Measurement of the W boson mass with the CMS experiment

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LHC seminar

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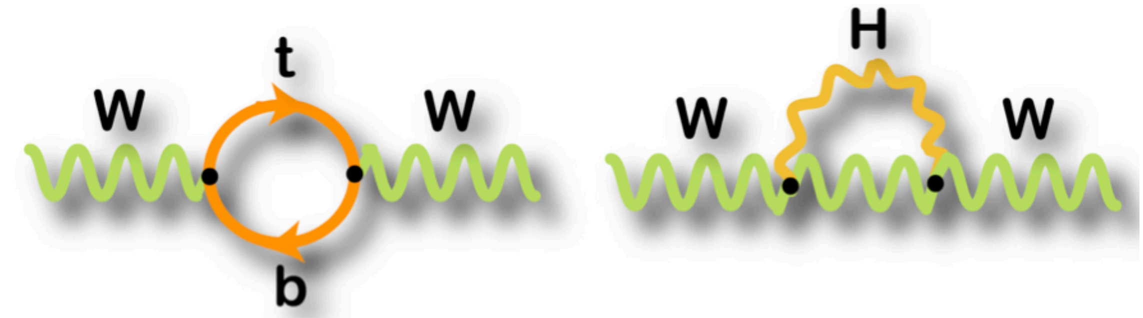
The W boson in the standard model

The standard model (SM) predicts precise theoretical relationships among its fundamental parameters

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



- loop corrections, mainly from Higgs boson and top quark …
- … maybe also new physics?

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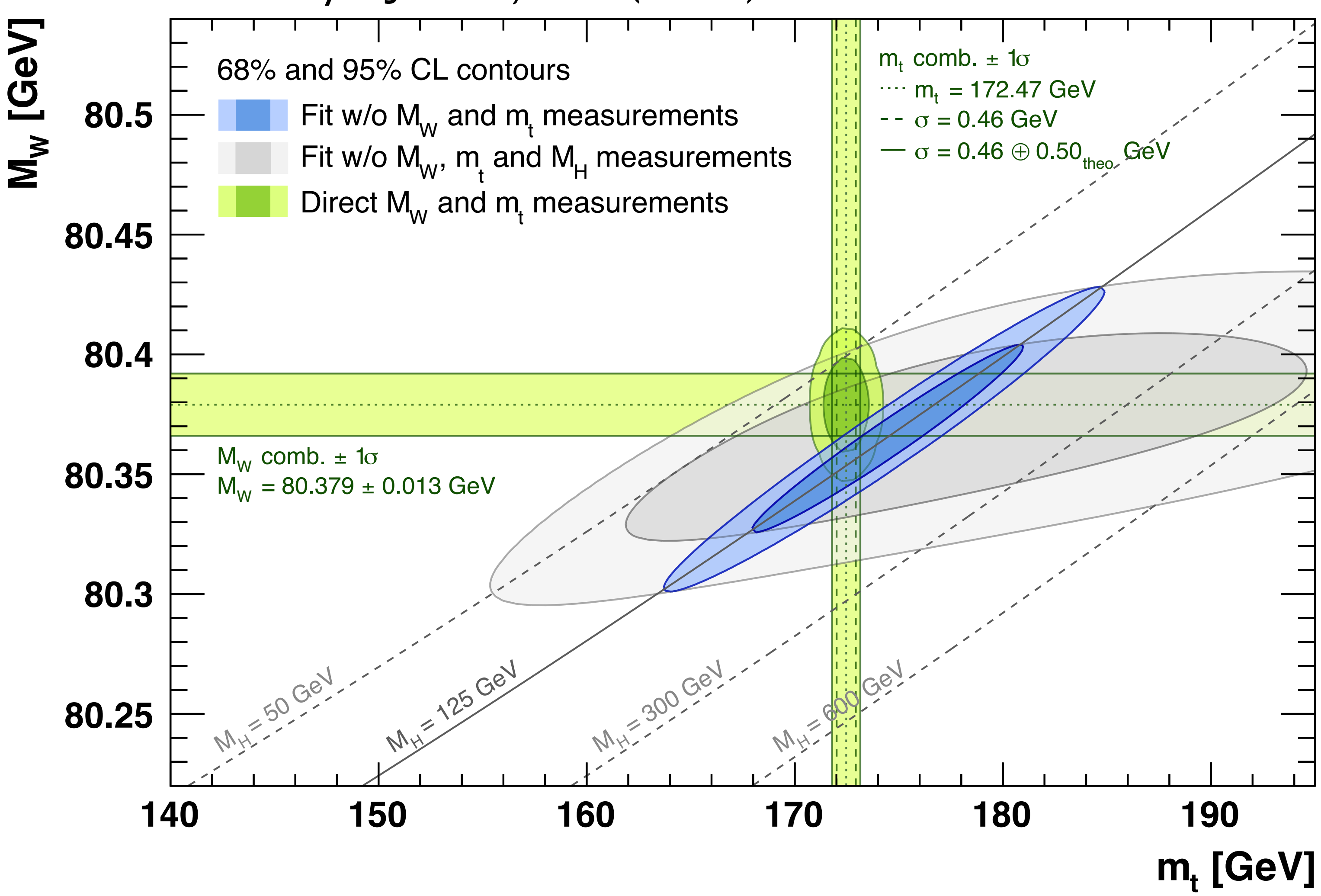
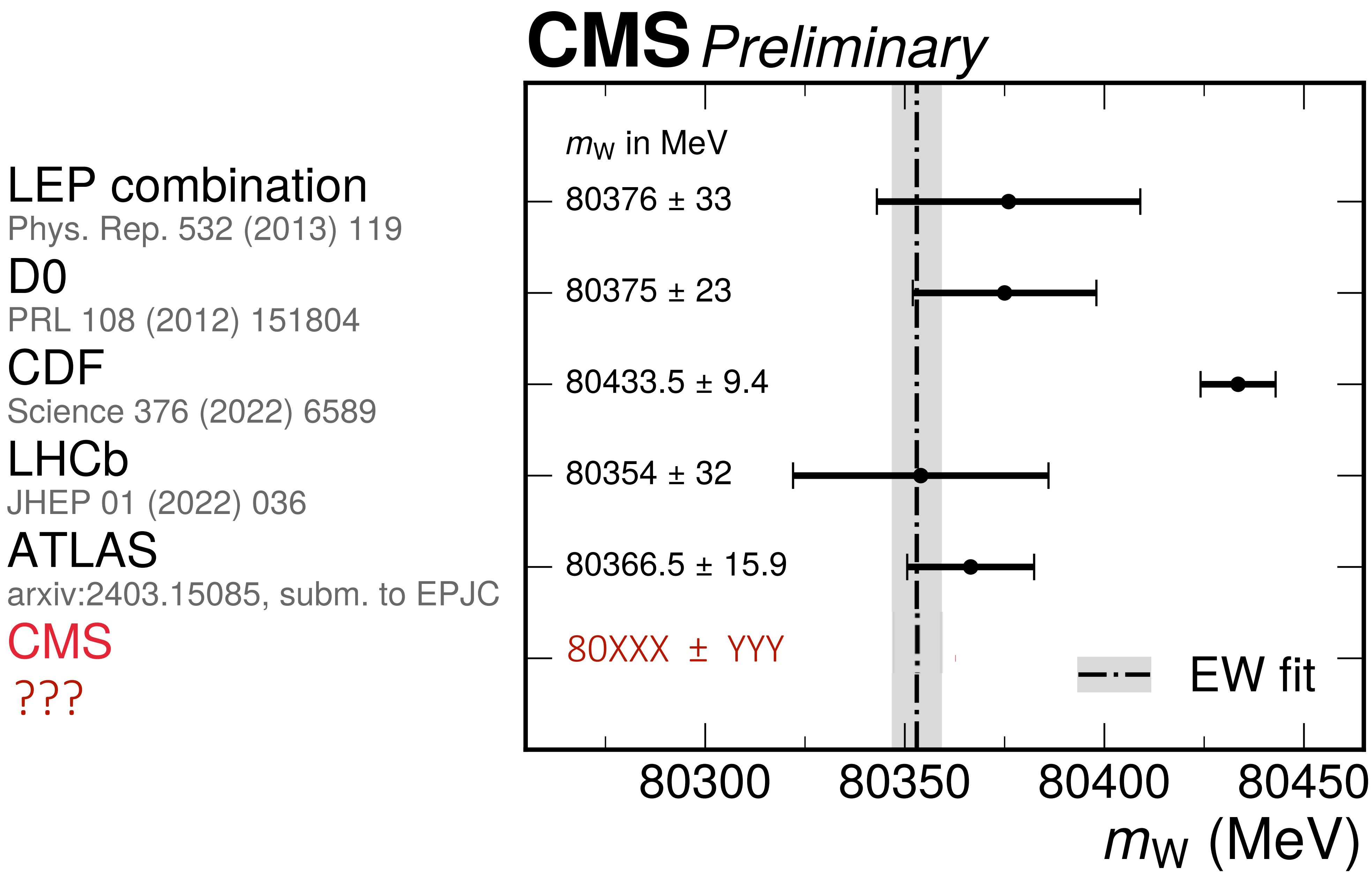


Higgs boson discovery and mass measurement make the SM overconstrained

- Unprecedented opportunity to test its internal consistency

The W boson *mess*

- **"Theoretical" prediction** from global electroweak (EW) fit: **m_W = 80 353 ± 6 MeV**
- **Experimental average** (excluding CDF 2022, see here) : **m_W = 80 369.2 ± 13.3 MeV**
- Mot recent CDF result in significant tension with SM and other measurements



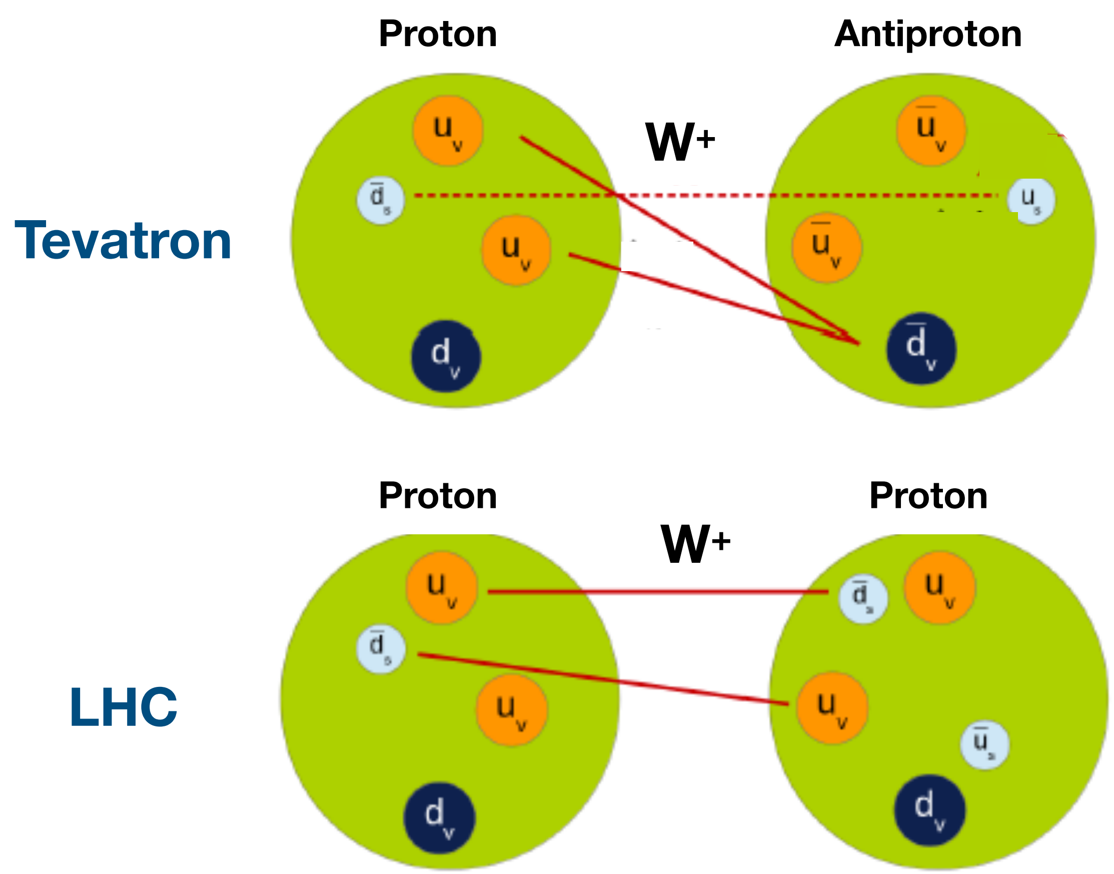
W bosons at hadron colliders

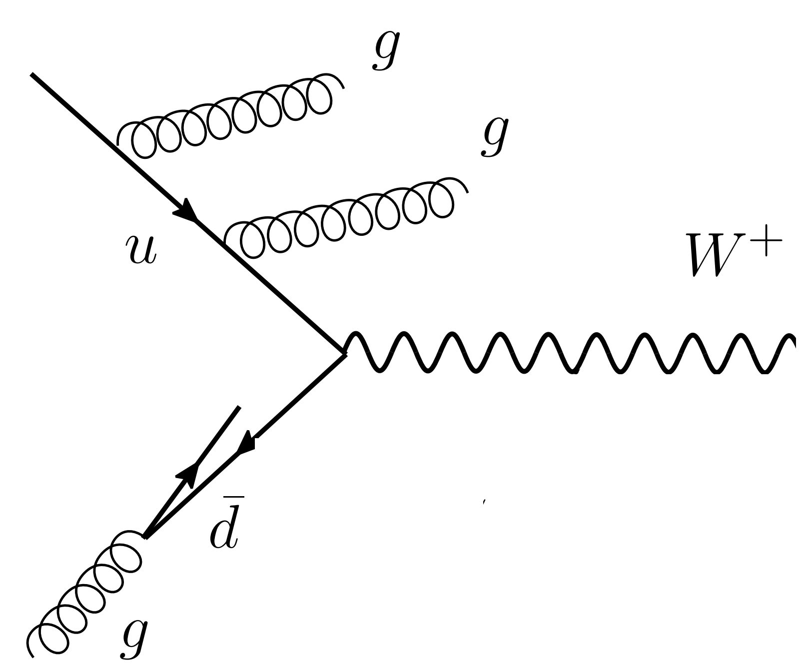
Leading order production from q$\bar{q}$' (possibly initiated by gluons)

- valence-sea quarks at the LHC, while valence-valence at Tevatron

Flavour and momentum of initial-state particles determined by the parton distribution functions (PDF) of the proton

- Unknown center-of-mass boost along beam axis
- Can exploit momentum conservation only in transverse plane (orthogonal to beams)

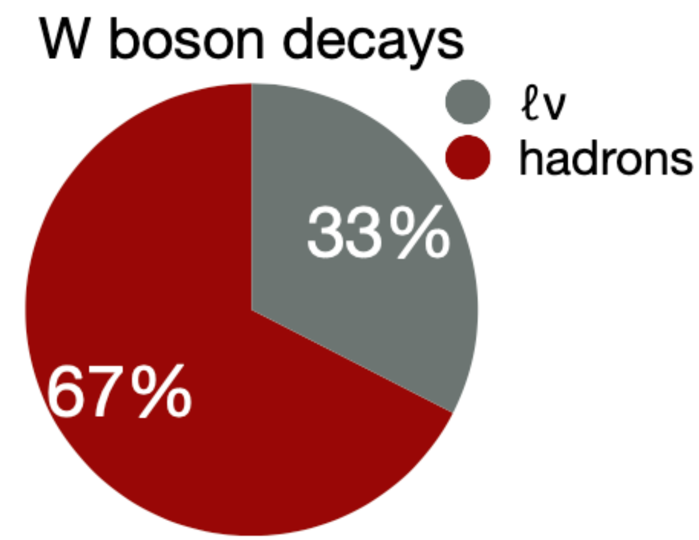




Choice of decay channel

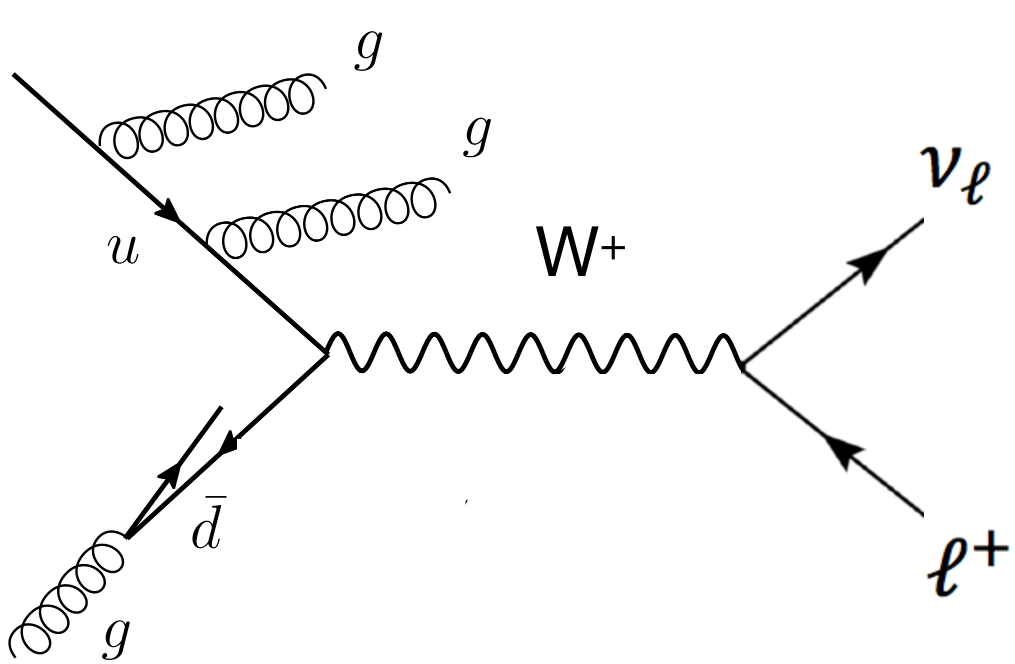
Hadronic decay not feasible at the LHC

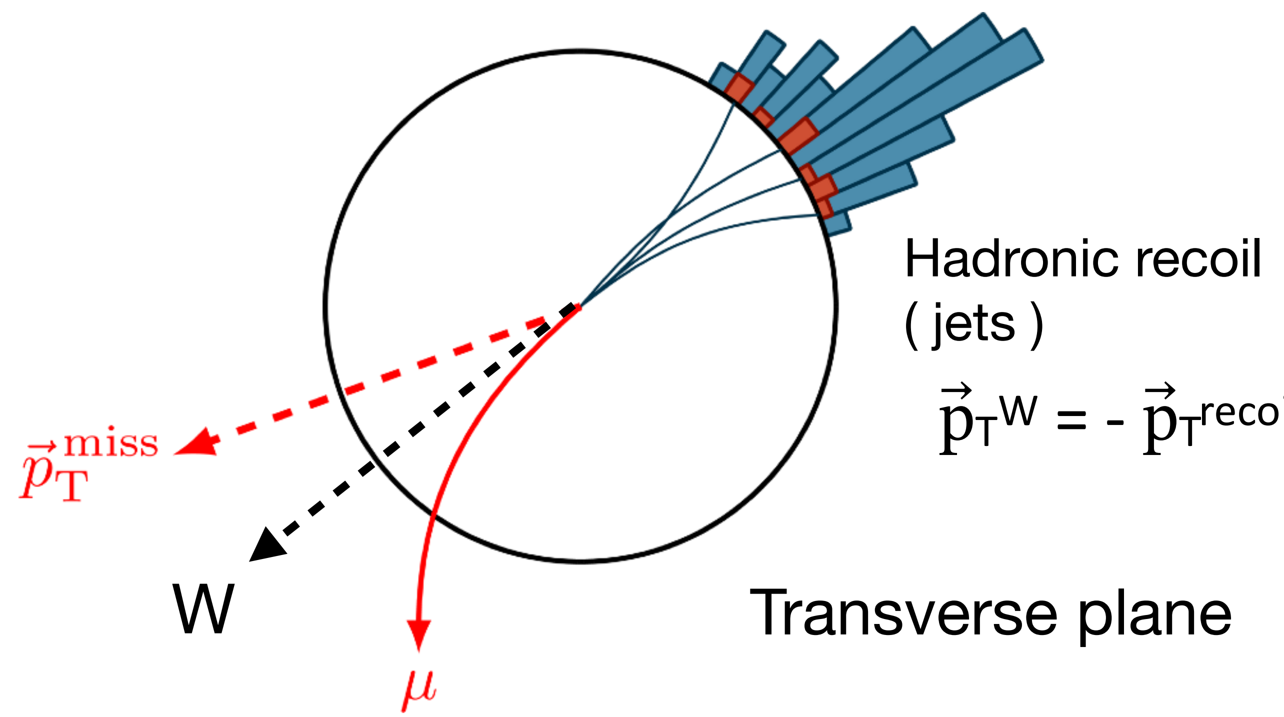
- Huge QCD multijet backgrounds
- Jet energy resolution about 5-20%



Choose leptonic decay

- Single muon or electron, well measured
- Undetected neutrino, cannot reconstruct full final state
- Estimate p_T^{ν} as missing transverse momentum $\vec{p}_T^{\,miss} = -(\vec{p}_T^{\,\ell} + \vec{p}_T^{\,recoil})$

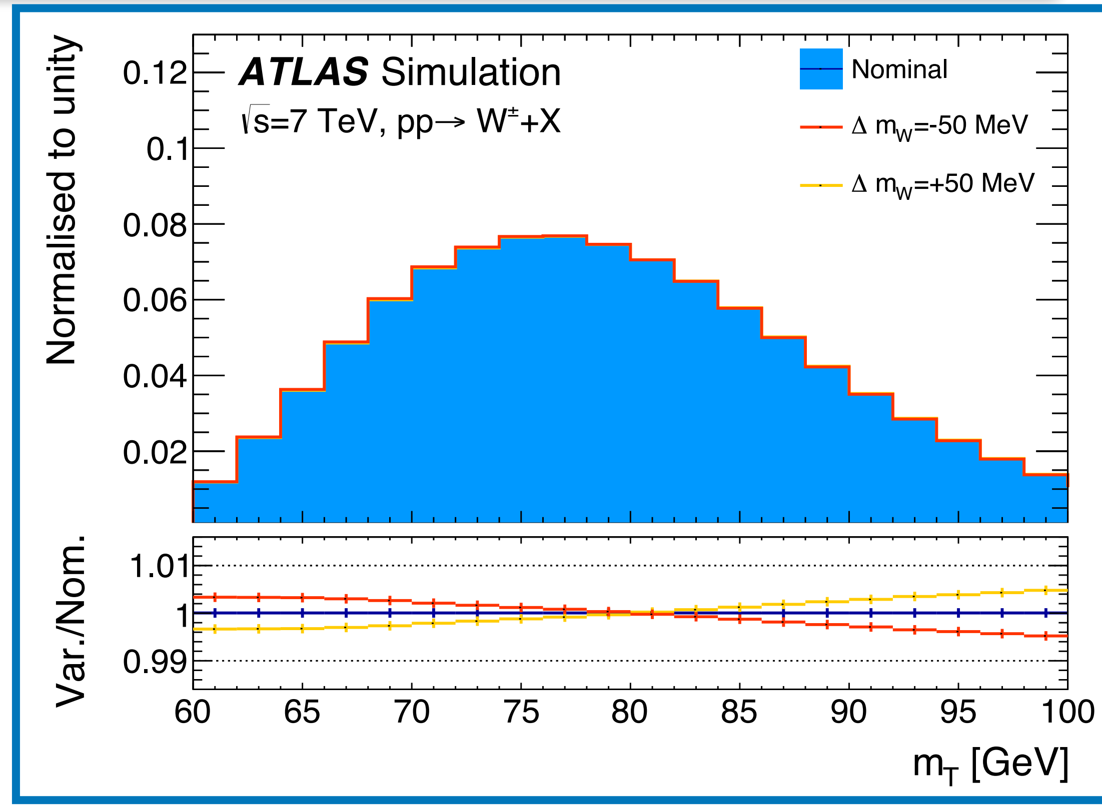




Choice of observables

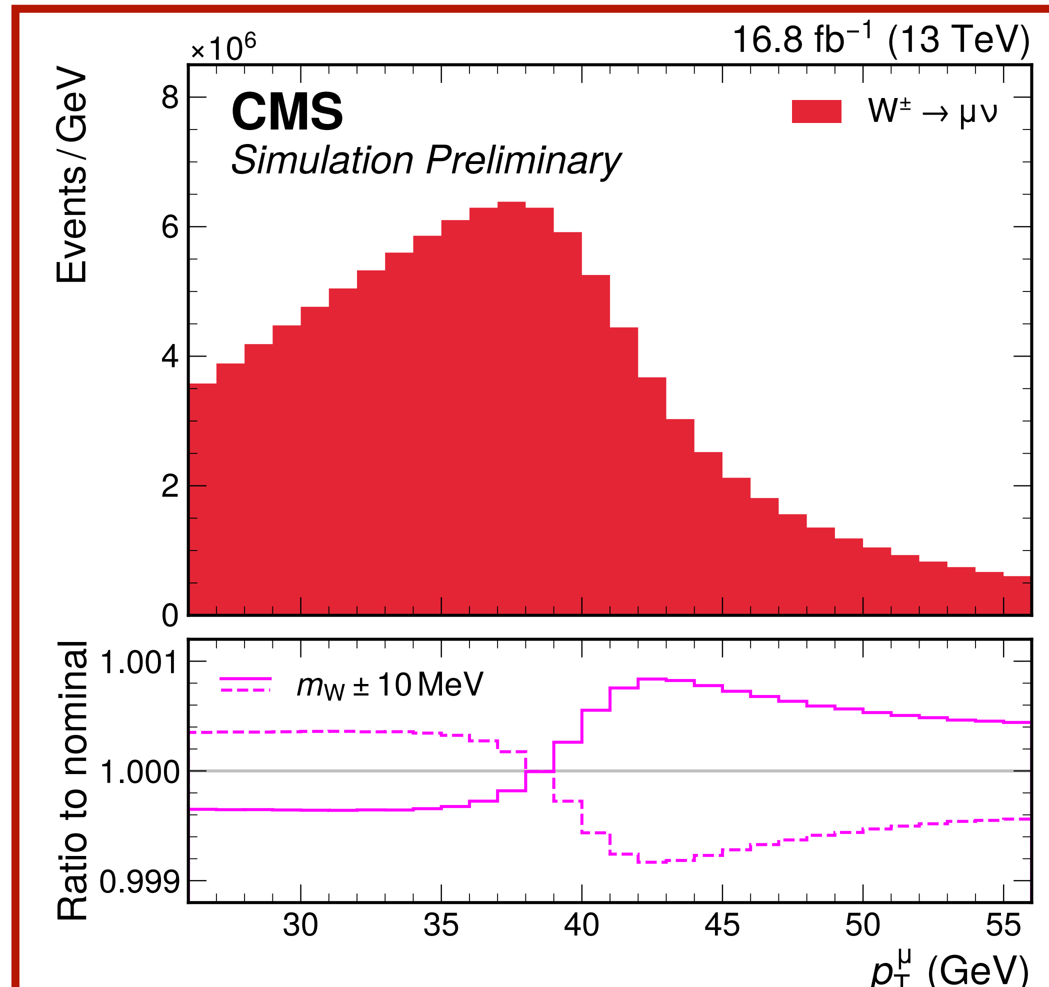
Lepton-neutrino transverse mass m_T

- $$m_T = \sqrt{2 \cdot p_T^{\ell} \cdot p_T^{miss} \cdot (1 - \cos \Delta\phi_{\ell\nu})}$$
- Limited precision from p_T^{miss} resolution
- Almost Lorentz invariant, minor p_T^W dependency



Charged lepton p_T^{ℓ}

- Most precisely measured (~ 0.1% accurate)
- Very sensitive to PDFs (W polarization) and p_T^W



- Δm_W = 10 MeV implies < 0.1% variation in yields
- Need outstanding control over experimental and theoretical uncertainties

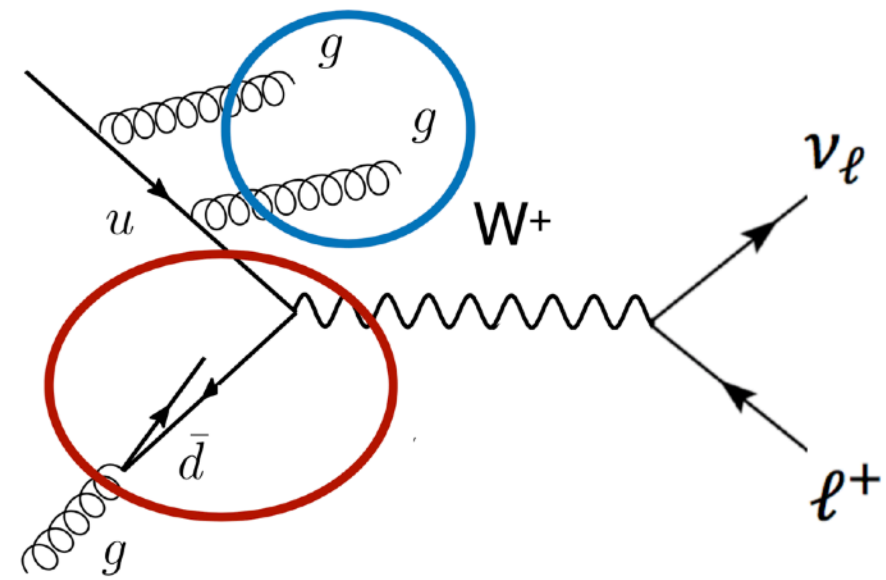
Theoretical considerations: p_T^W

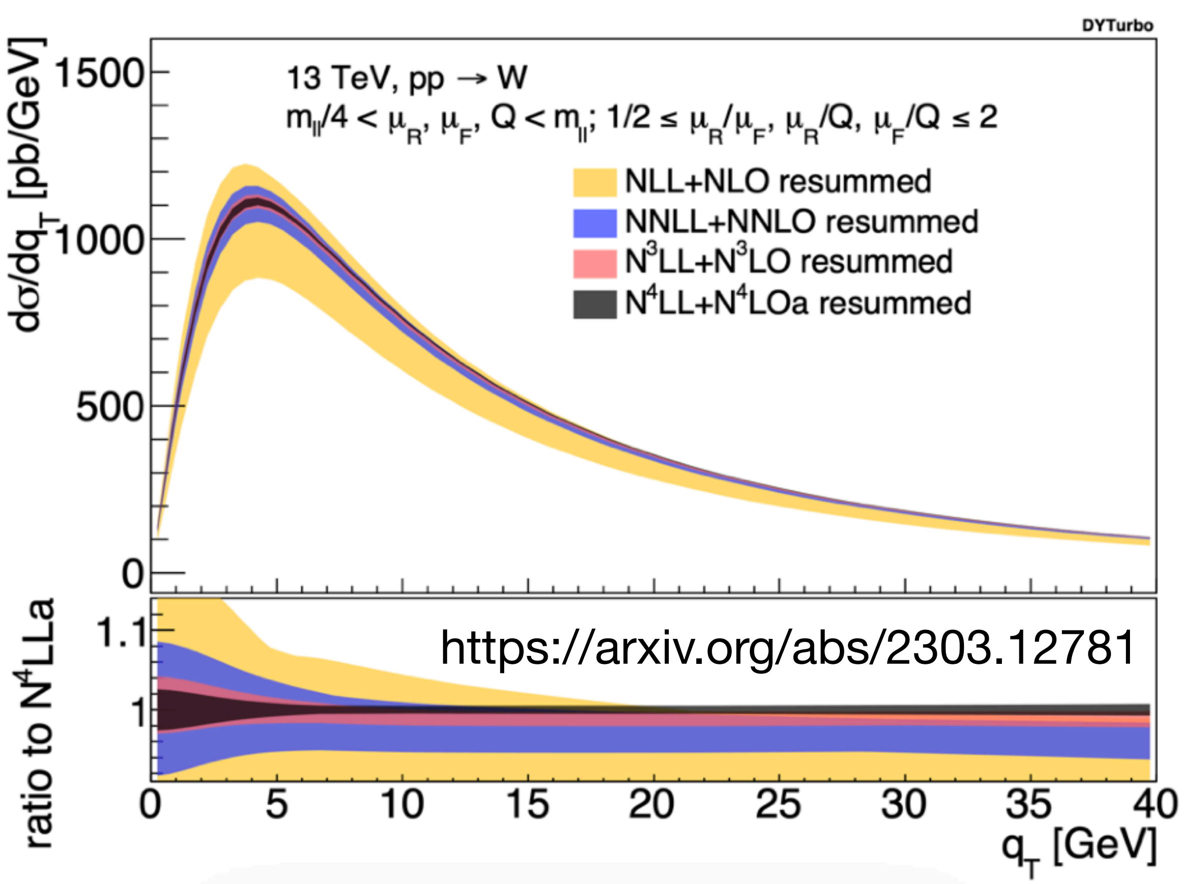
Lorentz boost of ℓν pair determined by p_T^W

- High p_T^W region precisely described by fixed order calculations (perturbative QCD)

Large theoretical uncertainties at low p_T^W

- **Soft gluon emission** (need resummation)
- **Non-perturbative effects**: quarks' flavour, masses, and intrinsic p_T (PDF related)





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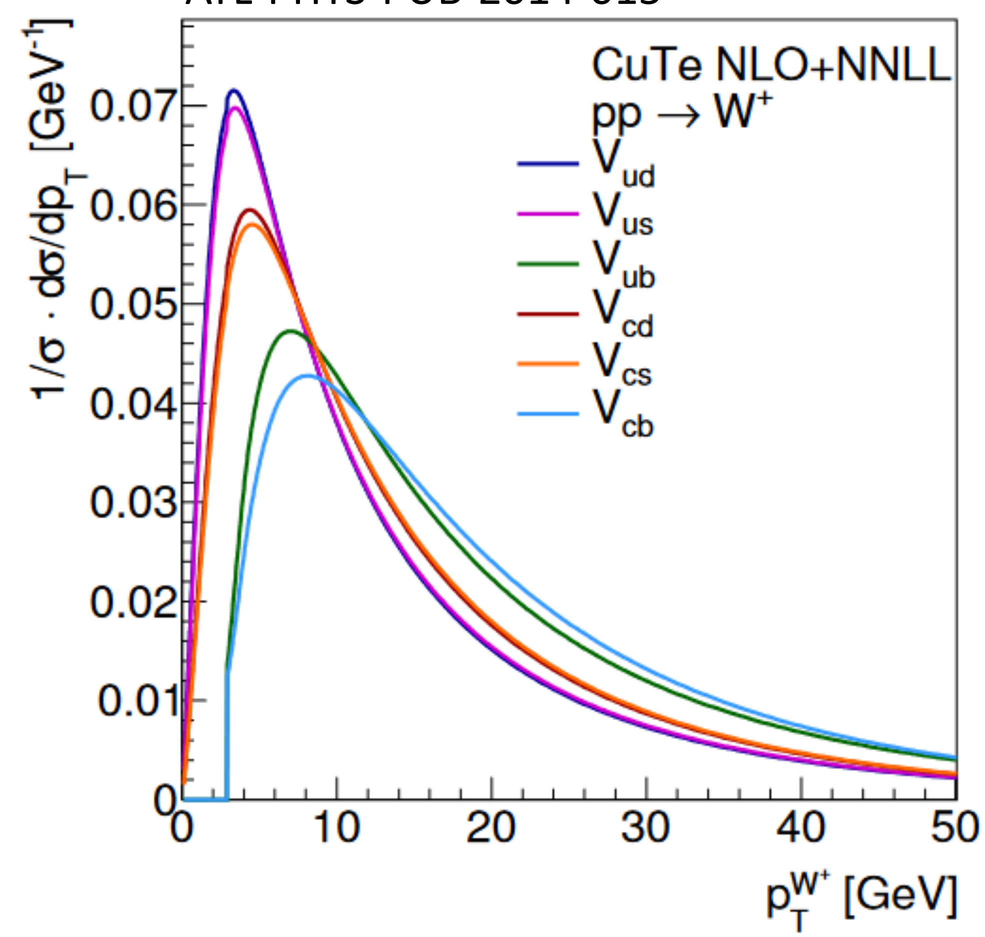
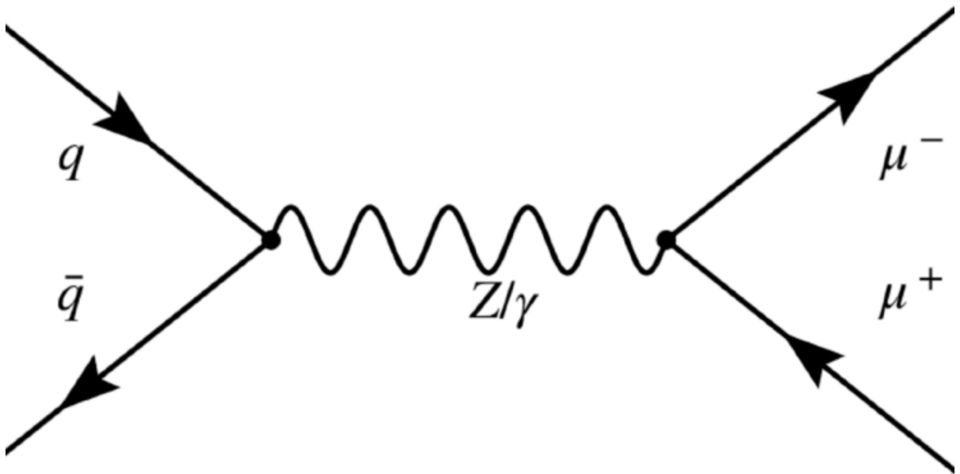
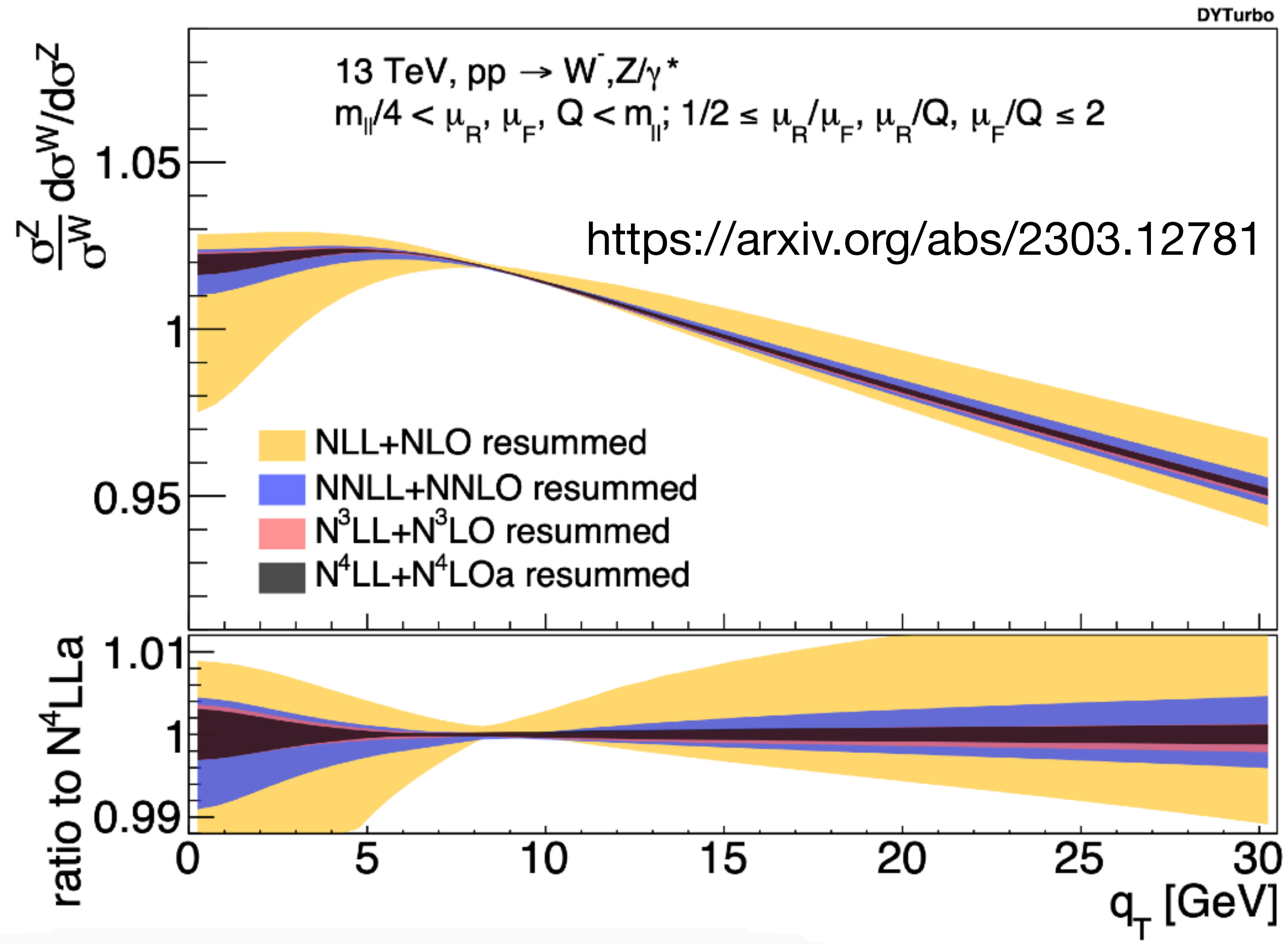


p_T^V and QCD uncertainties





Conventional wisdom:

1. tune simulated p_T^Z on precisely measured $Z \to \ell^+\ell^-$ data
2. predict p_T^W from theoretical W/Z cross section ratio

- **However:** cancellation of uncertainties subject to model dependent assumptions, with no robust theoretical prescription to properly deal with correlations (see here)

CMS strategy: construct best possible theoretical model for p_T^W and **constrain uncertainties in-situ with W data**, reserving **Z data ONLY for validation**

W/Z production and angular dependence

Decay encoded in 1+8 angular coefficients A_i

- Or helicity cross sections $\sigma_i = \sigma_{UL} \cdot A_i$, with A_i dependent on p_T^V and rapidity Y^V

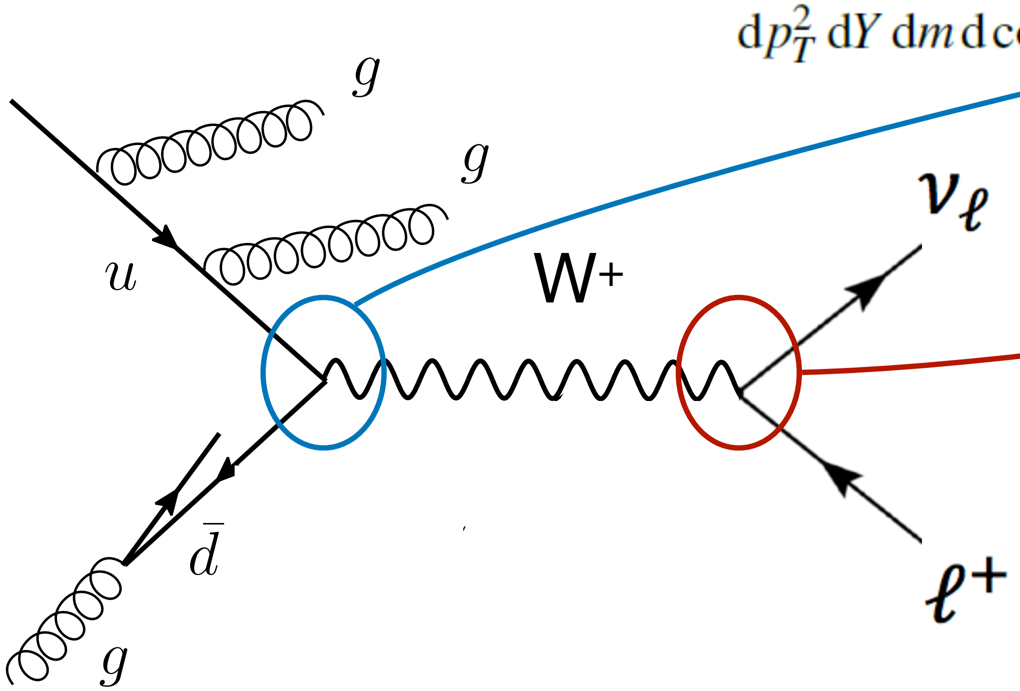
$$Y^V = \frac{1}{2} \cdot \log \frac{E + p_z}{E - p_z}$$

Given m_W, cross section predicted by SM up to uncertainties from PDFs and QCD/EW higher orders

- Conversely, if uncertainties are under control, can extract m_W from $d\sigma$ measured as a function of suited experimental observables (m_T and p_T^ℓ)

Unpolarized cross section σ_{UL}

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

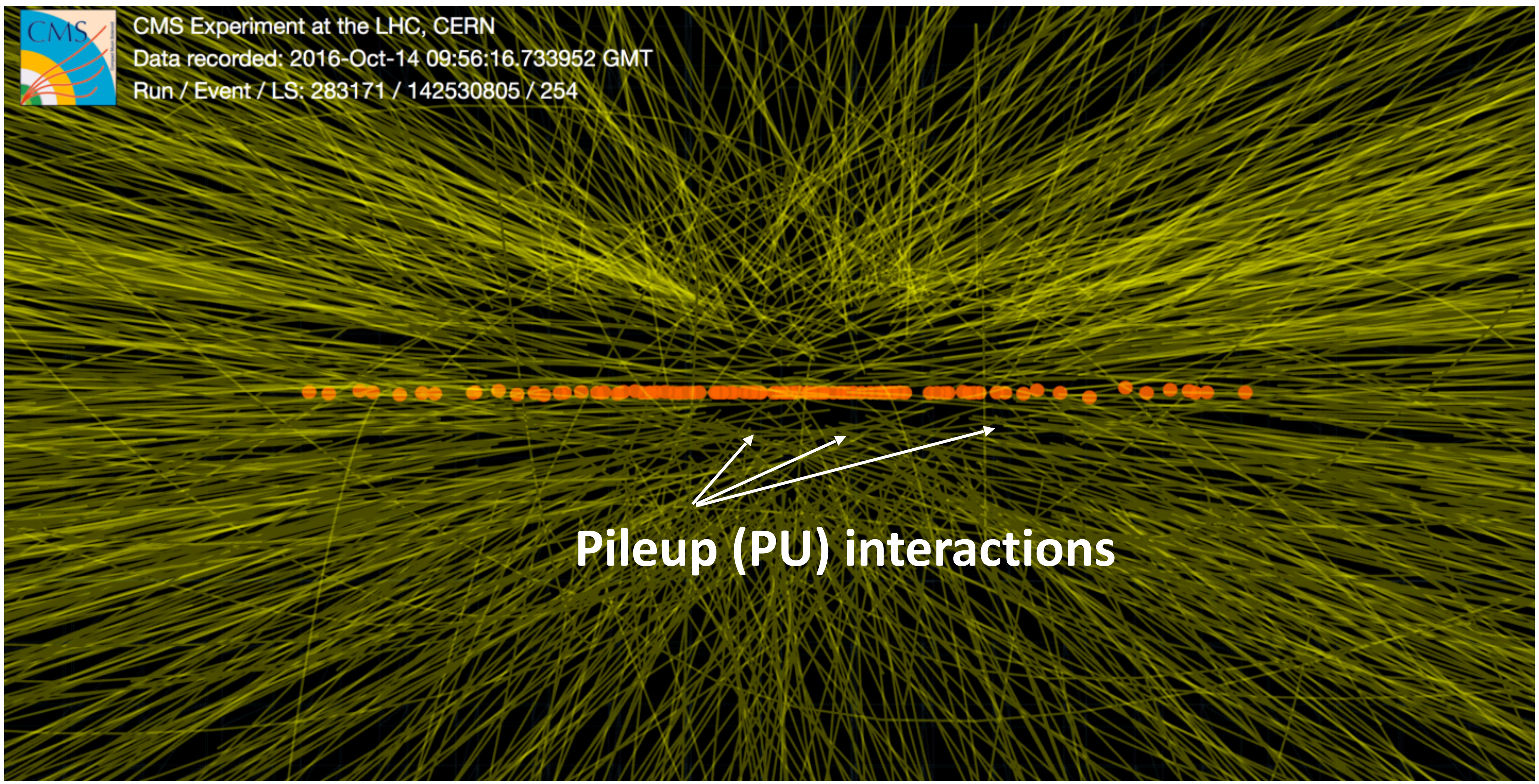


Angular decomposition valid at any order in QCD

Back to the experiment

- Pileup severely degrades resolution on p_T^{miss}
- p_T^{ℓ} based m_W measurement more suited in high pileup environment

