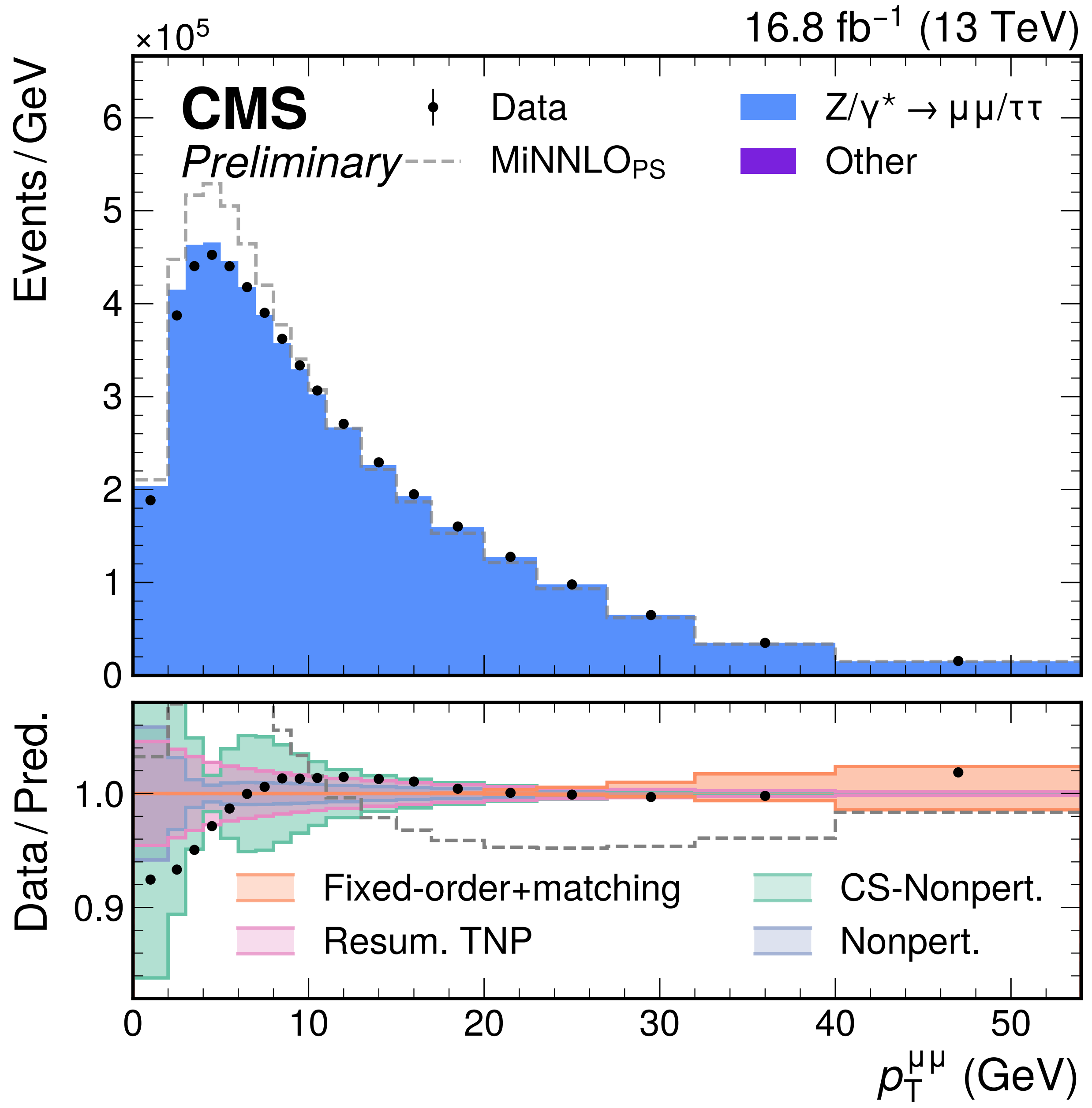
Theoretical model with in-situ constraints



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

How to determine the W transverse momentum

“Traditional”



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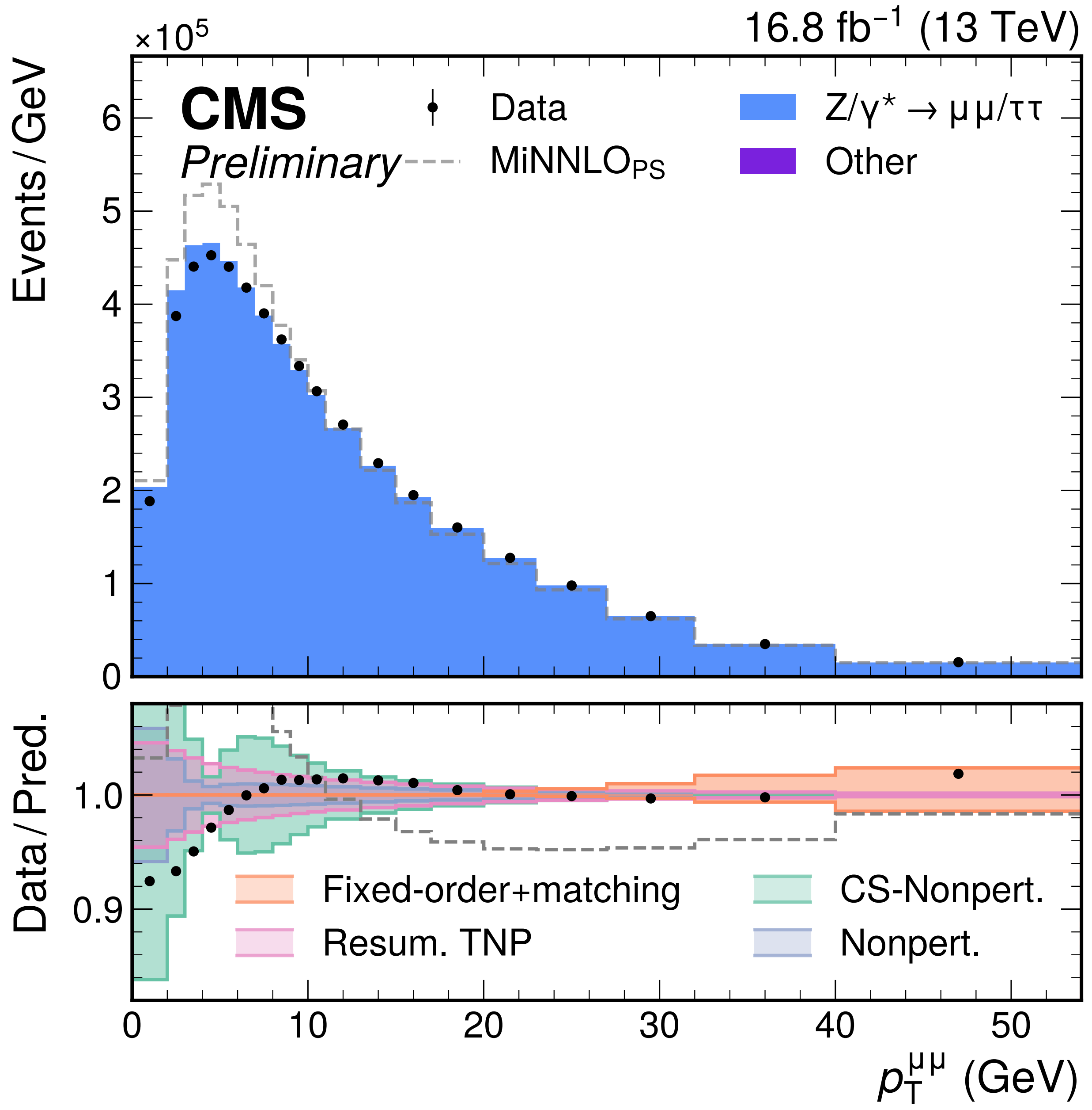


