Precise measurement of the W boson mass with the CMS detector at the CERN LHC

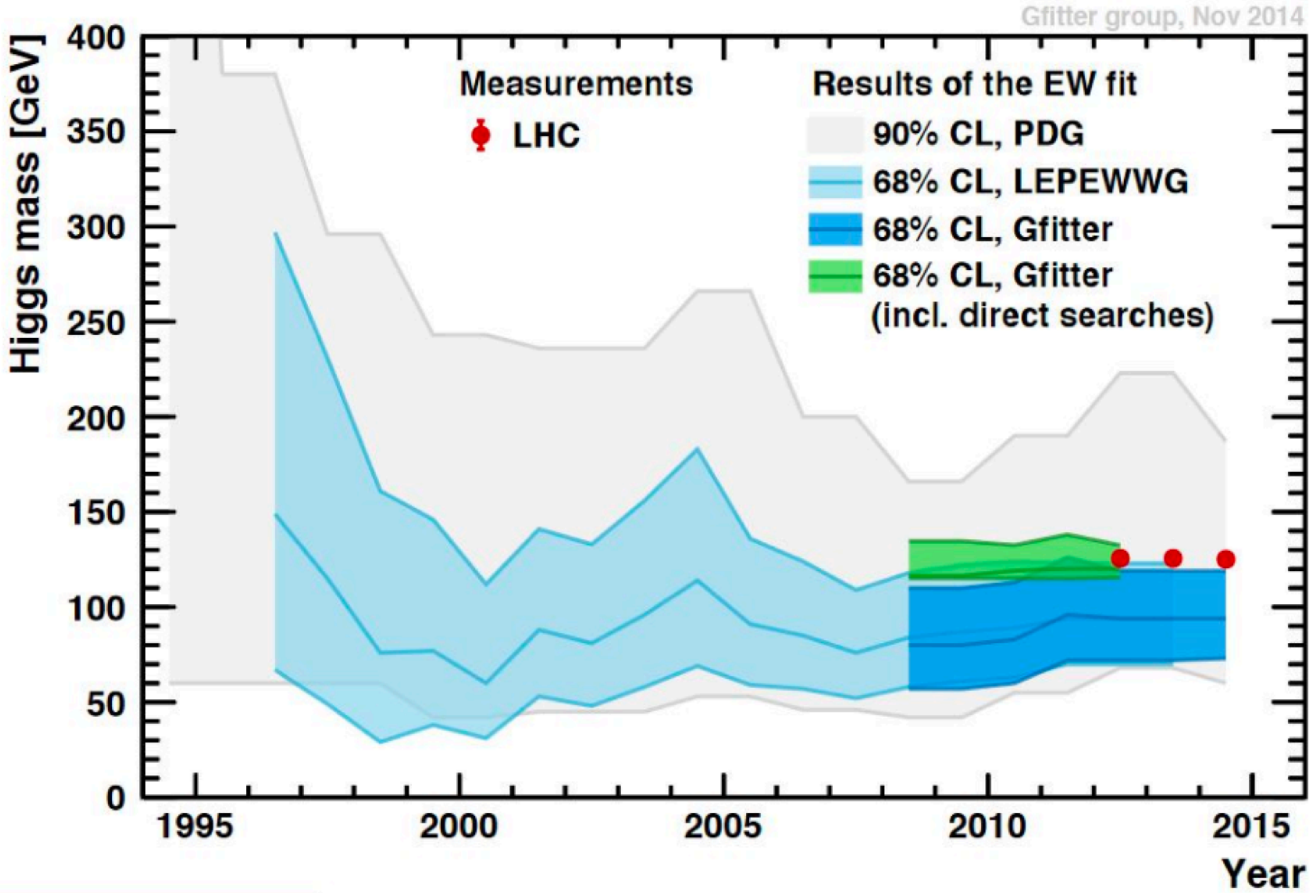
GDR m_W workshop

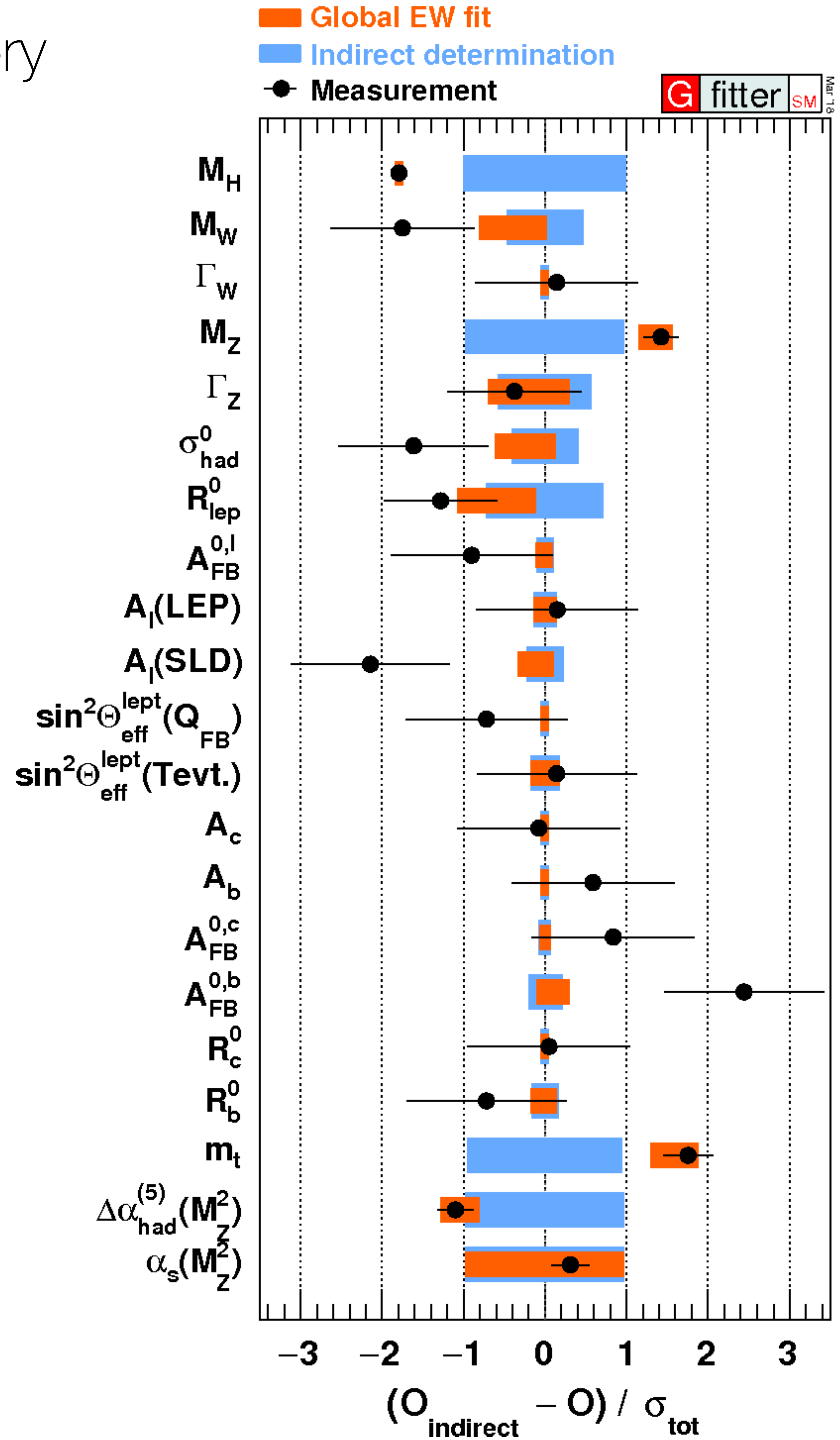
Kenneth Long

The standard model and its experimental landscape

- The standard model is a spectacularly precise and successful theory
  - Masses, couplings are fundamentally experimental
  - But with many **relationships exactly predicted**
- **The standard model is *surely incomplete***

➡ Measurements over-constrain the standard model
  - Test its self consistency, **give hints of new particles**…?