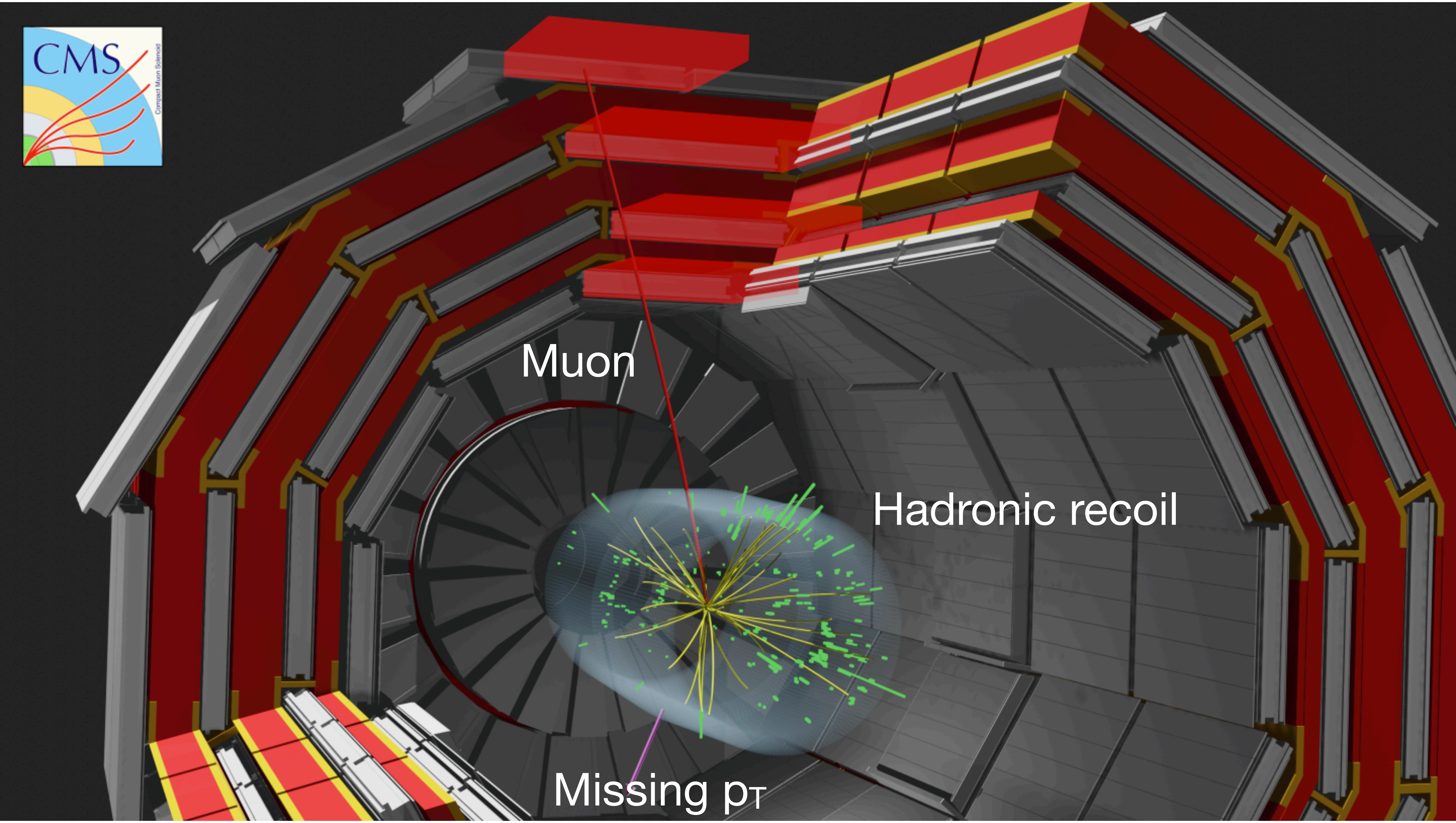
proton →



← proton

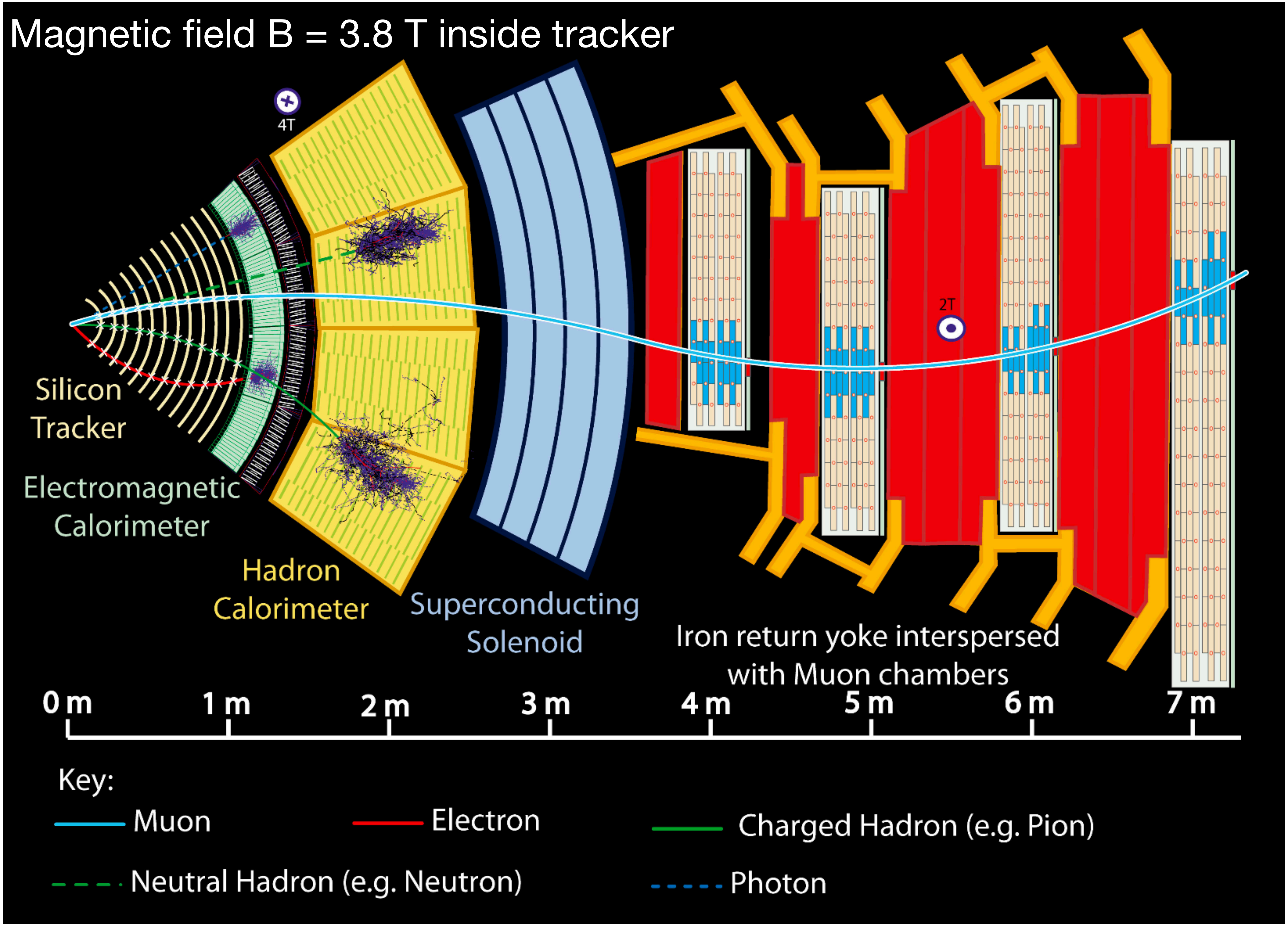
Do you see the muon track ?

A single muon event



Transverse slice of CMS (Compact Muon Solenoid)

"Particle flow" reconstruction



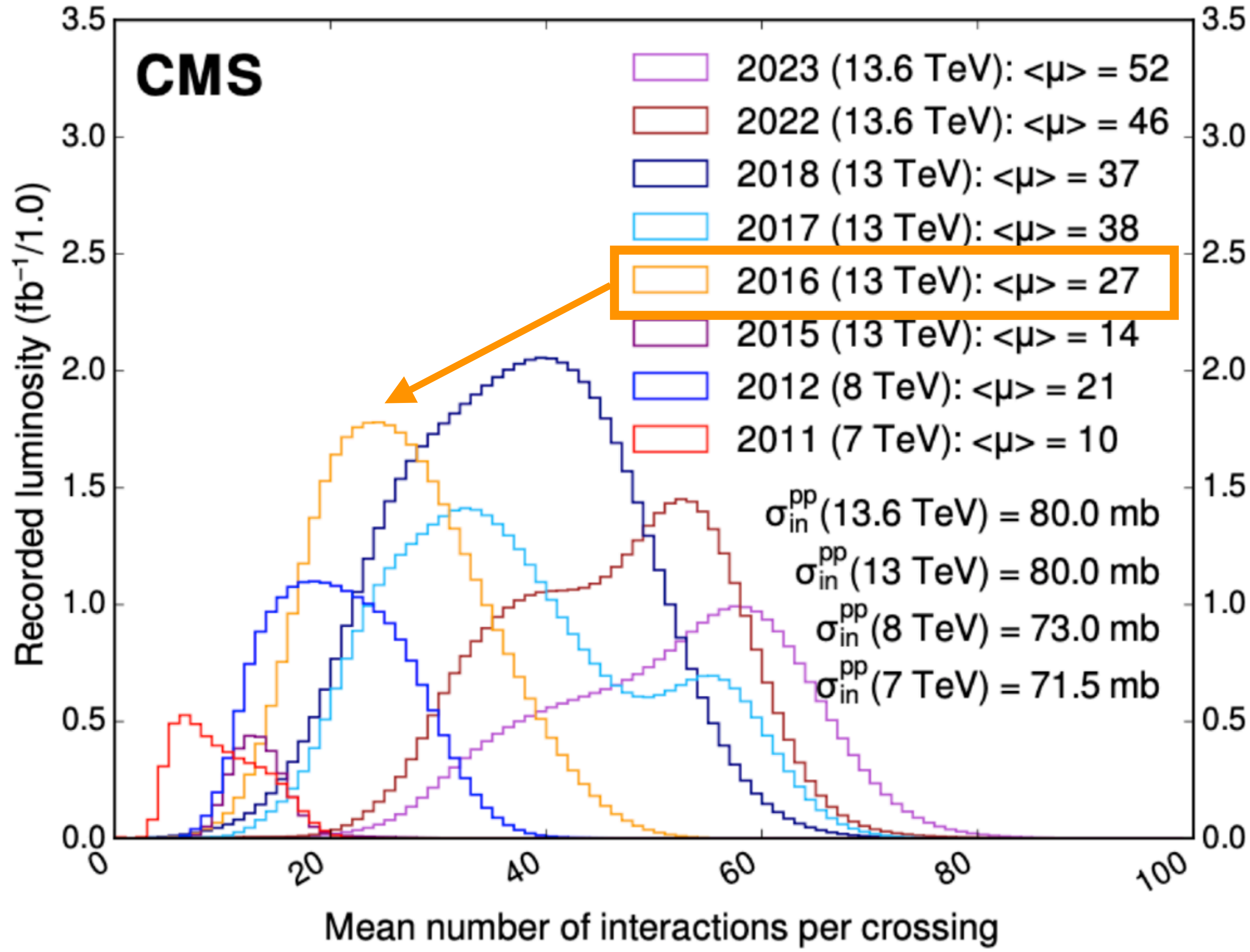
CMS measurement

Use 13 TeV data (higher PU than 7 TeV used by ATLAS)

- Well-understood subset: 16.8 fb^{-1} from later part of 2016
- ~100 M selected events, largest W sample ever used for m_W

Focus on muon channel and p_T^{μ} (resilient against PU)

- Larger systematic uncertainties for m_T or electrons at high PU



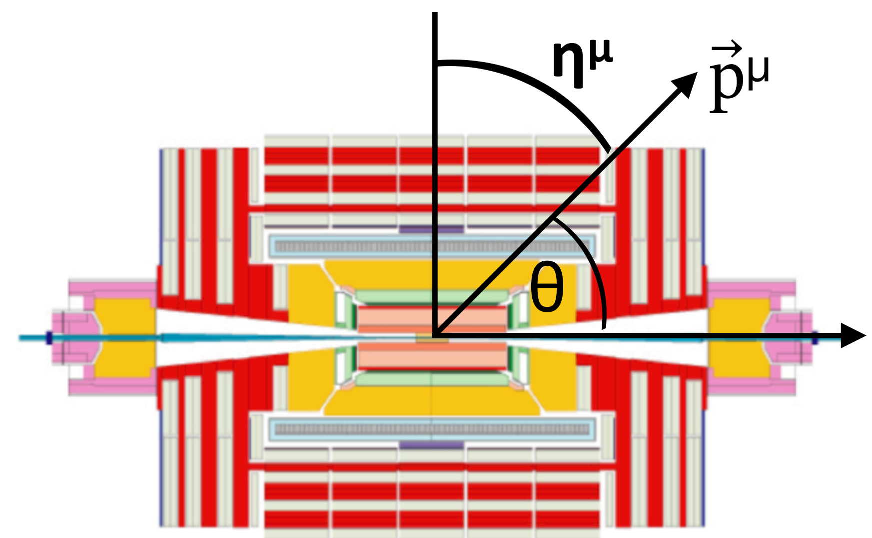
Analysis strategy

Binned profile maximum-likelihood fit to 3D p_T^μ-η^μ-q^μ distribution

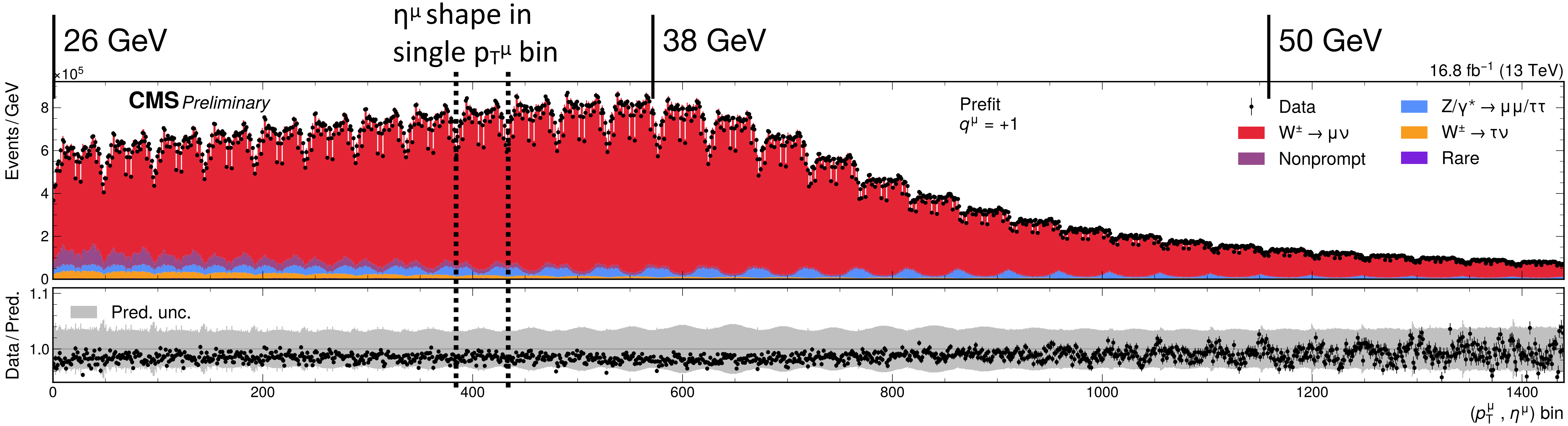
- Experimental techniques and tools developed for W rapidity-helicity measurement (2020), which established strong in-situ constraints on PDFs from fit to p_T^ℓ-η^ℓ-q^ℓ

- p_T^μ directly sensitive to m_W
- η^μ-q^μ maximally sensitive to PDFs (details in backup)

η^μ = - log[tan(θ/2)]



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

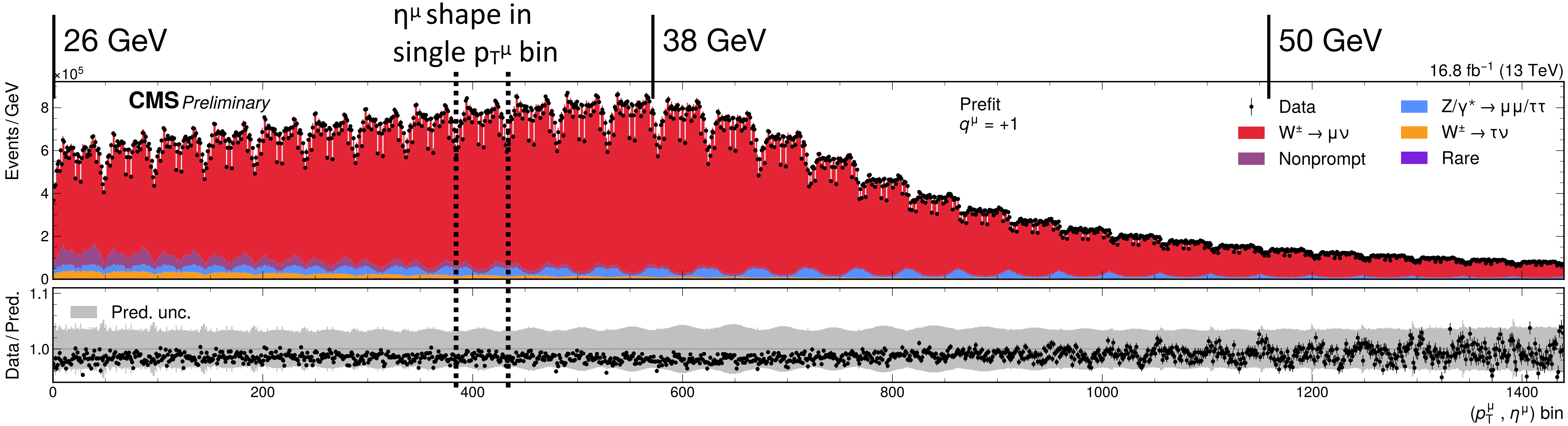


Analysis setup

Significant computational challenges (details in this EP/IT seminar)

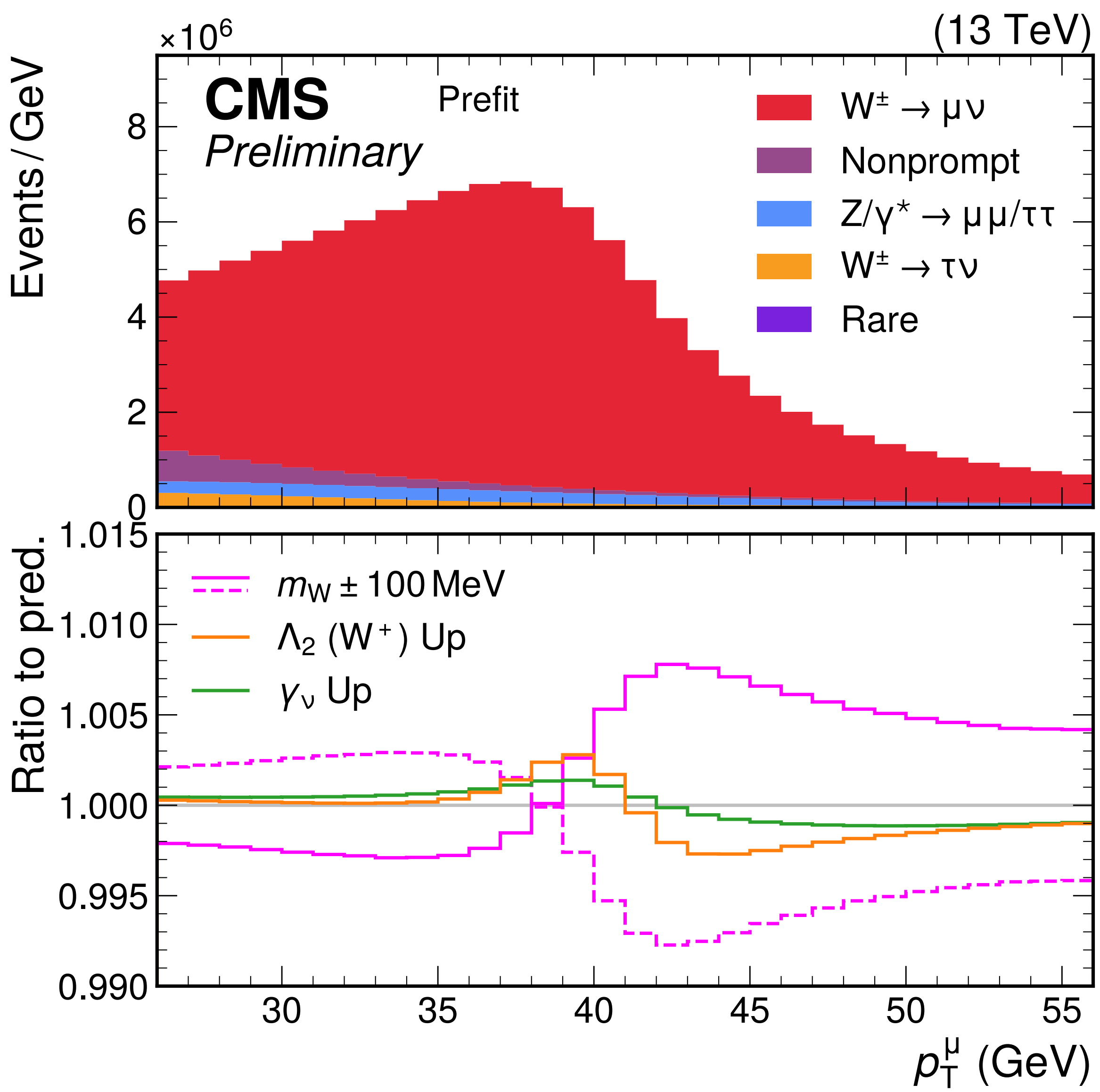
- 2880 bins to fit, with ~5k systematic variations
- Optimized fit framework based on Tensorflow (RooFit/Minuit not adequate)

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

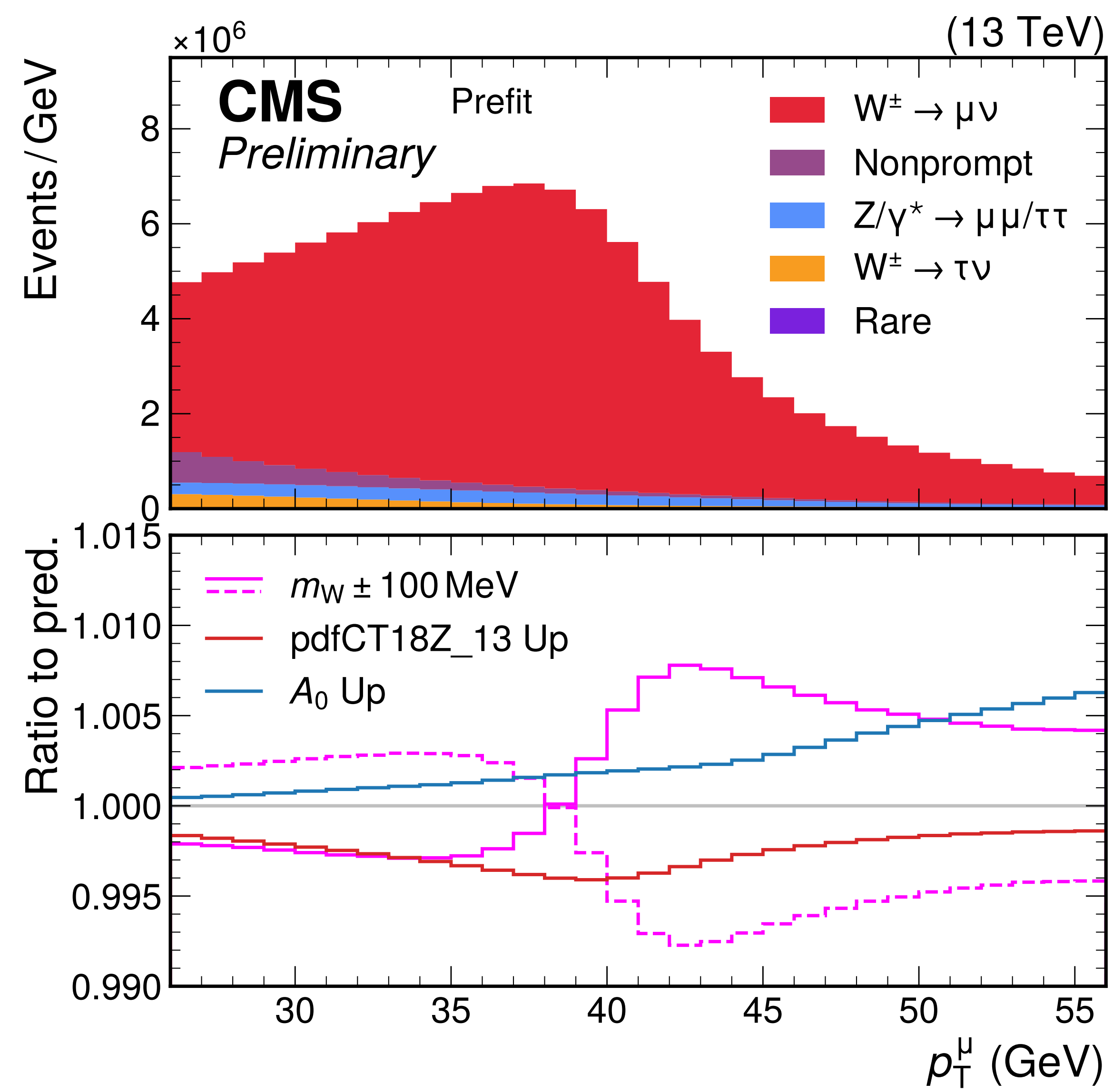


Enabling feature of the measurement

- Systematic variations in p_T^W, Y^W, decay angles, PDFs, have a different shape effect on p_T^μ-η^μ-q^μ with respect to a shift in m_W
- Many systematic uncertainties constrained in-situ by the data



- Some nuisance parameters controlling the shape of p_T^W



- Single PDF variation from CT18Z
- A_0 angular coefficient

Event selection

Single muon selection

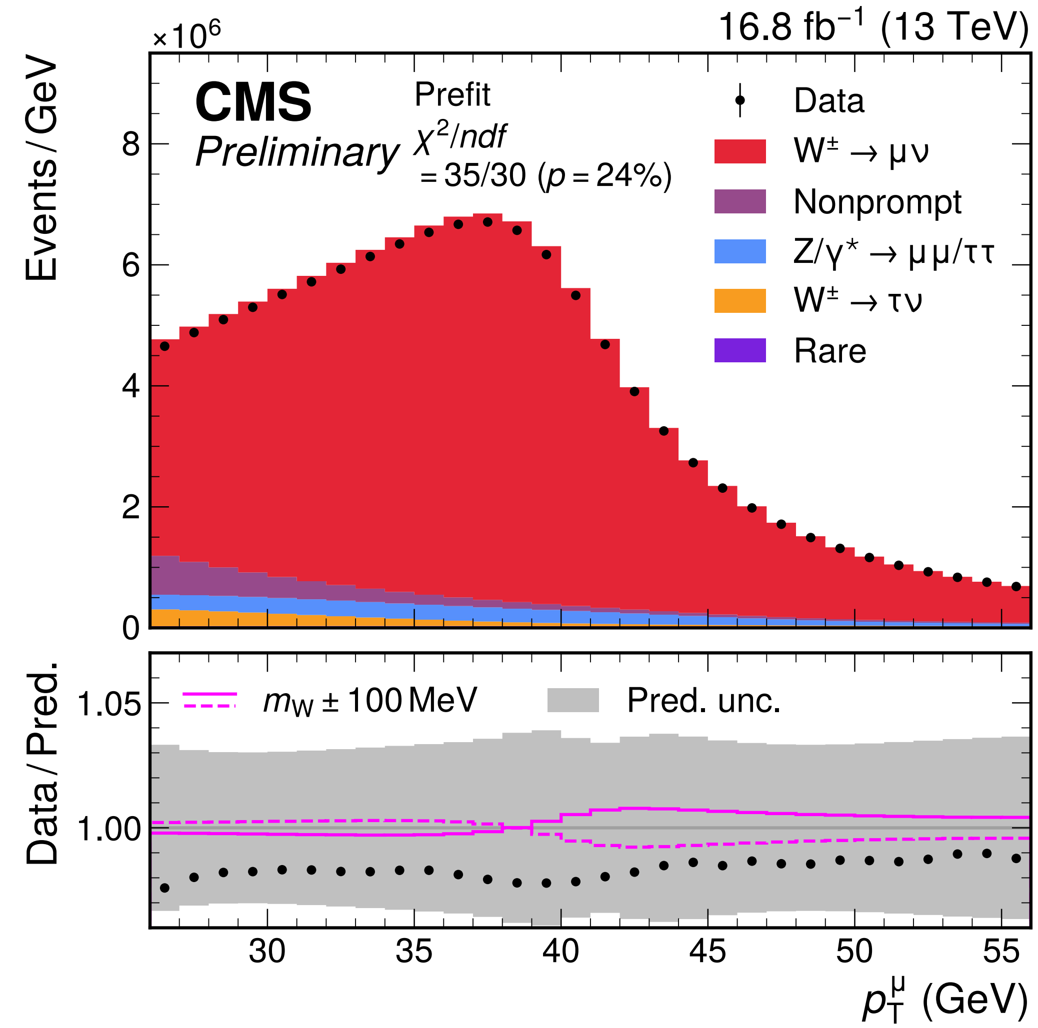
- Track quality criteria ("global" muon)
- Muon ID and isolation
- $m_T > 40$ GeV

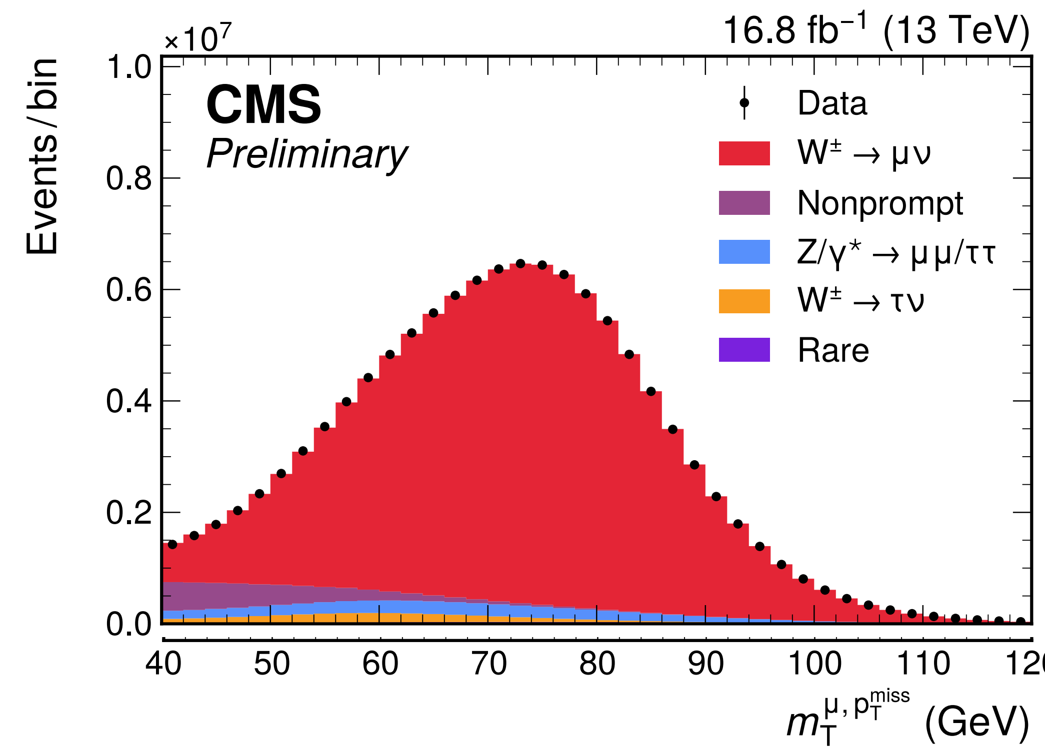
Prompt backgrounds: from simulation, with all relevant corrections/uncertainties

- Z → μμ (mainly with 1 out-of-acceptance μ)
- W → τν and Z → ττ, with τ decays into μ
- Rare: top quark decays, boson pair production, and muons from photon-induced processes

Nonprompt background: estimated from data

- Mainly QCD multijet events with muons from B/D decays (small contribution also from k/π)
- Suppressed by m_T cut





W-like m_Z analysis

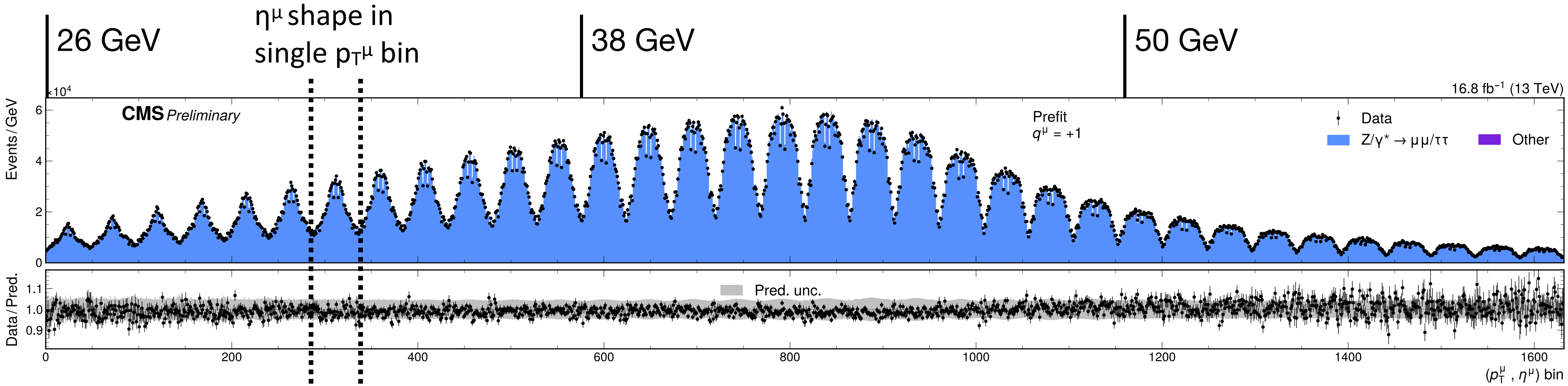
Measure m_Z in $Z \rightarrow \mu\mu$ events using single muon p_T^μ-η^μ-q^μ

- Other muon summed to p_T^{miss}
- Analyse μ^+ (μ^-) from even (odd) events to get statistically independent samples

Validate technique and many experimental aspects in background-less environment

- Also essential tool to check theory model and understand implications for p_T^μ-η^μ-q^μ

Example for positive charge (1632 p_T^μ-η^μ bins)
48 η^μ bins in [-2.4, 2.4] x 34 p_T^μ bins in [26, 60] GeV



The path towards m_W

Ancillary measurements, all kept "blind" until all relevant aspects were finalized

- Sequential unblinding strategy

m_Z in dimuon

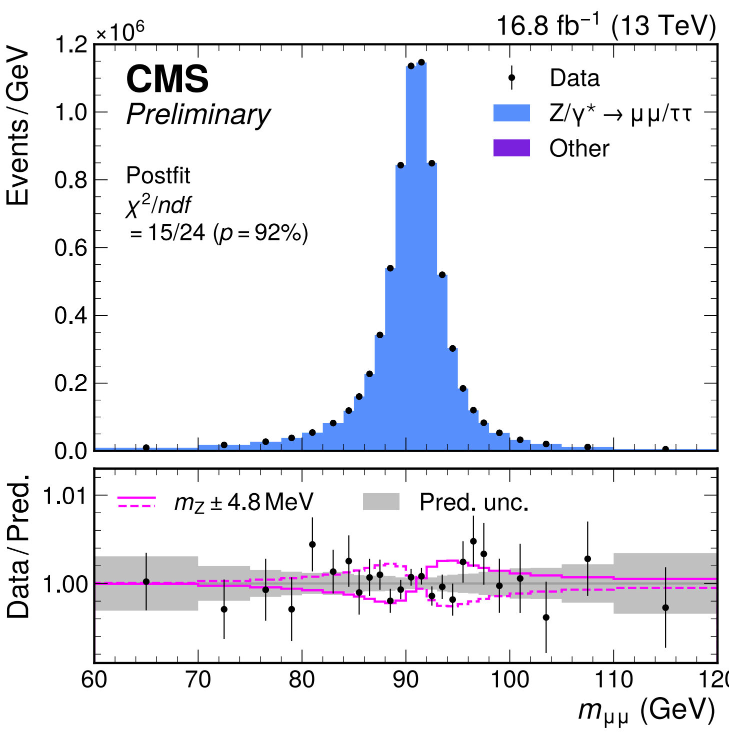
- Validate muon momentum scale calibration

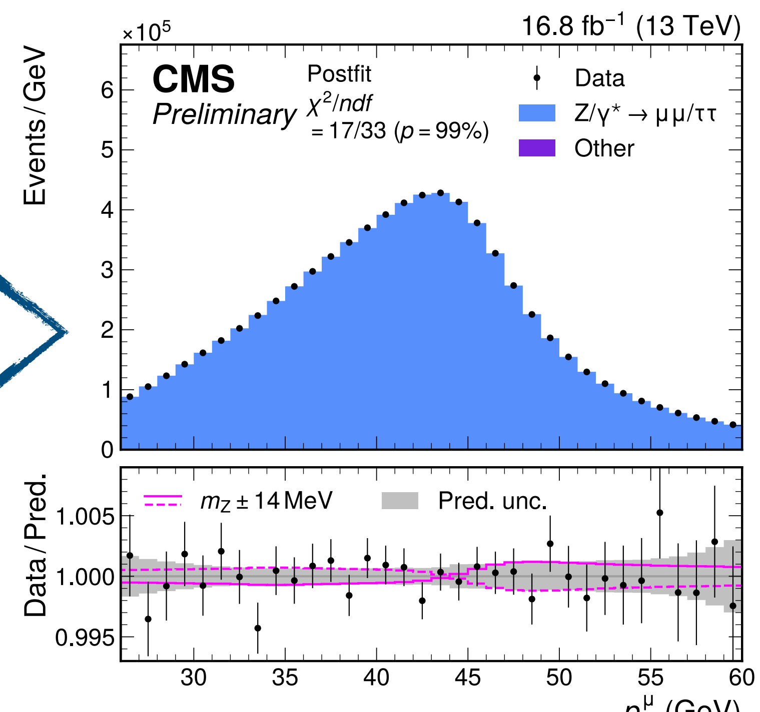
W-like m_Z with one muon

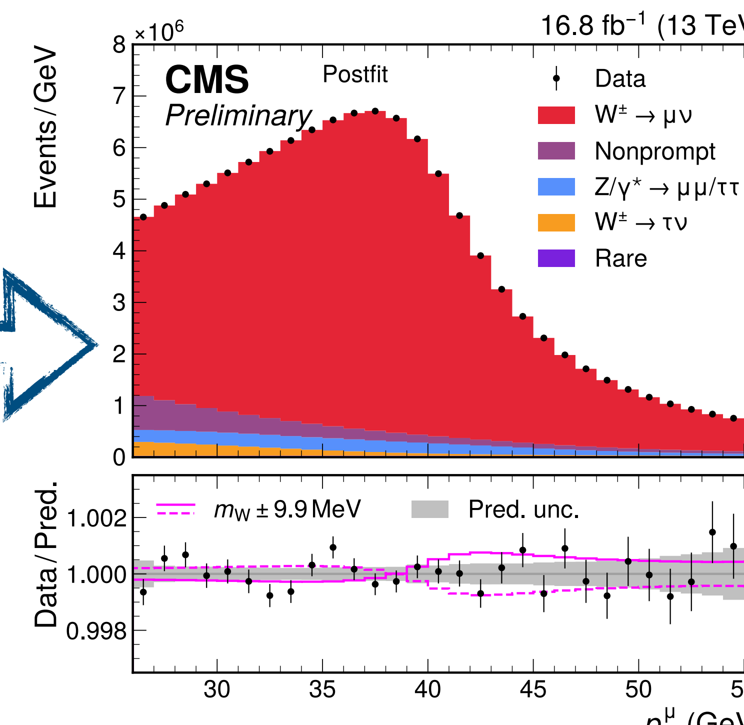
- Validate analysis technique, and (some) experimental and theoretical inputs

m_W

- Additional challenges: prompt/nonprompt backgrounds, orthogonal theory uncertainties







Experimental aspects

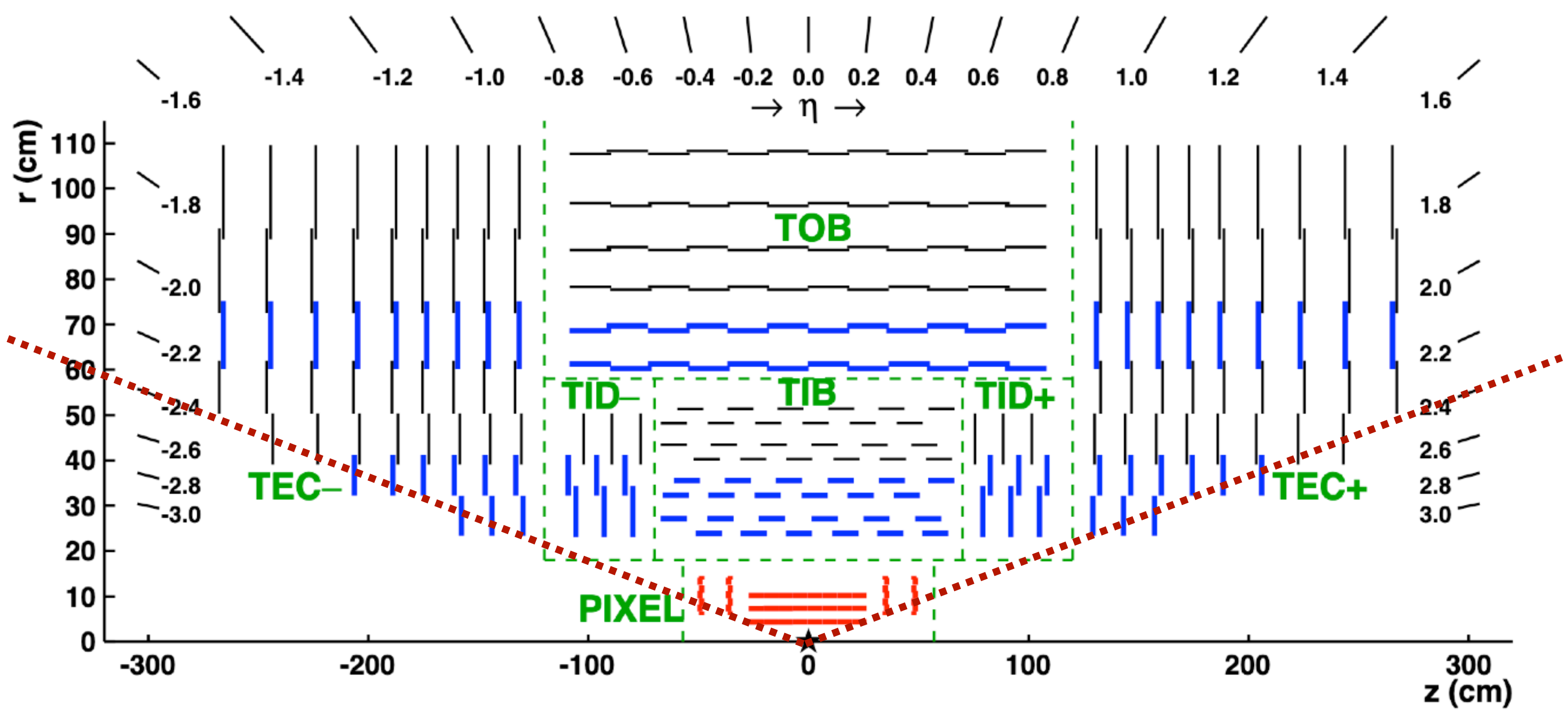
Muon scale calibration

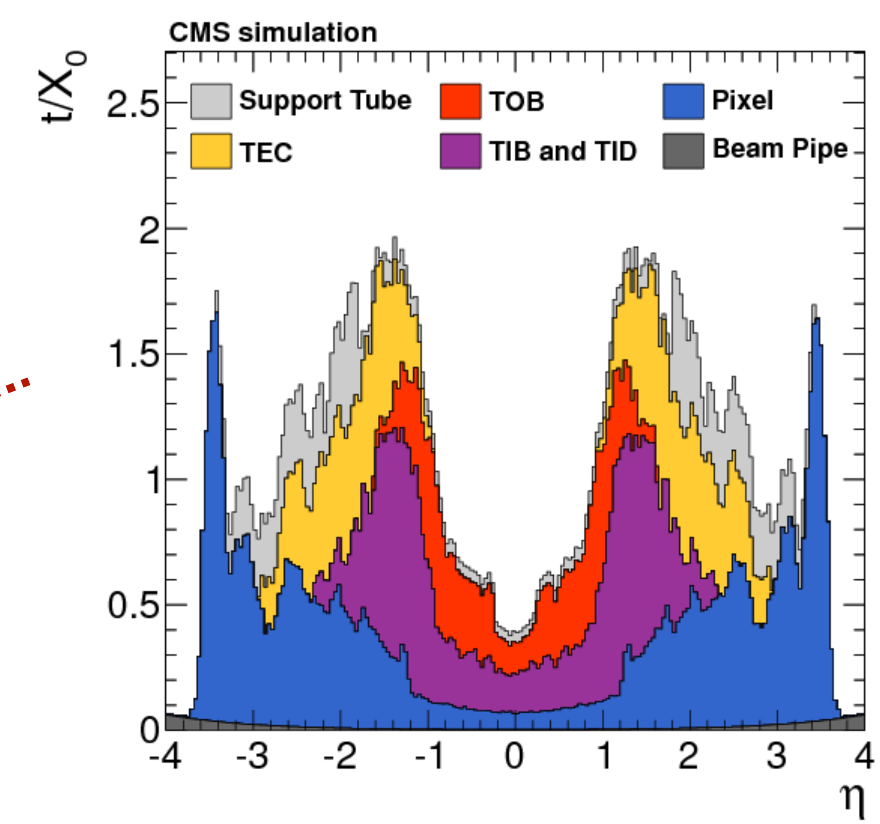
For p_T^{μ} < 200 GeV, momentum measurement driven by inner tracker