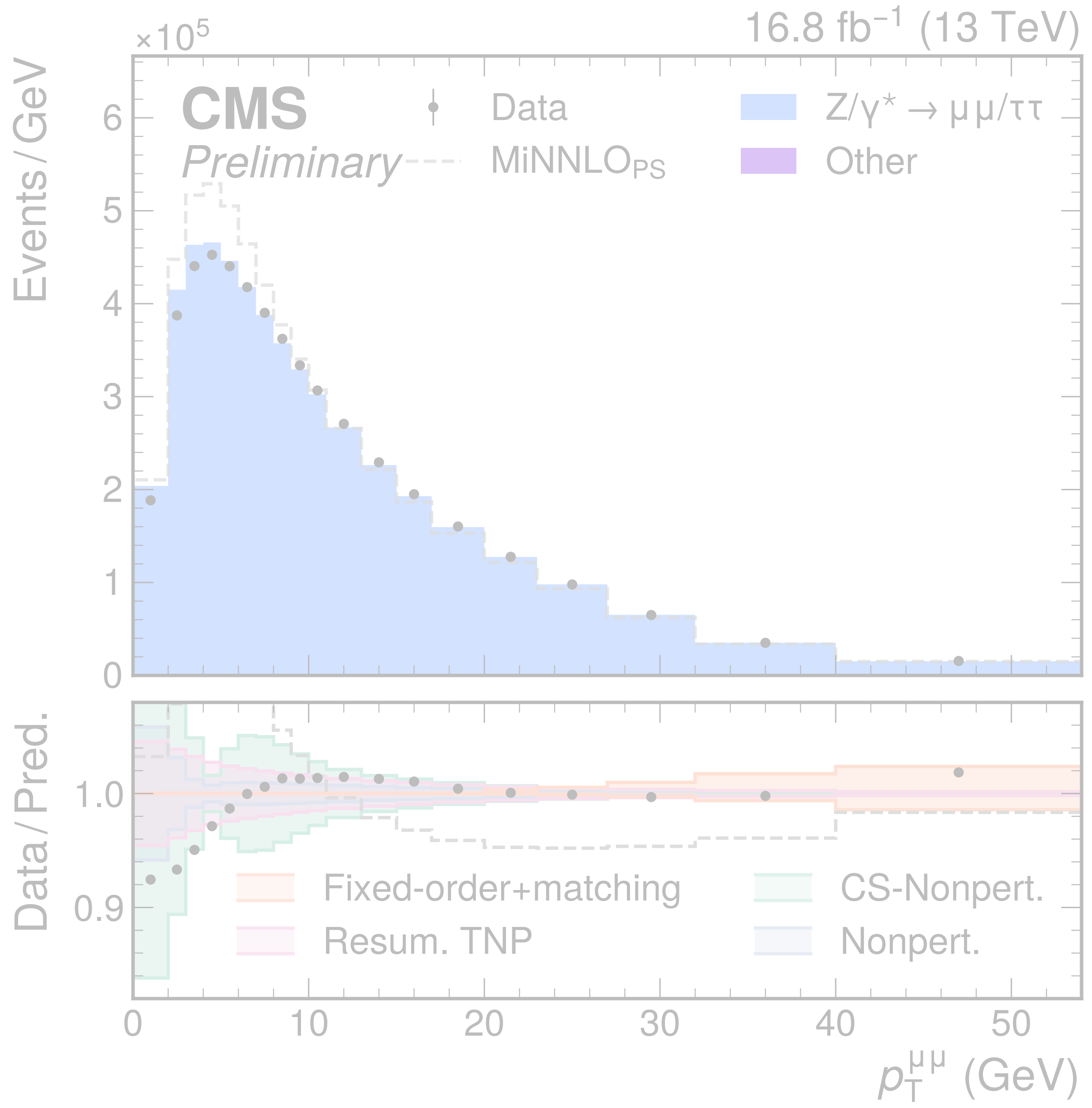
Use constraining power of the data to adjust the value of the parameters of the model while fitting for the W mass

Inferred from data

Exploit the full constraining power of the data to determine the W production while measuring the W mass relaxing the dependence from a specific model

How to determine the W transverse momentum

“Traditional”



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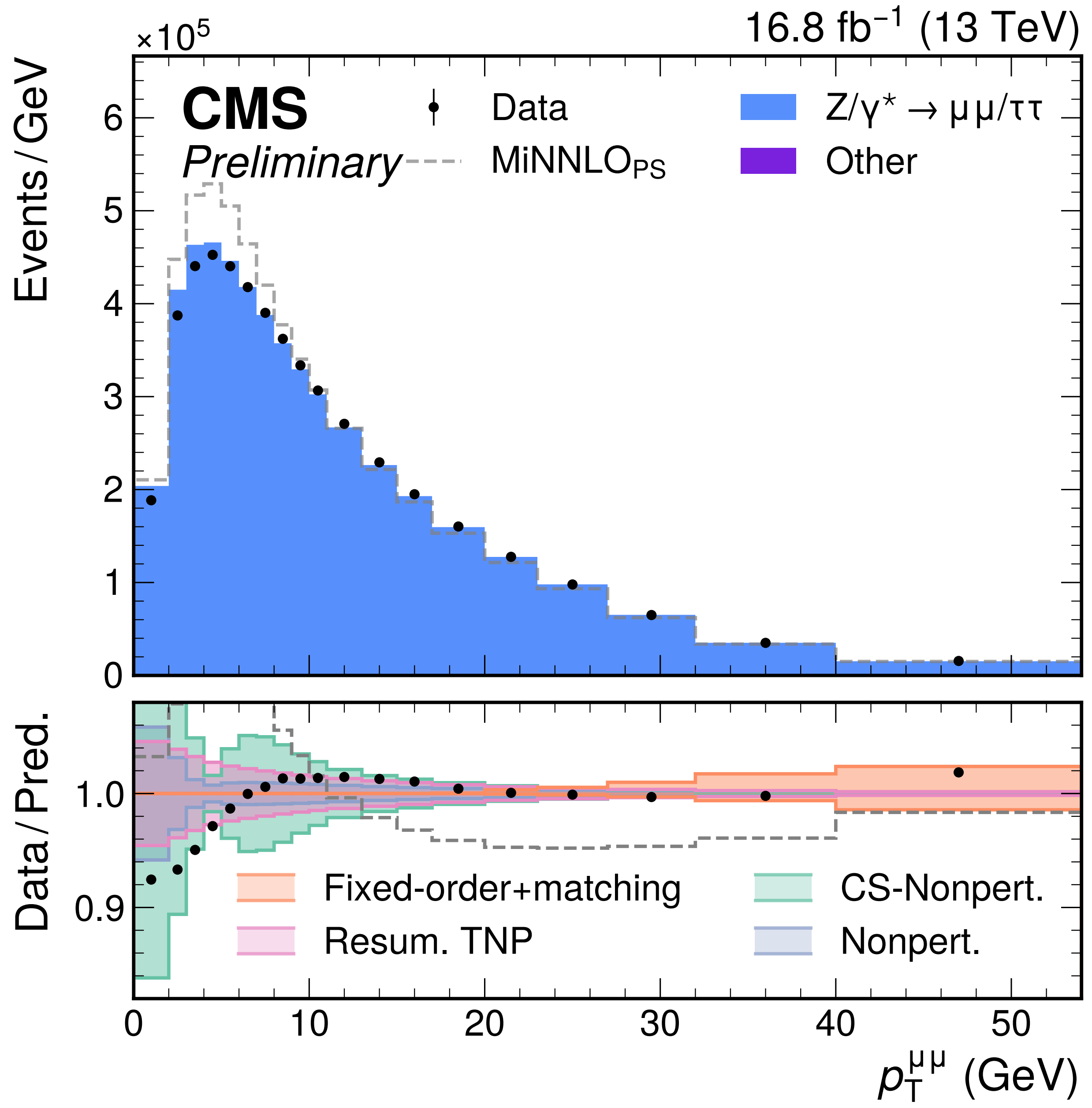