Kenneth Long

The W boson mass and other experimental parameters

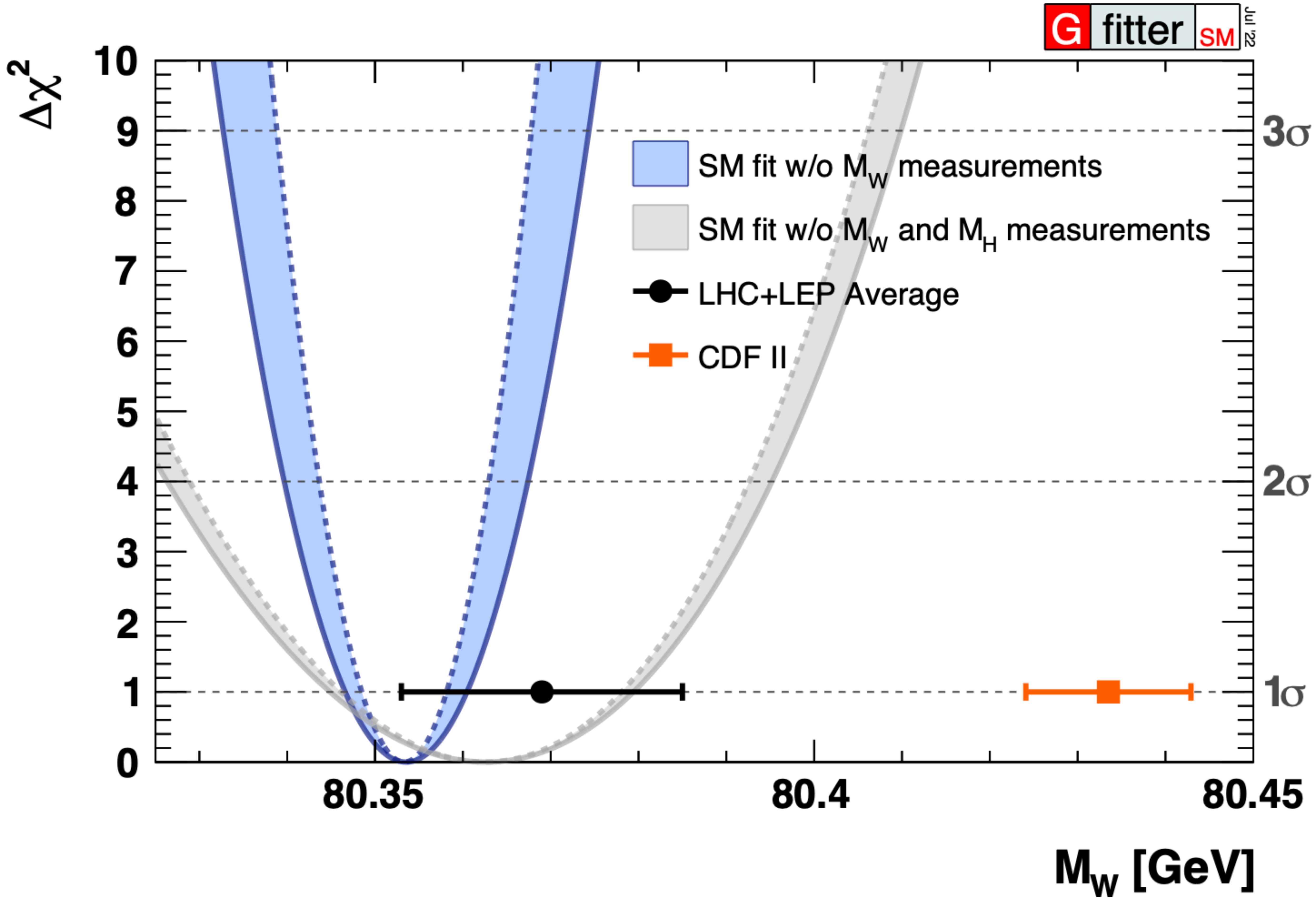
Higher-order corrections
Depend on m_t, m_H, … m_{BSM}?