- External muon chambers only used for trigger and identification

Momentum calibration fully focused on silicon tracker (pixel + strip)

- Fiducial acceptance up to |η| = 2.4
- Up to ~17 points per track, single-hit resolution of 9-50 μm
- **Challenge**: significant amount of material in tracker volume





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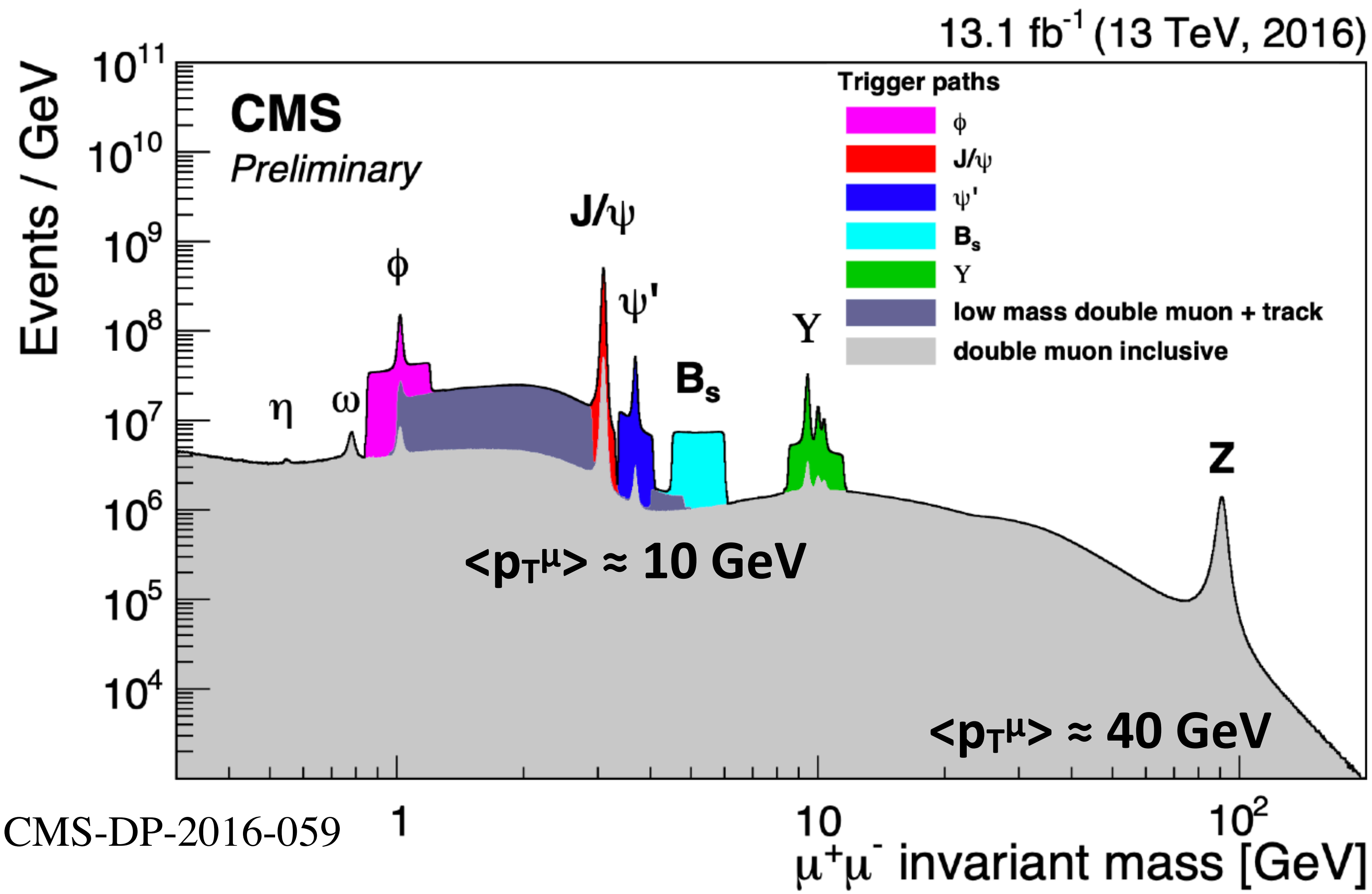
Muon scale calibration

Performed with quarkonia: mainly $J/\psi \to \mu\mu$ (can add Υ_{1S} too)

- **Z used ONLY as an independent cross check** to validate corrections and uncertainties
  - Different from ATLAS, similar to CDF
- Extrapolation from J/ψ to W and Z **requires extreme control over the p_T dependence**



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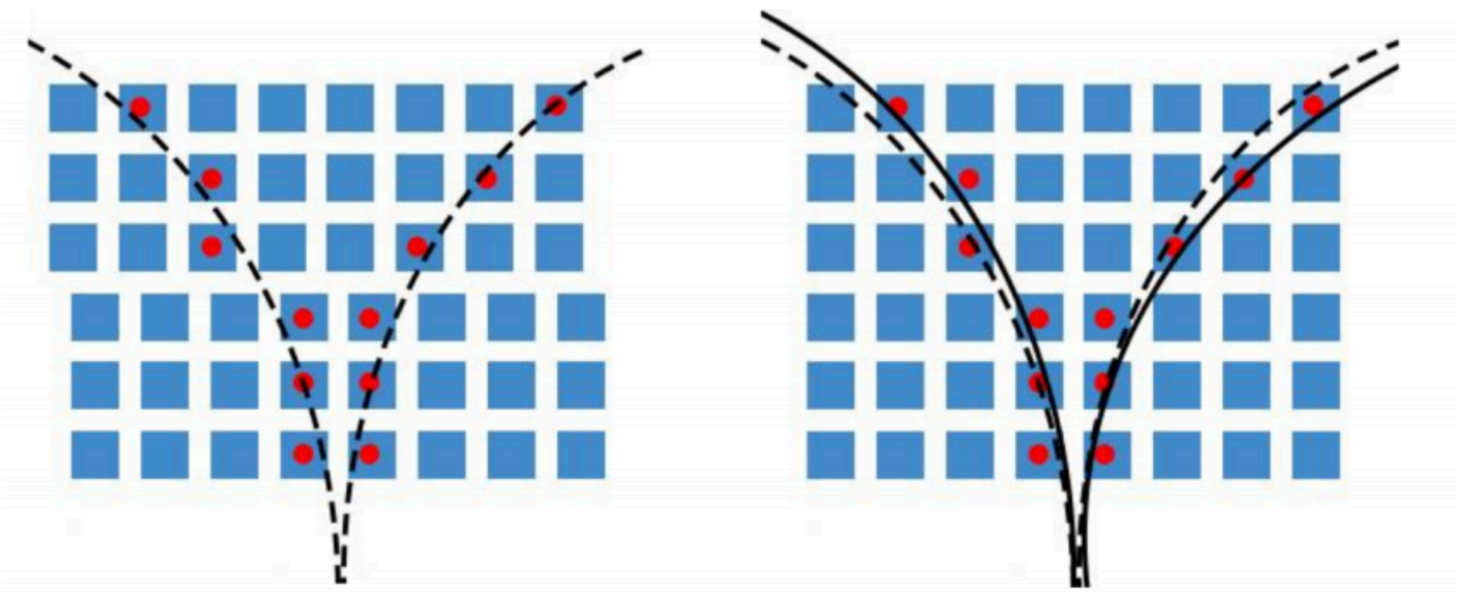
Muon scale calibration

Physics-motivated model to predict p_T scale bias arising from:

- Magnetic field (A)
- Energy loss due to material (ε)
- Alignment (M)

$$\frac{\delta k}{k} = A - \epsilon k + qM/k$$

$k = 1/p_T$



If the tracker is misaligned and we don't know it...

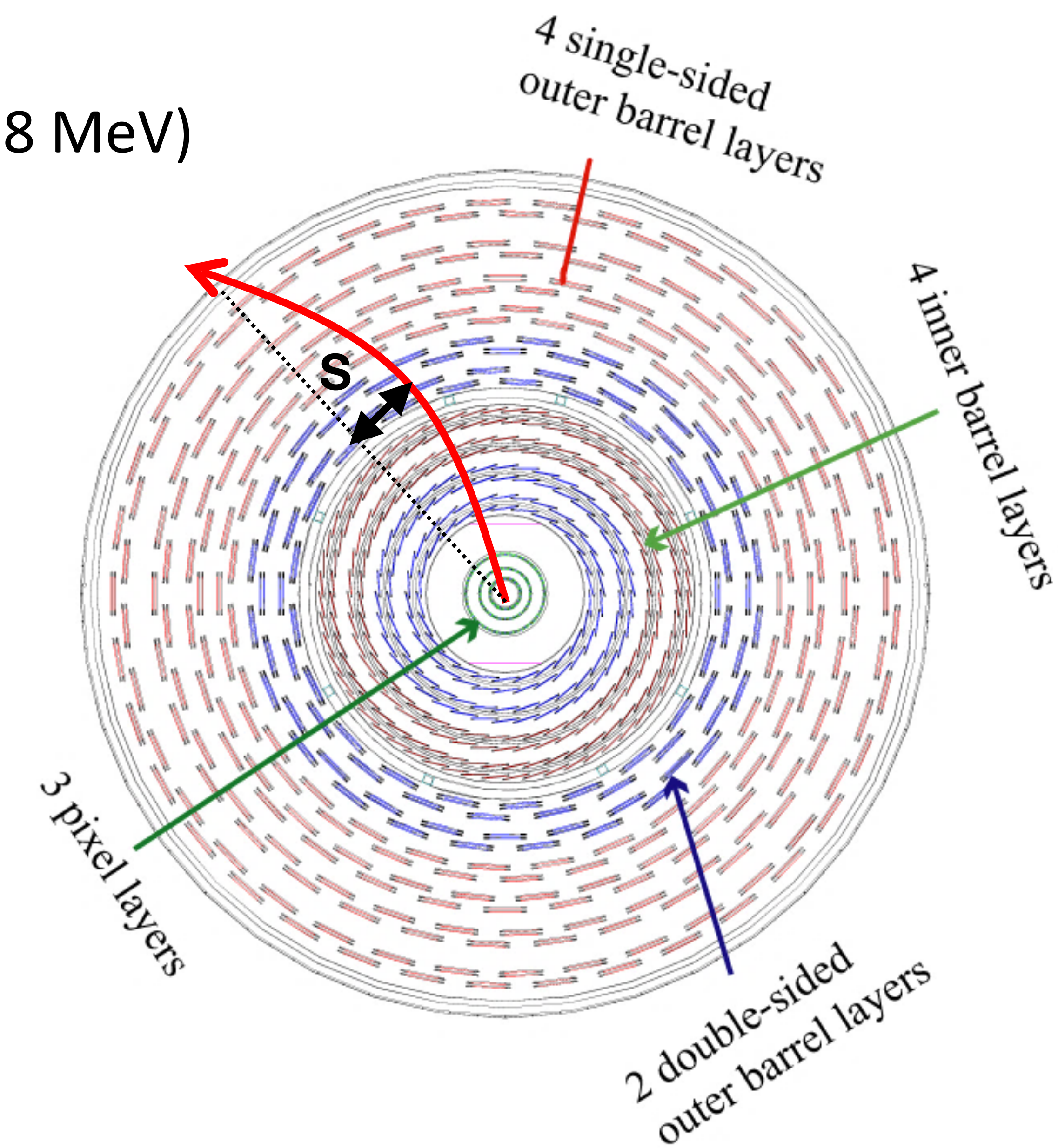
...the track will be reconstructed as if the tracker was aligned

N.B. in a silicon tracker, multiple scattering must be explicitly accounted for in track fit

- local biases in magnetic field, material, alignment (or small biases in simulation or reconstruction), can lead to additional non-trivial p_T^{μ} dependence of curvature bias

Challenges for precise momentum scale

- Target for ~40 GeV muons: $\frac{\delta p_T^{\mu}}{p_T^{\mu}} \lesssim 10^{-4}$ (δm_W ~ 8 MeV)
- Translates to $|\delta s| \lesssim$ 600 nm for sagitta



However

- Relative **alignment** of all tracker modules NOT known to this level
- **Material** only known within 10%
- A priori knowledge of **B-field** ~ 10^{-3}

Accurate calibration in data mandatory

- Also in simulation itself …

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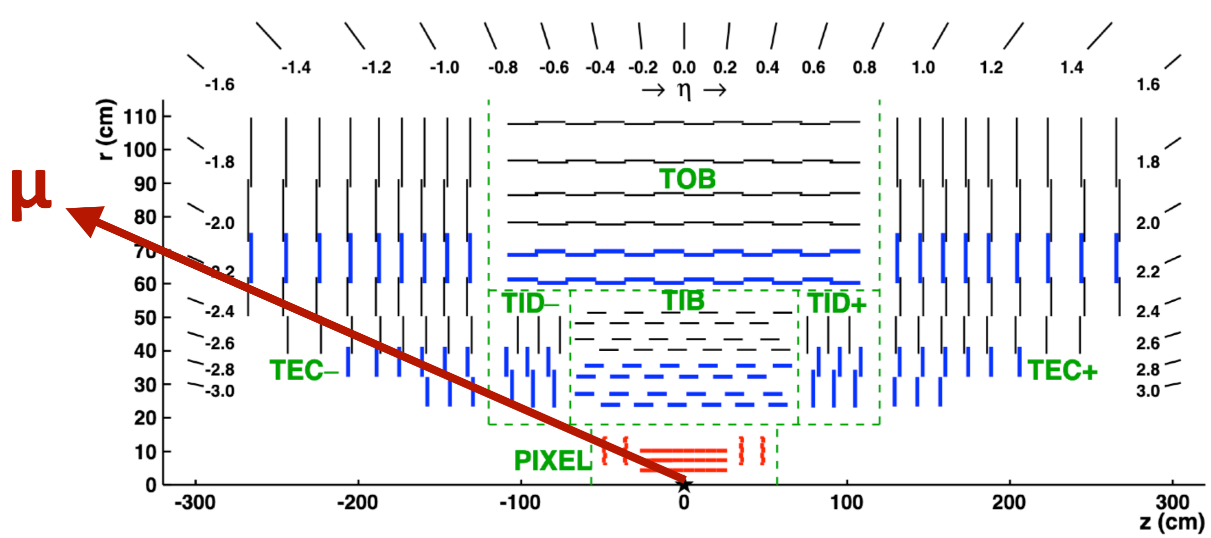
Out-of-the box picture

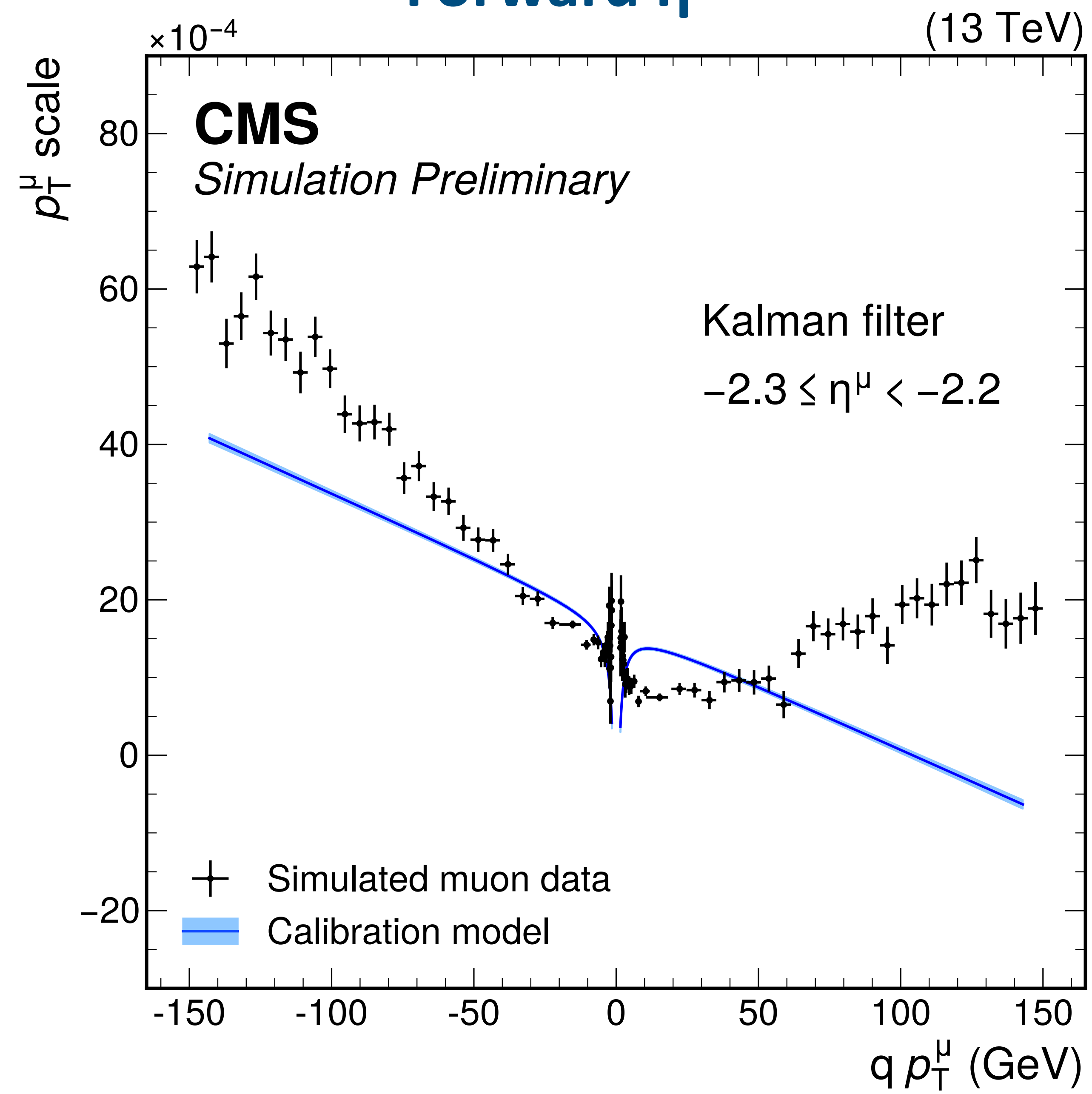
- p_T^μ scale bias versus $q^\mu \cdot p_T^\mu$ in simulation
- Significant bias and inaccurate model

$$\frac{\delta k}{k} = A - \epsilon k + qM/k$$

$k = 1/p_T$



Forward η^μ



Out-of-the box picture

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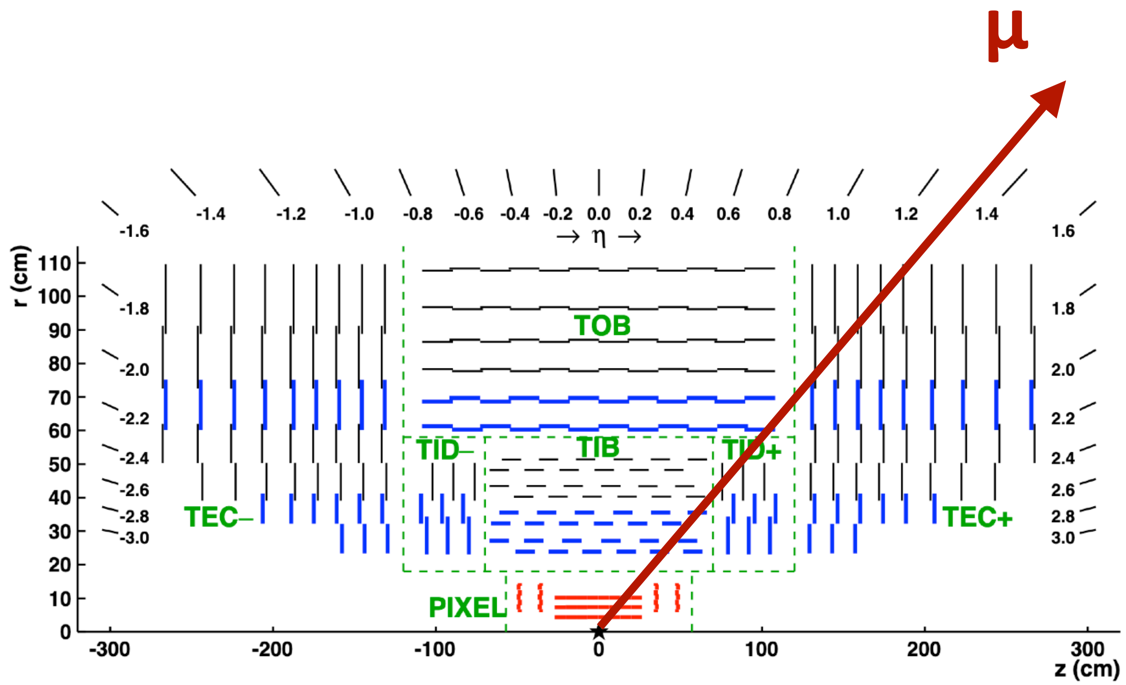
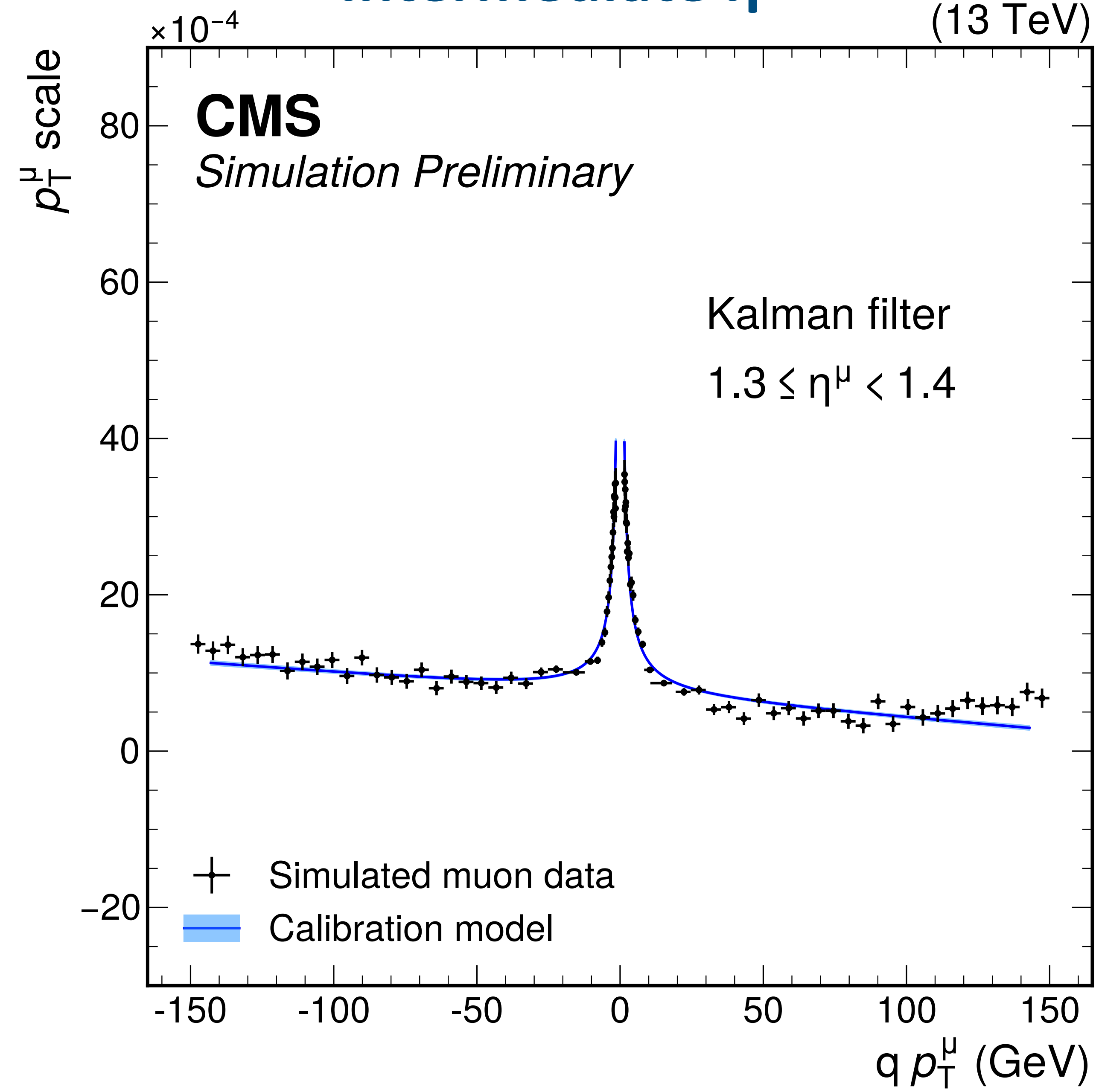


Intermediate η^μ



Muon calibration: sequential strategy

1. **Fix/improve nominal precision of simulation**
   - Approximations in track-surface intersection point in Geant4

2. **Refit tracks with new method specifically developed for this analysis**
   - Continuous Variable Helix (CVH), replacing Kalman Filter
   - Prioritize accuracy over speed (10x slower)
   - Geant4e propagator with refined treatment of material and multiple scattering

3. **Generalization of global alignment procedure to correct local biases**
   - Module-level ("layer-by-layer") corrections to B-field and energy loss, with additional degrees of freedom for translations and rotations
   - Based on track pairs from $J/\psi \rightarrow \mu\mu$ with common vertex and mass constraint

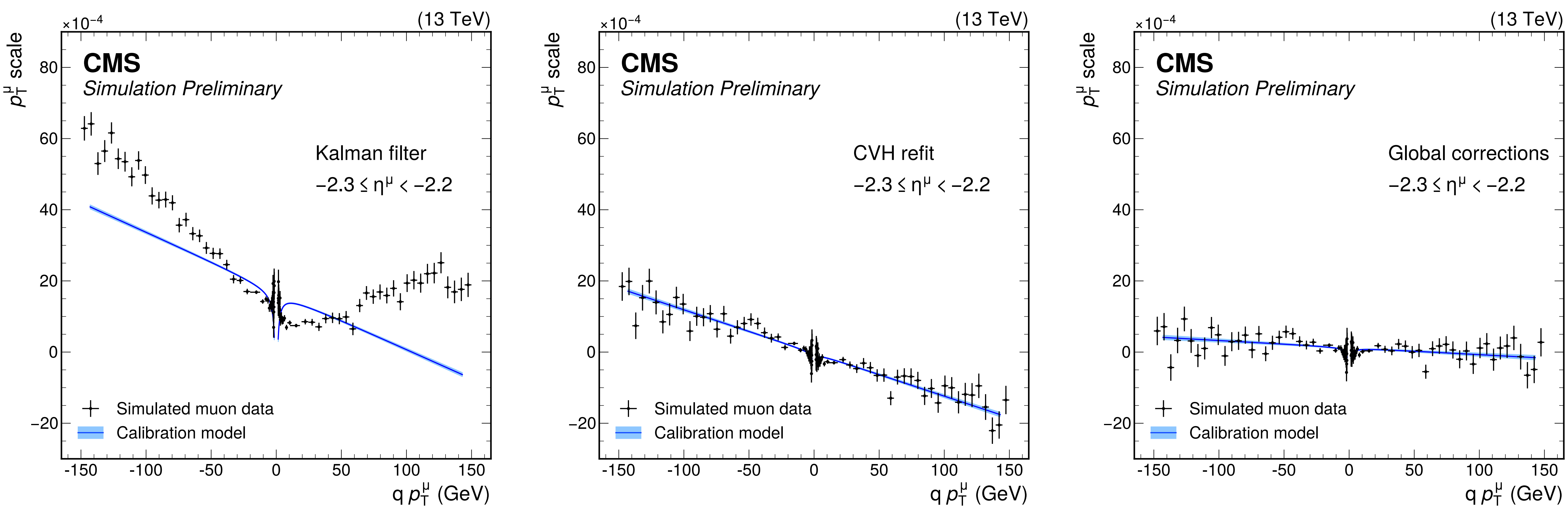
4. **Final scale corrections for residual differences between data and simulation**
   - Mass fits to $J/\psi \rightarrow \mu\mu$ events
   - Residual resolution corrections from J/ψ and $Z \rightarrow \mu\mu$ using related parametrization for multiple scattering, hit resolution, and correlation terms

Muon calibration in action

- Evolution of p_T^{μ} scale bias versus p_T^{μ}-q^{μ} in simulation in the forward η^{μ} bin
- Both CVH refit and global corrections are needed to restore the model validity

$$\frac{\delta k}{k} = A - \epsilon k + qM/k$$

$\delta m_W \sim 400$ MeV → $\delta m_W \sim 80$ MeV → $\delta m_W \sim 20$ MeV



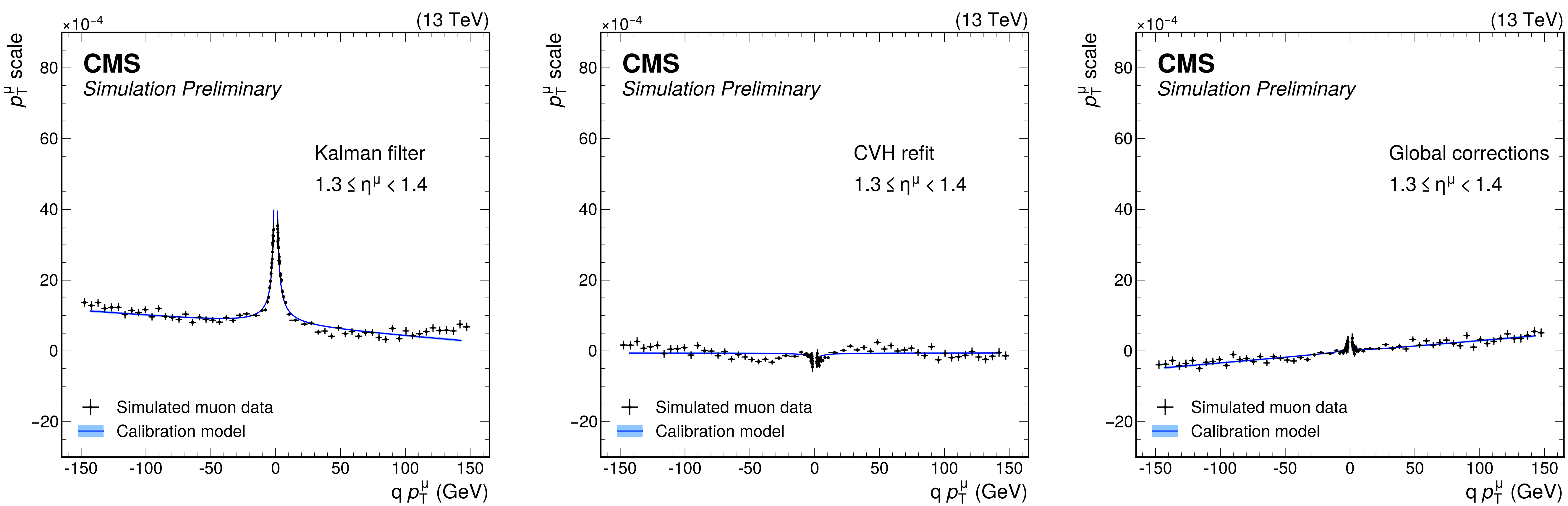
Muon calibration in action

- Same in more central η^{μ} bin
- Start with significant material mis-modeling, already improved by CVH track fit

Note: model eventually accurate up to p_T^{μ} = 150 GeV

- For W and Z, mostly care up to p_T^{μ} ~ 50 GeV

$$\frac{\delta k}{k} = A - \epsilon k + qM/k$$



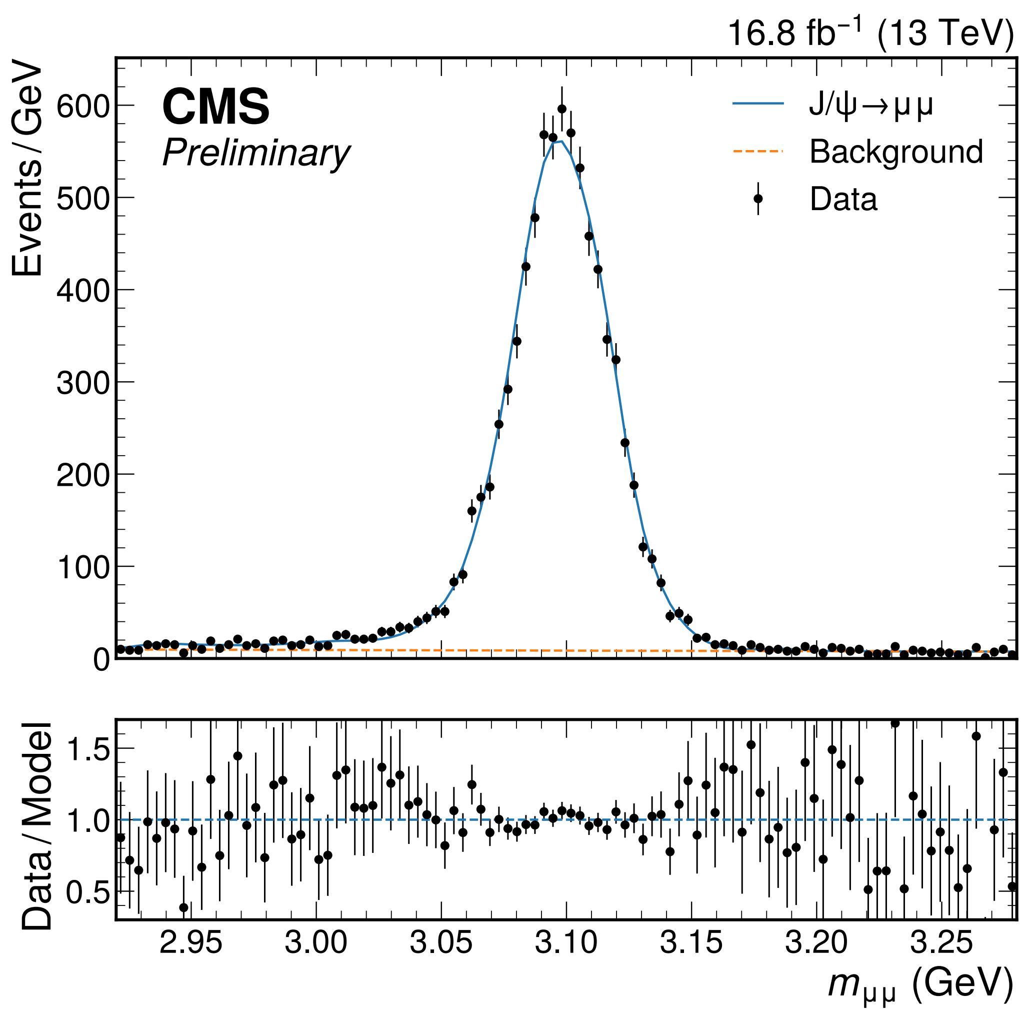
Final parametrized corrections

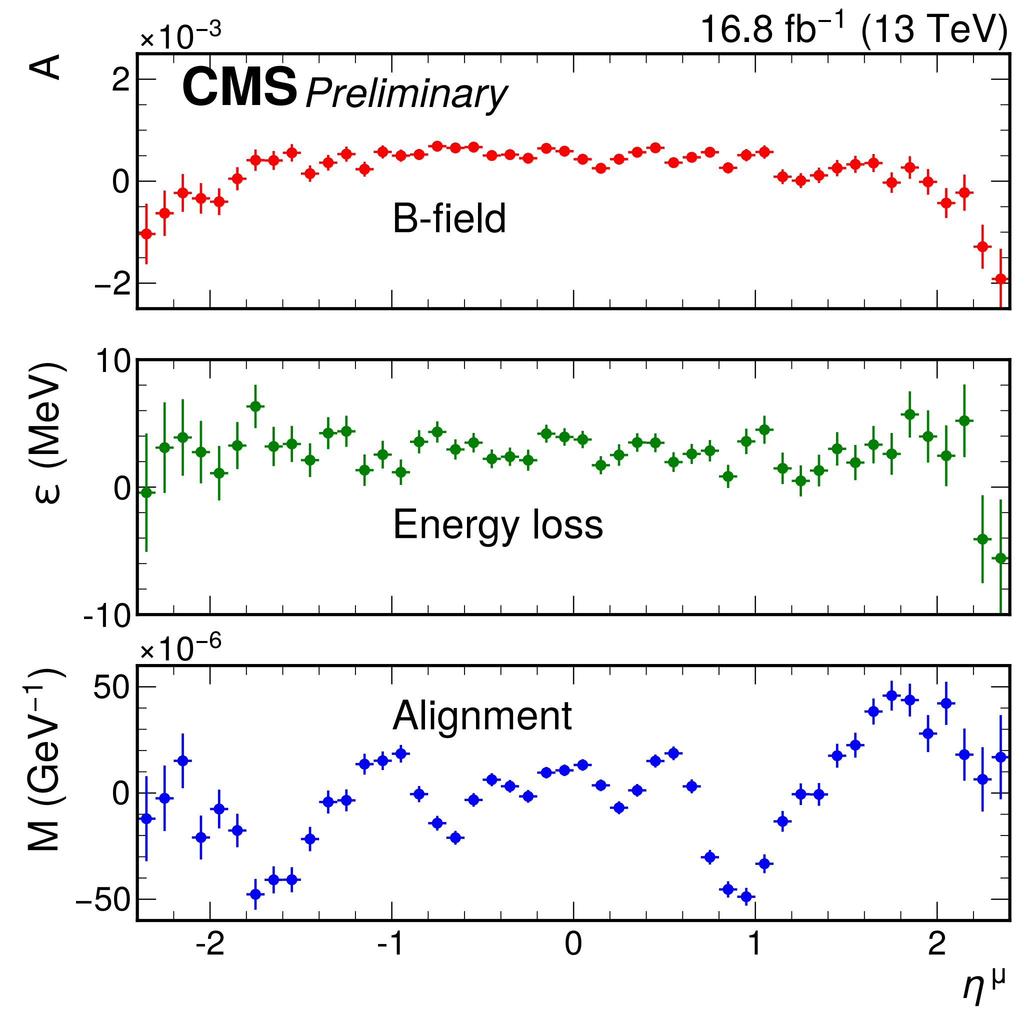
- Derived from mass fits to $J/\psi \rightarrow \mu\mu$ events in fine 4D bins ($p_T^{\mu+}, \eta^{\mu+}, p_T^{\mu-}, \eta^{\mu-}$)
- Global $\chi 2$ constructed and minimized over N 4D bins to **extract calibration parameters at single muon level,** binned in η^{μ} (index *i,j*) and parametrized vs p_T^{μ}

$$\chi^2 = \sum_N v^T C^{-1} v$$

$$v = \left(1 + A_+^i - \epsilon_+^i k + \frac{M_+^i}{k_+^i}\right)\left(1 + A_-^j - \epsilon_-^j k - \frac{M_-^j}{k_-^j}\right)_N - \left(\text{scale}^2\right)_N$$

One mass fit among N=*O*(10^4)





$$\frac{\delta k}{k} = A - \epsilon k + qM/k$$

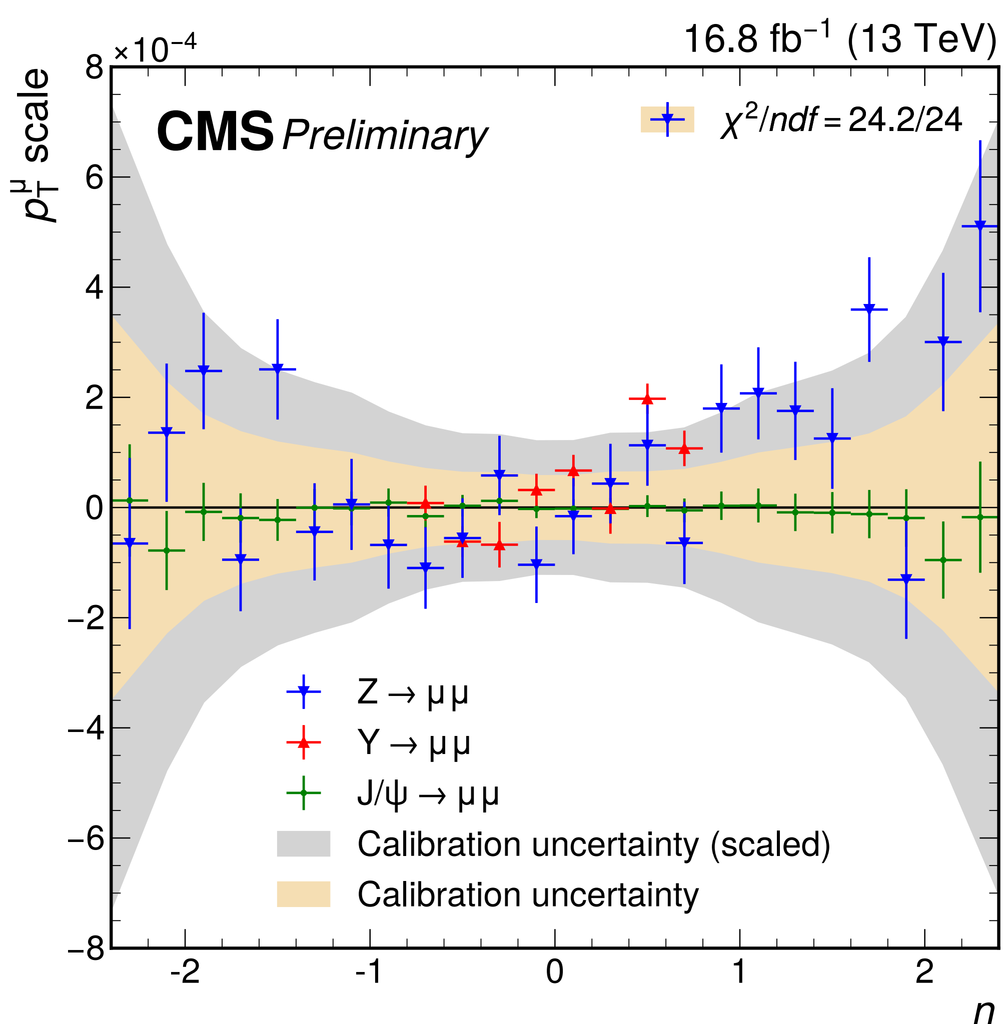
Validation and uncertainties

Calibration validated by correcting muon scale and refitting resonance mass

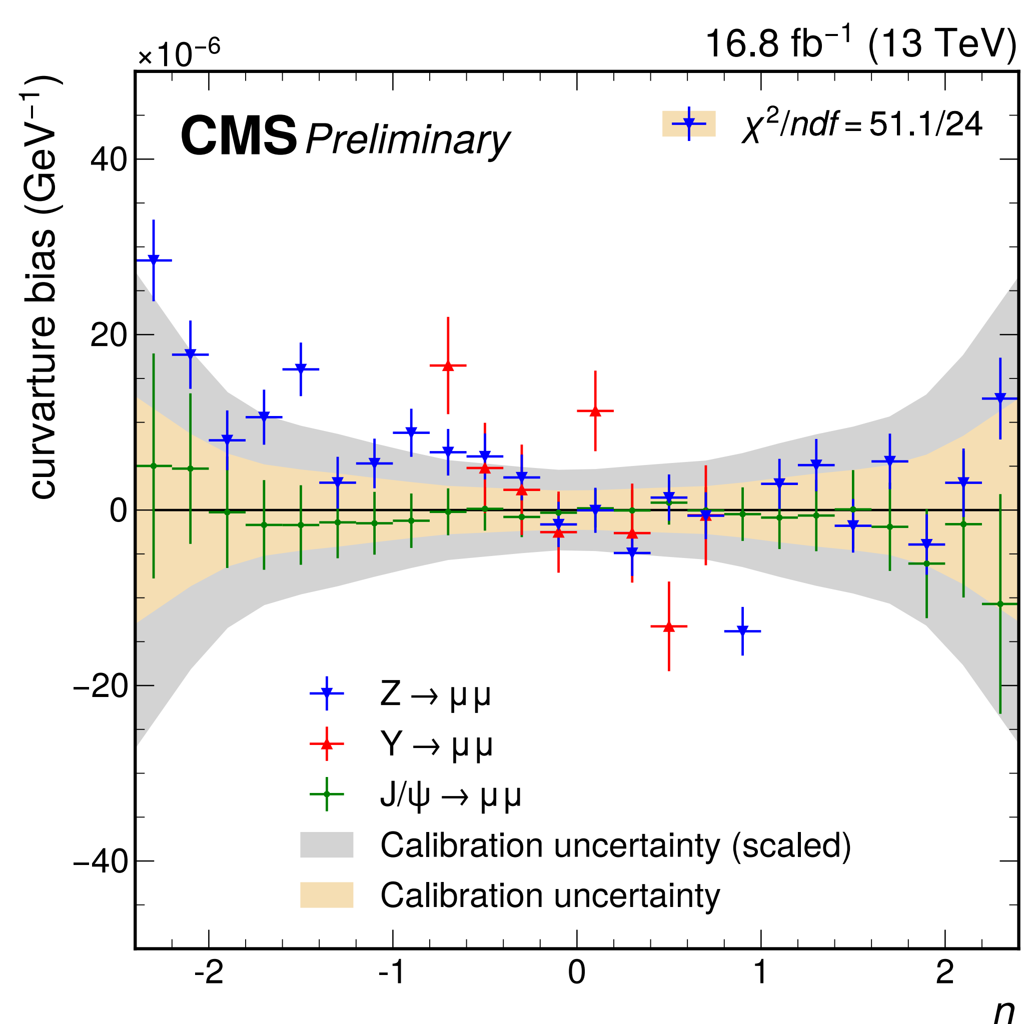
- Residual non-closure (e.g. from kinematic differences between J/ψ and Z)

Stat. unc. on J/ψ calibration parameters scaled by 2.1 to cover all possible correlated patterns of bias across η from systematic effects not explicitly accounted for

- Checked with bias tests: inject non-closure, target m_W bias < calibration uncertainties



Charge independent closure (B field)



Charge dependent closure (alignment)