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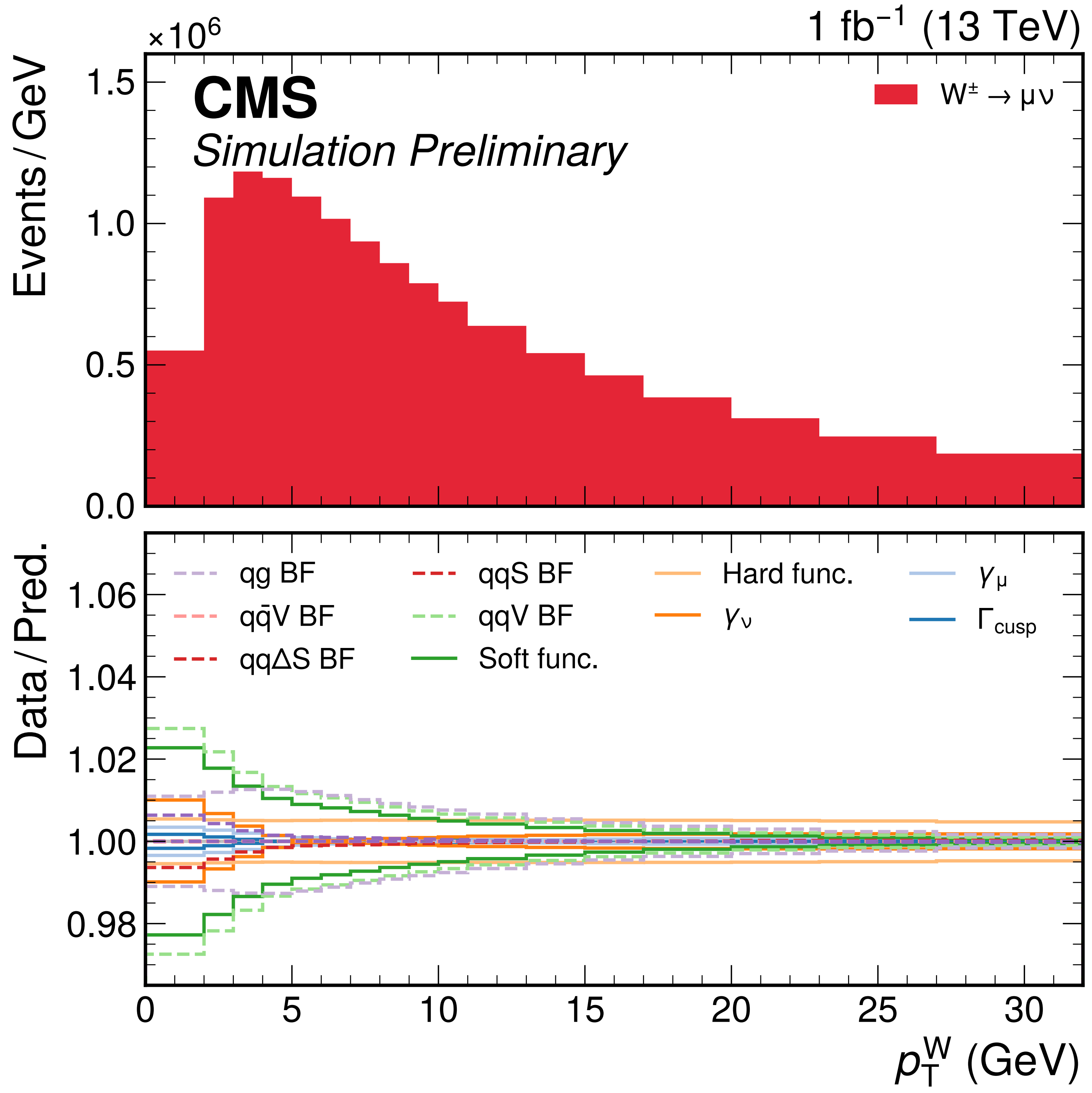
Inferred from data

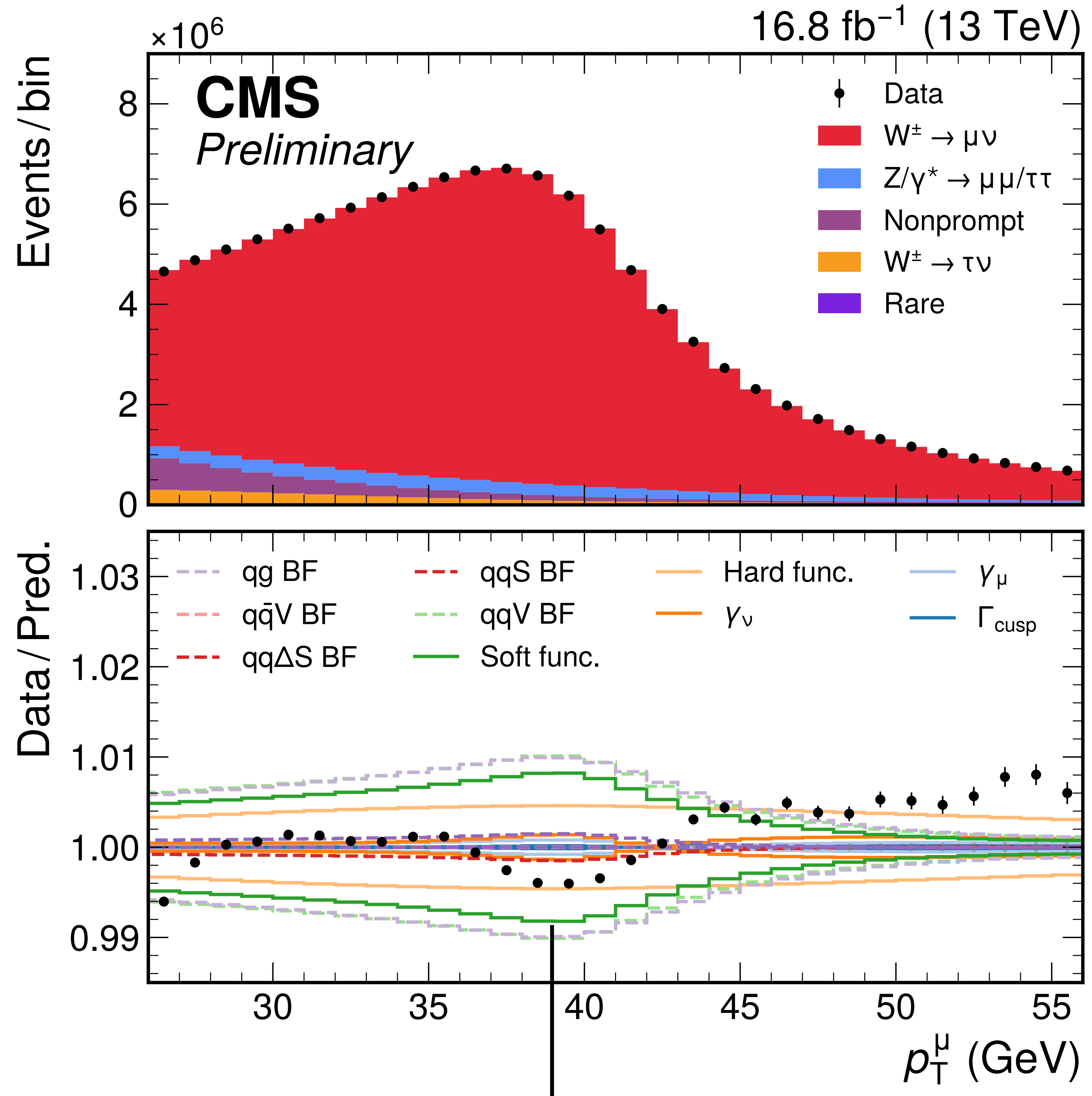
Exploit the full constraining power of the data to determine the W production while measuring the W mass relaxing the dependence from a specific model

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



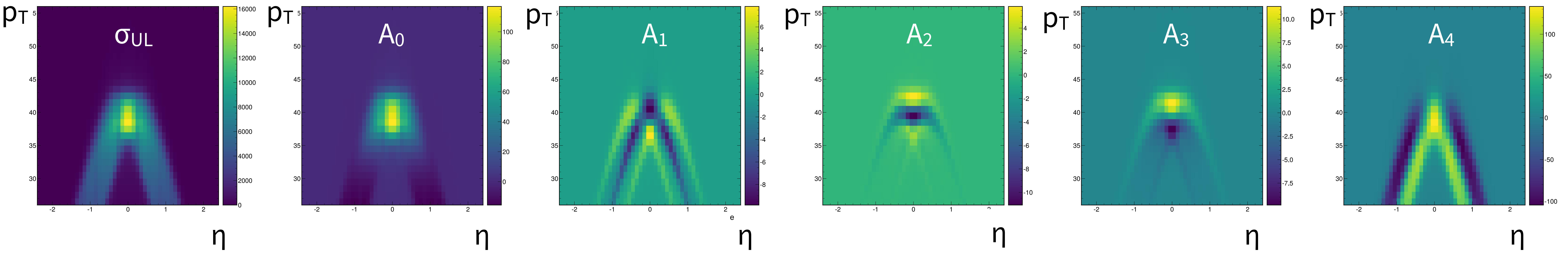
Let data choose the preferred curve

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



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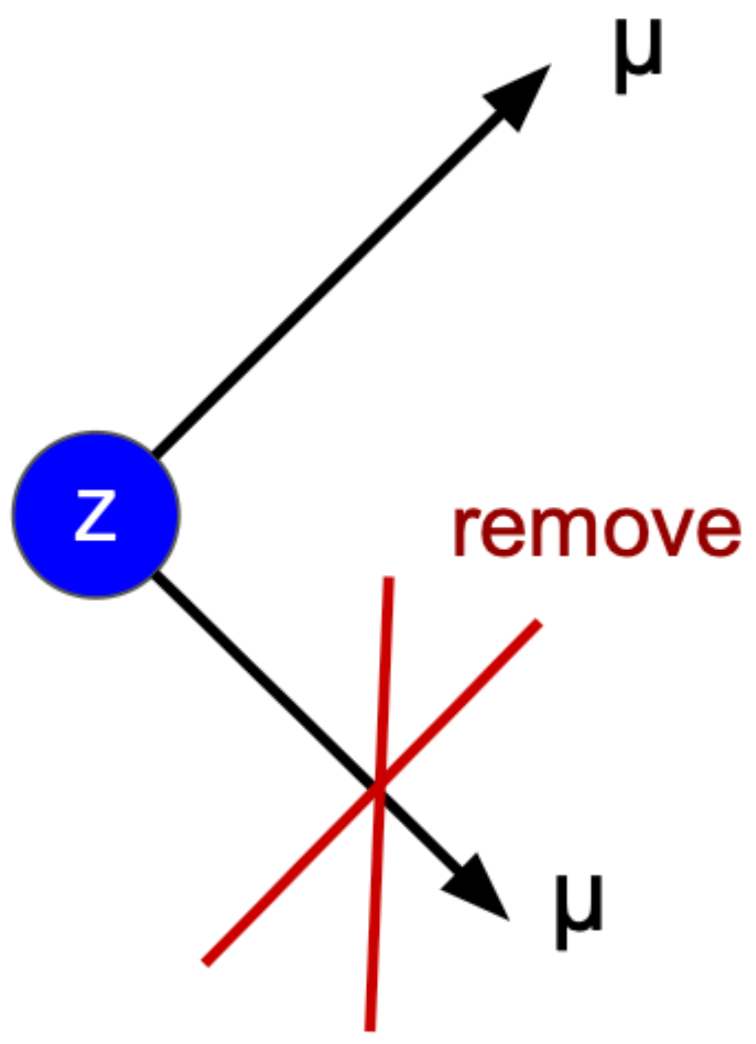
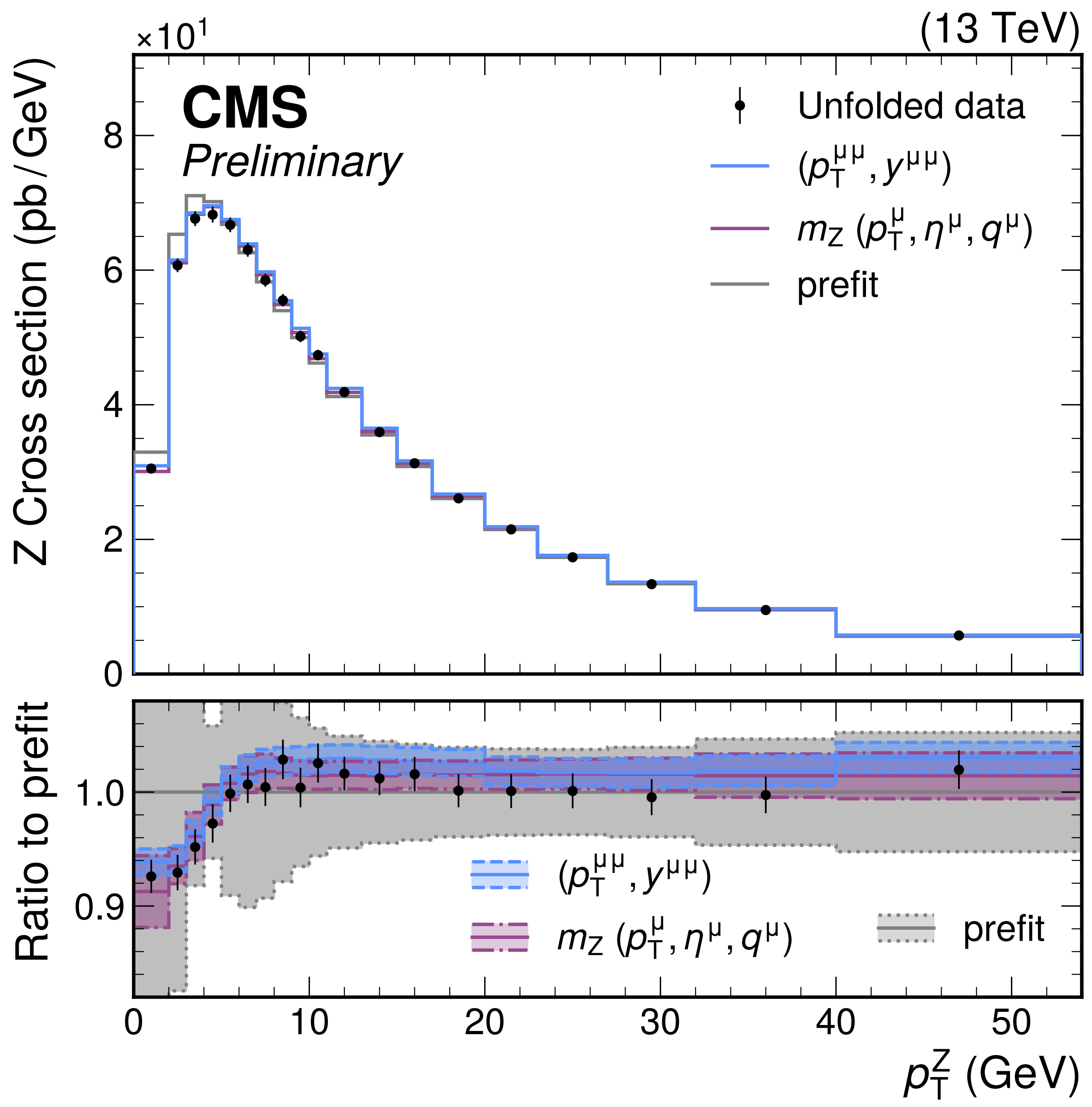
Does the procedure work? The “W-like” analysis

By treating one of the muons as a neutrino, we can construct a “W-like” event to test if the analysis works