Uncertainty model for m_W

Statistical uncertainties associated with J/ψ versus Z closure

- They are the precision with which the calibration is validated

m_Z uncertainty from LEP measurement (m_Z = 91187.6 +- 2.1 MeV)

Small additional uncertainty for resolution

- Subtle effects from pixel hit multiplicity resulting in some increase for the overall resolution uncertainties

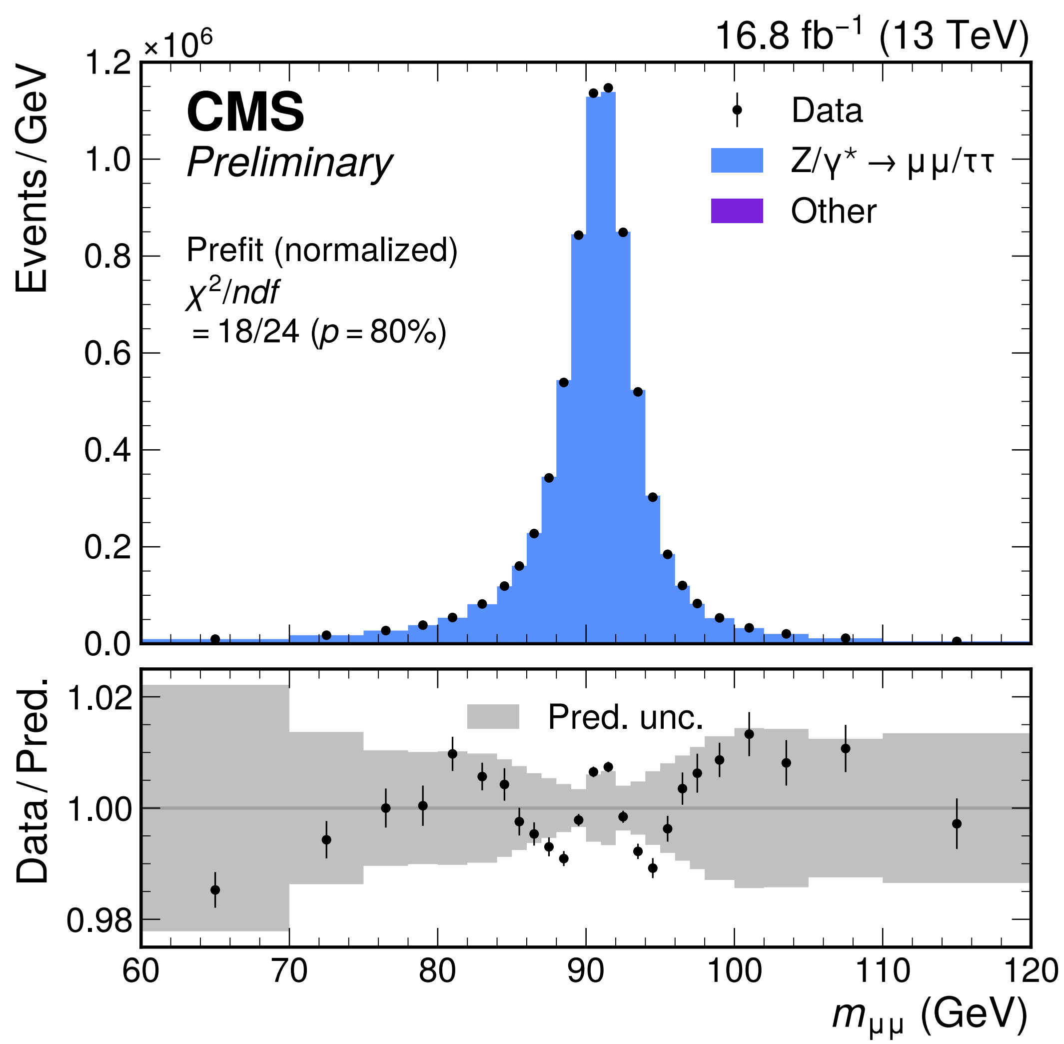
Source of uncertainty	Nuisance parameters	Uncertainty in m_W (MeV)
J/ψ calibration stat. (scaled $\times 2.1$)	144	3.7
Z closure stat.	48	1.0
Z closure (LEP measurement)	1	1.7
Resolution stat. (scaled $\times 10$)	72	1.4
Pixel multiplicity	49	0.7
Total	314	4.8

The ultimate validation: extraction of m_Z

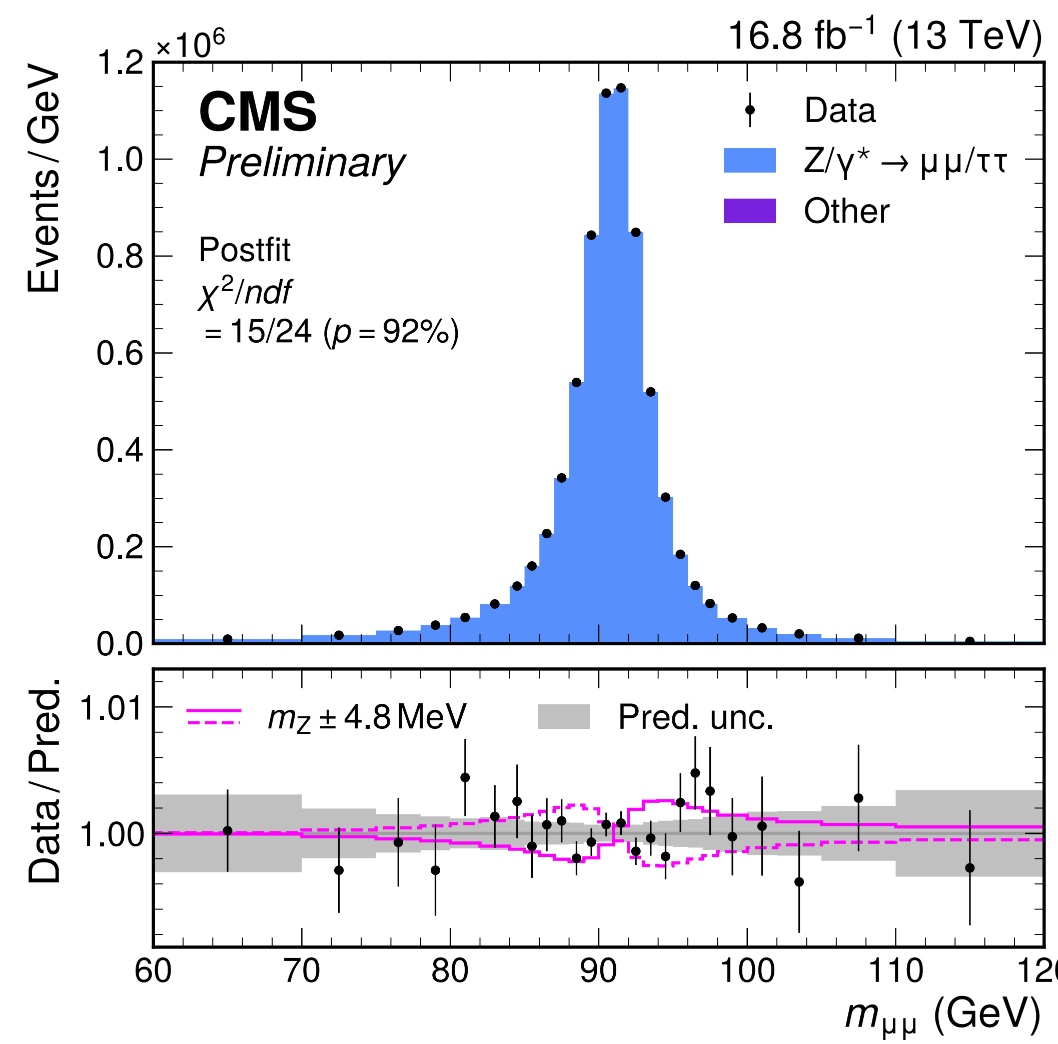
- 2D profile-likelihood fit to $m_{\mu\mu}$ and η^{μ} of the most forward muon
- $m_Z - m_Z^{LEP} = -2.2 \pm 4.8$ MeV =
  -2.2 ± 1.0 (stat) ± 4.6 (calib) ± 0.8 (other syst) MeV

Not (yet) a fully independent measurement for inclusion in the world average

- J/ψ versus Z closure was used to tune the calibration, and enters uncertainty model



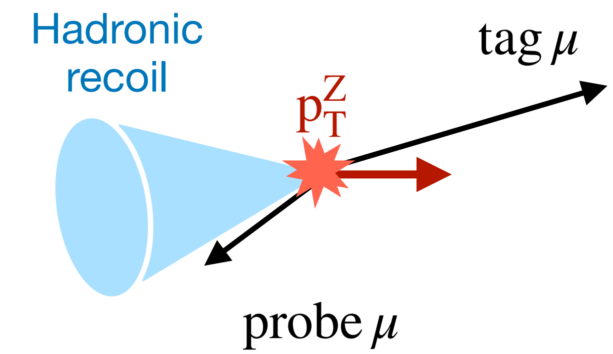
Prefit (normalized)



Postfit

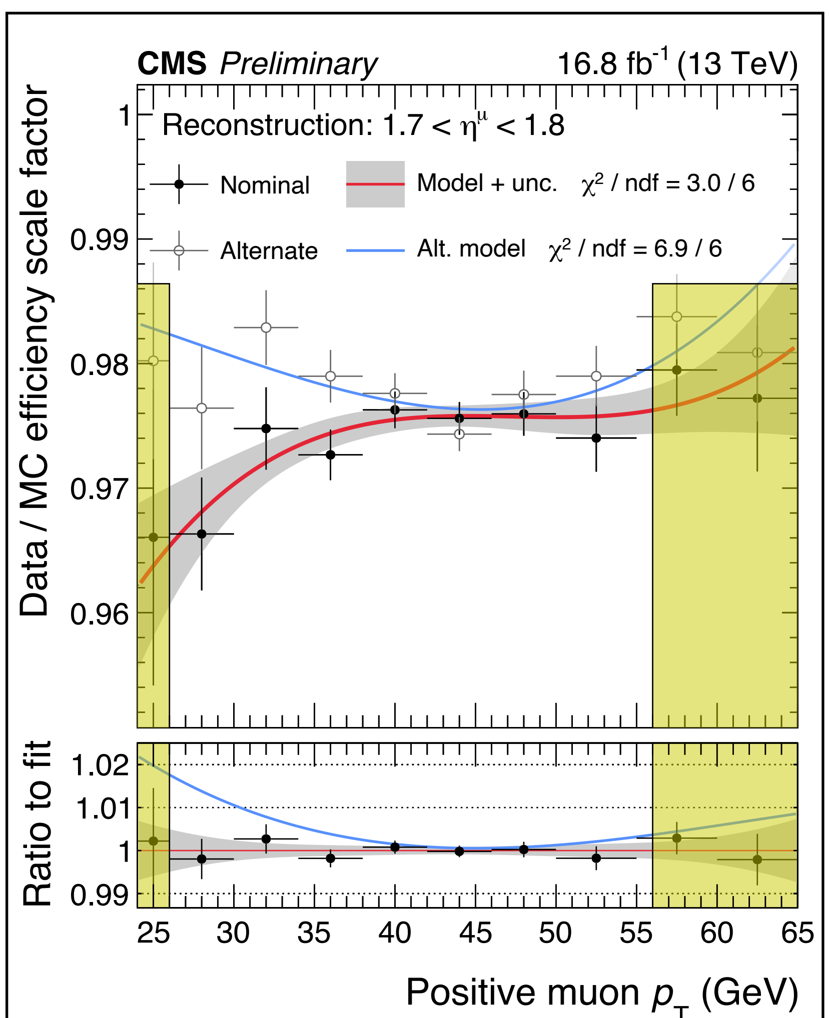
Muon efficiencies

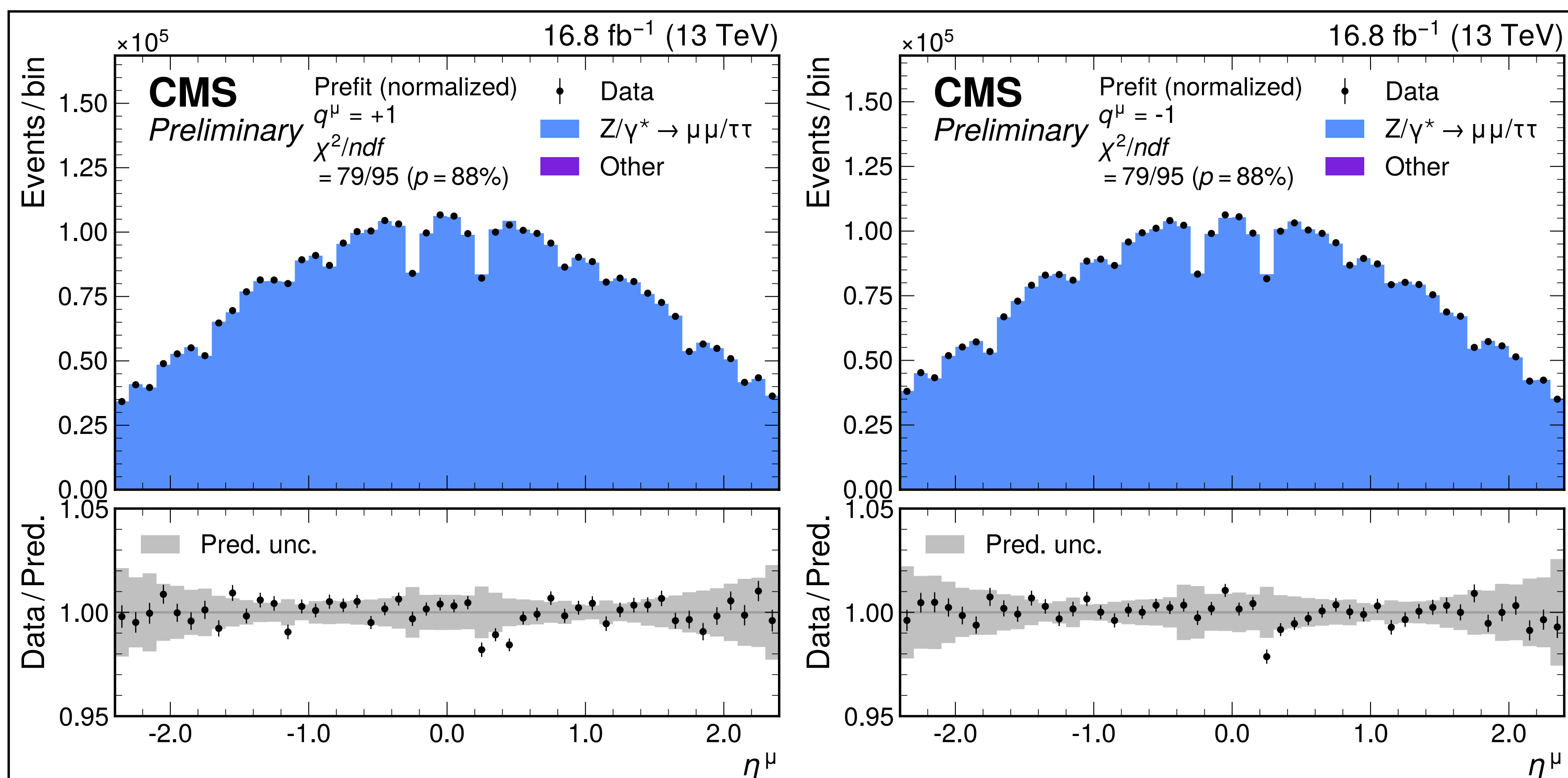
Data/MC scale factors (SF) measured in $Z \to \mu\mu$ events with tag&probe, differentially in μ selection stage and p_T^μ-η^μ-q^μ



- Reconstruction * tracking * identification * trigger * isolation
- Trigger/isolation also binned in u_T to account for contribution of hadronic recoil to isolation sums (different between W and Z)
- Smoothing of SF with 1D(2D) polynomials versus p_T^μ($-u_T$)

$$u_T = \frac{\vec{p}_T^{\,Z} \cdot \vec{p}_T^{\,\mu}}{|\vec{p}_T^{\,\mu}|}$$





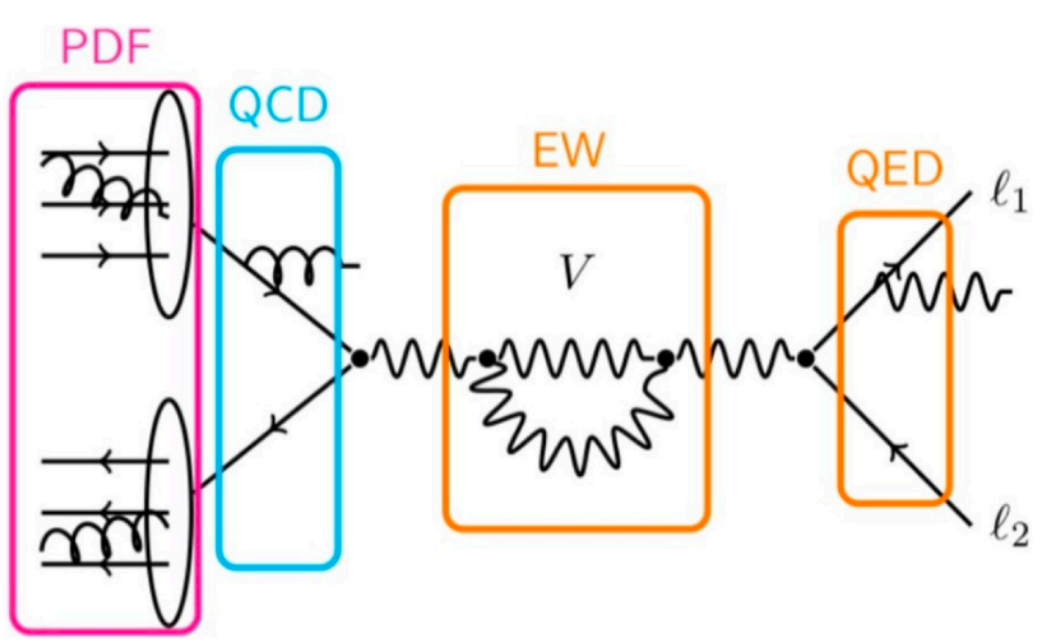
$\delta m_W \sim 3$ MeV

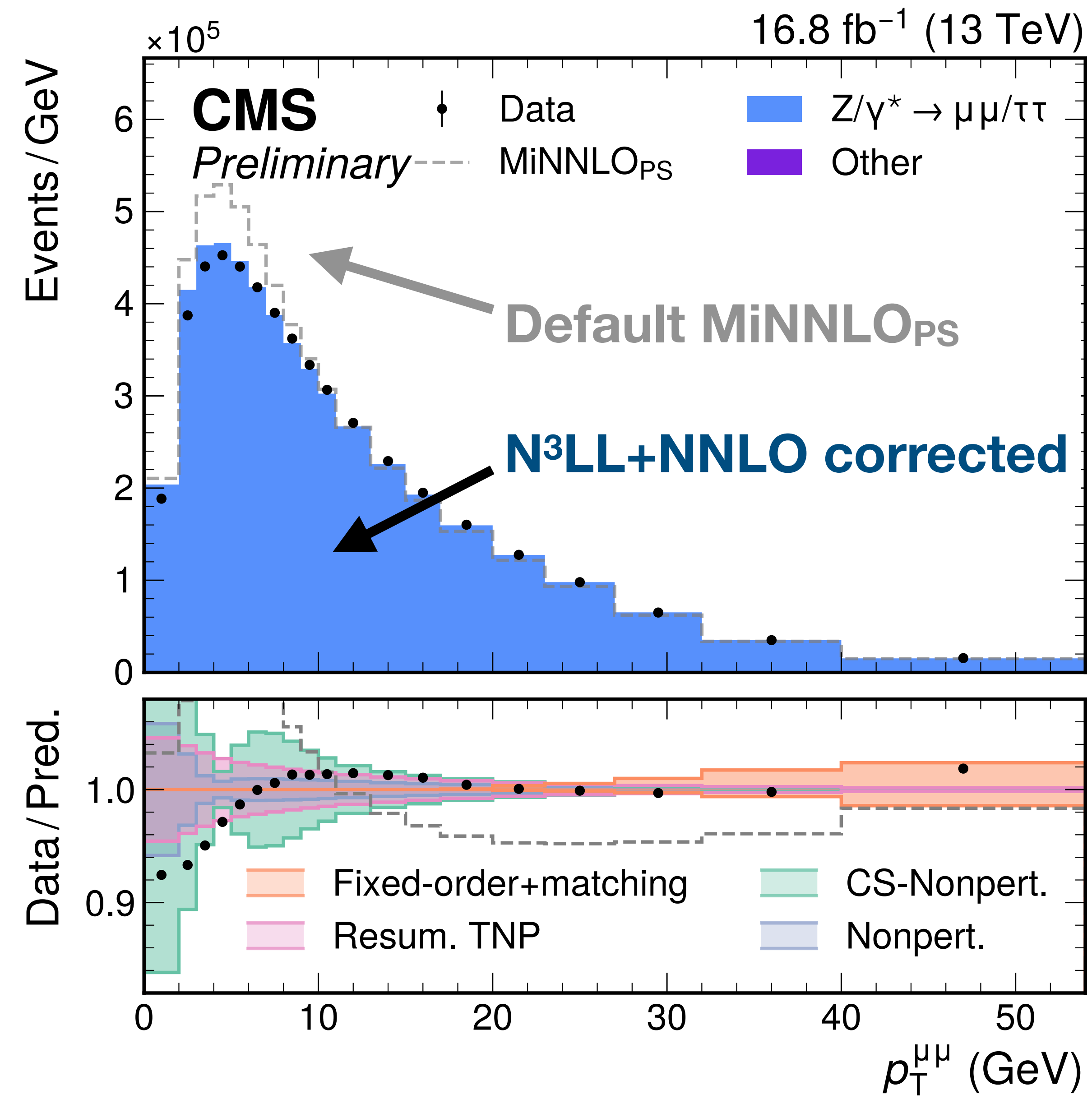
Theory modelling

Simulated W and Z samples

POWHEG+MiNNLO$_{PS}$, interfaced to PYTHIA8 and PHOTOS++

- NNLO in α_S, but limited accuracy at low p_T^V (leading logarithm, LL)
  - **N^{3}LL+NNLO corrections from SCETlib+DYTurbo**
- ~NLO QED accuracy for photon final state radiation (FSR) with PHOTOS ($\gamma \to \ell\ell$ pair production also included)
- Weights for several modern PDF sets
- ~4/0.4 B W/Z MC events, δm_W^{MCstat} ~ 1.5 MeV





Angular coefficients and uncertainties

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

Kinematics of W/Z

Angular coefficiencts (Predicted by pQCD)

Spherical harmonics of decay angles in Collins-Soper frame, ref)

A_i predicted by MiNNLO$_{PS}$ at NNLO accuracy

- Uncertainties assessed through MiNNLO$_{PS}$ μR, μF scale variations decorrelated vs A_i
- Validated against other fixed-order predictions (e.g. DYTurbo, MCFM)

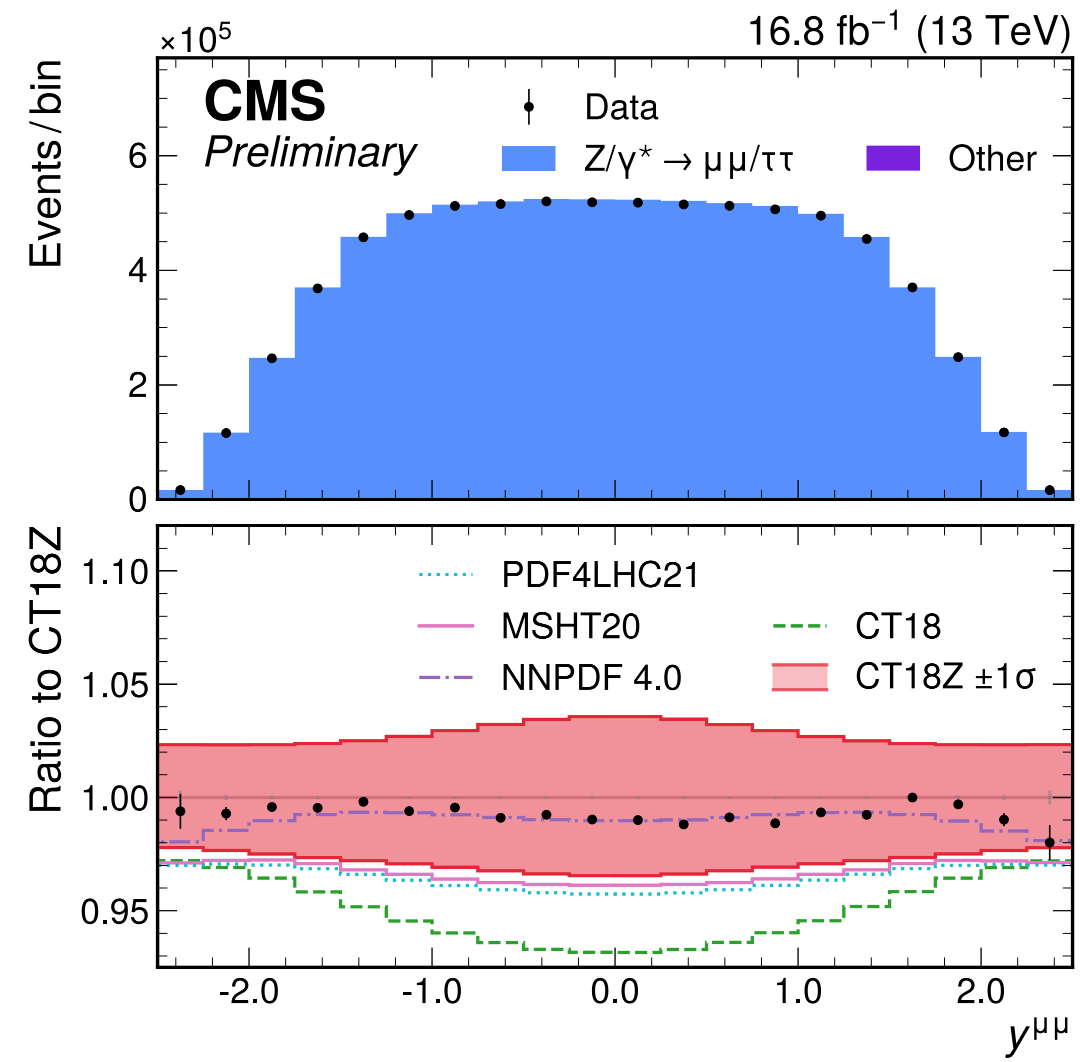
Differences between W and Z coupling to leptons

- Translate into distinct angular distributions, so the uncertainties are also decorrelated in 10 bins of p_T^V and between W and Z (but correlated in boson rapidity and charge)

PDFs

- **GOOD**:
  PDFs come with well defined uncertainty models and correlations across phase space and between W and Z (suited for profiling)

- **BAD**:
  in recent precision measurements at hadron colliders, e.g. α_S [1] or $\sin^2\theta^{\ell}_{eff}$[2], often significant spread of results, not always covered by PDF uncertainties



We enforce consistency among all sets

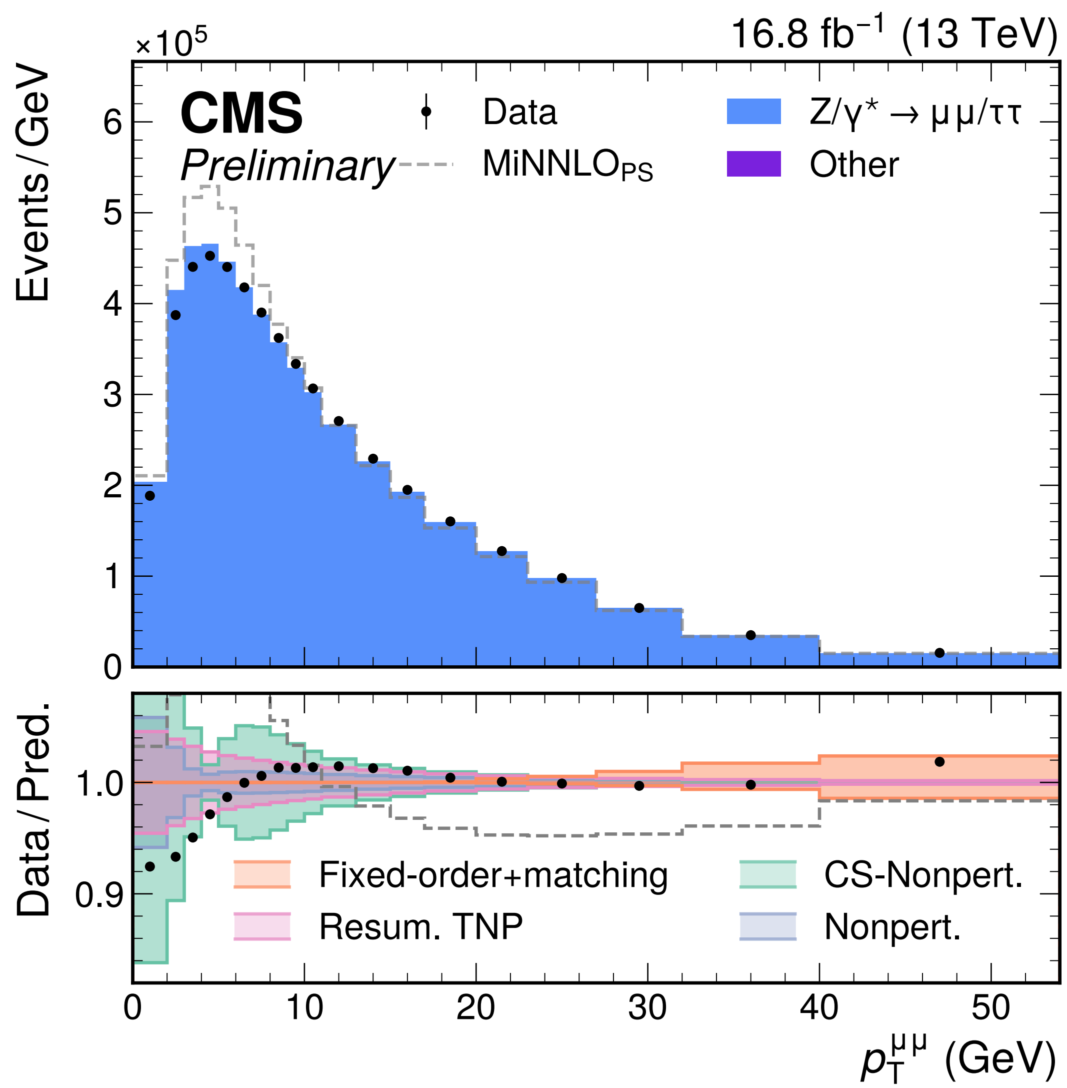
- Bias tests on m_W: one PDF set as prediction, another as pseudo data
- Inflate PDF uncertainty for failing sets
- CT18Z covers all PDFs without inflation, chosen as nominal to extract m_W

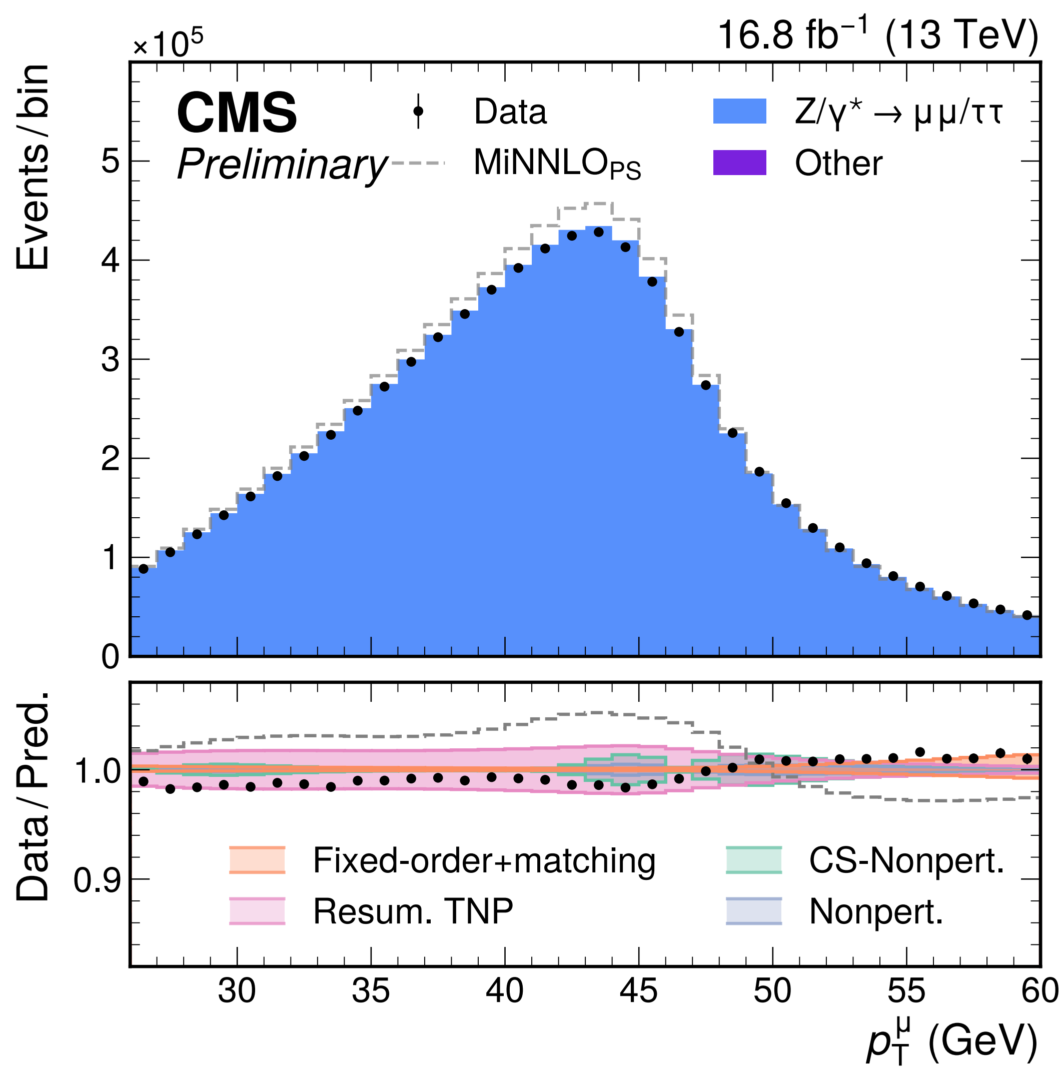
PDF set	Scale factor	Impact in m_W (MeV) Original σ_{PDF}	Impact in m_W (MeV) Scaled σ_{PDF}
CT18Z	–	4.4	
CT18	–	4.6	
PDF4LHC21	–	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0

p_T^V modeling uncertainties

- **Fixed-order** (perturbative, mainly high p_T^V): missing higher orders in α_s for σ_{UL} assessed through variations of the μ_R , μ_F scales from DYTurbo
  - plus additional uncertainty for matching between fixed order and resummation

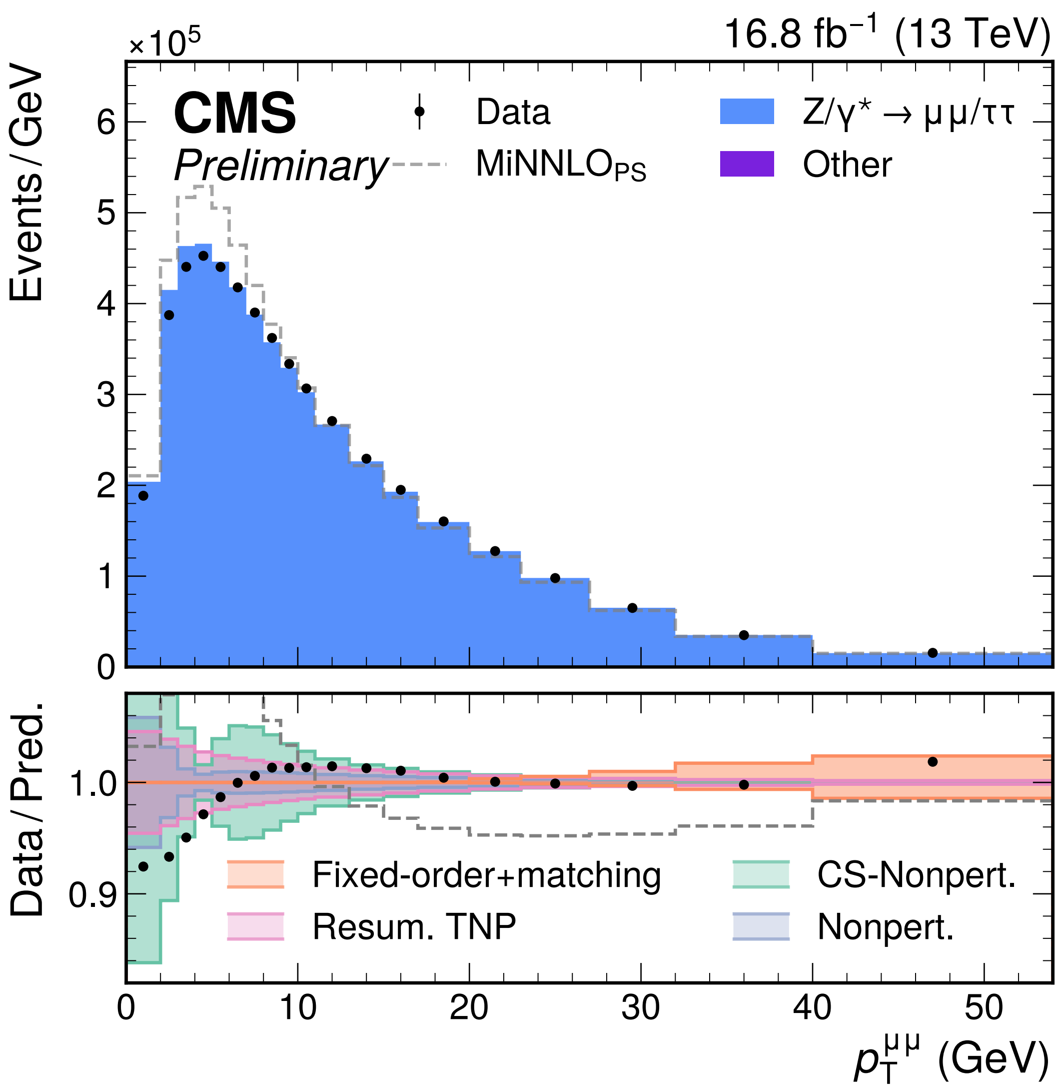
- **Resummation** (perturbative, lower p_T^V): from "Theory Nuisance Parameters" (TNP)

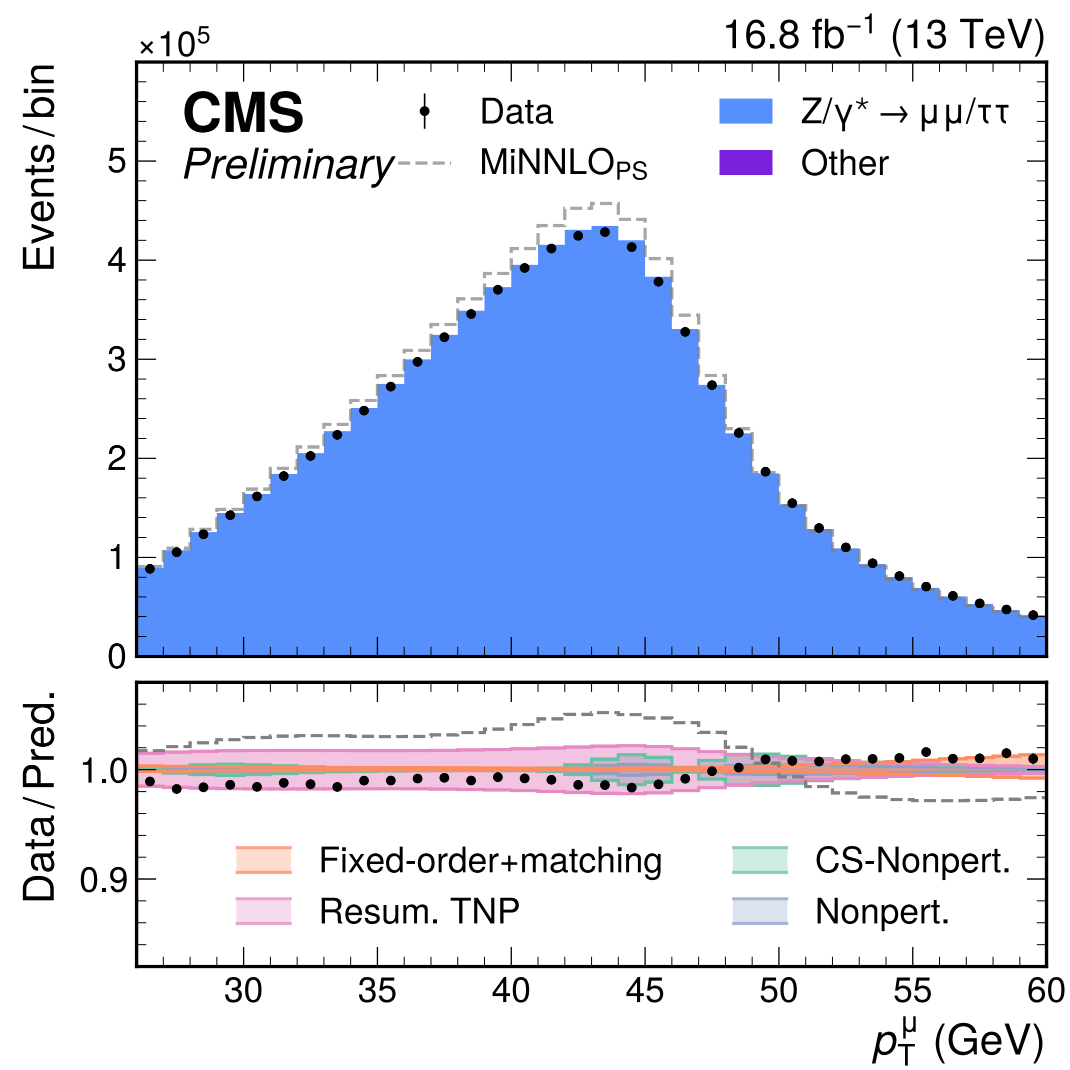




p_T^V modeling uncertainties

- **Non-perturbative**: intrinsic partons' p_T and non-perturbative component of resummation uncertainties
  - Empirical model inspired by transverse momentum dependent (TMD) PDFs
  - Associated parameters not predicted a priori, they must be determined from data (or lattice calculations)
  - Arbitrary initial values and large uncertainties, intended to be constrained from data





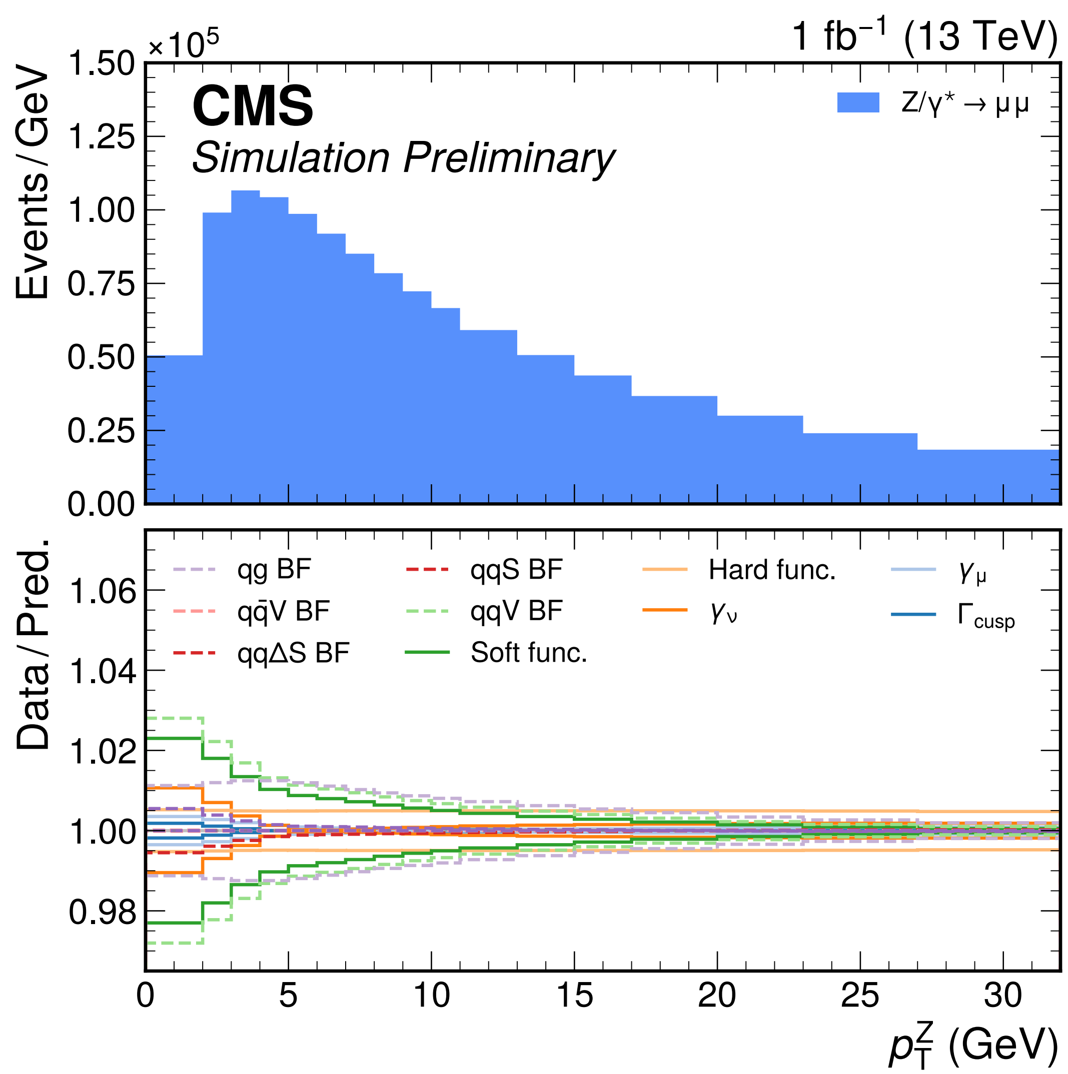
Resummation and theory nuisance parameters