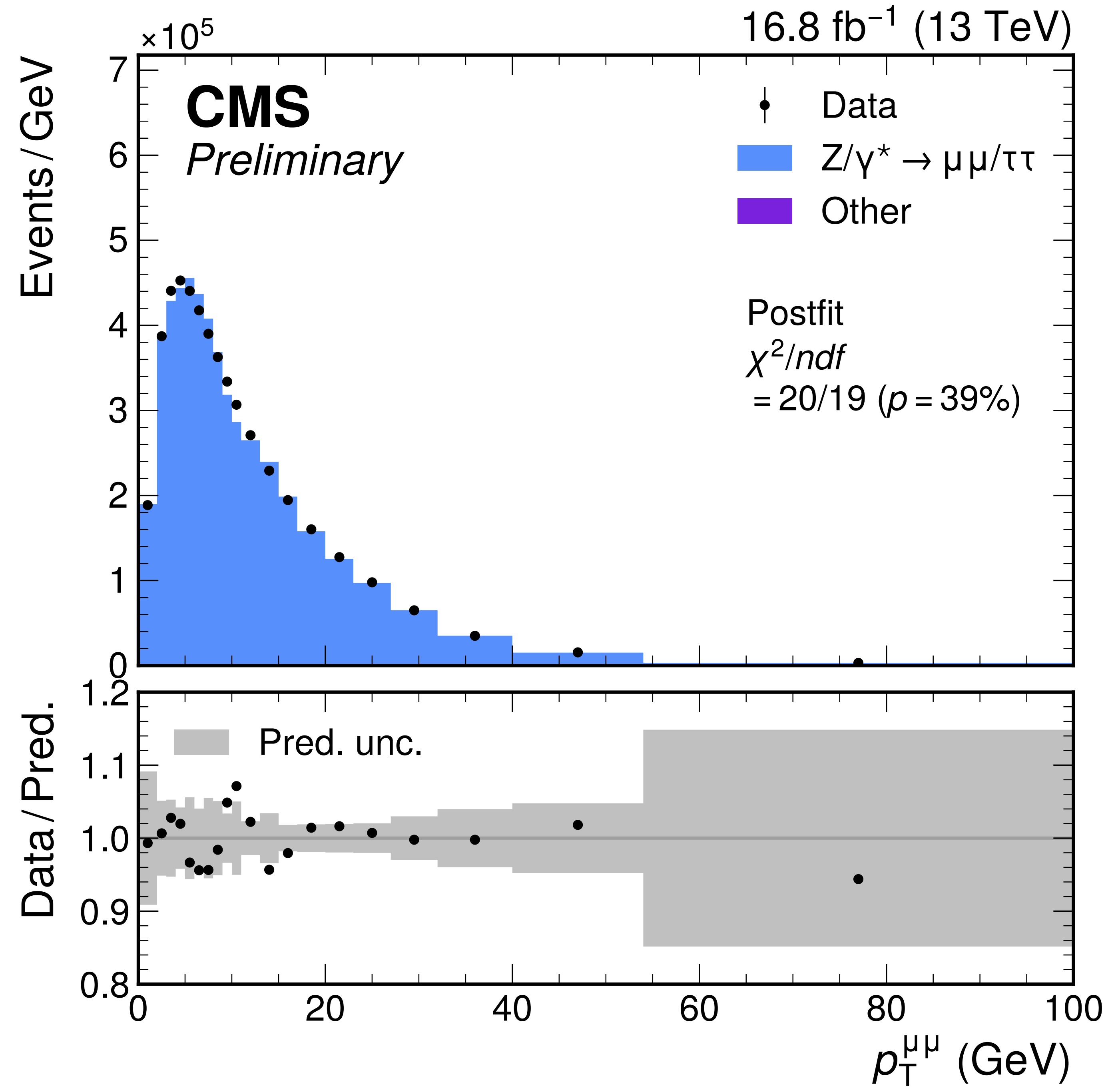
Theory Nuisance Parameters

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



Helicity Fit

$m_Z - m^{PDG}_Z = -4 \pm 14$ MeV



Putting all together

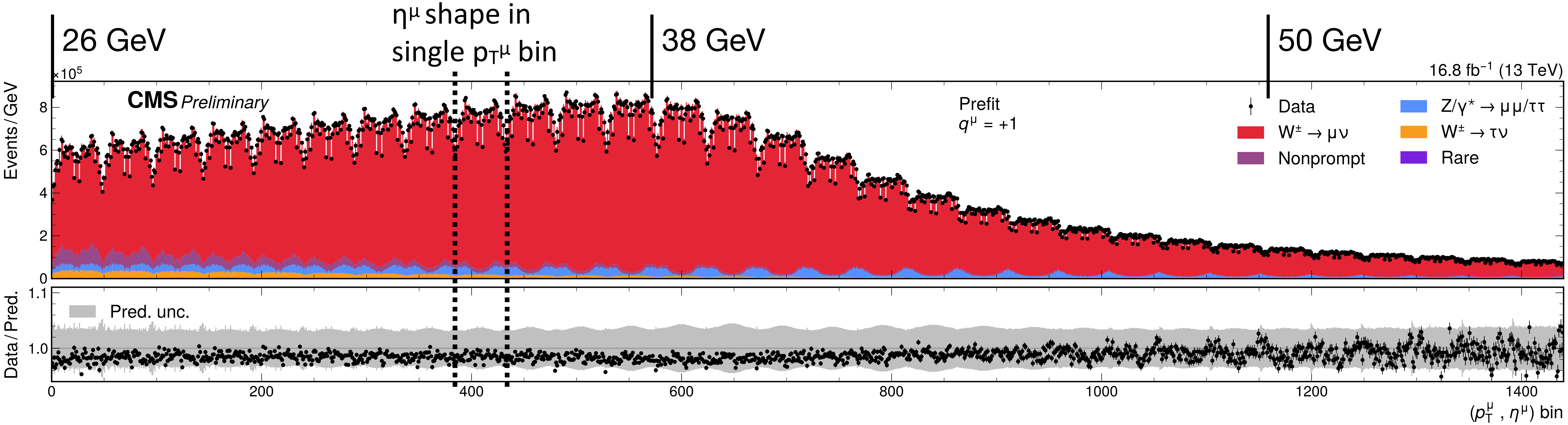
Dataset used is a fraction of 2016 corresponding to 16.8 fb^{-1} , O(100 M) W analyzed

Muon transverse momentum and η distribution unrolled in one dimension

Fit 1440 bins per charge and ~5k systematic variations

Technical details about the software used

Example for positive charge (1440 p_T^μ-η^μ bins)
48 η^μ bins in [-2.4, 2.4] x 30 p_T^μ bins in [26, 56] GeV