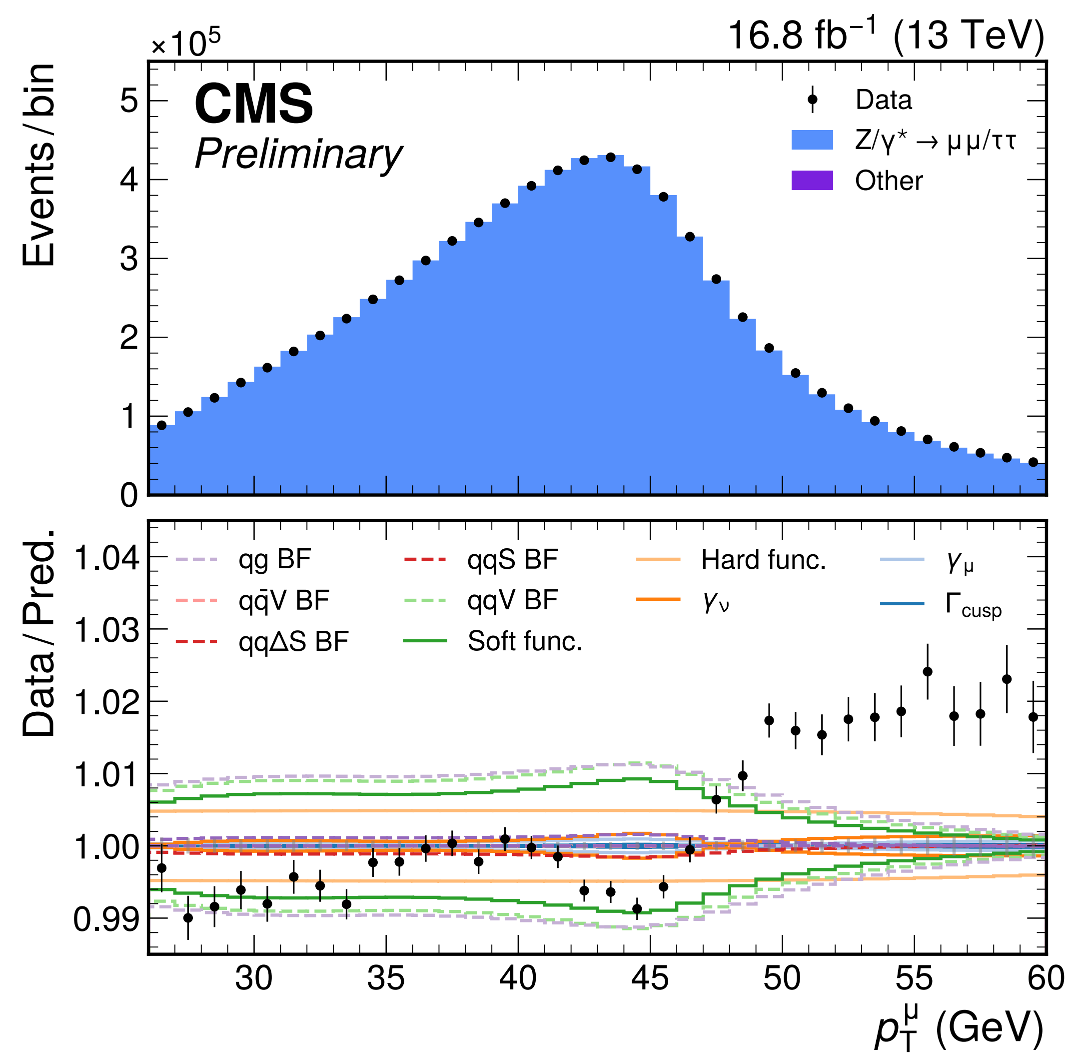
TNP account for coefficients in known internal structure of $d^2\sigma/dp_T^V dy^V$ cross section

- Innovative approach used for the first time (proposed by F. Tackmann, see e.g. here)

Well defined correlation model across phase space and between W and Z

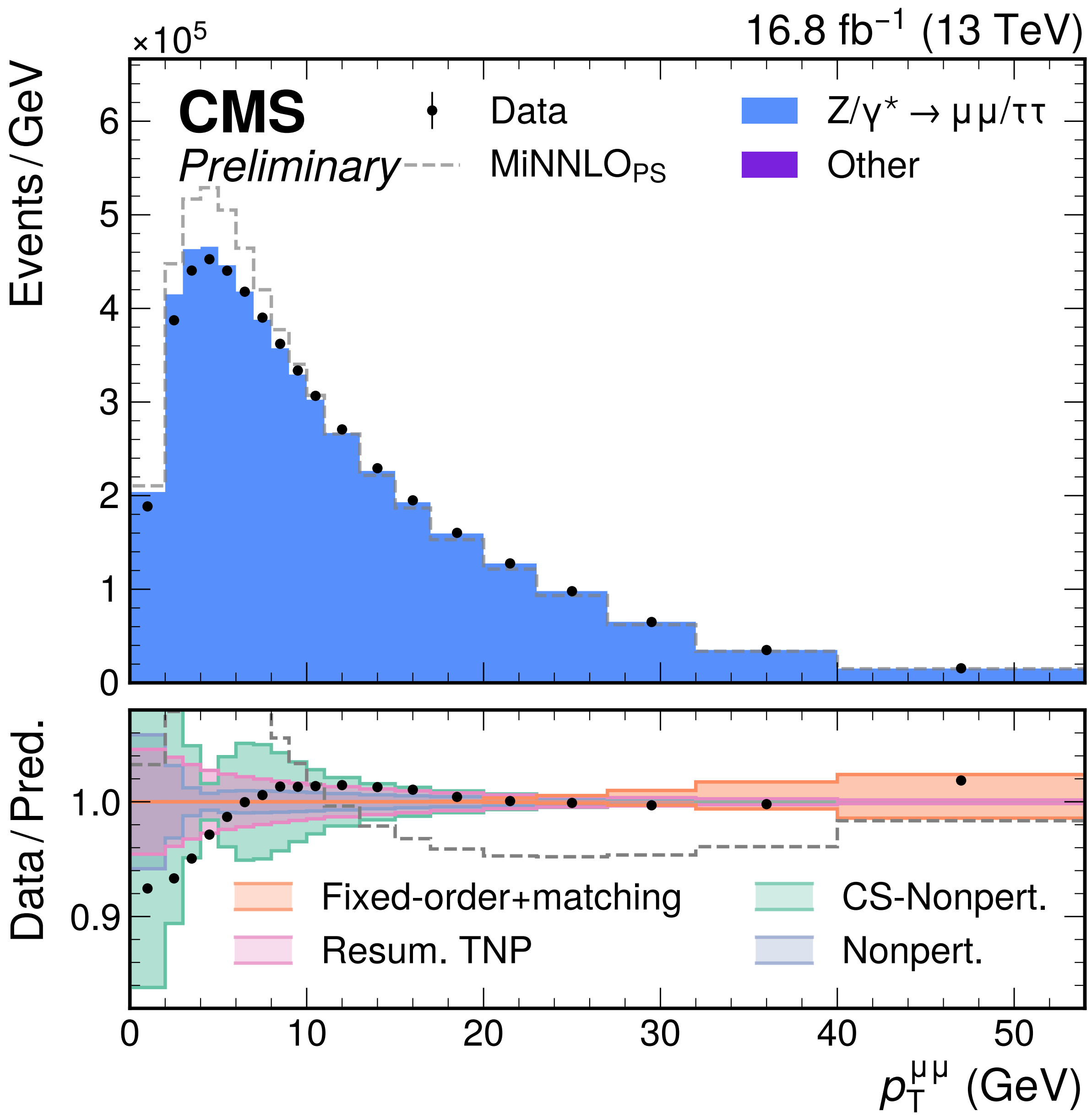
- Suited for likelihood profiling, proper statistical interpretation if pulled/constrained
- In contrast to scale variations, which lack these features

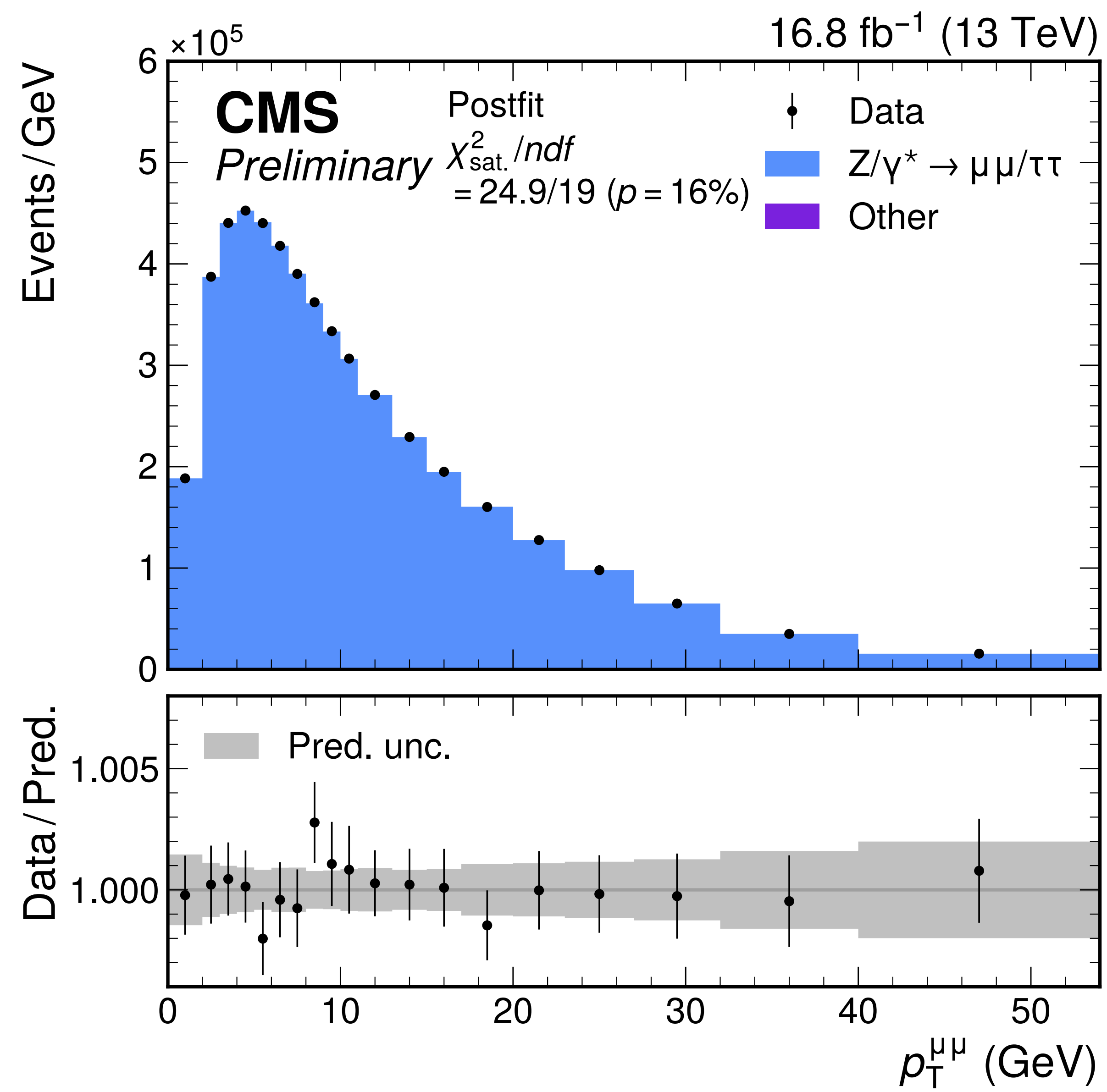




Validation of p_T^V modeling with Z→μμ

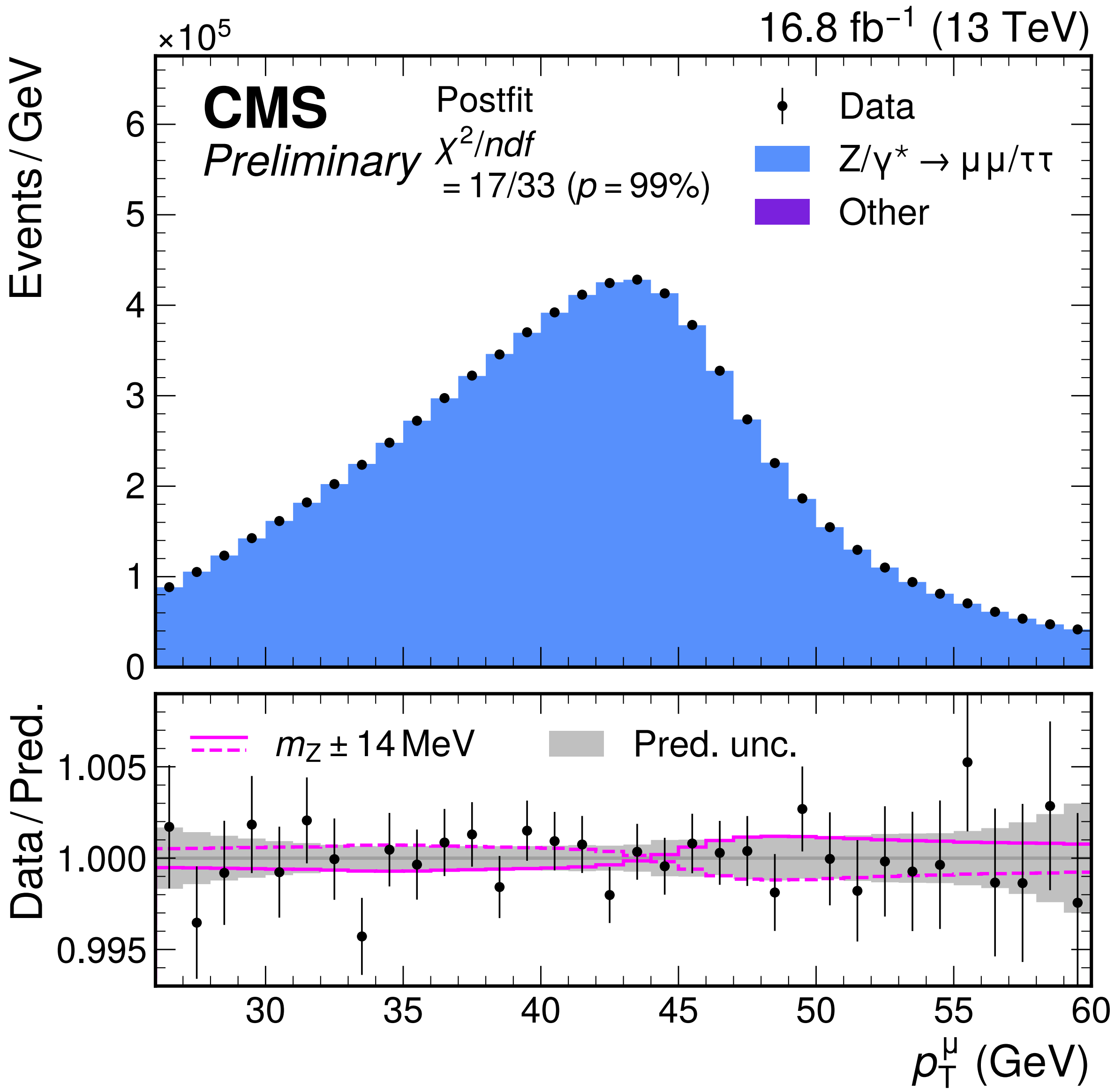
- Z→μμ events offer a clean way to test theory model and uncertainties
- When fitting directly $p_T^{\mu\mu}$, theory model is able to describe the Z data
- Postfit description of the spectrum at 0.1% level

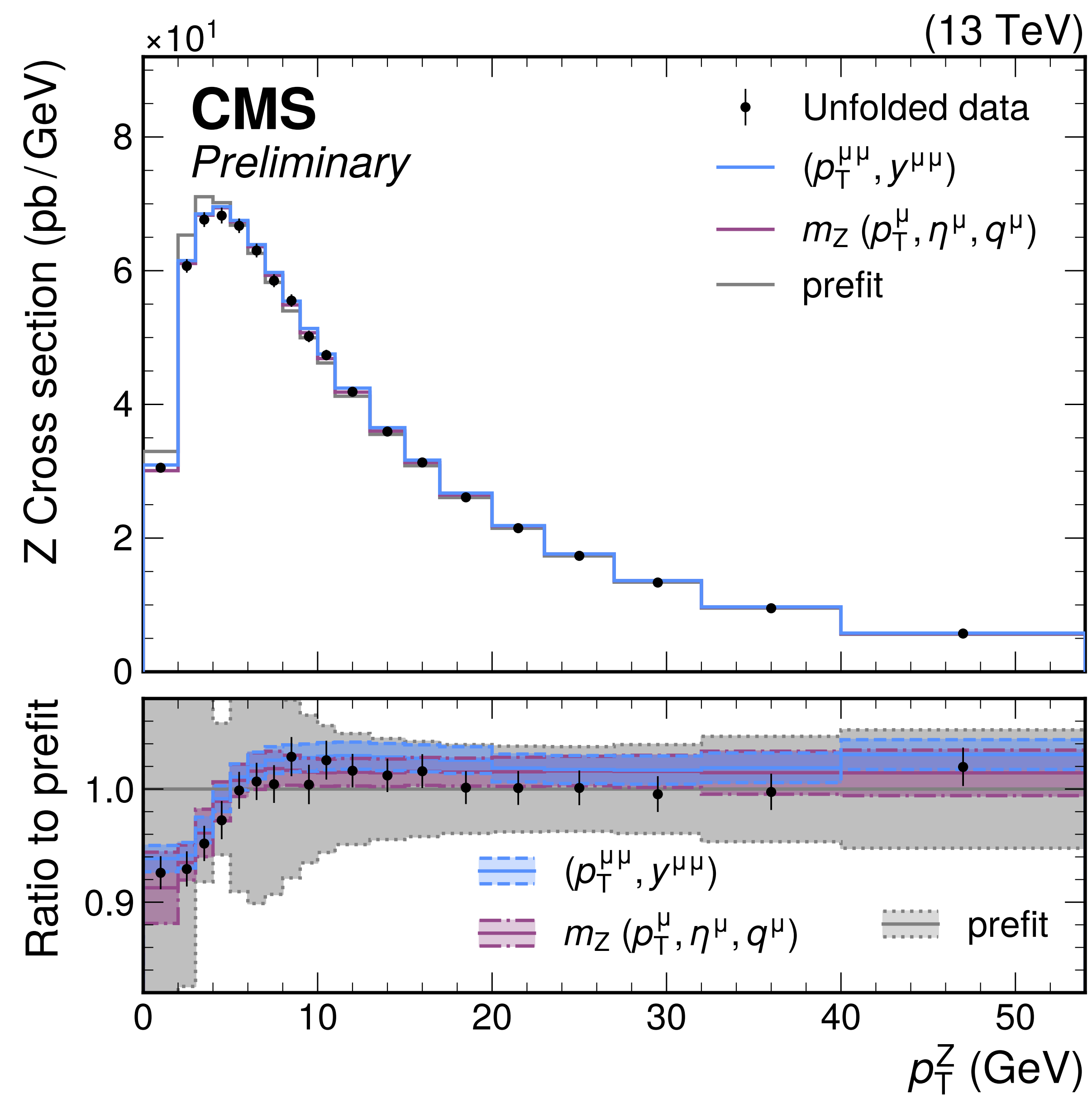




Validation of p_T^V modeling with W-like Z

- When running W-like fit to single muon p_T^μ-η^μ-q^μ , theory model is also able to accommodate the muon p_T spectrum very precisely
- Consistent postfit shape of p_T^V between Z fits, in agreement with unfolded $p_T^{\mu\mu}$ data
- p_T^μ-η^μ-q^μ disentangles m_V from p_T^V: **can extract m_W without tuning p_T^W on Z**



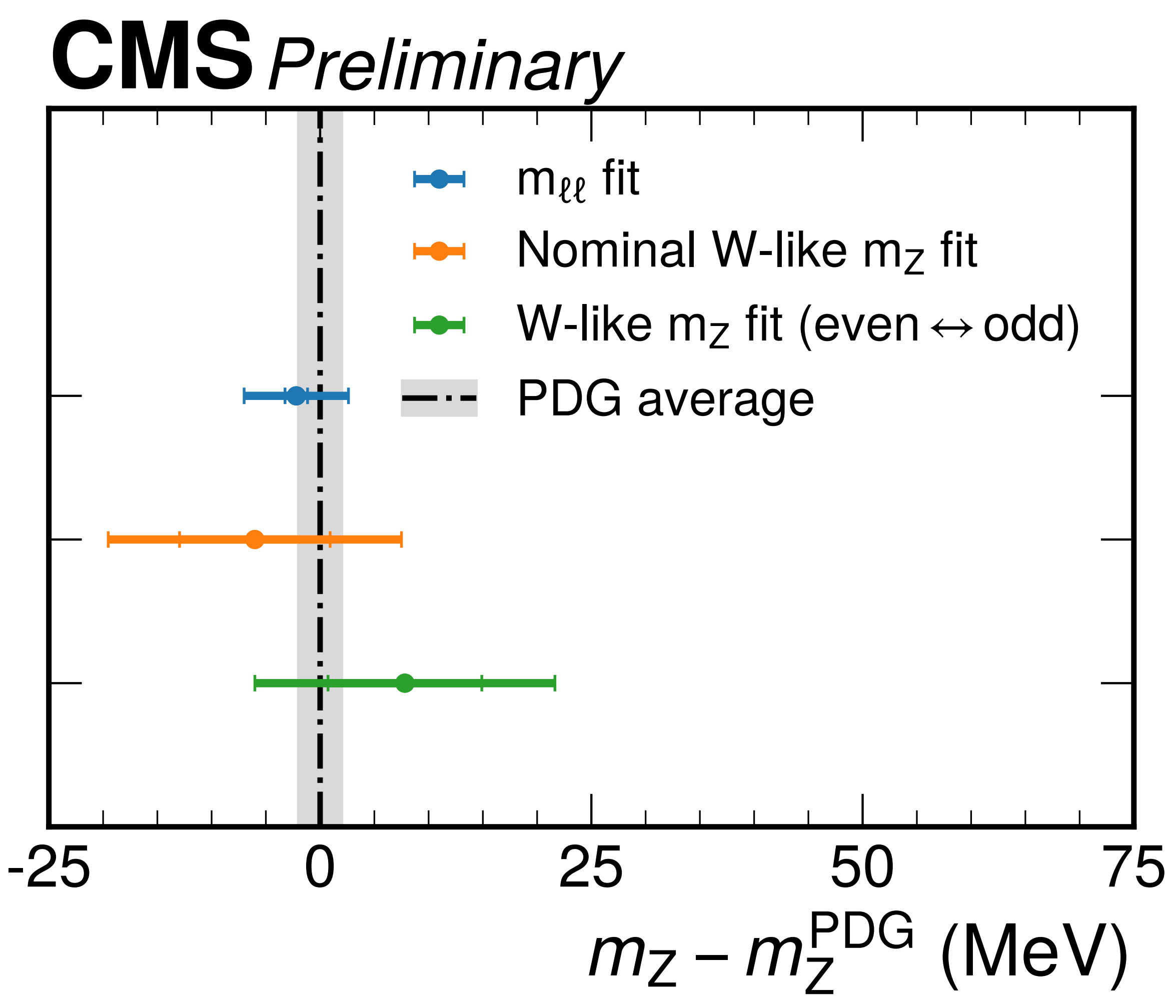


Results

W-like m_Z measurement

- $m_Z - m_Z^{PDG} = -6 \pm 14$ MeV
- Inverting odd/even selection (nearly statistically independent sample) one gets

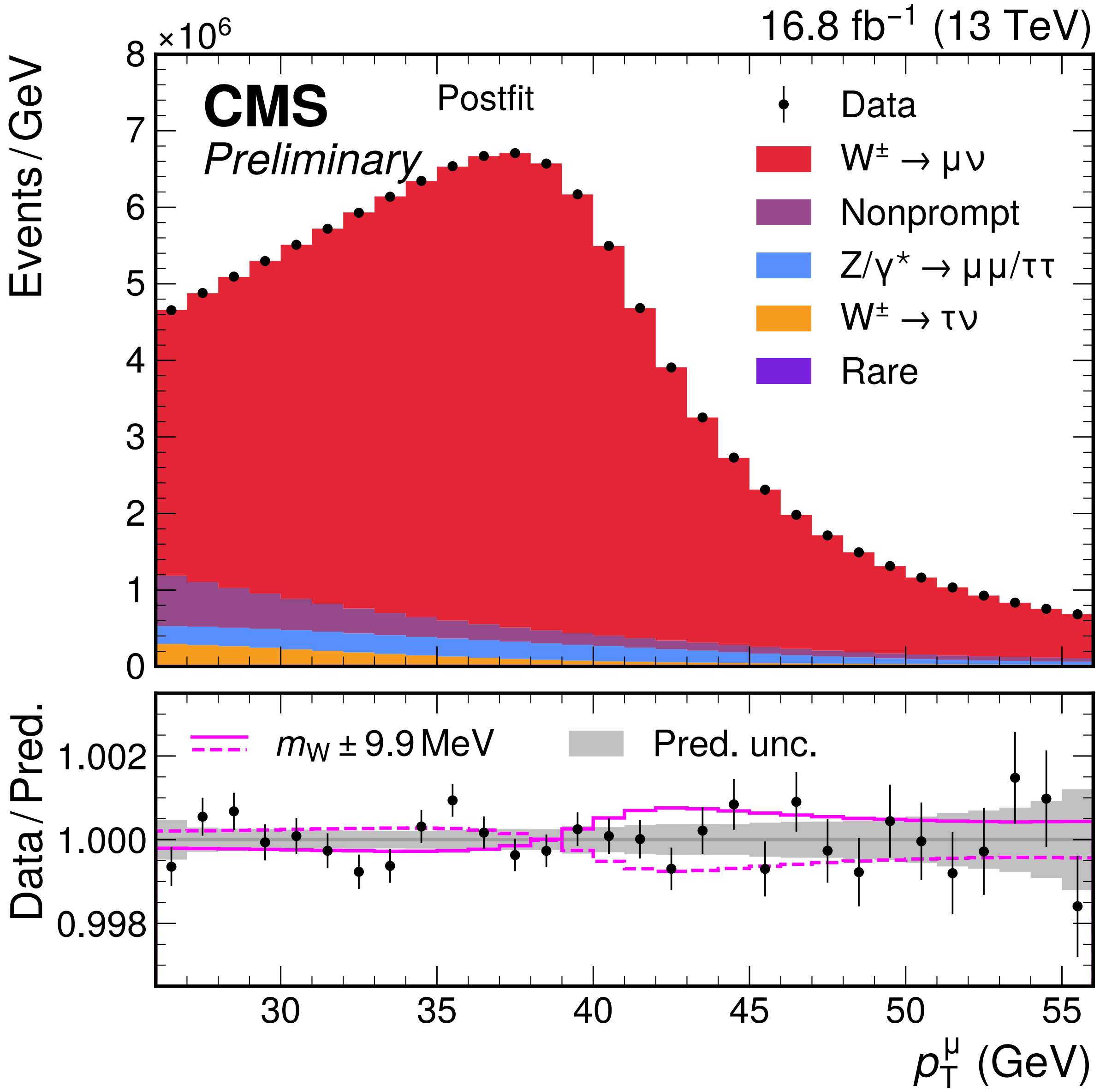
  $m_Z - m_Z^{PDG} = +8 \pm 14$ MeV
- Uncertainty dominated by **statistics**, muon **calibration**, and **angular coefficients**
  - Breakdown of uncertainties not unique (details later)



Source of uncertainty	Impact (MeV) Nominal	Impact (MeV) Global
Muon momentum scale	5.6	5.3
Muon reco. efficiency	3.8	3.0
W and Z angular coeffs.	4.9	4.5
Higher-order EW	2.2	2.2
p_T^V modeling	1.7	1.0
PDF	2.4	1.9
Integrated luminosity	0.3	0.2
MC sample size	2.5	3.6
Data sample size	6.9	10.1
Total uncertainty	13.5	13.5

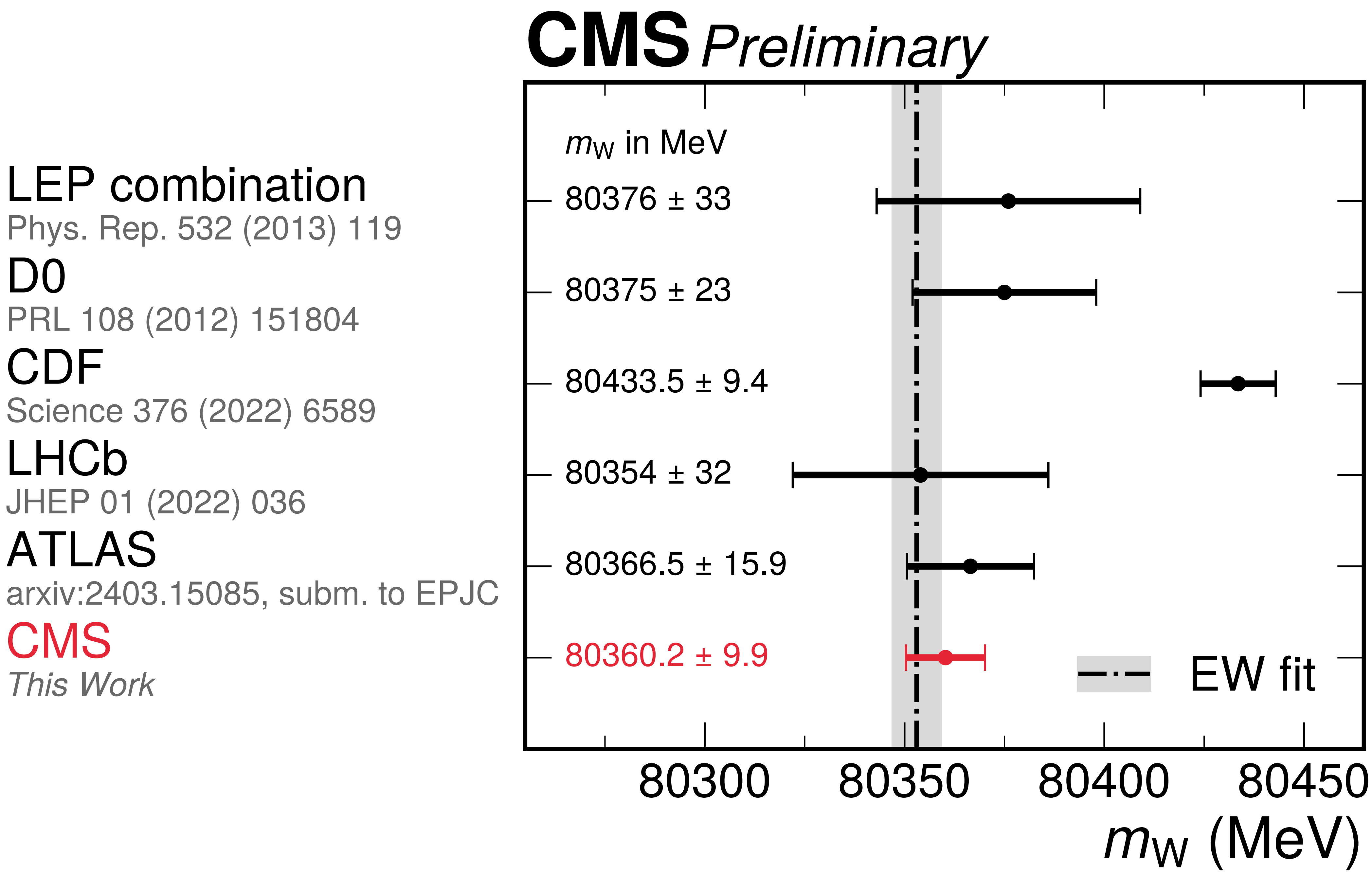
Finally: assembling all pieces

- Most precise m_W measurement at the LHC
- 9.9 MeV total uncertainty, similar to CDF
- When uncertainties are constrained in-situ, "global" impacts (used in ATLAS 2024 m_W measurement, arXiv:2307.04007) tend to count them as part of statistical uncertainties



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

The summary picture



- EW fit prediction: 80353 ± 6 MeV
- CMS measurement: 80360.2 ± 9.9 MeV

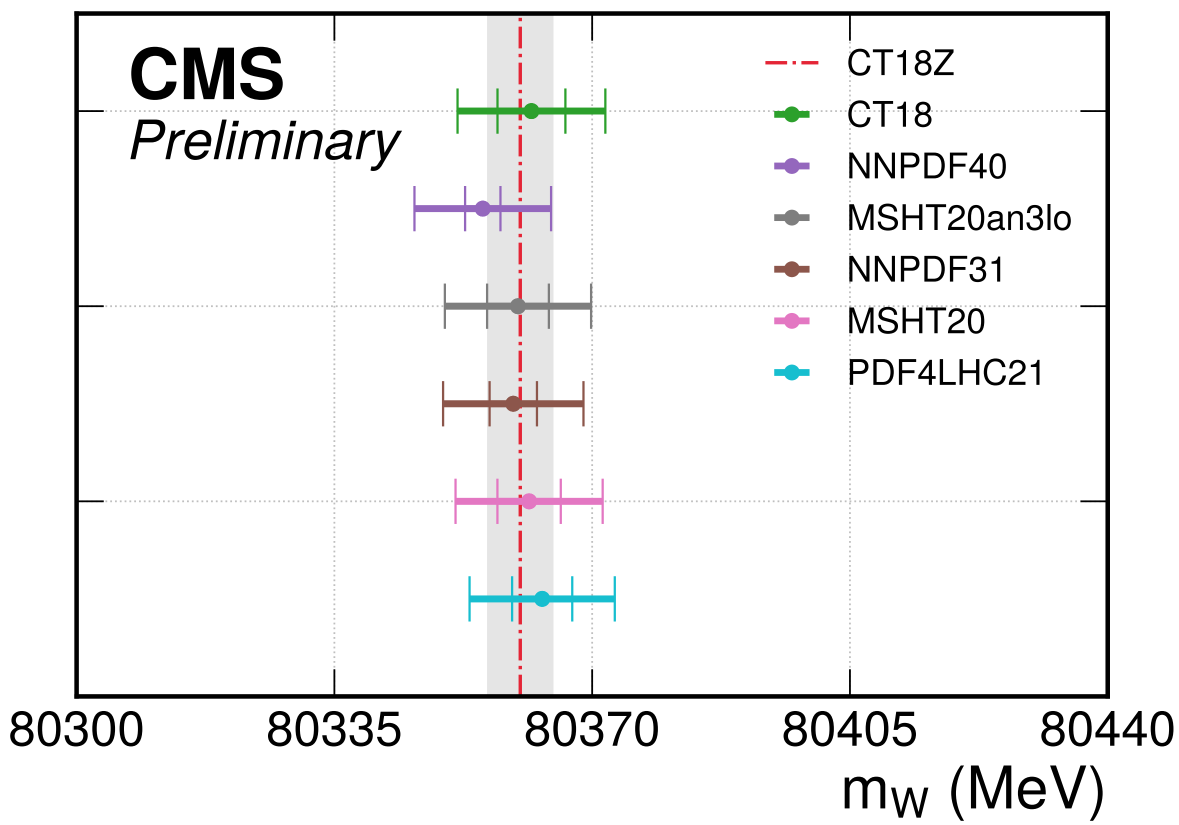
The SM is still alive

Further checks: stability with PDFs

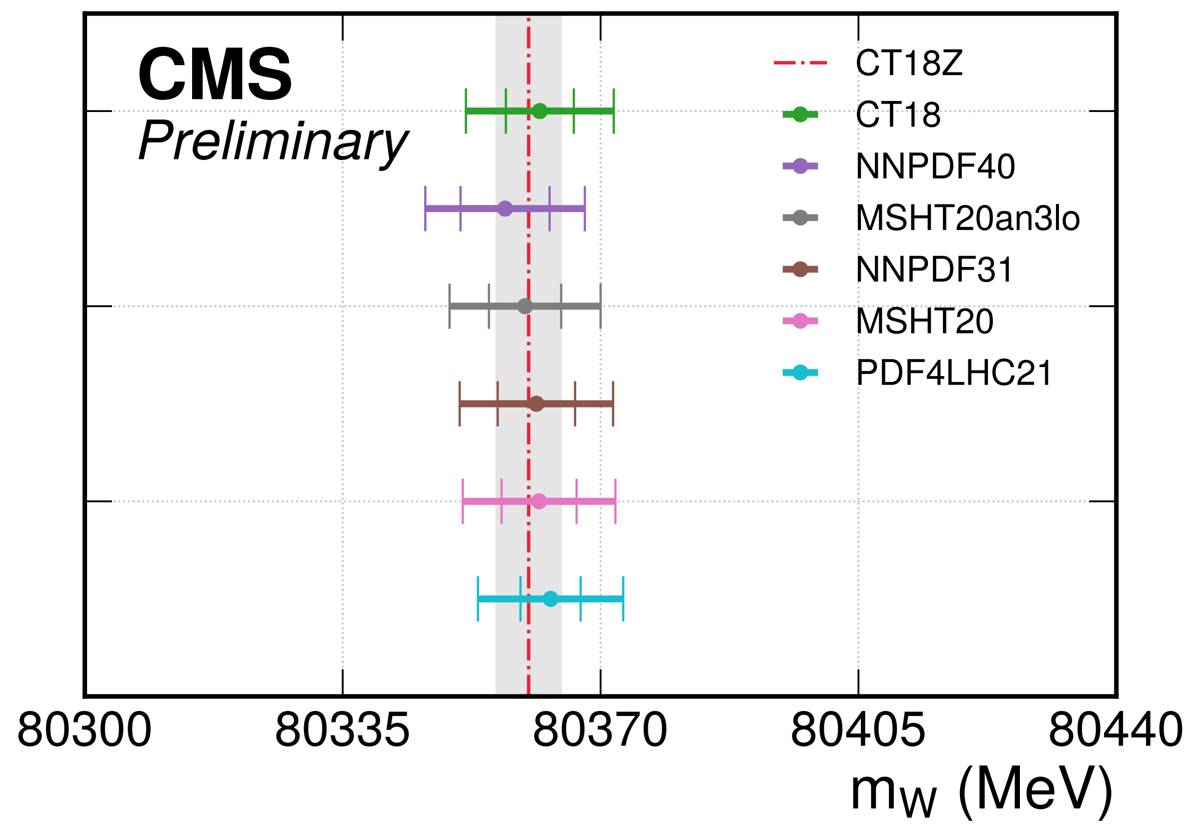
- Good stability of measured m_W across PDF sets within PDF uncertainty, but only after scaling uncertainty for some sets (most notably NNPDF40)
- Reminder: nominal value CT18Z doesn't require any scaling

PDF set	Extracted m_W (MeV) Original σ_{PDF}	Scaled σ_{PDF}
CT18Z	$80\,360.2 \pm 9.9$	
CT18	$80\,361.8 \pm 10.0$	
PDF4LHC21	$80\,363.2 \pm 9.9$	
MSHT20	$80\,361.4 \pm 10.0$	$80\,361.7 \pm 10.4$
MSHT20aN3LO	$80\,359.9 \pm 9.9$	$80\,359.8 \pm 10.3$
NNPDF3.1	$80\,359.3 \pm 9.5$	$80\,361.3 \pm 10.4$
NNPDF4.0	$80\,355.1 \pm 9.3$	$80\,357.0 \pm 10.8$

Without scaling

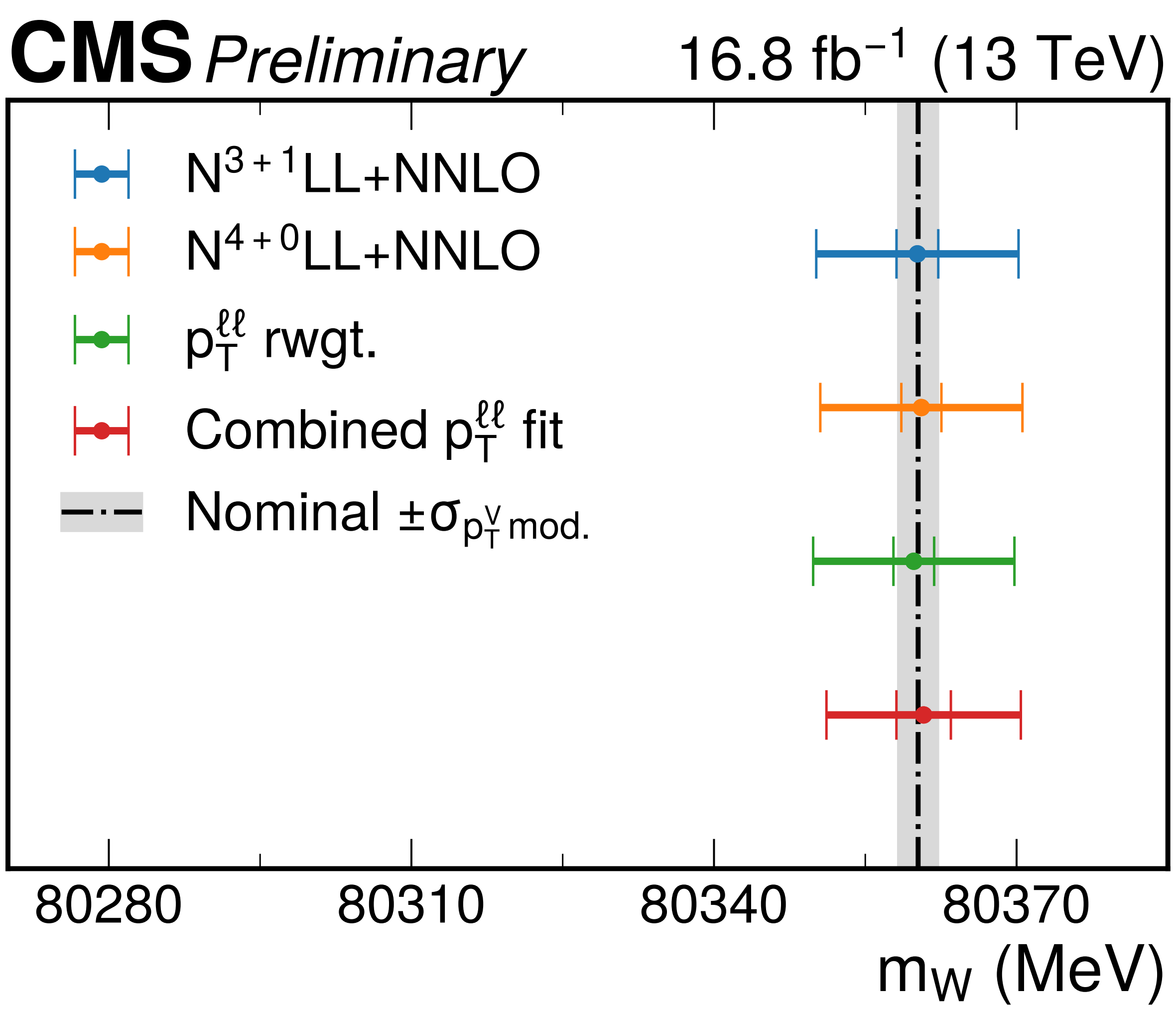


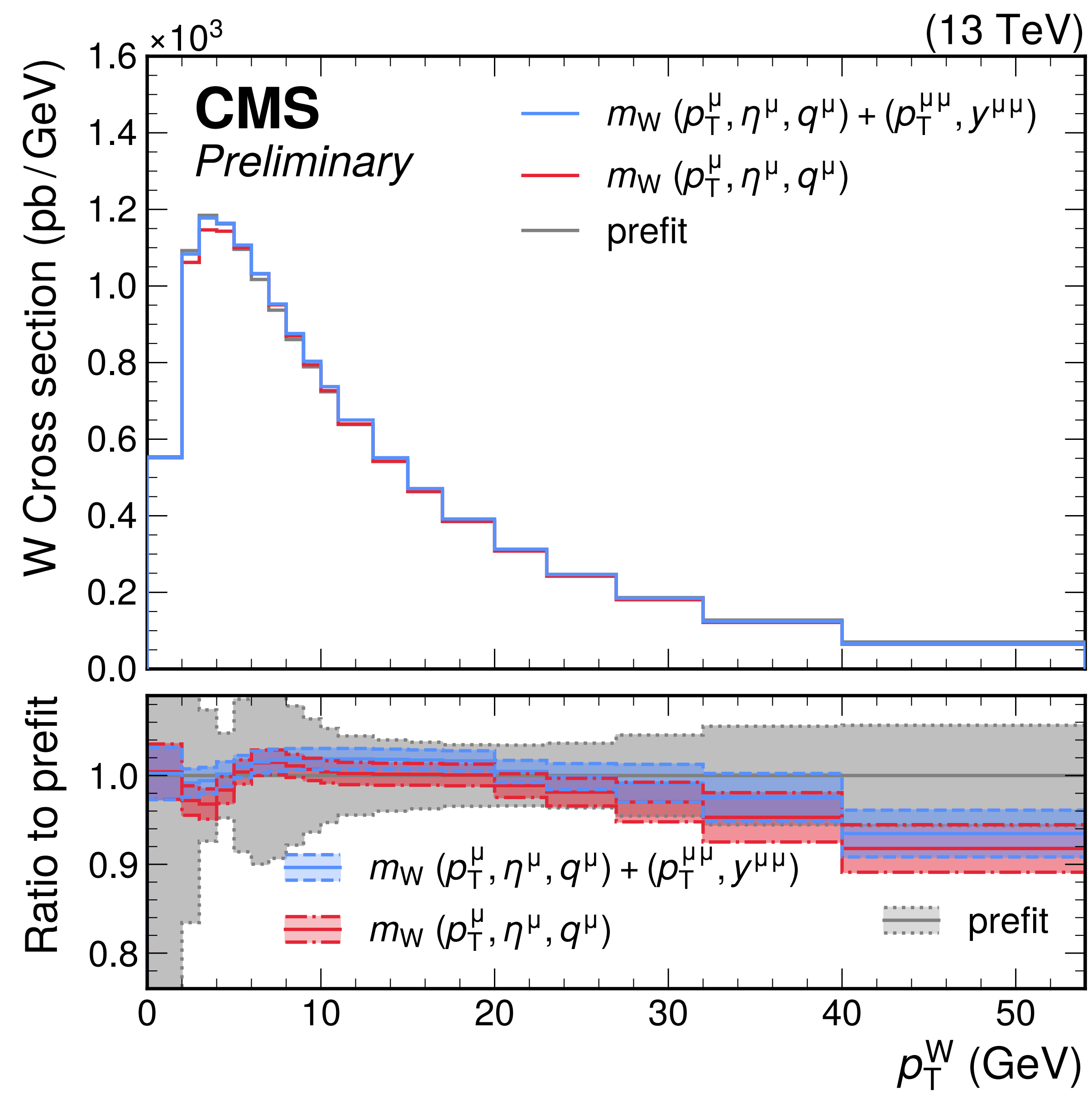
With scaling



Testing alternative p_T^V modeling

- Alternative parametrization of resummation uncertainties from TNP (nominal: $N^{3+0}LL$)
- Reweighting p_T^W by data/simulation ratio of p_T^Z (keep same theory uncertainties)
- Can also test simultaneous fit of p_T^{μ}-η^{μ}-q^{μ} for W and $p_T^{\mu\mu}$-$y^{\mu\mu}$ for Z, with mostly uncorrelated theoretical uncertainties: Δm_W = +0.6 MeV and δm_W = 9.6 MeV





Helicity cross section fit

Beyond SM effects can modify expected cross section

- A less model-dependent m_W measurement is desirable

Alternative fit strategy: parametrize standard theory uncertainties in terms of helicity cross sections $\sigma_i = \sigma_{UL} \times A_i$ and corresponding variations binned in p_T^V-$|y^V|$

- Simultaneous fit of σ_i and m_W
- Trade theory assumptions for larger statistical uncertainty