26 GeV

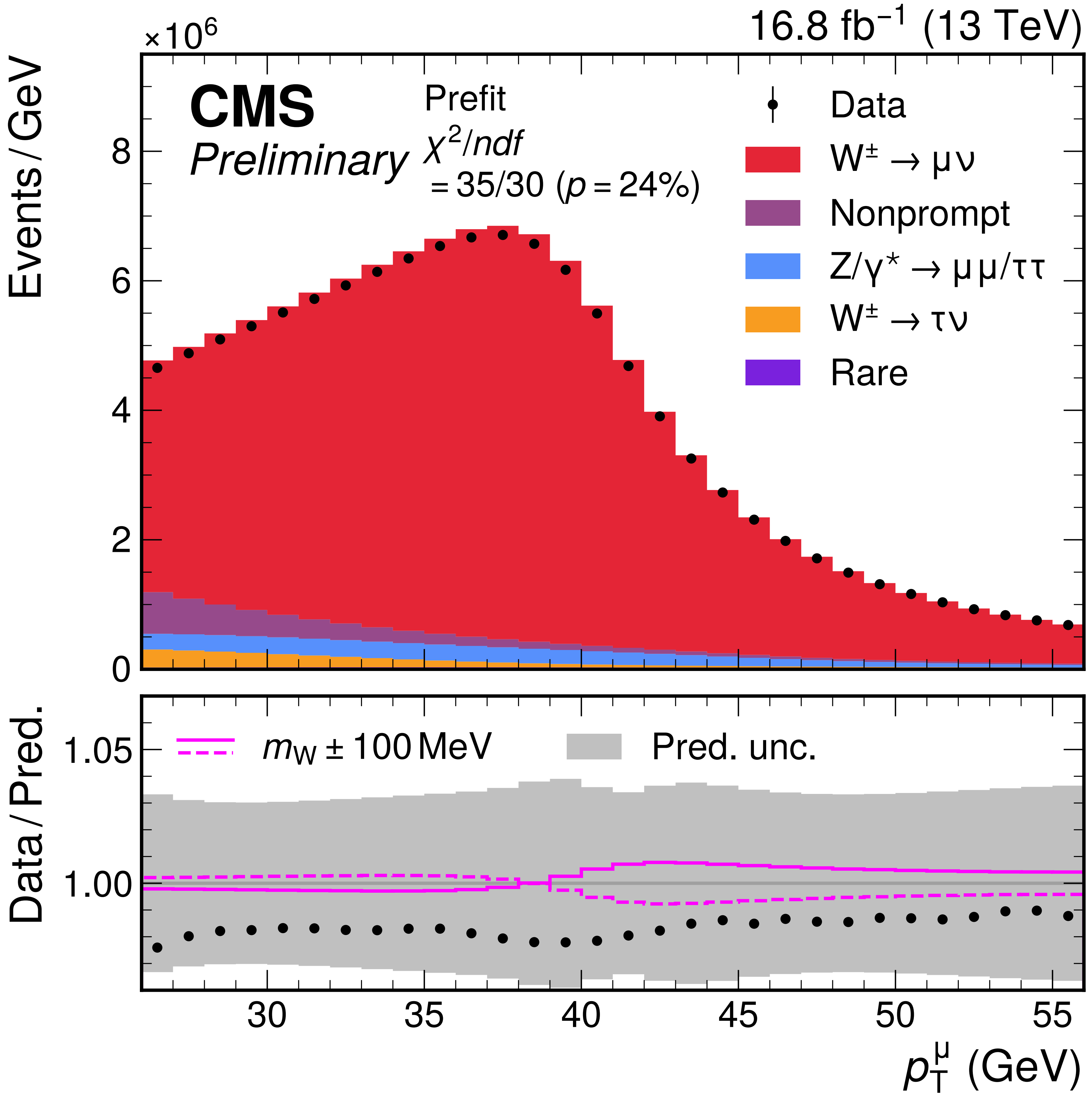
η^μ shape in single p_T^μ bin

38 GeV

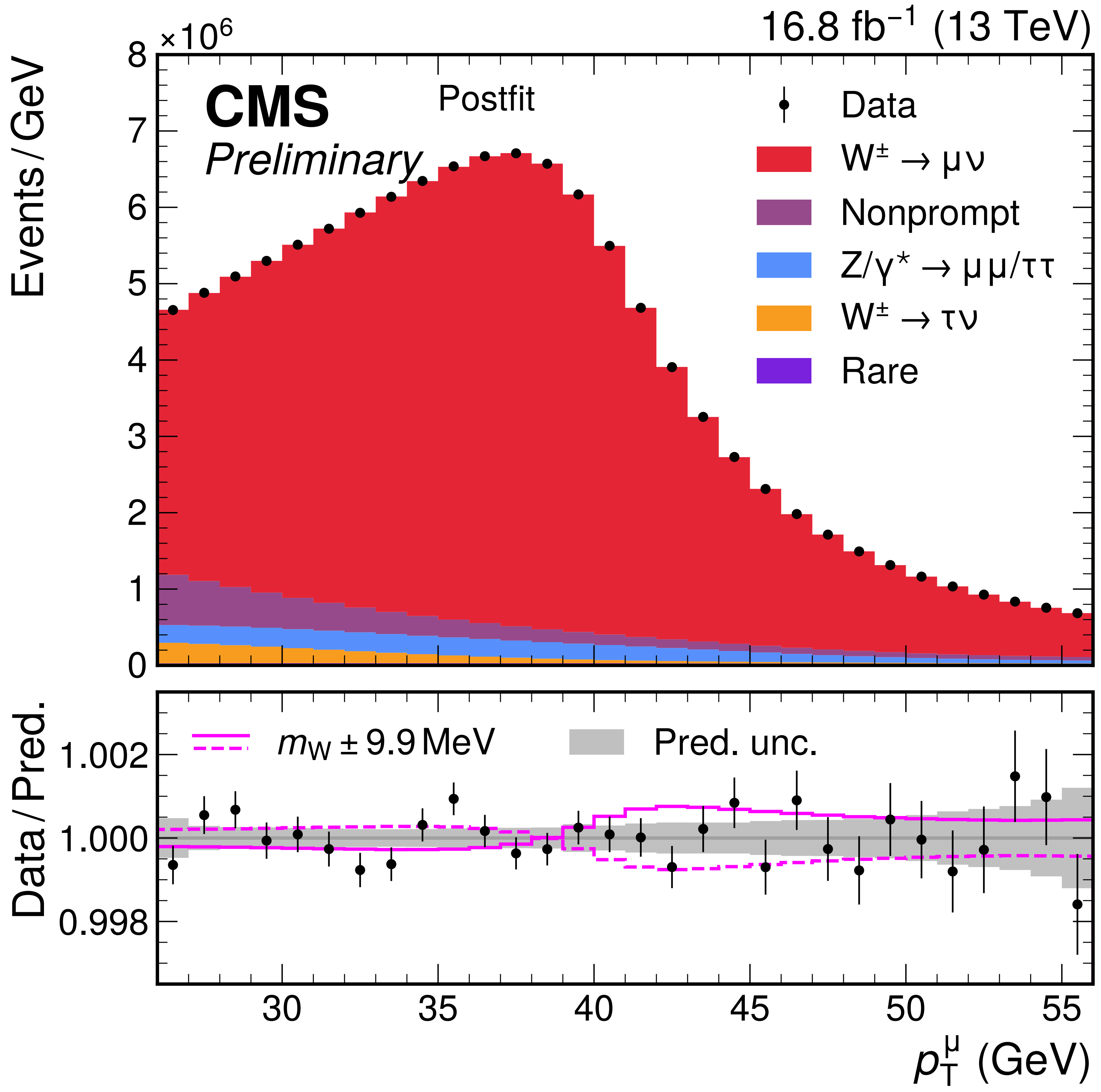
50 GeV

Distributions before and after the fit

Muon transverse momentum before the fit

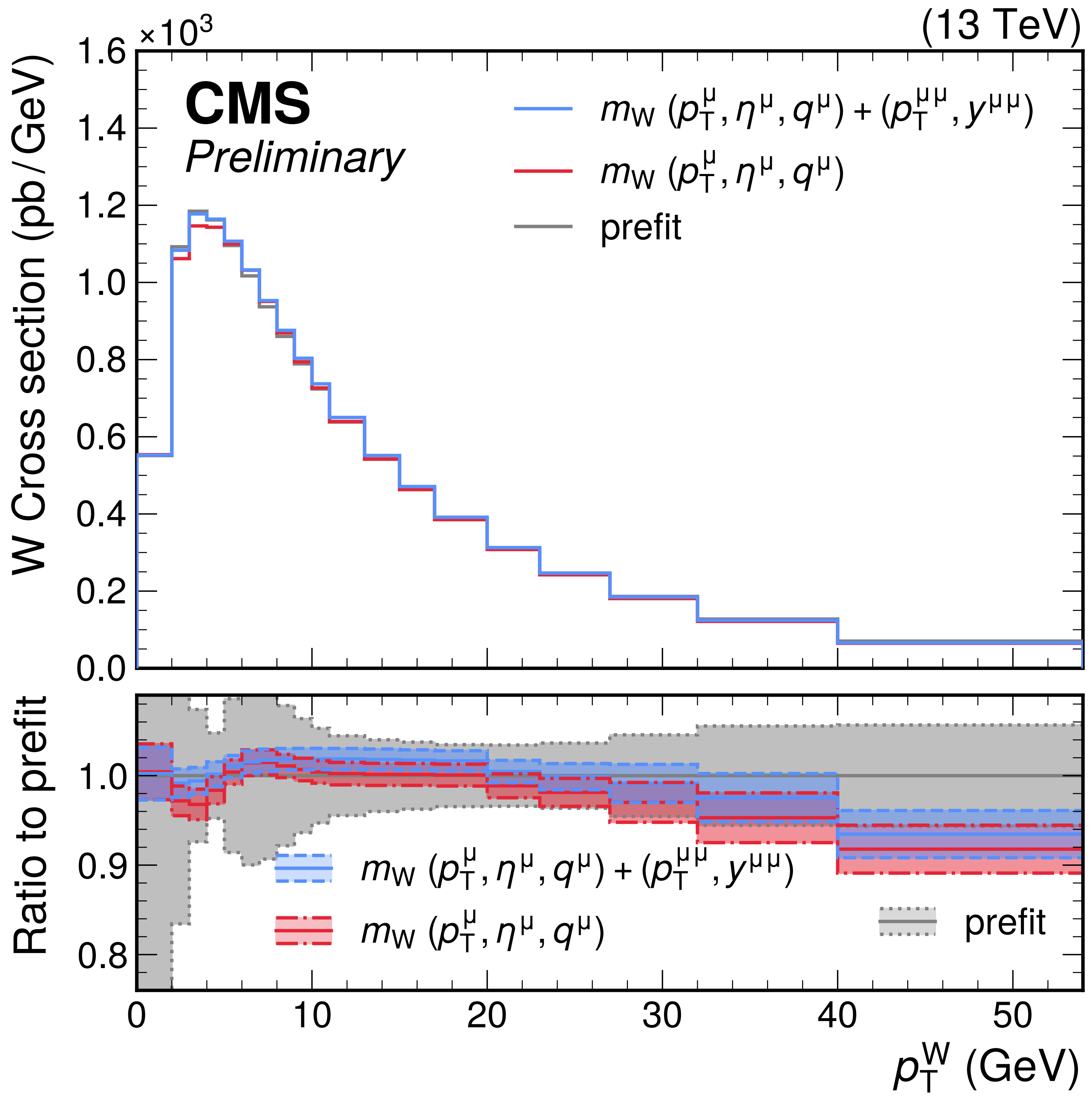


Muon transverse momentum after the fit

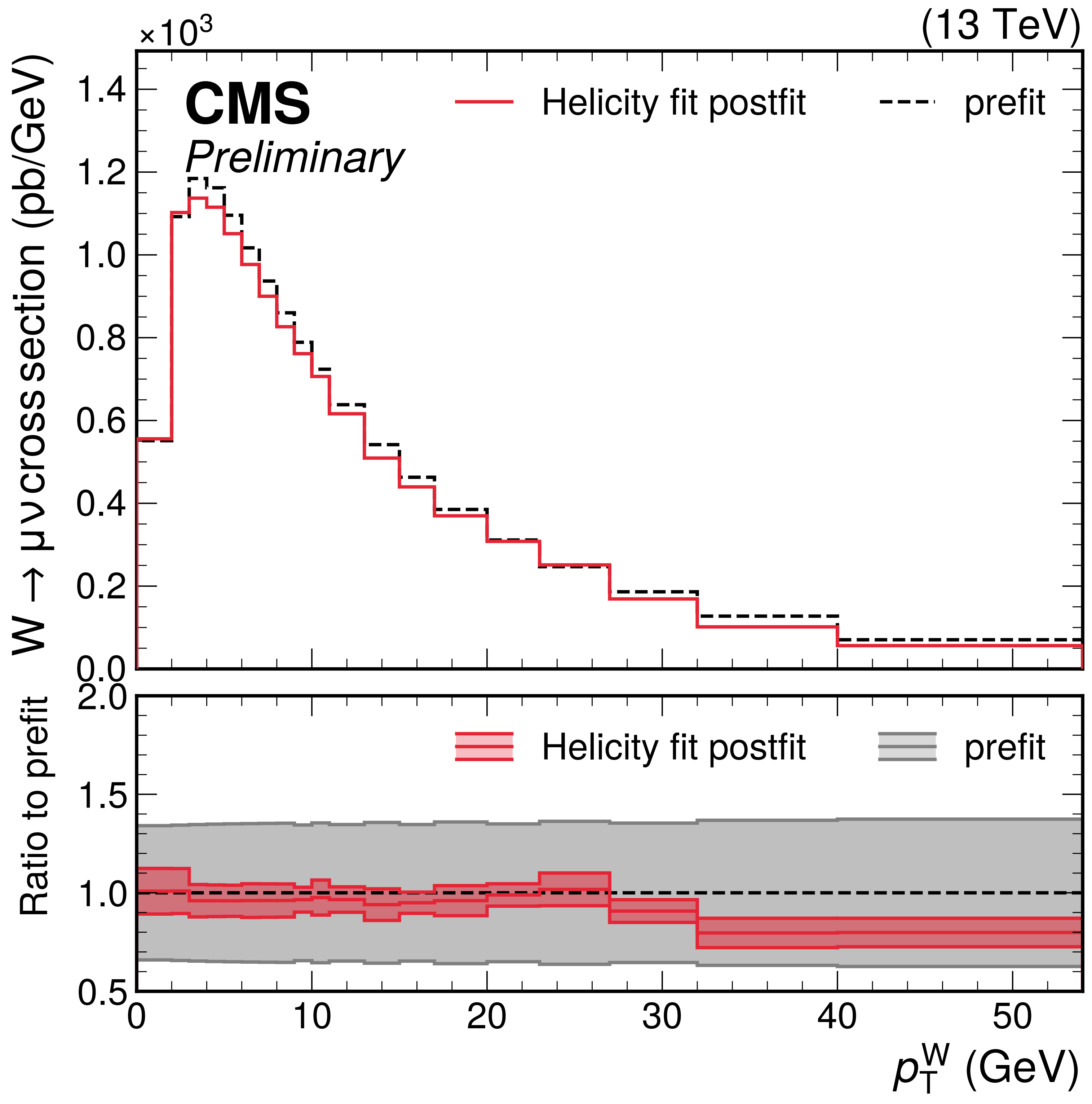


Extraction of W transverse momentum

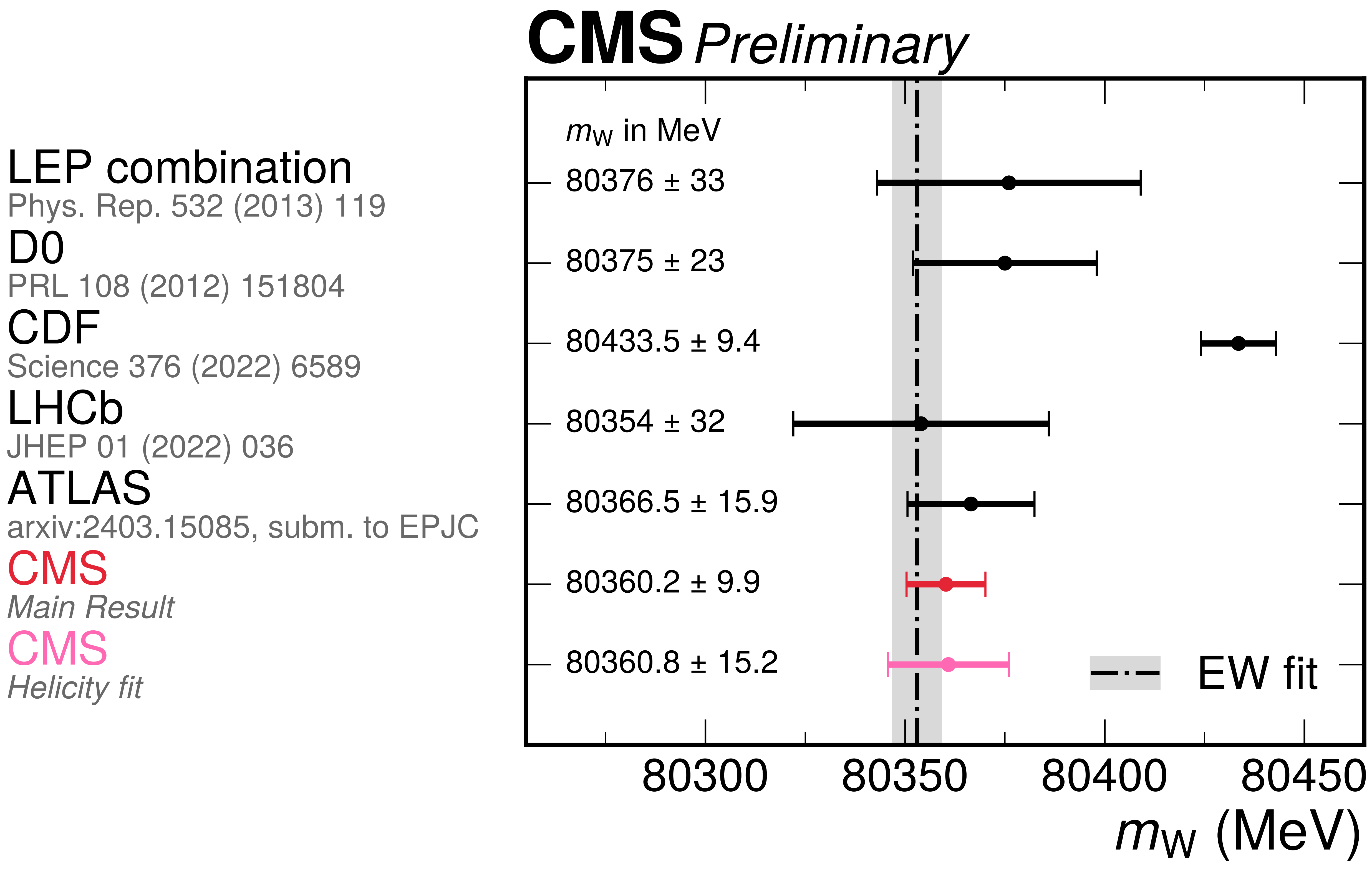