Unpolarized cross section σ_{UL}

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

$\sigma_4 = \sigma_{UL} \times A_4$ related to forward-backward asymmetry, and encodes parity violation in W decays

Helicity cross section fit

Limitation: size of 2016 data set and p_T^μ-η^μ-q^μ fit not sufficient to constrain all terms

Implementation: loose priors assigned to σ_i (i = UL, 0, …, 4) binned in p_T^V-$|y^V|$

- σ_{UL} and σ_4: conservative priors of 50% (100%) of predicted cross section
- σ_0, σ_1, σ_2, σ_3: priors constructed from envelope of standard theory uncertainties
- Most of relevant theory uncertainties also retained (different correlations)

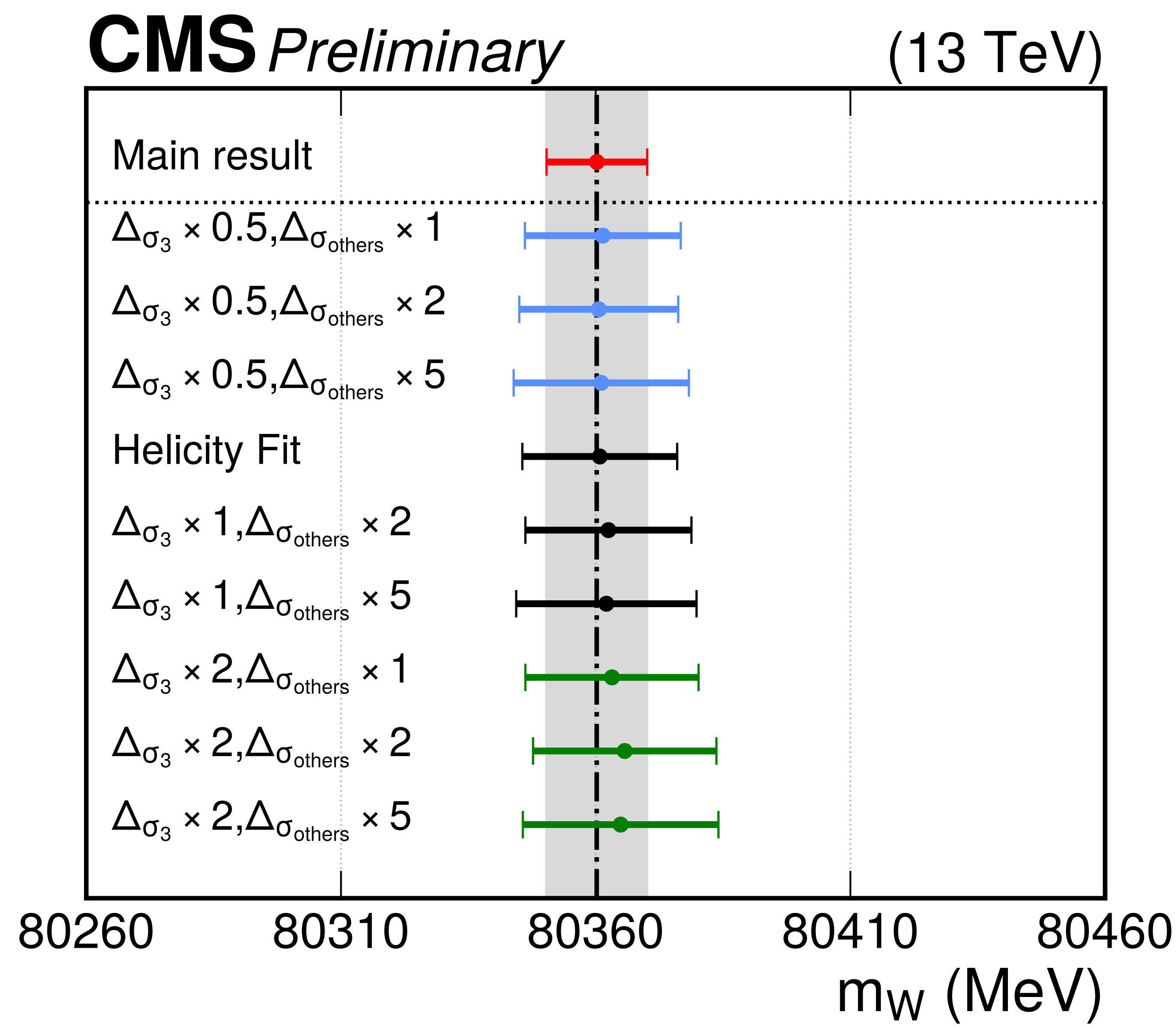
Unpolarized cross section σ_{UL}

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

$\sigma_4 = \sigma_{UL} \times A_4$ related to forward-backward asymmetry, and encodes parity violation in W decays

Helicity cross section fit

- m_W = 80360.8 ± 15.2 MeV
- In agreement with main result
- Stability of result and uncertainty with looser or tighter priors on σ_i

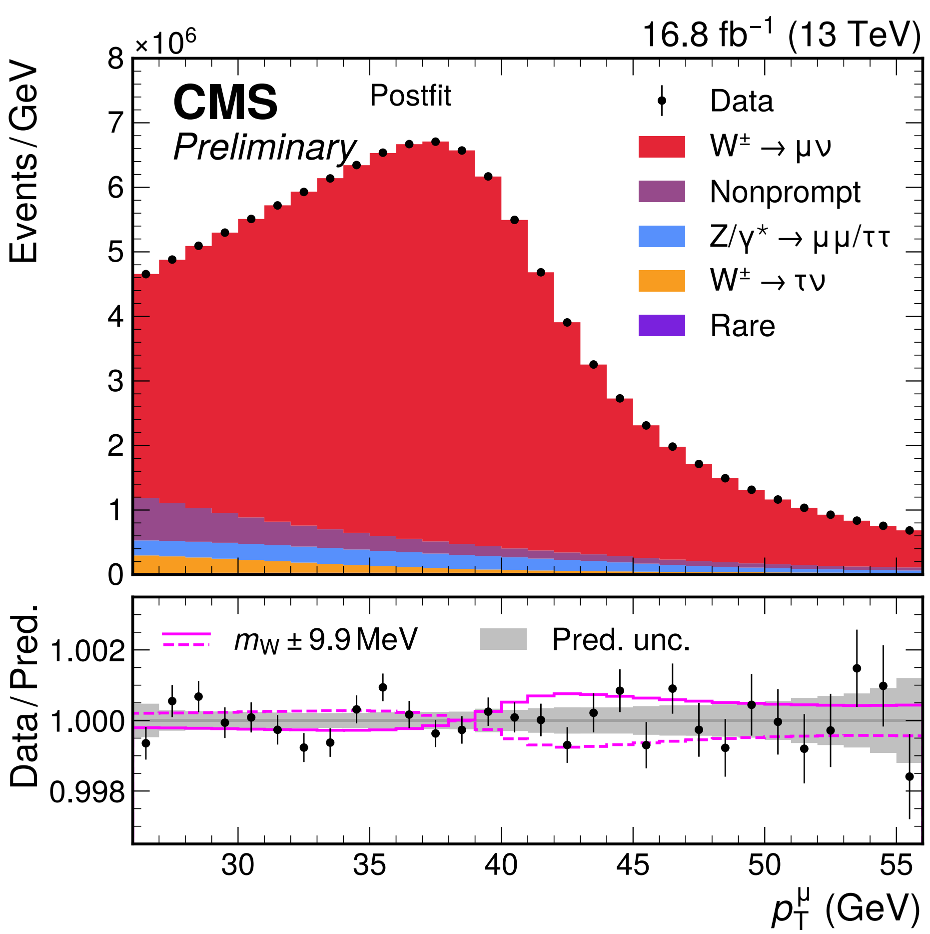


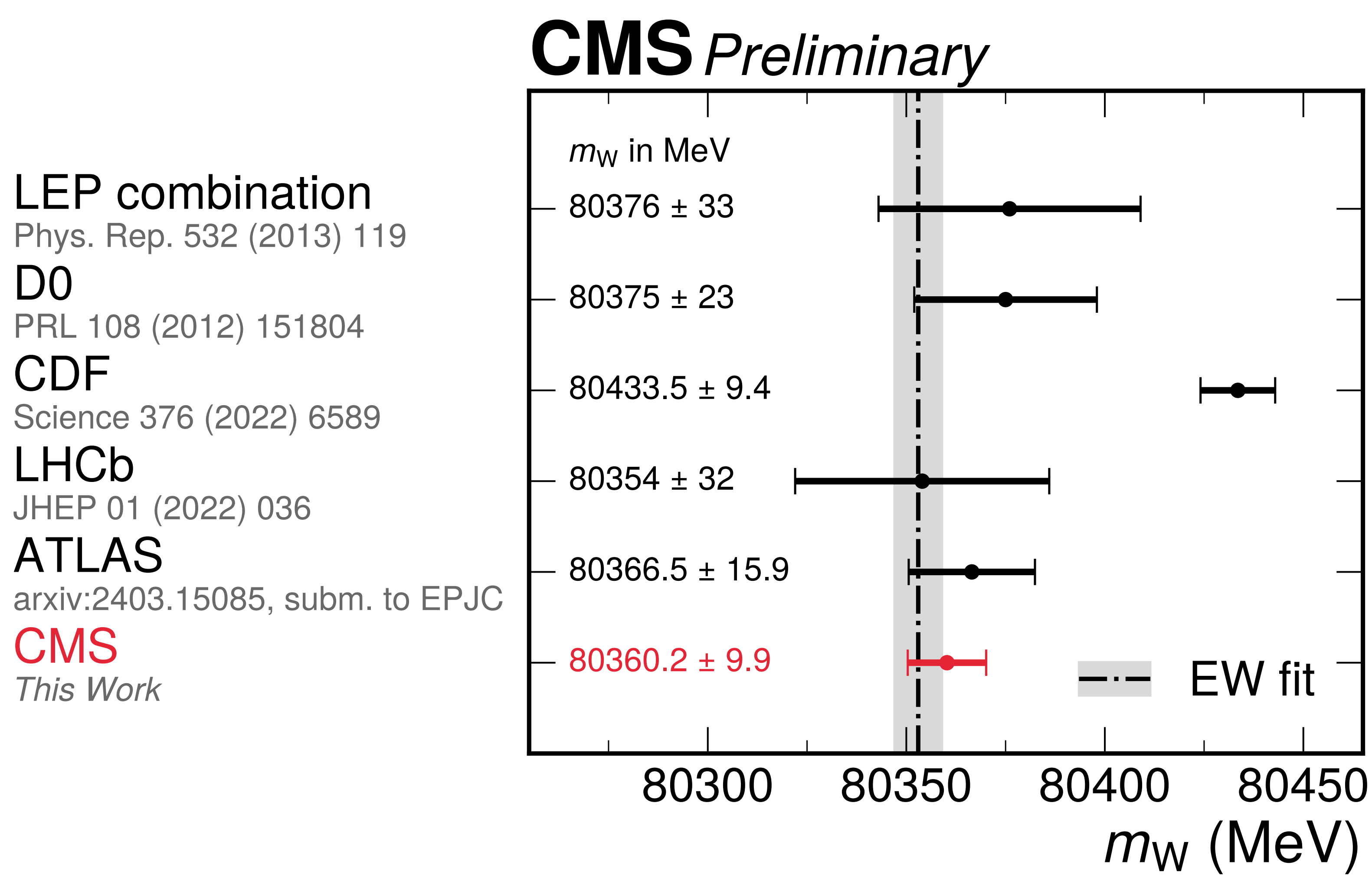
- Shape variation of p_T^μ-η^μ-q^μ induced by σ_3 is degenerate with m_W, can't assign too loose prior with current observables

Summary

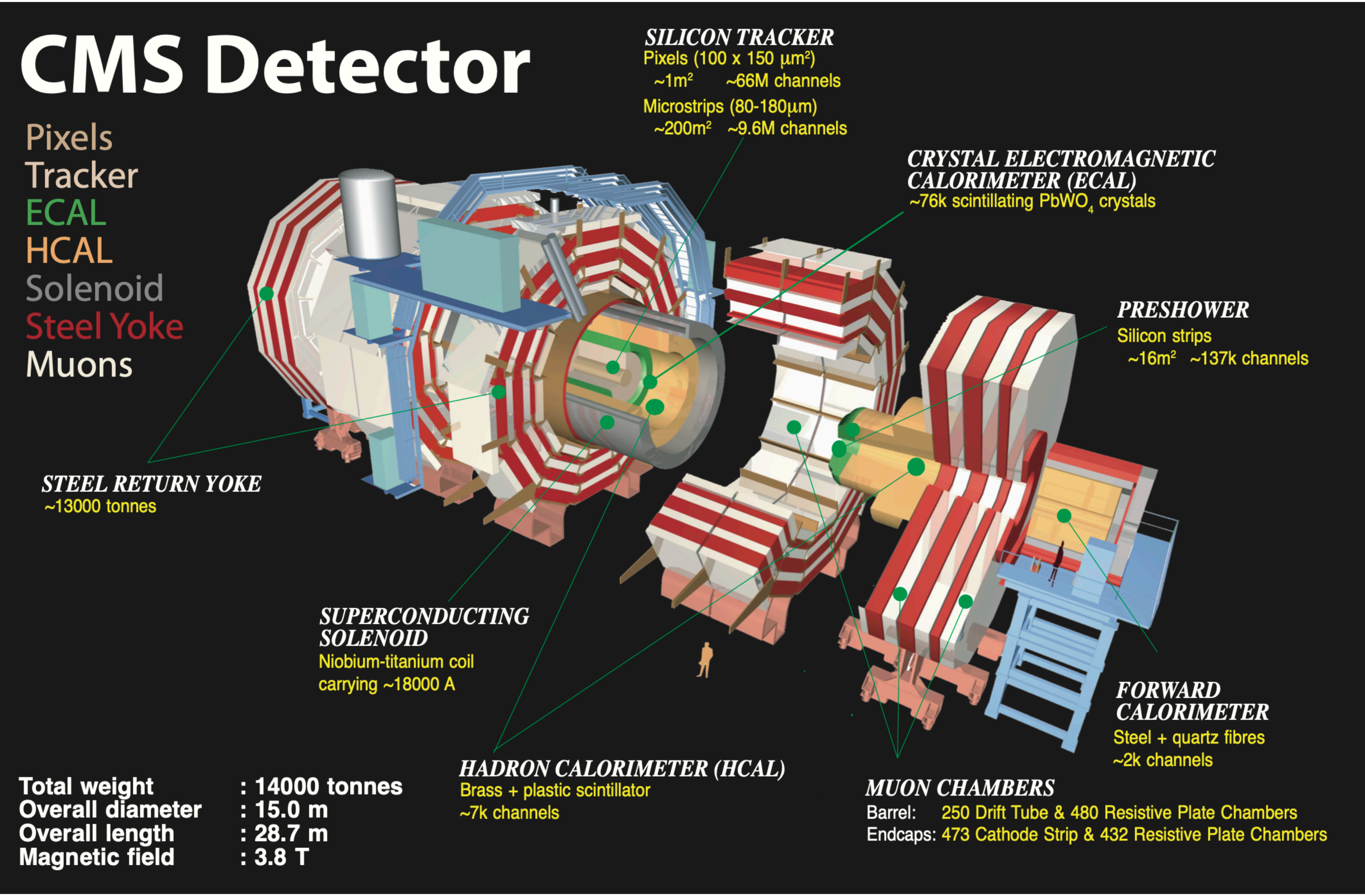
The first CMS measurement of m_W has finally happened

- Several innovations in terms of modelling of experimental/theoretical uncertainties
- Most precise at the LHC, consistent with the SM but in significant tension with CDF
- Performed with ~10% of Run 2 data, a lot of room for future improvements





BACKUP


CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating $PbWO_4$ crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 473 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Event selection

Exactly 1/2 muon(s) for W/Z passing muon veto selection (reject additional muon)

- $p_T > 15$ GeV, $|\eta| < 2.4$
- Loose muon POG ID
- $dxy_{bs} < 0.05$ cm
  - Defined wrt to beamspot to avoid biases from primary vertex selection (no dz cut for same reason)

Selected muon satisfies tighter criteria

- $26 < p_T < 56$ GeV, $|\eta| < 2.4$
- Medium muon POG ID
- *"Vertex agnostic"* PF rel. iso (ΔR=0.4) < 0.15
- Matched to trigger object (ΔR<0.3) for (HLT_isoMu24 || HLT_isoTkMu24)

We restrict to global muons, also for veto selection

- Simplifies definition of reco and tracking efficiencies
- Additional quality criteria for global muons
  - Standalone $p_T > 15$ GeV
  - ΔR(in,out tracks) < 0.3
  - Inner track has highPurity flag
  - Standalone track has >= 1 valid hits

Further selection criteria

- $m_T(\mu, p_T^{miss}) > 40$ GeV (45 GeV for Z W-like, but removed for Z dilepton)
- $m_{\mu\mu}$ in [60, 120] GeV for Z events
- beam background and anomalous p_T^{miss} filters
- Reject events if any electron is found which satisfies the following selection:
  - $p_T > 10$ GeV, $|\eta| < 2.4$
  - $dxy_{bs} < 0.05$ cm, $dz < 0.2$ cm
  - EGamma POG cut-based loose ID

With these requirements we get:

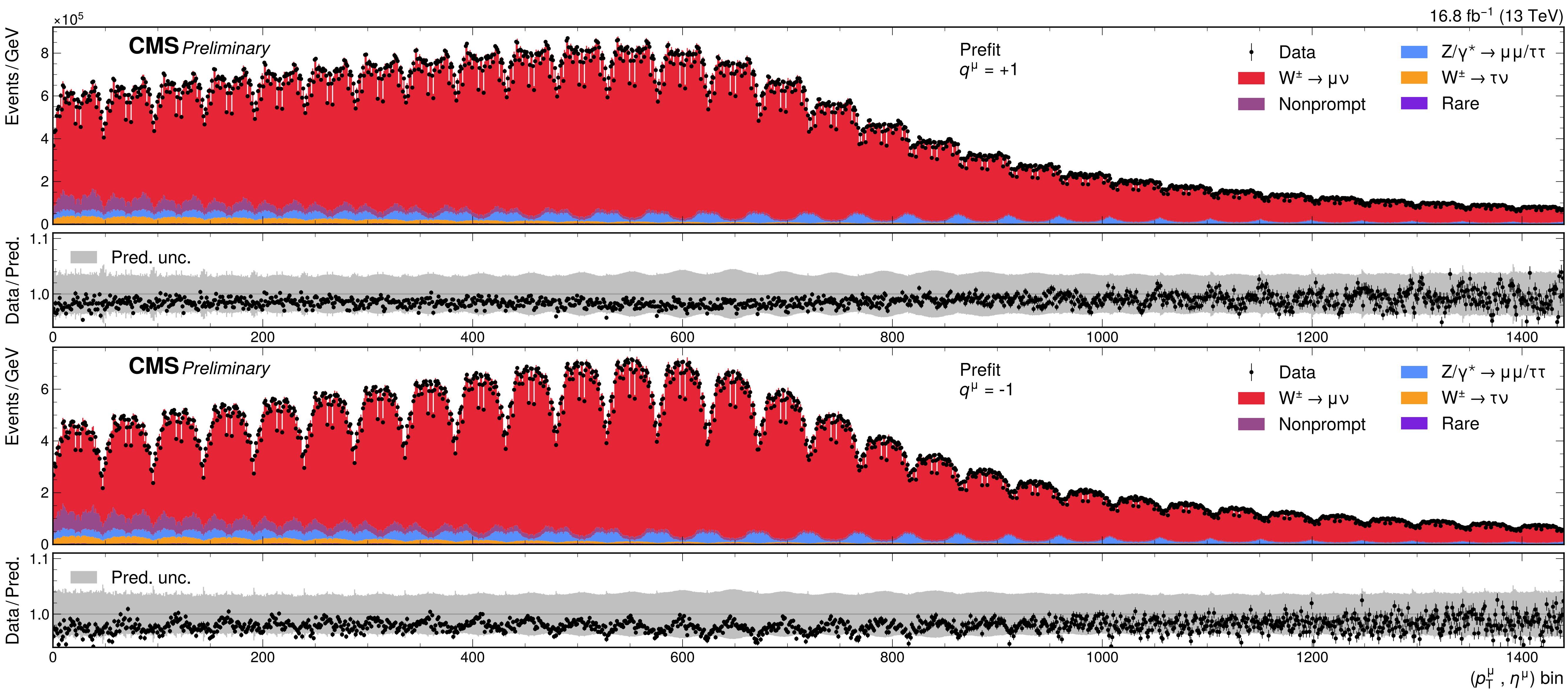
100 M selected $W\rightarrow\mu\nu$ events
- ~87% signal

7.4 M selected $Z\rightarrow\mu\mu$ events
- ~99.5% signal

Prefit distributions for W

Profile likelihood fit to 3D muon p_T^{μ}-η^{μ}-q^{μ} distribution (resilient against PU)

- Experimental techniques and tools developed for W rapidity-helicity measurement (2020), which established strong in-situ constraints on PDFs from fit to p_T^{ℓ}-η^{ℓ}-q^{ℓ}
- Different shape between charges stemming from W rapidity and polarization



W polarization and PDF uncertainty at the LHC

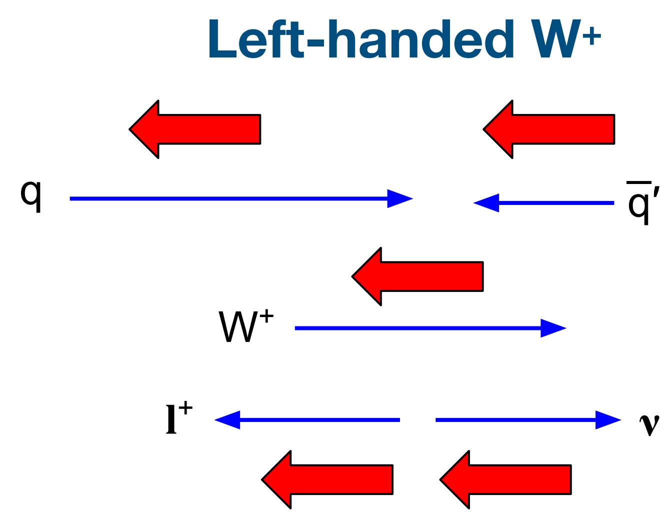
Pure left handed coupling of W bosons to fermions strongly correlates W polarization (h^W) and rapidity (Y^W) with direction of incoming quark vs antiquark

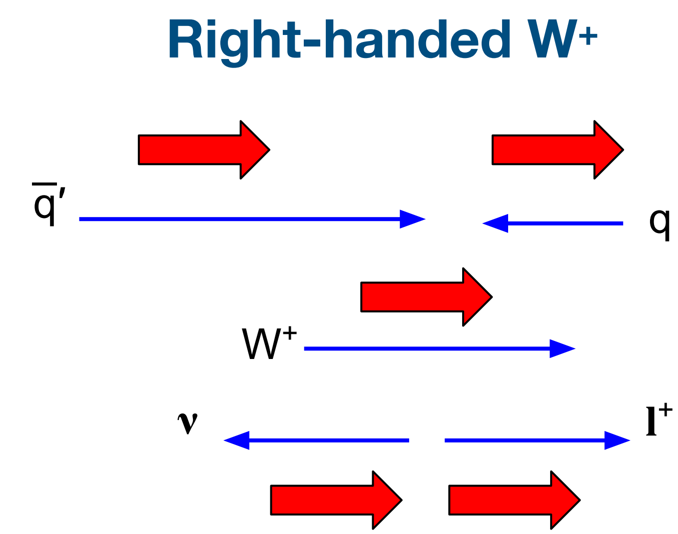
- And subsequently with direction of outgoing charged lepton

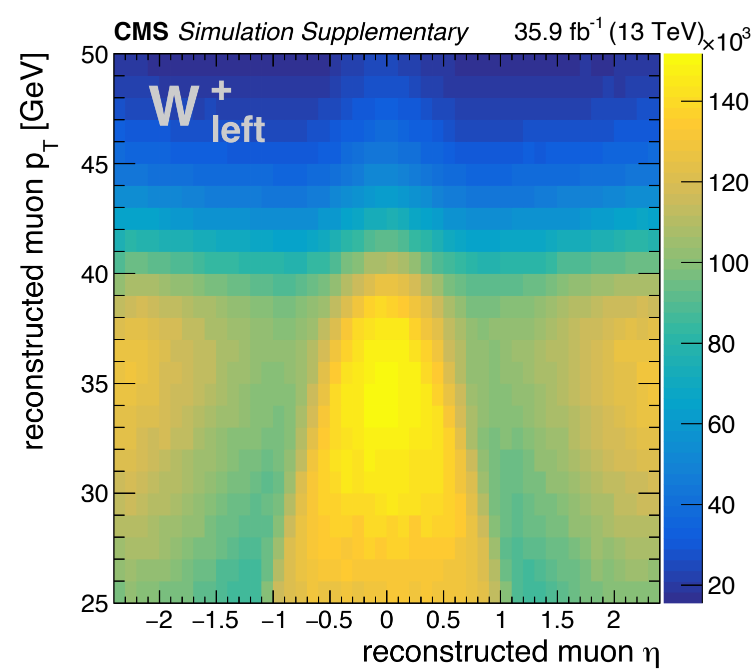
1) h^W and Y^W fully determined by PDFs

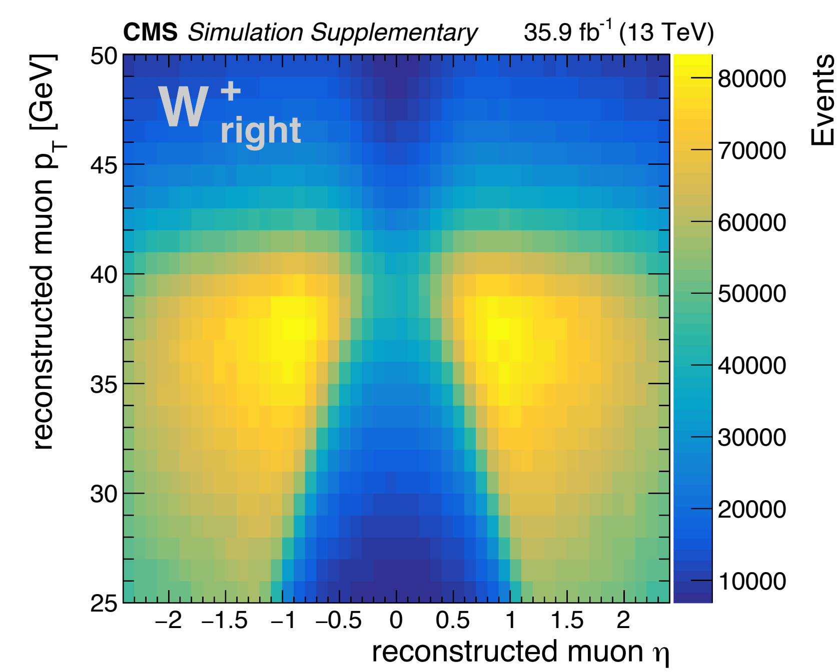
2) h^W/Y^W affect p_T^μ-η^μ-q^μ through spin correlations

3) p_T^μ-η^μ-q^μ carries information about PDFs









Negative W bosons produce even more different shapes

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W polarization at the LHC

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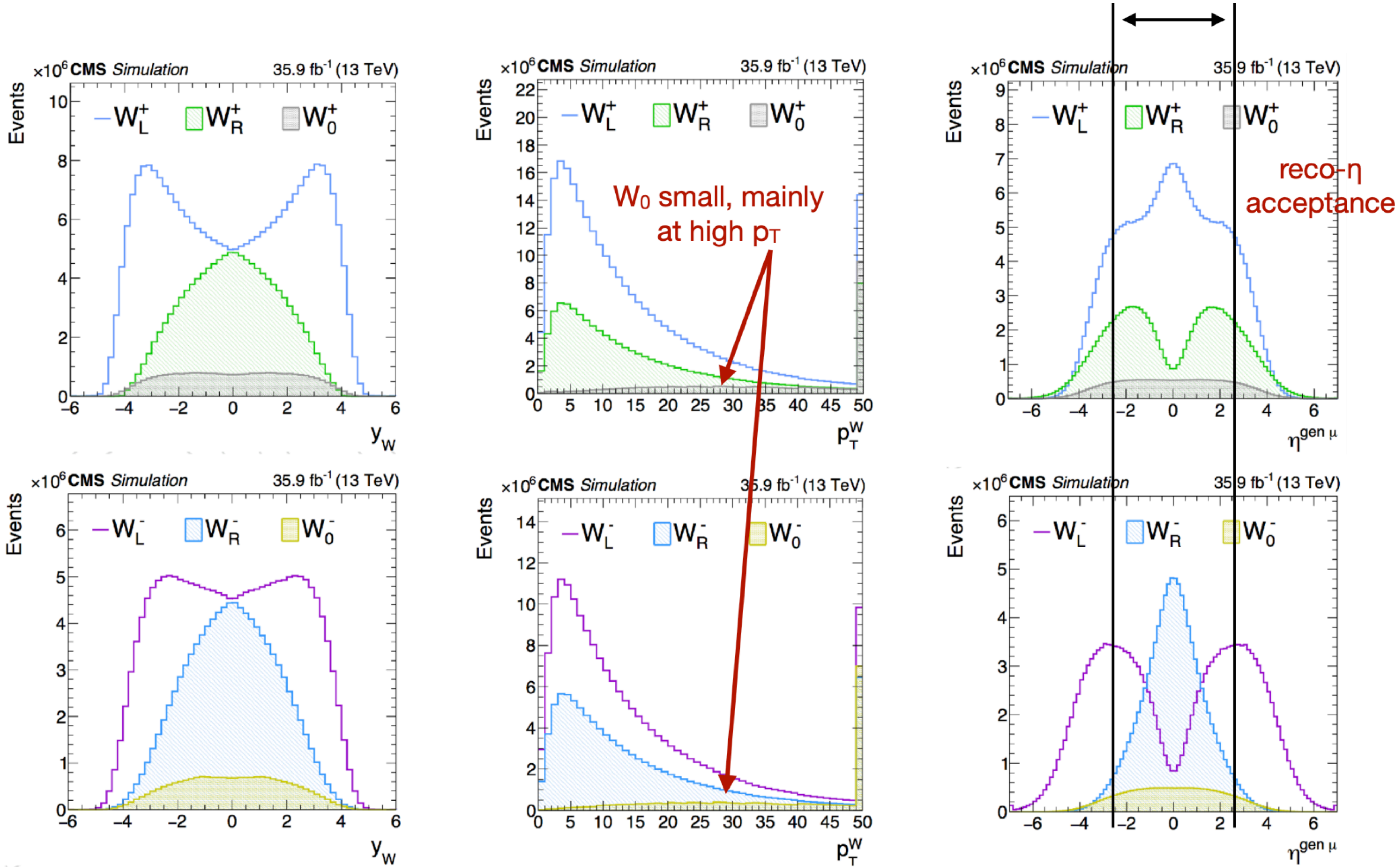

Vector boson production

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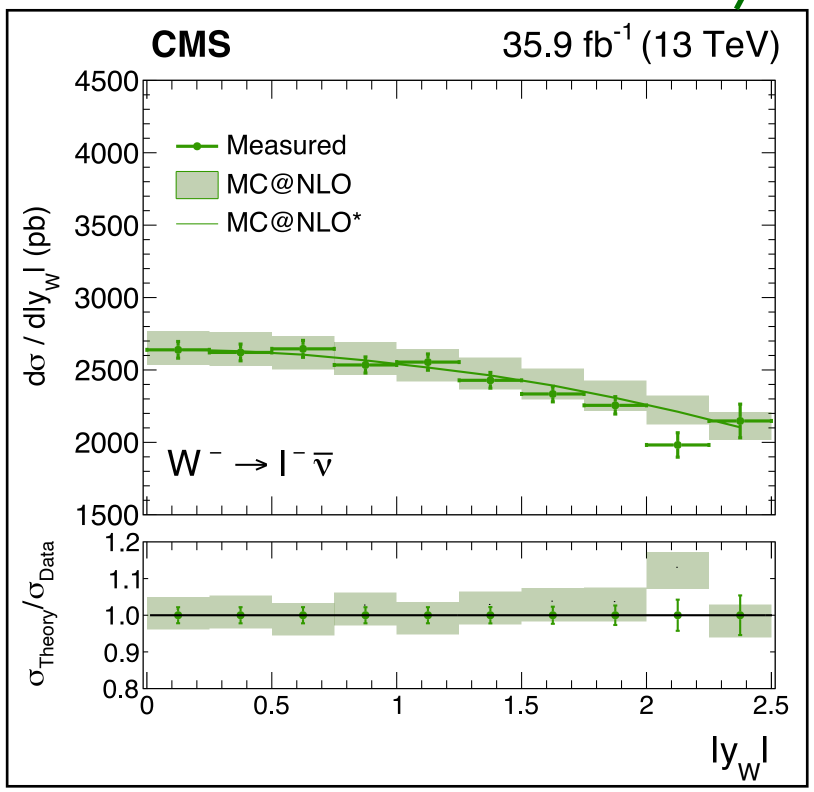
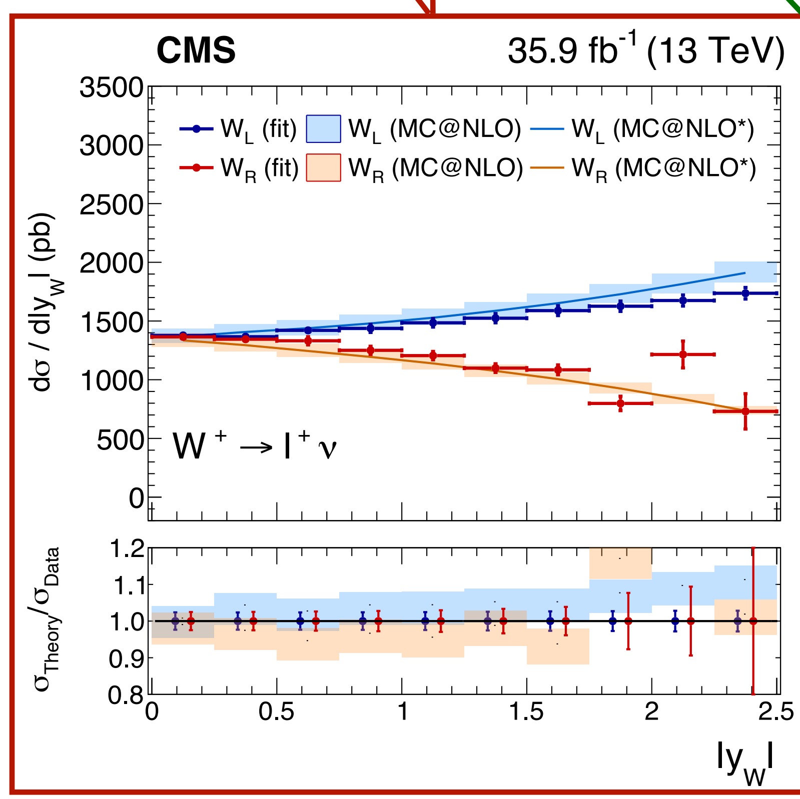
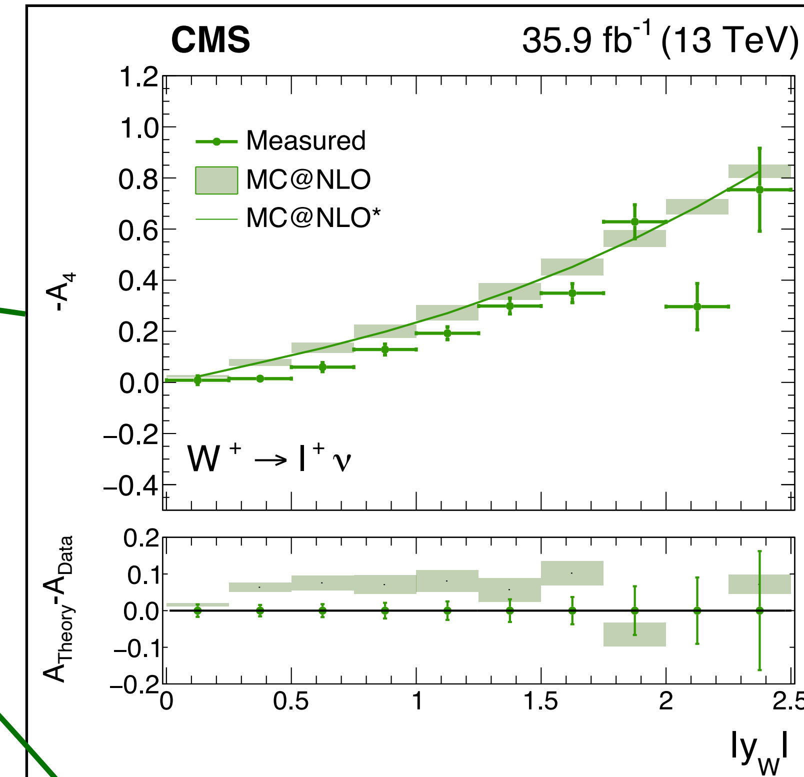
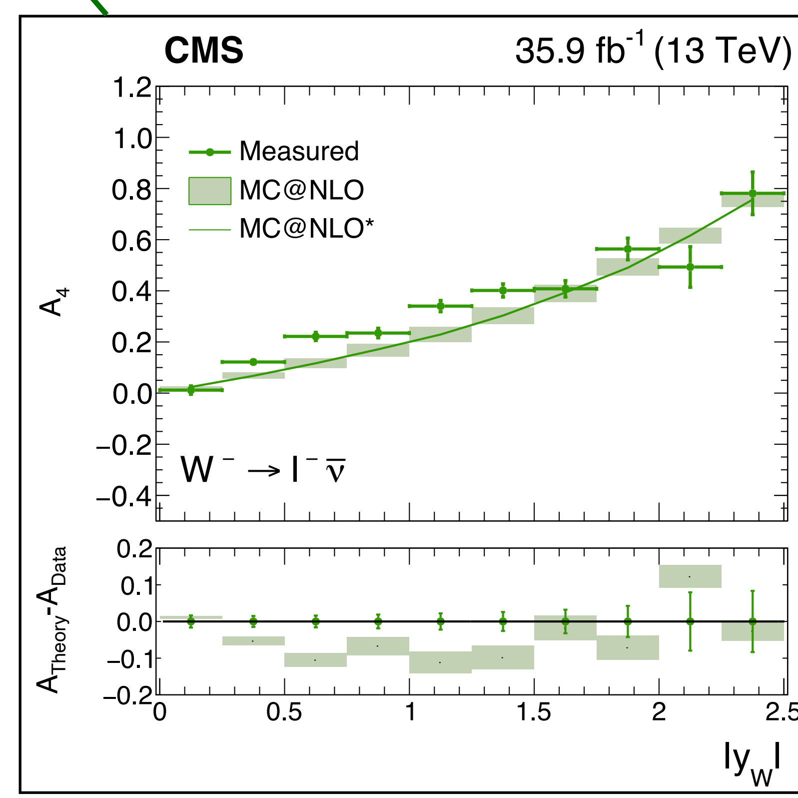
$$\frac{d^5\sigma}{dp_T^2\, dY\, dm\, d\cos\theta\, d\phi} = \frac{3}{16\pi}\frac{d^3\sigma}{dp_T^2\, dY\, dm} \times \Big[(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta) + A_1 \sin 2\theta\cos\phi + A_2\frac{1}{2}\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin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









$$f_L(Y_W, p_T^W) = \frac{1}{4}\left[2 - A_0(Y_W, p_T^W) + A_4(Y_W, p_T^W)\right]$$

$$f_R(Y_W, p_T^W) = \frac{1}{4}\left[2 - A_0(Y_W, p_T^W) - A_4(Y_W, p_T^W)\right]$$

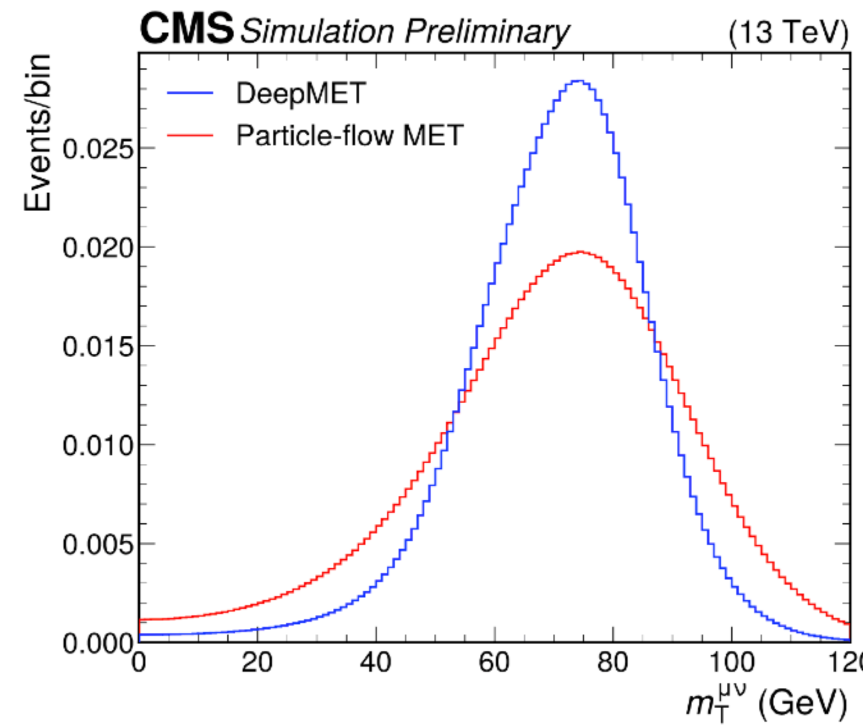
$$f_0(Y_W, p_T^W) = \frac{1}{2}A_0(Y_W, p_T^W)$$

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} \simeq \frac{3}{8}(1+\cos\theta^*)^2 \cdot f_L + \frac{3}{8}(1-\cos\theta^*)^2 \cdot f_R + \frac{3}{4}\sin^2\theta^* \cdot f_0$$

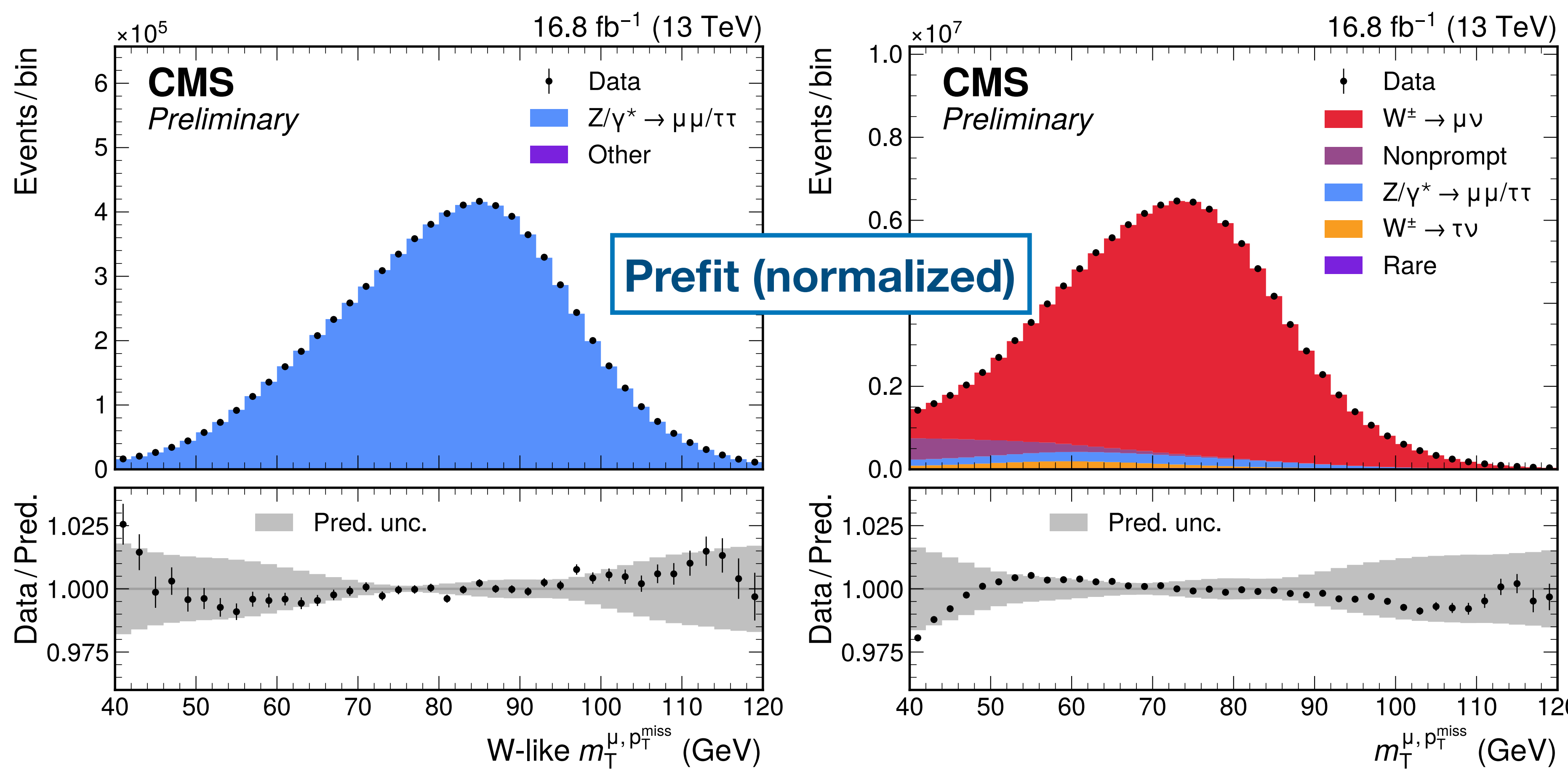
Hadronic recoil and calibration

With high PU, machine learning greatly improves p_T^{miss} and recoil resolution

- DNN-based “DeepMET” algorithm calibrated and commissioned for high PU analyses
- DeepMET only used indirectly to select signal region (m_T > 40 GeV) and define control regions for nonprompt background estimation
- Recoil response calibrated with Z → μμ events



- Recoil uncertainties negligible in p_T^{μ} driven measurement



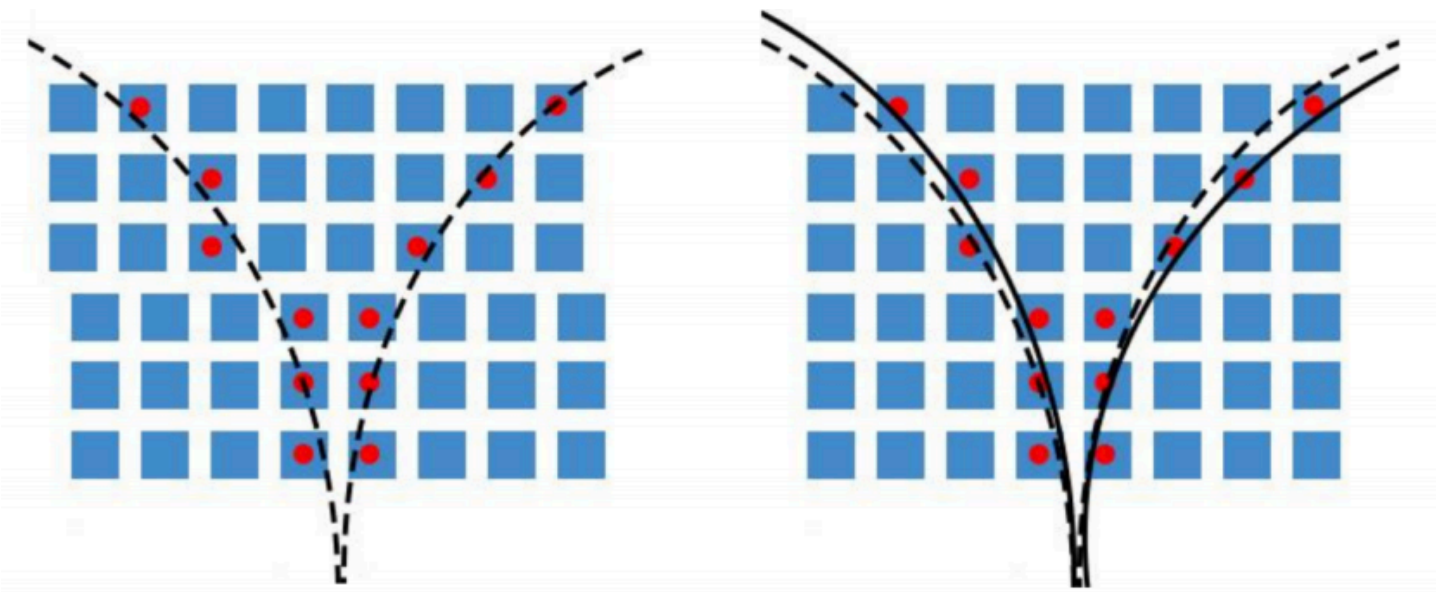
Muon scale calibration

Physics-motivated model to predict p_T scale bias arising from:

- Magnetic field (A)
- Energy loss due to material (ε)
- Alignment (M)

$$\frac{\delta k}{k} = A - \epsilon k + qM/k$$

$k = 1/p_T$



- Complemented by related momentum resolution parametrization for multiple scattering (a), hit resolution (c), and correlation terms (b,d)

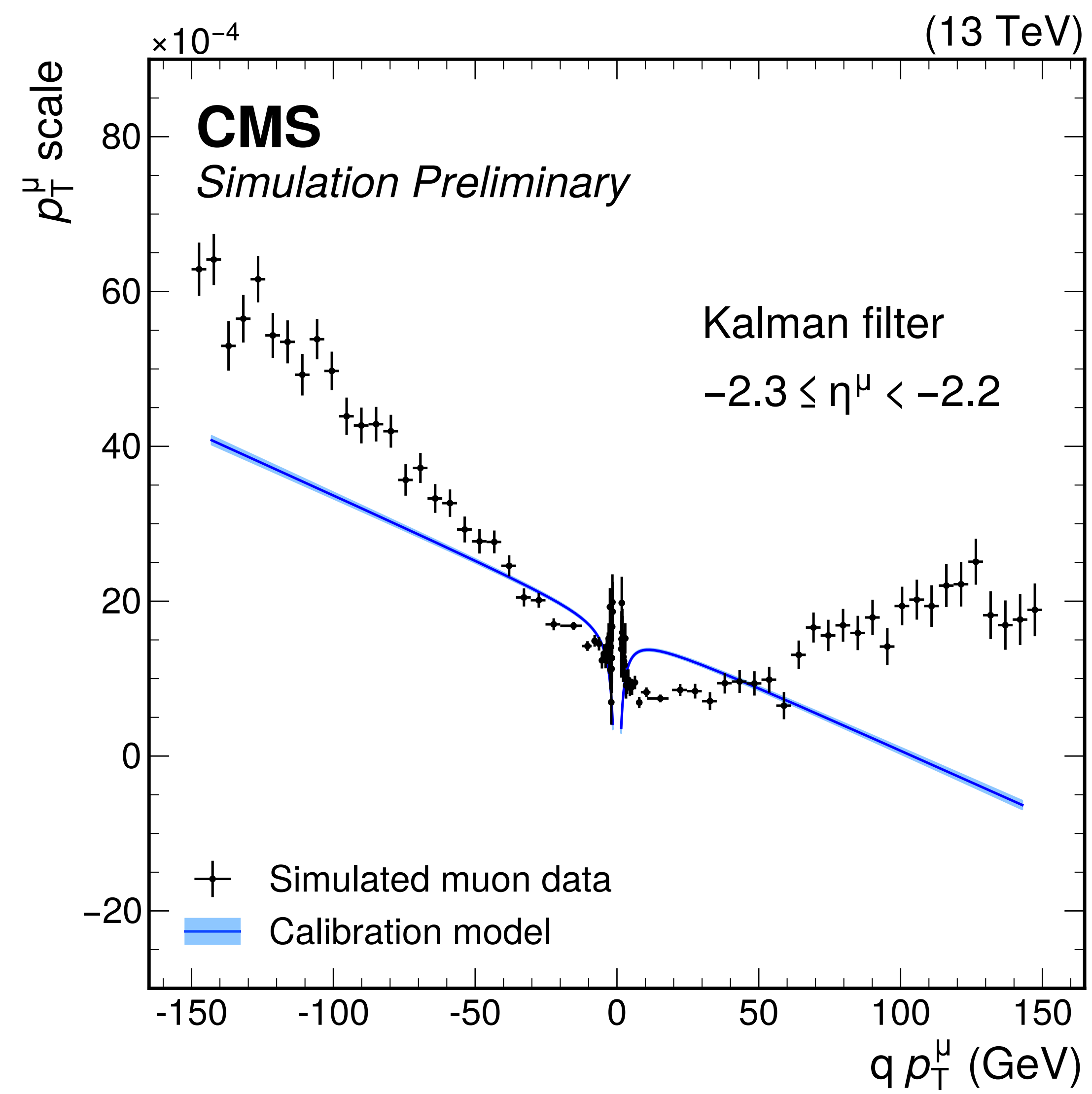
$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = a^2 + c^2 \cdot p_T^2 + \frac{b^2}{1 + \frac{d^2}{p_T^2}}$$

Calibration model revisited

- In a dense tracker, multiple scattering must be explicitly accounted for in the track fit (e.g. with Kalman Filter, Generalized Broken Line Fit, etc), in this case:

$$\frac{\delta k}{k} = A - \epsilon k + qM/k + \sum_{l}^{m} \frac{A_l - \epsilon_l k + qM_l/k}{1 + d_l^2 k^2}$$

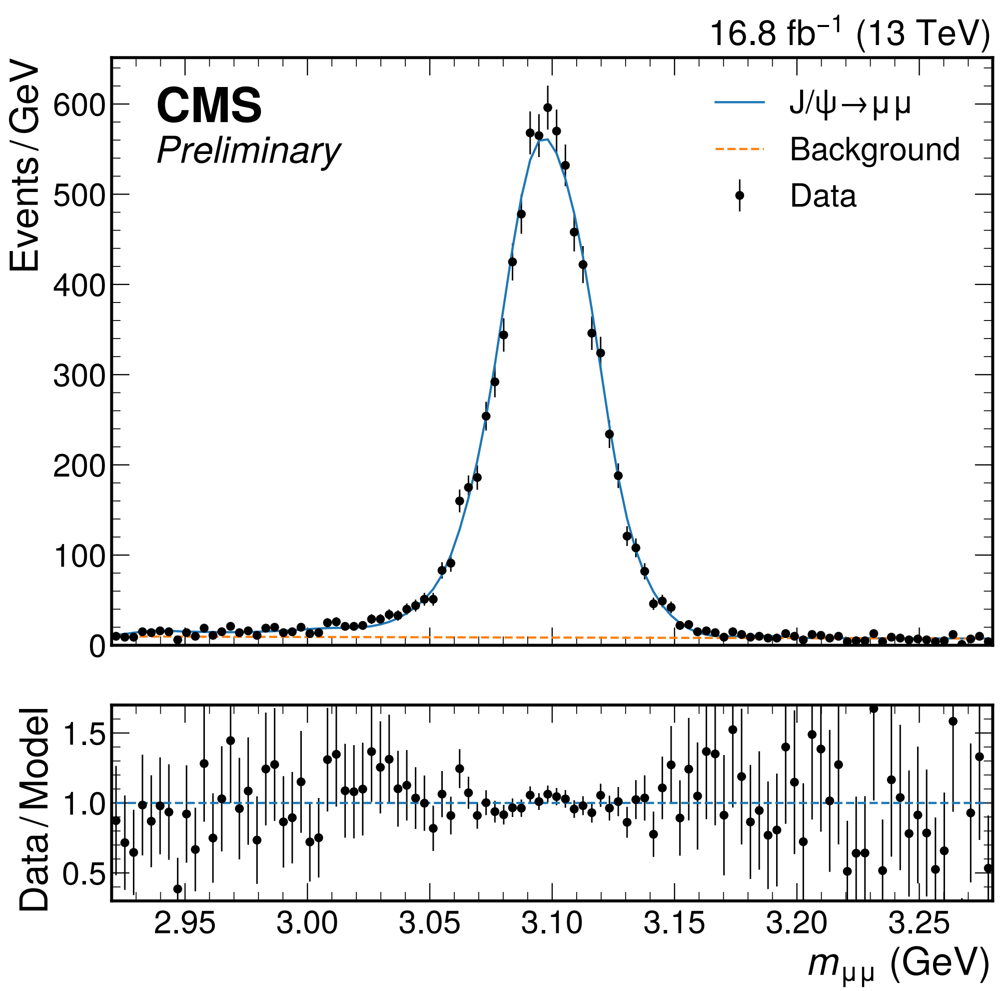
- The “extra” terms are generated by local biases in magnetic field, material or alignment, which effectively receive a momentum-dependent weight $1/(1+d_l^2k^2)$ due to the competition between hit resolution and multiple scattering in the track fit
  - Sum runs over *m* layers of material traversed by the track
- Extended model is found to describe the observed bias, but is way more complex



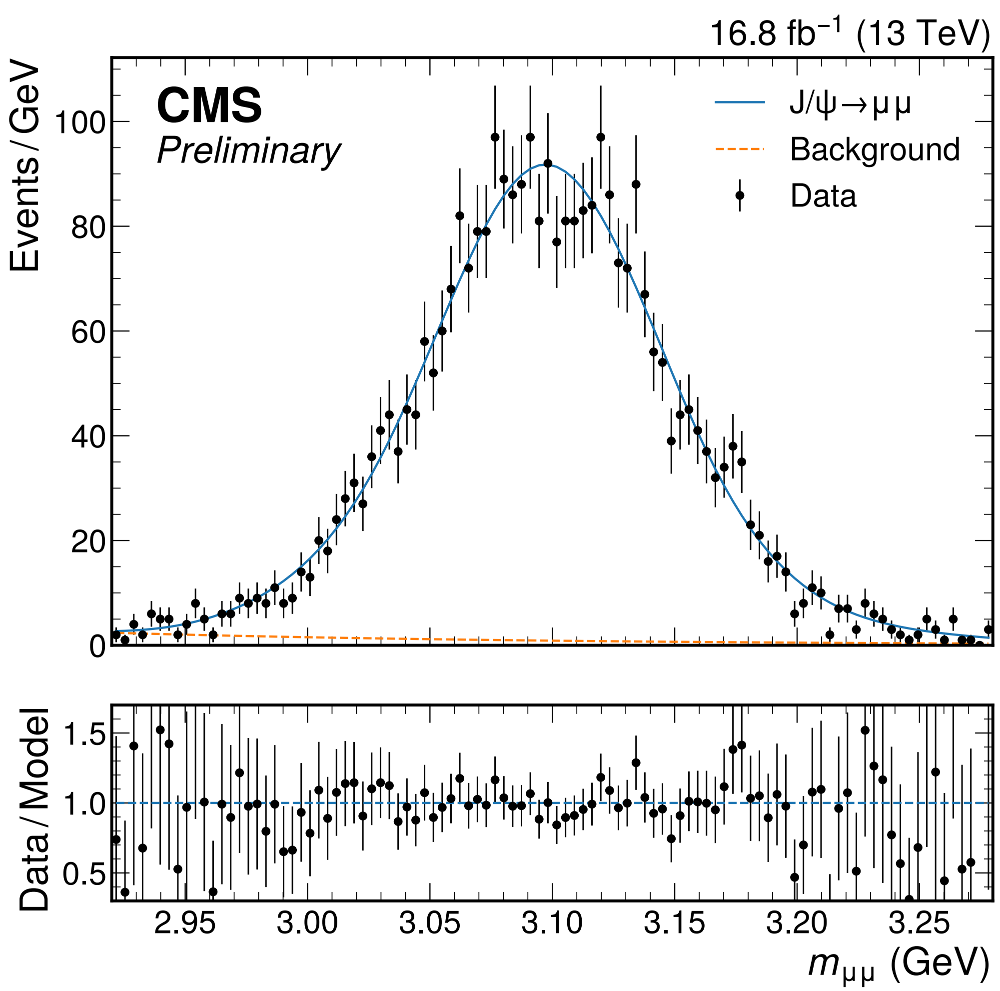
Last stage of p_T^{μ} calibration: mass fits to J/ψ

- Final corrections in fine 4D bins ($p_T^{\mu+}$, $\eta^{\mu+}$, $p_T^{\mu-}$, $\eta^{\mu-}$) from mass fits to J/ψ→μμ events
- With respect to track fit, can account for other physics effects: final-state radiation of photons, or non-resonant backgrounds

Barrel η bin



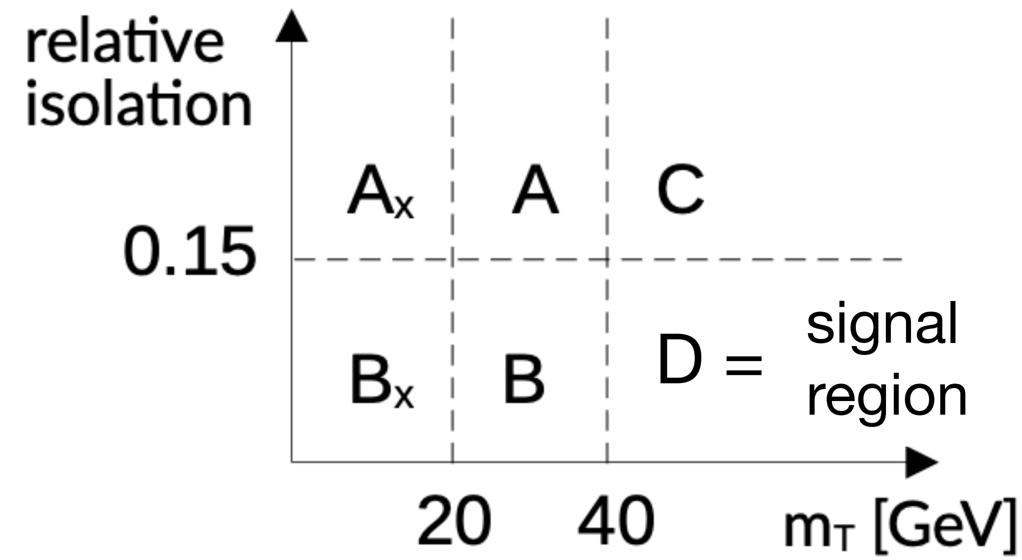
Endcap η bin



ABCD: the “*E-Z*” way to nonprompt backgrounds

Data-driven “ABCD” method in the 2D space of muon isolation and m_T

- “Extended” ABCD method (<u>here</u>) with 3 m_T bins to account for correlation between isolation and m_T
- Nonprompt yields in non-D regions obtained by subtracting from data the events with prompt muons, estimated from simulation
- Nonprompt binned distributions in each region regularized versus p_T^{μ} with polynomials



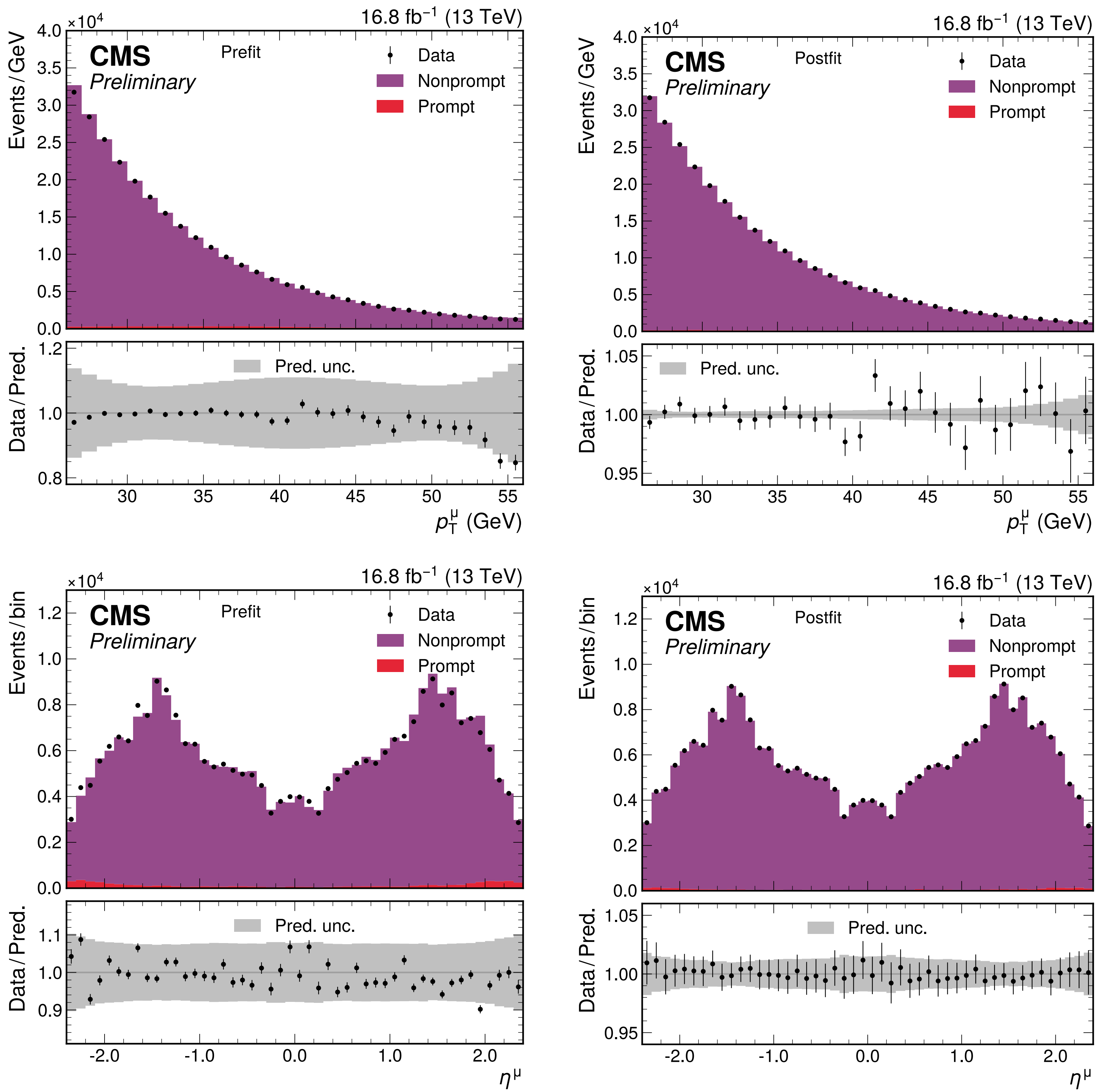
$$D = C \cdot \frac{A_x B^2}{B_x A^2}$$

Prediction in D derived for each single p_T^{μ}-η^{μ}-q^{μ} bin

- Uncertainties in prompt yields consistently propagated to nonprompt by reevaluating the subtraction, and accounting for proper (anti-)correlations in pass/fail iso regions

ABCD validation

- Method tested both with QCD MC and real data events from control regions enriched in muons from secondary vertices (SV), mostly from D/B hadron decays



SV data control regions, enriched in nonprompt muons from b,c quark decays

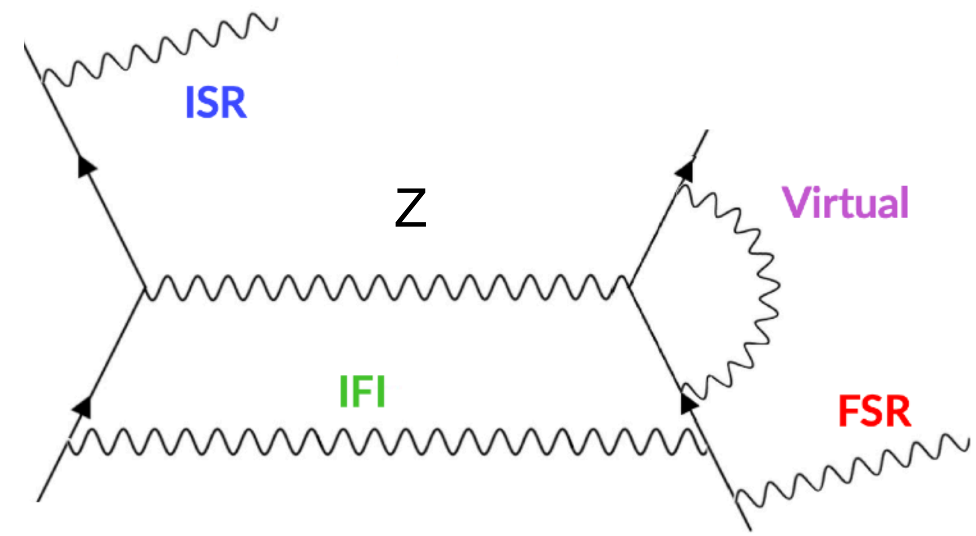
15% correction applied for normalization in region D (consistent between SV control region and QCD MC)

Additional normalization and shape uncertainties to cover residual differences

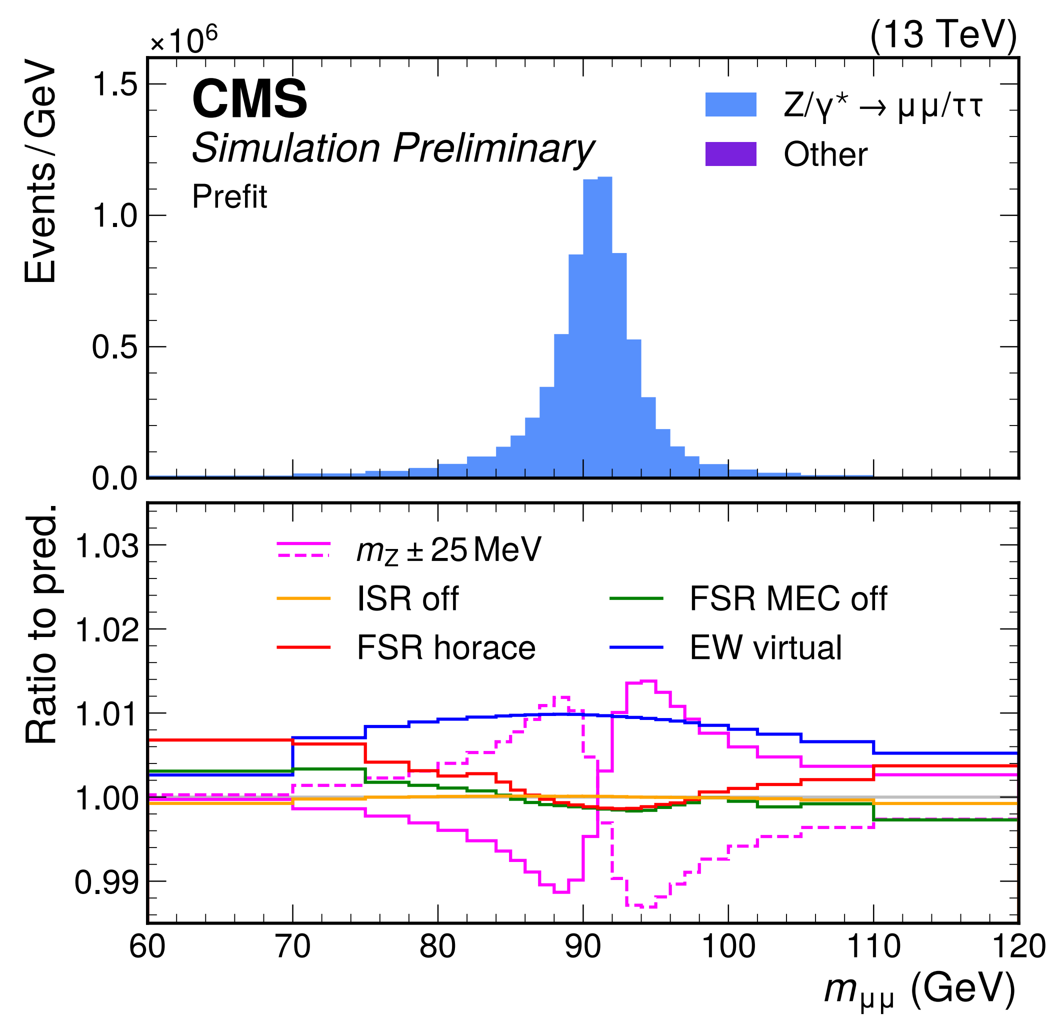
δm_W ~ 3.2 MeV

Higher order EW uncertainties

Main EW effect from FSR already included in our MiNNLO MC through PHOTOS++ with NLO QED, including γ→ee/μμ pair production



- **ISR** uncertainty < 0.1 MeV
  - Switching on/off QED ISR in Pythia
- **FSR** uncertainty ~0.3 MeV
  - Alternative QED FSR from Horace
  - Photos Matrix Element Corrections on/off
- **Virtual** uncertainty ~1.9 MeV
  - Z: Powheg NLO+HO EW
  - W: ReneSANCe NLO+HO EW
- **IFI** (initial-final state interference) expected to be at the 0.1 MeV level (see here)
  - neglected for now

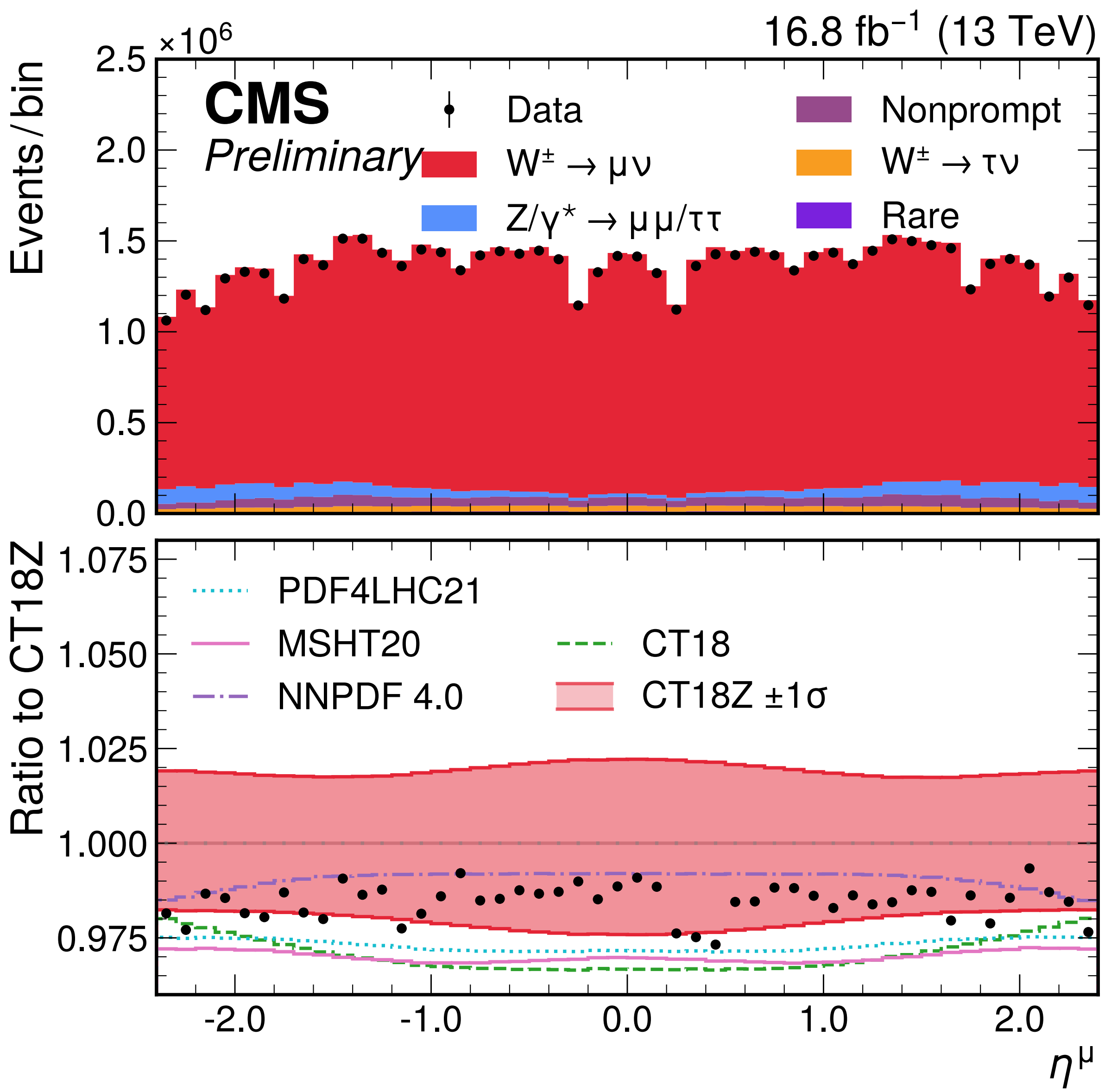


ATLAS: Pythia vs. Photos (6 MeV unc.)
CDF: 2.7 MeV unc. (Horace)

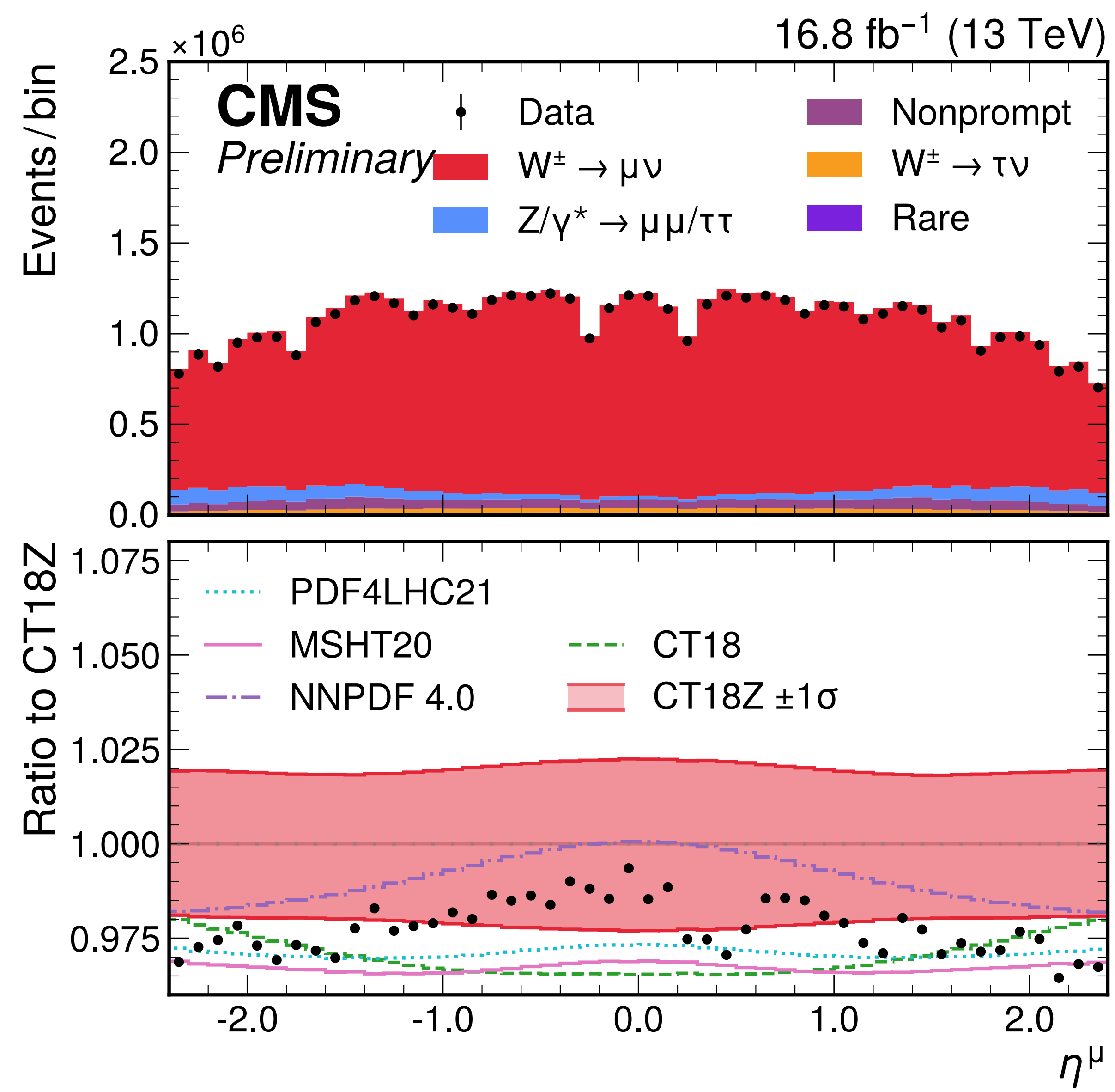
Prefit η^{μ} distributions in W events

- Prefit shape agreement largely modified by choice of PDFs
- Local discontinuities at the 1-2% level in the data/MC ratio, but several experimental systematic uncertainties are decorrelated in bins of η^{μ} (efficiencies, nonprompt background, …) and can cover the discrepancies

W+



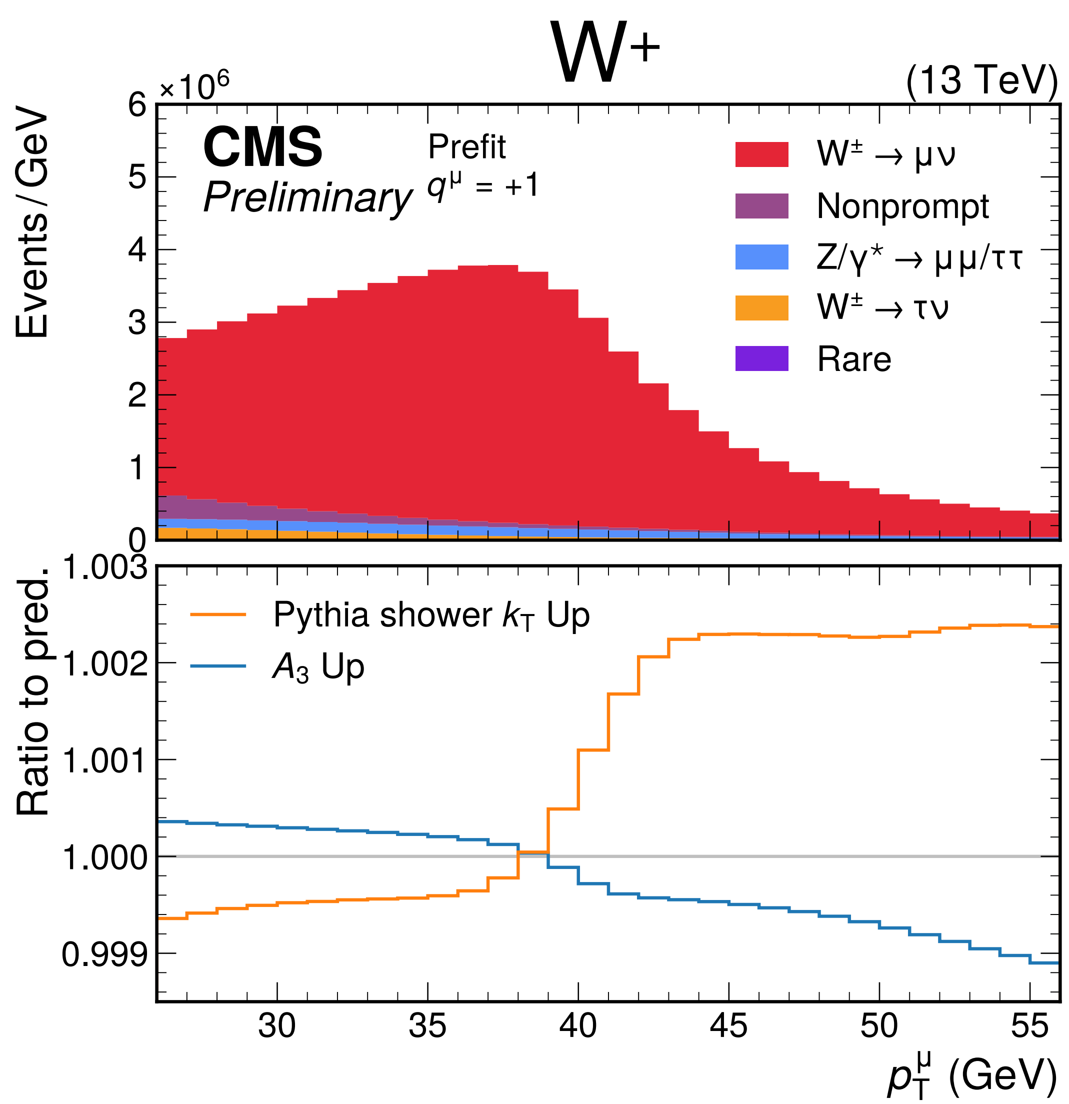
W-

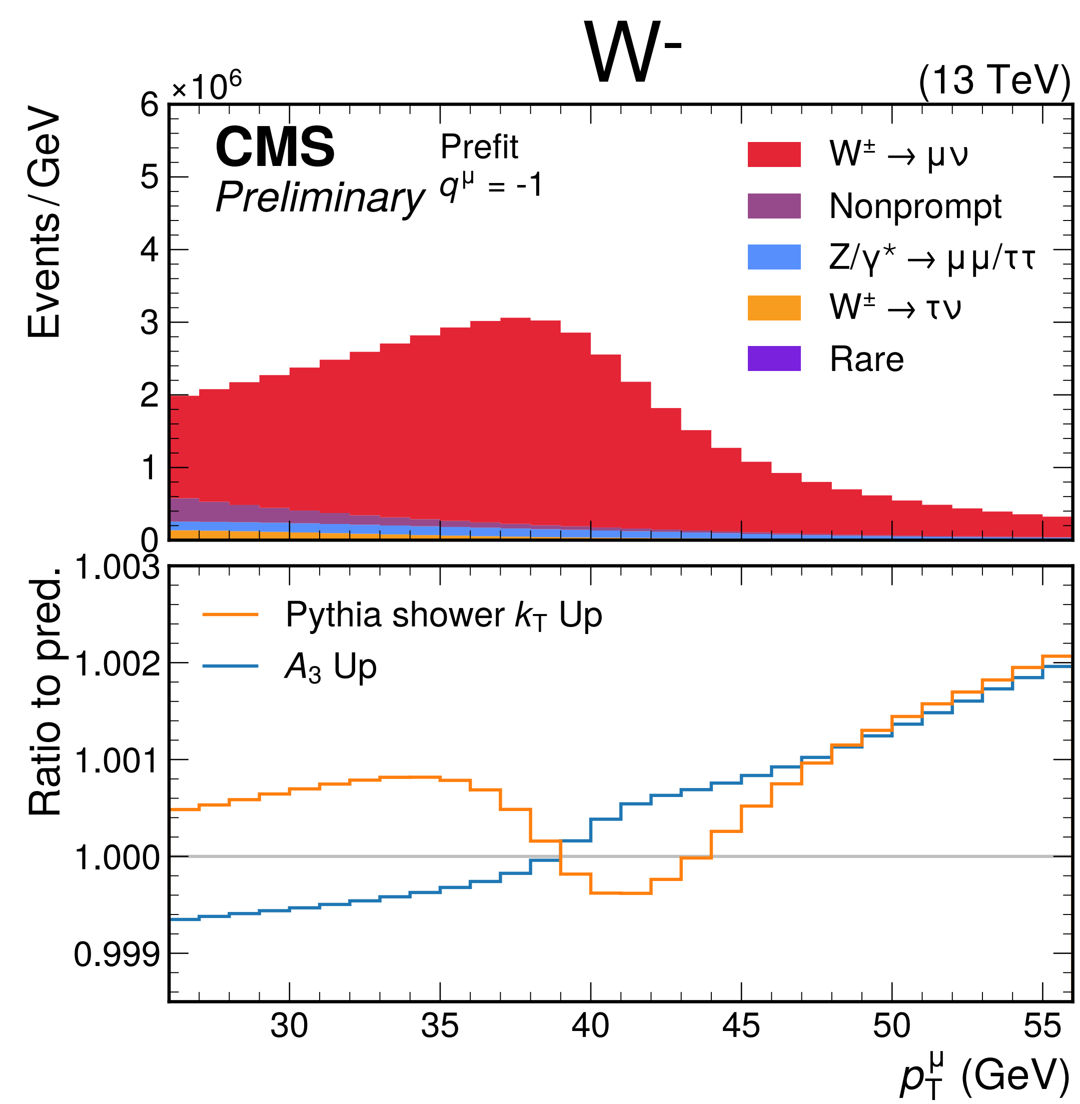


Angular coefficients and uncertainties

Uncertainties assessed through NNLO μ_R, μ_F scale variations in MiNNLO samples, with partial decorrelation in p_T^V and between W and Z

- Validated against MCFM and DYTurbo fixed-order (FO) predictions
- While MiNNLO$_{PS}$ predicts angular coefficients consistent with FO calculations, Pythia “intrinsic k_T” treatment actually modifies them: this effect may or may not be physical, so we conservatively propagate the full difference as an additional uncertainty

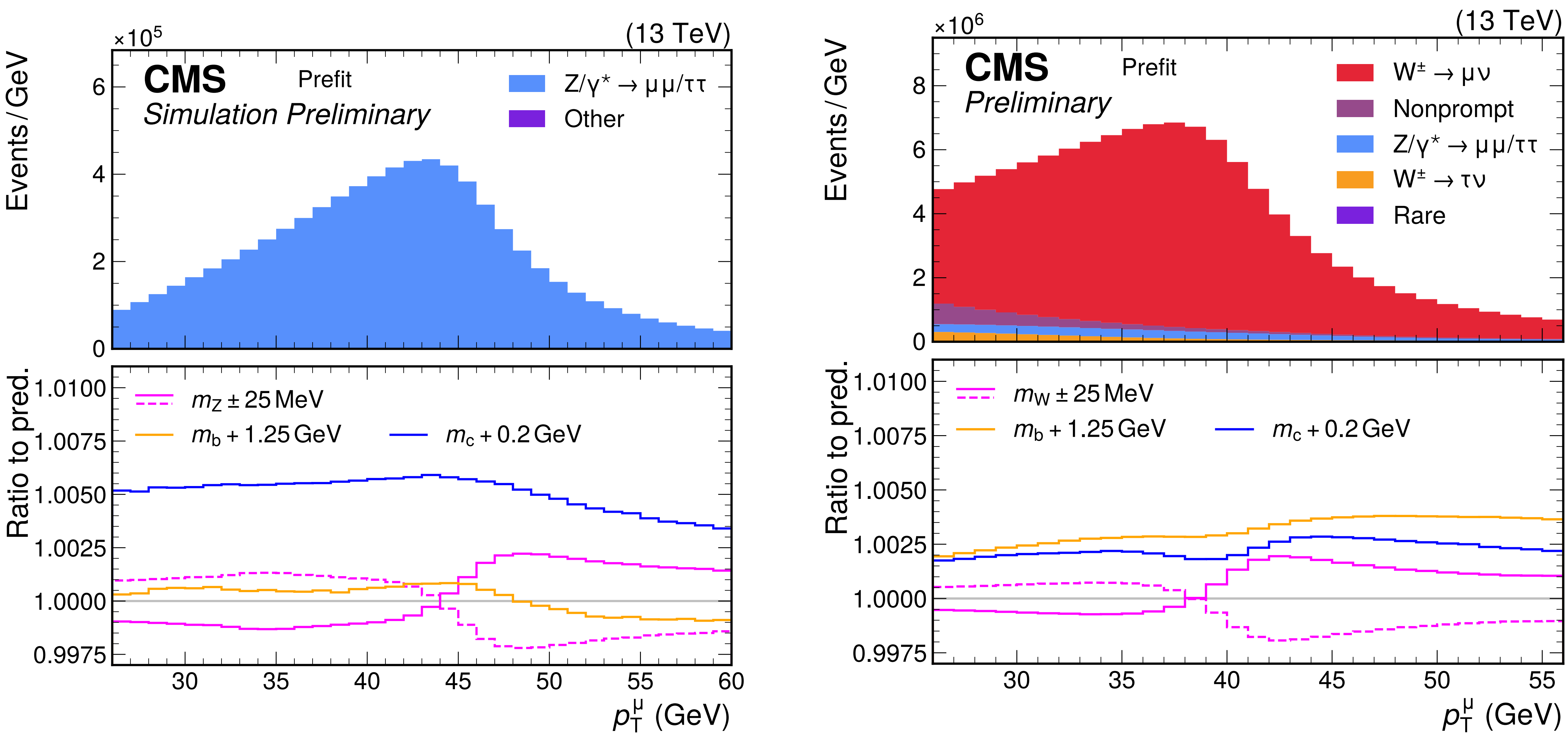




Quark masses

PDFs assume massless quarks, but p_T^V spectrum sensitive to finite quarks' mass

- Different effect in W and Z, potential bias if tuning p_T^W on p_T^Z
- Uncertainties from alternative predictions based on MSHT20 PDFs with massive c, b
- Developing a more refined model accounting for massive quarks and with proper W/Z correlations is crucial for a simultaneous fit of W and Z data



MC statistical uncertainty

> 4B simulated W events (~ 4x equivalent data luminosity after event selection)

- MC stat (bin-by-bin, BBB) uncertainty treated with Barlow-Beeston lite approach

Systematic uncertainties encoded by alternate templates from MC

- Statistical fluctuations in alternate template bins not explicitly accounted for
- Can lead to spurious constraints, artificially reducing total systematic uncertainty
    - Can be checked running the fit without BBB and half MC stat to fill templates
    - Issue is present if total uncertainty decreases with half MC stat
- Discussed in this paper from Pisa's authors
    - See also this presentation

Ad-hoc solution to mitigate the issue (proper solution would require MC stat → ∞)

- Inflate BBB uncertainty by 25% when running the fit
- scaling determined from studies with toys to assess proper coverage

This is a statistics problem arising with likelihood fits based on MC templates

- Many HEP analyses could be affected: should always check the impact by comparing the nominal result with the one produced with half MC stat