Theory Nuisance Parameters



Helicity Fit

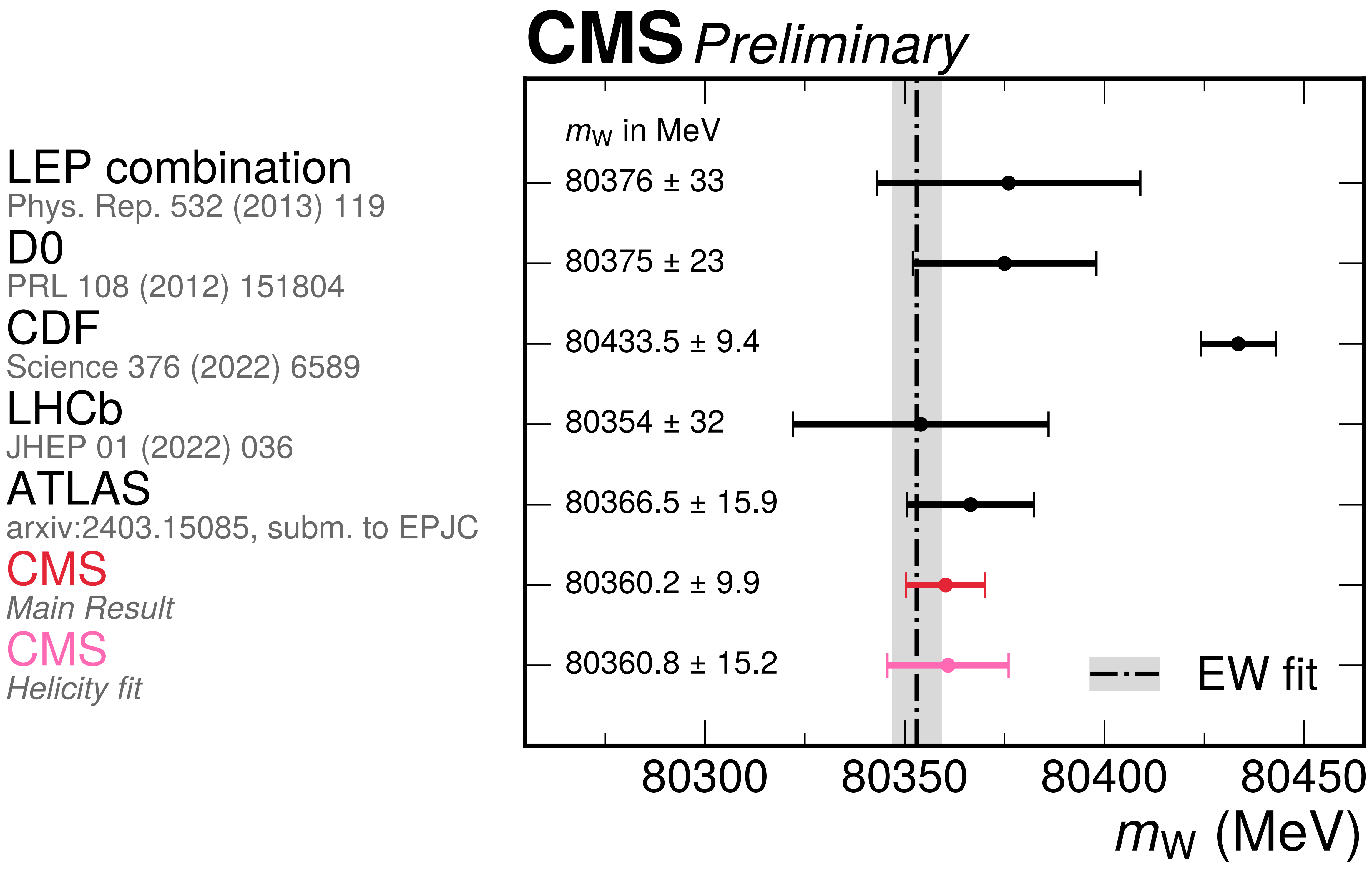


The W mass measurement



Reveals full compatibility with the Standard Model

The W mass measurement

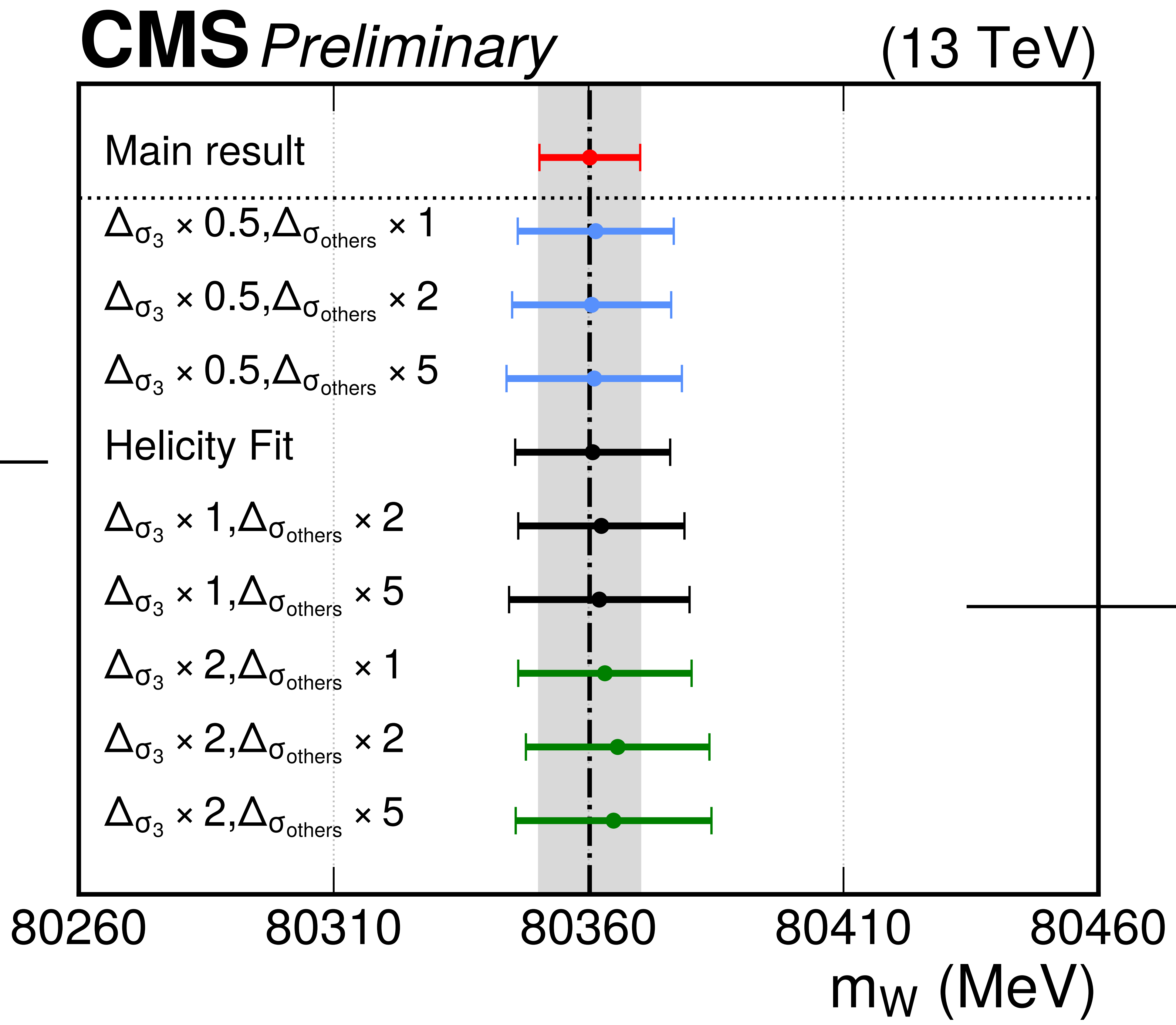


Source of uncertainty	Impact (MeV)	
	Nominal	Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample size	2.4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

Reveals full compatibility with the Standard Model

The W mass measurement with the Helicity Fit

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



Some of the degrees of freedom can not be fully constrained from data so a loose prior is assigned and result studied as a function of the magnitude of the prior

This is the start, not the end!

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