Additional stability and consistency checks

Configuration	Δm_W in MeV	Auxiliary parameter
$26 < p_T < 52\,\text{GeV}$	-0.75 ± 10.03	—
$30 < p_T < 56\,\text{GeV}$	-1.11 ± 11.05	—
$30 < p_T < 52\,\text{GeV}$	-2.15 ± 11.17	—
W floating	-0.47 ± 9.98	$\mu_W = 0.979 \pm 0.026$
Alt. veto efficiency	0.05 ± 9.88	—
Hybrid smoothing	-1.58 ± 9.88	—
Charge difference	0.34 ± 9.89	$m_W^{\text{diff.}} = 56.96 \pm 30.30\,\text{MeV}$
η sign difference	-0.01 ± 9.88	$m_W^{\text{diff.}} = 5.8 \pm 12.4\,\text{MeV}$
$\lvert\eta\rvert$ range difference	-0.61 ± 9.90	$m_W^{\text{diff.}} = 15.3 \pm 14.7\,\text{MeV}$

Systematic uncertainties and nuisance parameters

- Almost 5k nuisance parameters
- Vast majority from statistical uncertainties in efficiency SF, mainly because of fine granularity and decorrelation in bins of η^{μ} for each step and charge

<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>

Electrons versus muons

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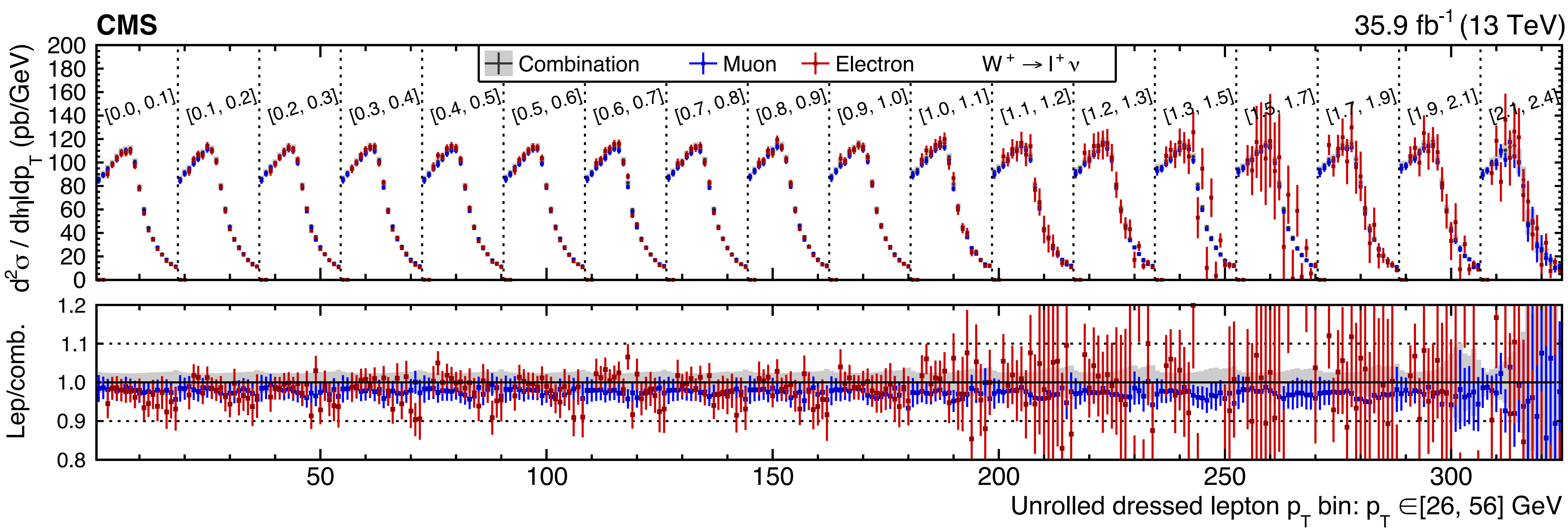
Significantly larger uncertainties for electrons, and challenges for calibrations

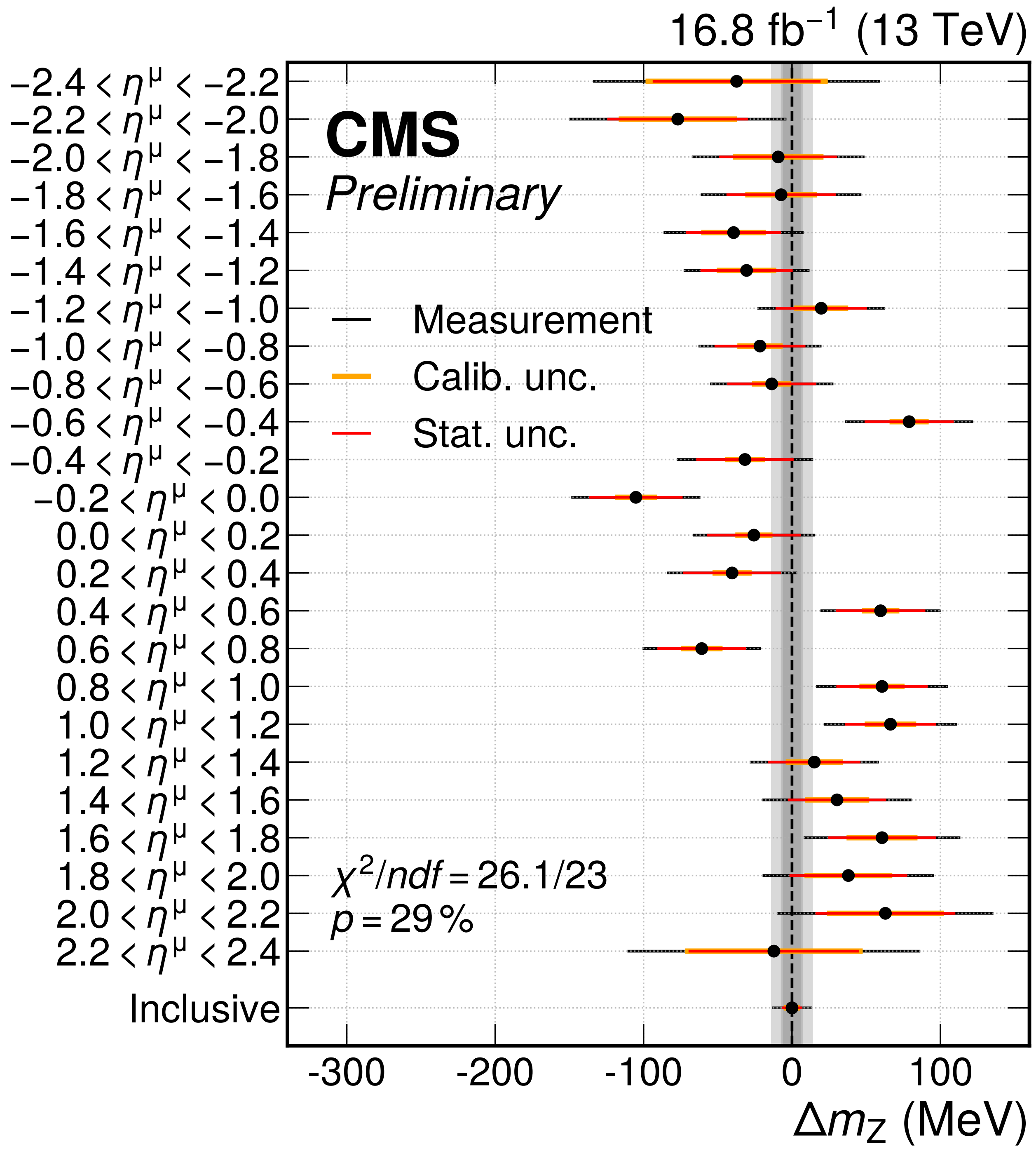
- Tighter L1/HLT criteria (reduced acceptance at low p_T, lower efficiency in endcaps)
- Larger systematics for energy scale calibration (no J/ψ, can only use Z)
- More nonprompt background (QCD multijet, with jets misidentified as electrons)
- Overall larger statistical uncertainties

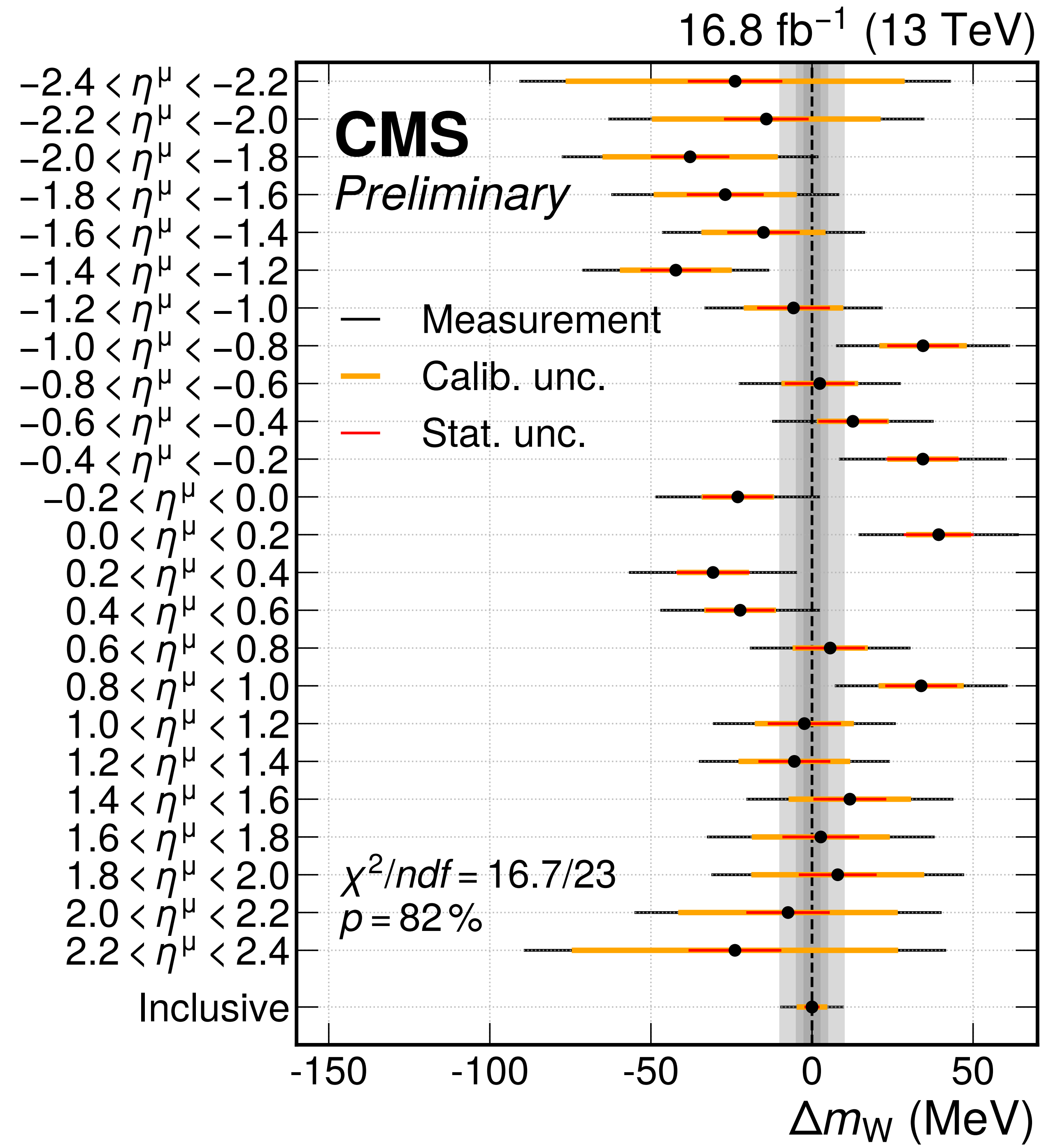
- **However**: electrons still have a lot of potential in future m_T based measurement, since worse performance compared to muons are diluted because of larger impact of p_T^{miss}



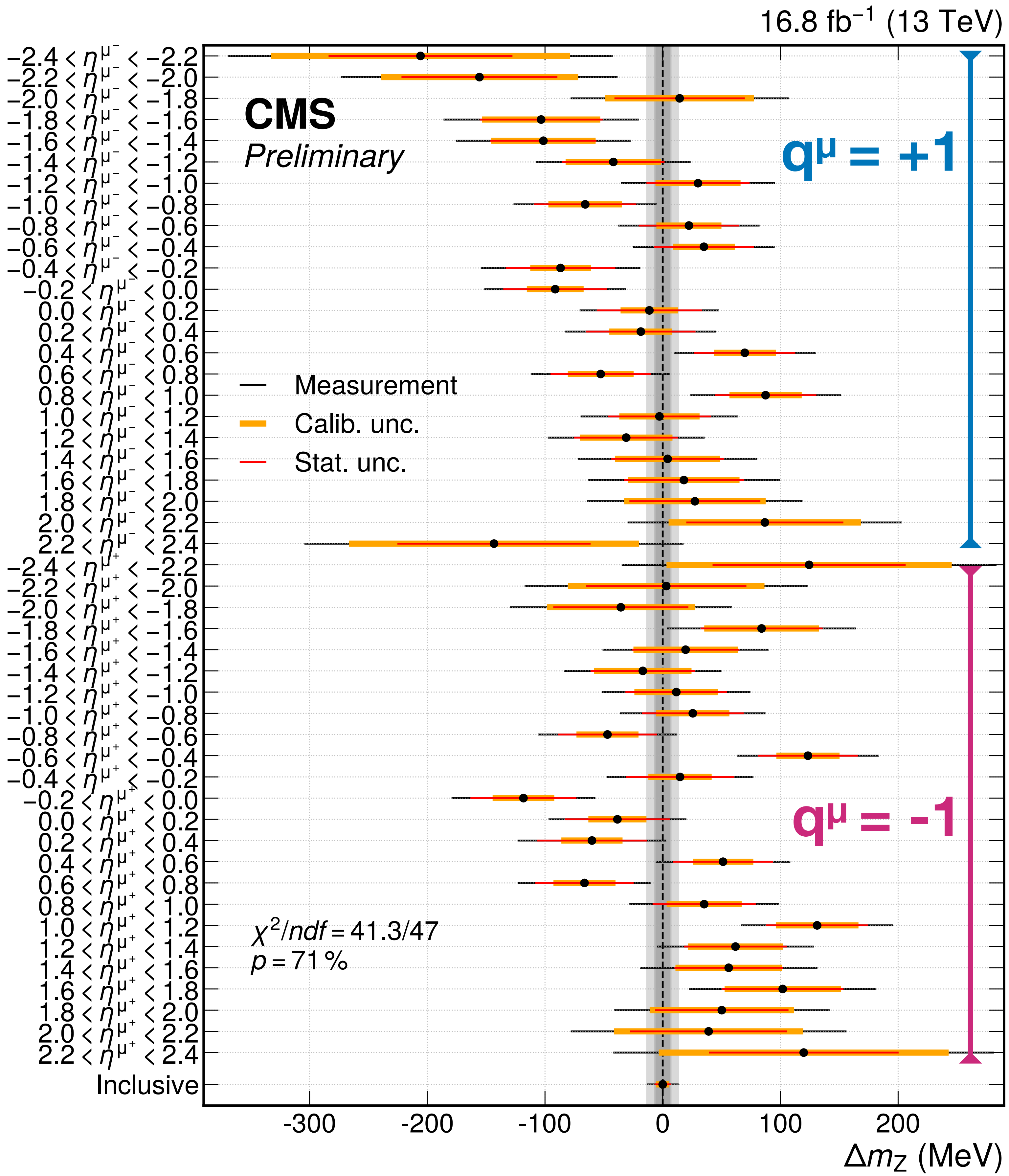
m_V stability versus η^μ

- Fit with one independent mass parameter for different η^μ ranges
- No evidently problematic region in the detector



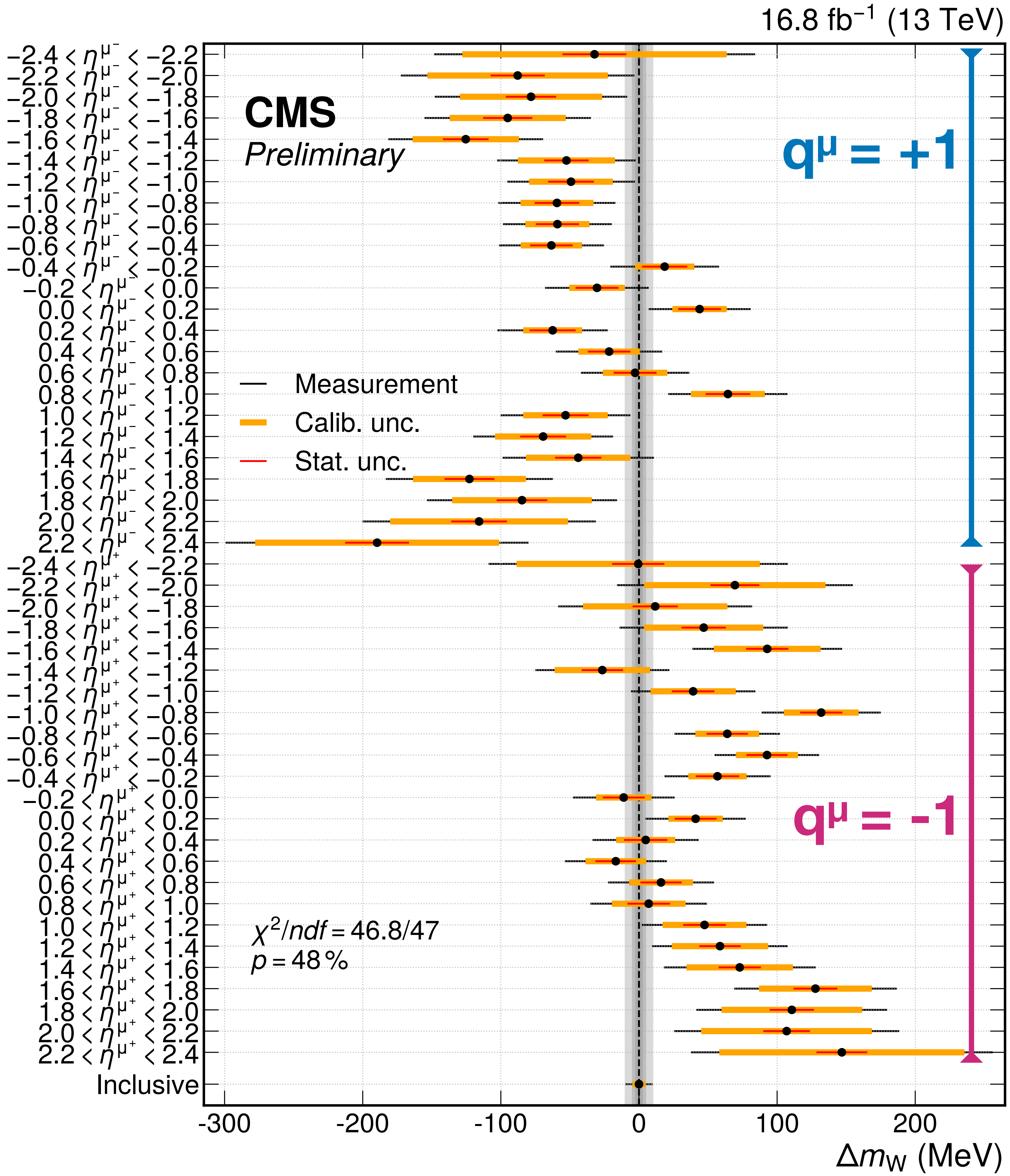


W-like m_Z fit: charge difference



- 48 independent mass parameters split by charge and 24 η^{μ} bins
- η^{μ} - sign difference: $m_Z^{\eta>0} - m_Z^{\eta<0} = 34 \pm 20$ MeV
- Charge difference: $m_Z^{+} - m_Z^{-} = 31 \pm 32$ MeV
- Charge difference with reverse odd/even selection: $m_Z^{+} - m_Z^{-} = 6 \pm 32$ MeV

m_W fit: charge difference



- 48 independent mass parameters split by charge and 24 η^{μ} bins
- η^{μ} sign difference: $m_W^{\eta>0} - m_W^{\eta<0} = 6 \pm 12$ MeV
- Charge difference: $m_{W^+} - m_{W^-} = 57 \pm 30$ MeV
- Note: correlation between parameter for mass difference by charge and nominal m_W parameter is only 2% —> a large variation in mass difference by charge would only mildly affect charge inclusive m_W

Discussion on m_W charge difference

- Uncertainty on charge difference much larger than nominal m_W uncertainty
- Strong anti-correlations due to experimental uncertainties (alignment) and theory uncertainties related to W polarization (opposite-parity coupling of W to μ^+ and μ^-)
- Possible/plausible scenario: ~1σ off on alignment and angular coefficients A_i with ~1σ statistical fluctuation corresponds to totally negligible effect on m_W (0.1MeV)
- Data + MC stat. uncertainty for charge difference also not negligible: ~ 16 MeV
- Correlation between charge difference and m_W itself is only 2%

Configuration	$m_W^+ - m_W^-$ (MeV)	Δm_W (MeV)
nominal	57 ± 30	0
Alignment ~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 ~ 3 sigma up	-5 ± 30	0.6

Summary of impacts

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

arXiv:2403.15085

ATLAS m_W and Γ_W

Re-analysis of original 7 TeV result (published one year ago, recently updated again)

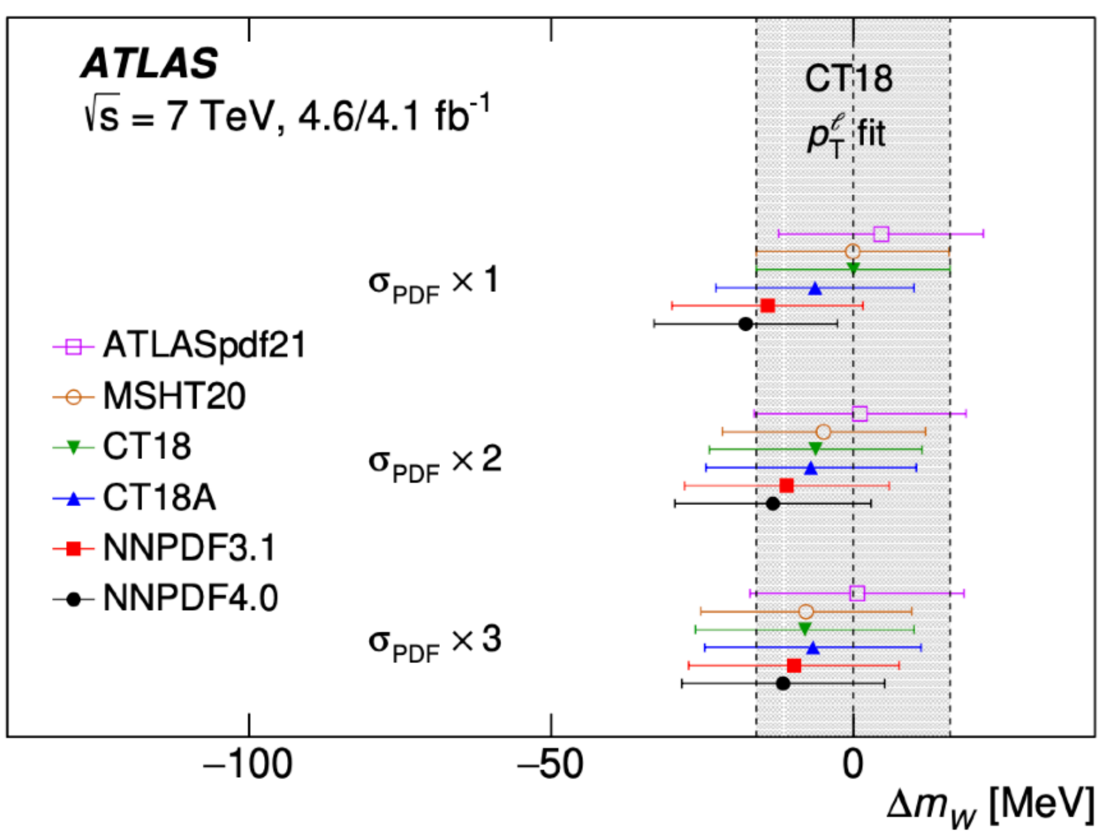
- Improved fit with likelihood minimization and uncertainty profiling rather than χ^2
- extended studies of PDFs, impact of profiling demonstrated by inflating pre-fit uncertainties
- m_W and Γ_W measured simultaneously or fixing one to SM

Updated m_W = 80366.5 ± 15.9 MeV (Γ_W fixed to SM)

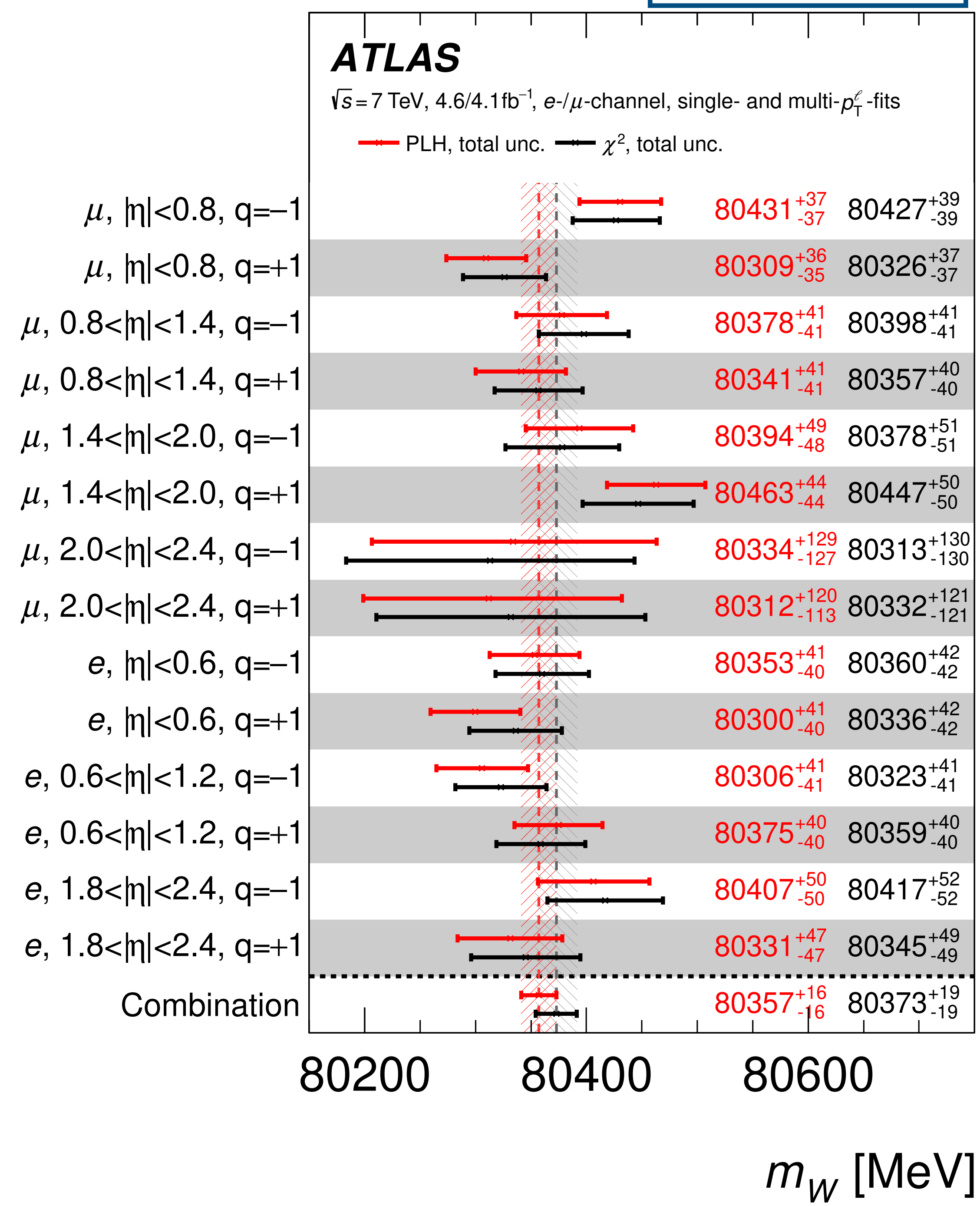
- It was δm_W ~ 19 MeV in 2017, with 9.2 MeV from PDFs

Using CT18 PDFs

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



Using CT10nnlo PDFs



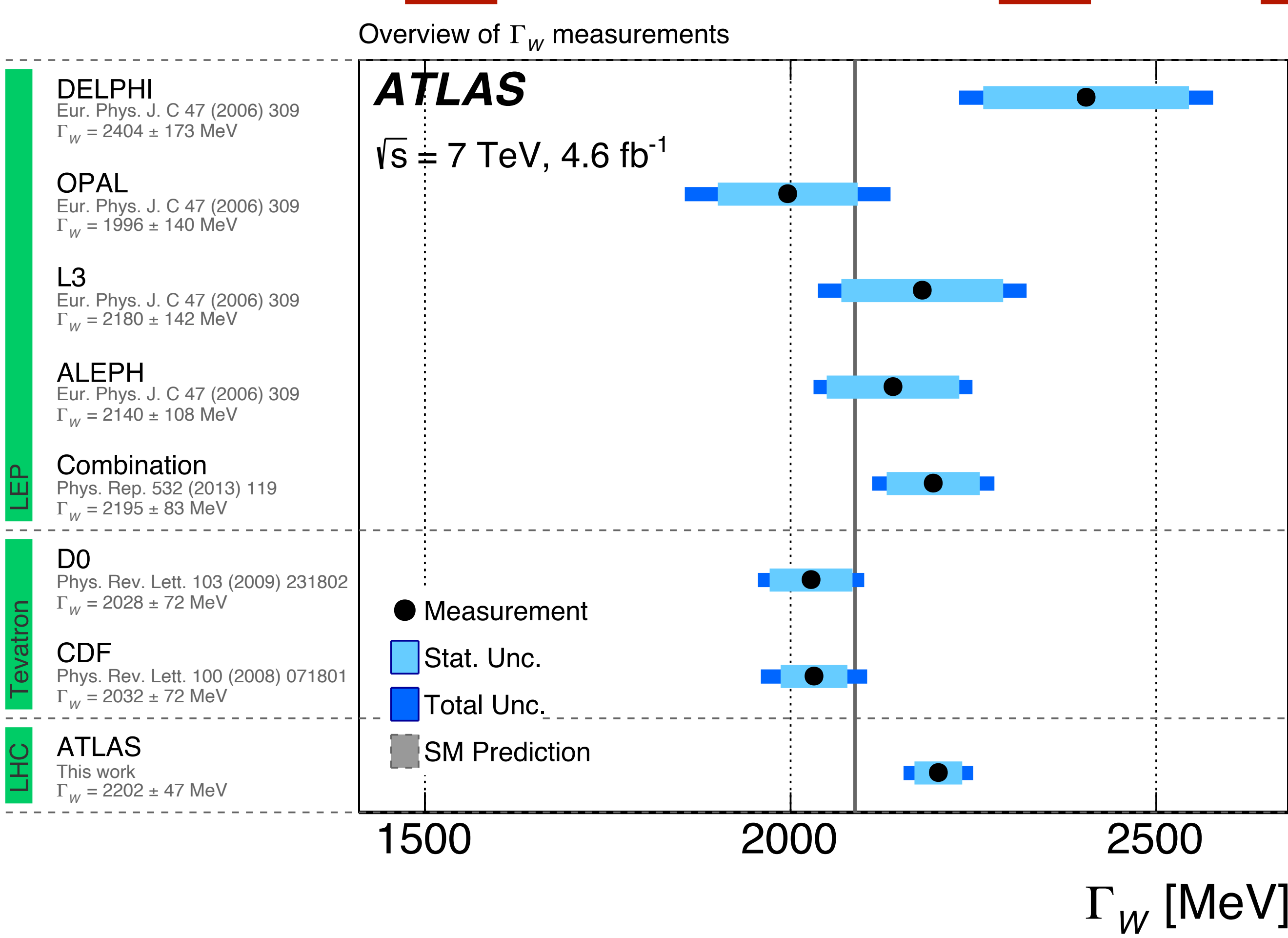
ATLAS m_W and Γ_W

First measurement of Γ_W at the LHC, most precise from single experiment

- Fixing m_W to SM, Γ_W = 2202 ± 47 MeV, ~2σ above SM
- Main uncertainty from MC modelling (shower tune variations) and recoil
- Smaller m_W value from simultaneous fit because of anticorrelation with Γ_W

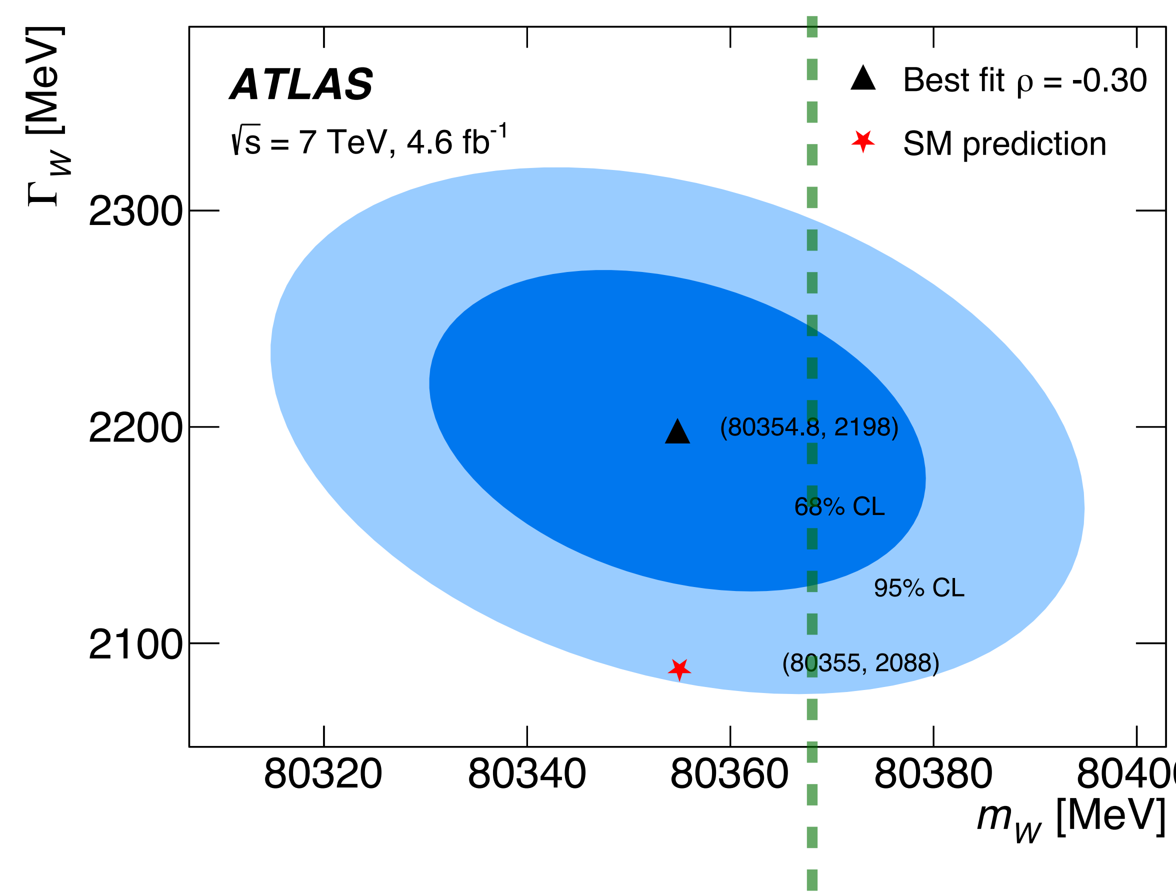
Using CT18 PDFs

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18



From simultaneous fit:

m_W = 80354.8 ± 16.1 MeV Γ_W =2198 ± 49 MeV



m_W with constrained Γ_W

Comparison with ATLAS

- Latest ATLAS (re)analysis uses "global impacts", as proposed in arxiv:2307.04007
  - Systematic component constrained by data is absorbed into statistical uncertainty
- CMS has larger data set, stronger constraints on PDFs, and better EW uncertainty (more recent PHOTOS version than ATLAS, includes pair production)
- Stronger constraints also on QCD theory uncertainties (without MC tuning on Z)

ATLAS

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

- CMS total calibration + muon eff. ~ 10% better, but Z-independent scale calibration
- ATLAS used both e/μ channels and p_T^ℓ/ m_T, CMS only exploited p_T^μ so far

CMS

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

Comparison with CDF

CDF has advantages from $p\bar{p}$ collider for theory (PDFs, flavour dependence), and from lower material in their tracker for calibration (< 0.2 X_0 compared to CMS ~1-2 X_0)

- But CDF didn't do a W-like m_Z measurement, owing to insufficient statistics
- Much lower PU at Tevatron than LHC makes m_T method very competitive

CDF runs a likelihood fit with no profiling: uncertainties from 1σ $^{\text{Up}}/_{\text{Down}}$ variations

- No distinction between "prefit" and "postfit" uncertainties in CDF
- Not possible to compare directly with CMS, where prefit systematic uncertainties are intended to be constrained by data and are often conservative or overestimated

CDF

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

CMS

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
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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

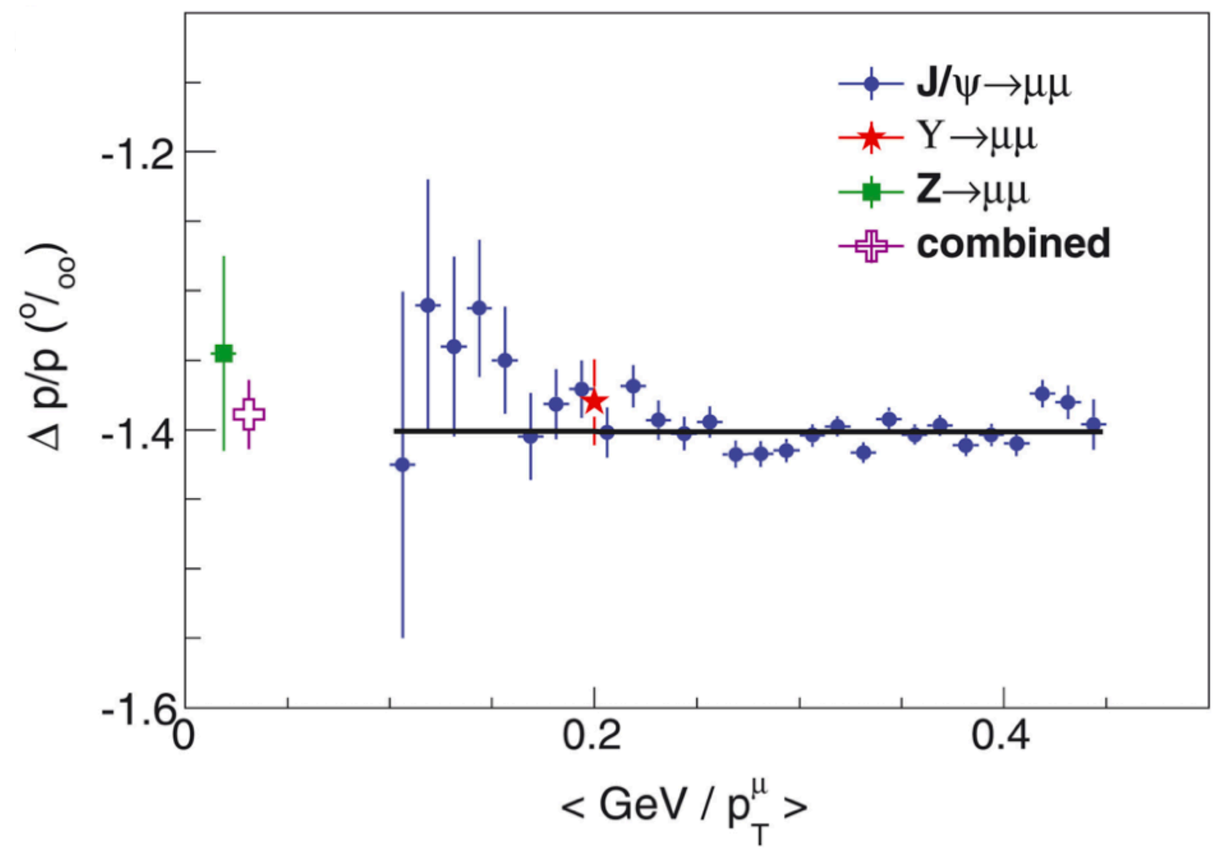
CDF momentum scale calibration

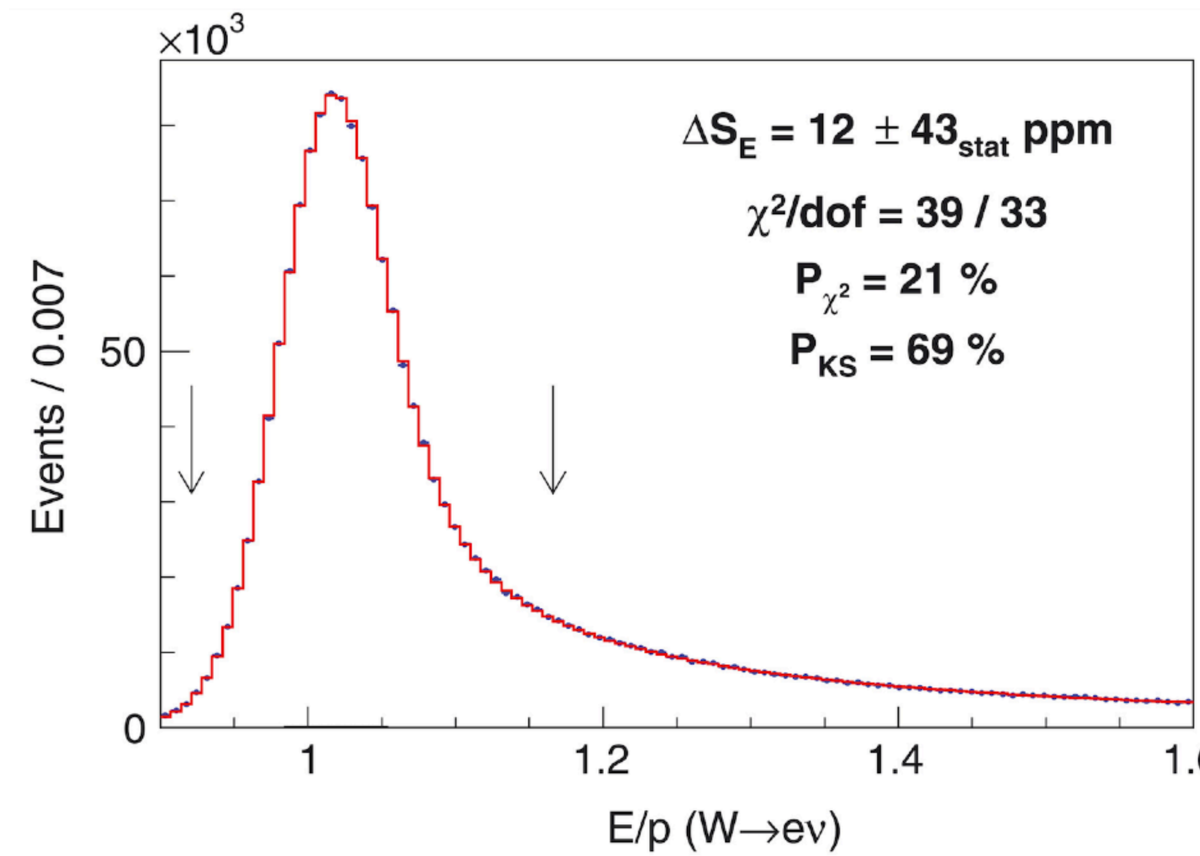
- CDF precisely calibrates their tracker to ~25 parts per million, using quarkonia
- Calibration validated measuring m_Z in dimuon events
- Then, for the m_W measurement they combine the scale from quarkonia and Z, **BUT** they don't assign an additional closure uncertainty from the statistical uncertainty of their m_Z measurement
- Their precise tracker calibration is then used to calibrate the calorimeter energy for electrons using E/p (possible thanks to the low material in their tracker)

$m_Z(\mu\mu) = 91192.0 \pm 6.4_{stat} \pm 4.0_{syst}$ MeV

$m_Z(ee) = 91194.3 \pm 13.8_{stat} \pm 7.6_{syst}$ MeV

$m_Z^{PDG} = 91187.6 \pm 2.1$ MeV





CDF measurements

Source of systematic uncertainty	m_T fit Electrons	m_T fit Muons	m_T fit Common	p_T^ℓ fit Electrons	p_T^ℓ fit Muons	p_T^ℓ fit Common	p_T^ν fit Electrons	p_T^ν fit Muons	p_T^ν fit Common
Lepton energy scale	5.8	2.1	1.8	5.8	2.1	1.8	5.8	2.1	1.8
Lepton energy resolution	0.9	0.3	-0.3	0.9	0.3	-0.3	0.9	0.3	-0.3
Recoil energy scale	1.8	1.8	1.8	3.5	3.5	3.5	0.7	0.7	0.7
Recoil energy resolution	1.8	1.8	1.8	3.6	3.6	3.6	5.2	5.2	5.2
Lepton $u_{\vert\vert}$ efficiency	0.5	0.5	0	1.3	1.0	0	2.6	2.1	0
Lepton removal	1.0	1.7	0	0	0	0	2.0	3.4	0
Backgrounds	2.6	3.9	0	6.6	6.4	0	6.4	6.8	0
p_T^Z model	0.7	0.7	0.7	2.3	2.3	2.3	0.9	0.9	0.9
p_T^W/p_T^Z model	0.8	0.8	0.8	2.3	2.3	2.3	0.9	0.9	0.9
Parton distributions	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
QED radiation	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Statistical	10.3	9.2	0	10.7	9.6	0	14.5	13.1	0
Total	13.5	11.8	5.8	16.0	14.1	7.9	18.8	17.1	7.4

Combination	m_T fit Electrons	m_T fit Muons	p_T^ℓ fit Electrons	p_T^ℓ fit Muons	p_T^ν fit Electrons	p_T^ν fit Muons	Value (MeV)	χ^2/dof	Probability (%)
m_T	✓	✓					$80\ 439.0 \pm 9.8$	1.2 / 1	28
p_T^ℓ			✓	✓			$80\ 421.2 \pm 11.9$	0.9 / 1	36
p_T^ν					✓	✓	$80\ 427.7 \pm 13.8$	0.0 / 1	91
m_T & p_T^ℓ	✓	✓	✓	✓			$80\ 435.4 \pm 9.5$	4.8 / 3	19
m_T & p_T^ν	✓	✓			✓	✓	$80\ 437.9 \pm 9.7$	2.2 / 3	53
p_T^ℓ & p_T^ν			✓	✓	✓	✓	$80\ 424.1 \pm 10.1$	1.1 / 3	78
Electrons	✓		✓		✓		$80\ 424.6 \pm 13.2$	3.3 / 2	19
Muons		✓		✓		✓	$80\ 437.9 \pm 11.0$	3.6 / 2	17
All	✓	✓	✓	✓	✓	✓	$80\ 433.5 \pm 9.4$	7.4 / 5	20