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

Very well measured

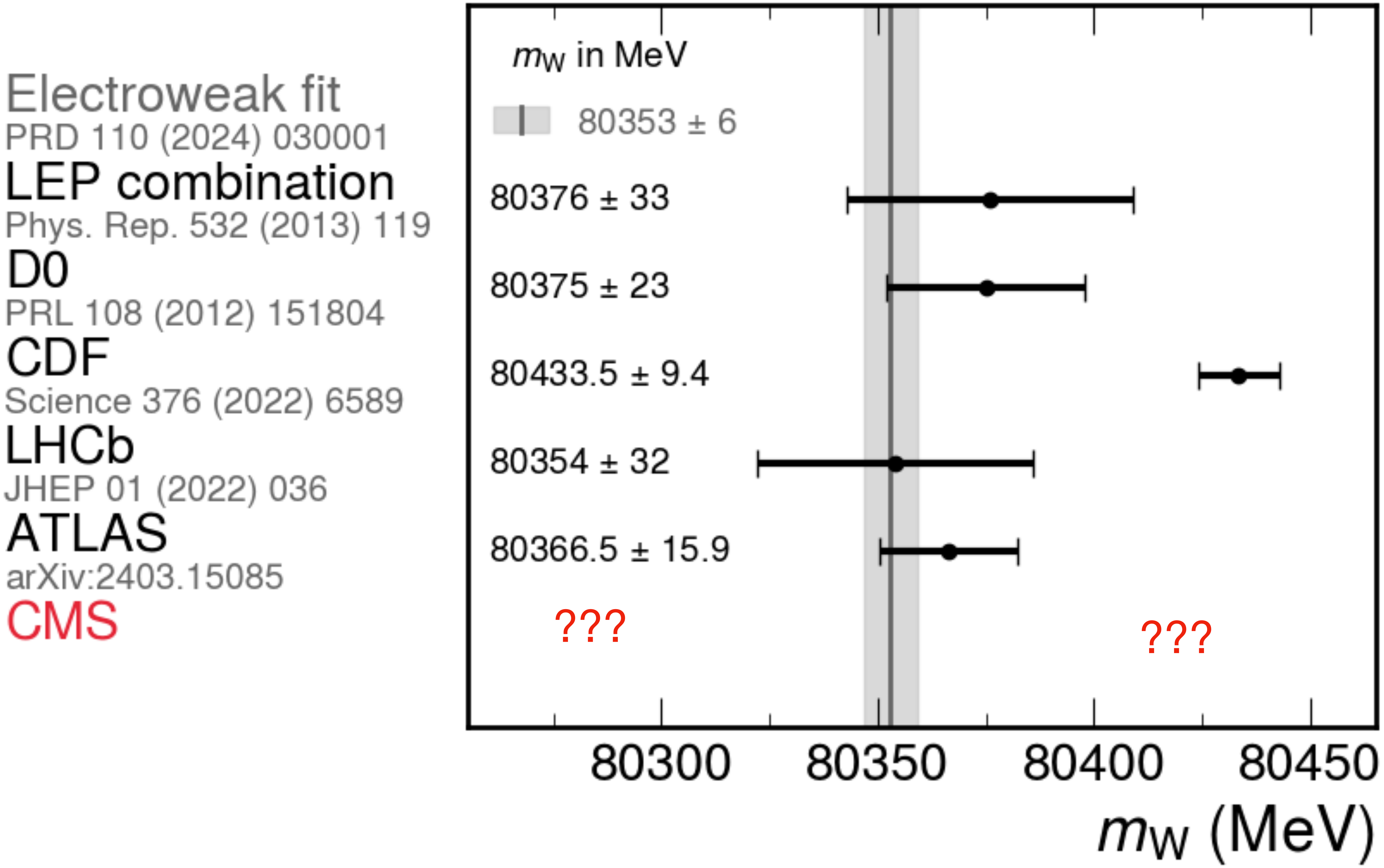
➡ m_W = 80,353 ± 6 MeV

e.g., ~80 times the mass of the proton



Measuring the W boson mass: the current landscape

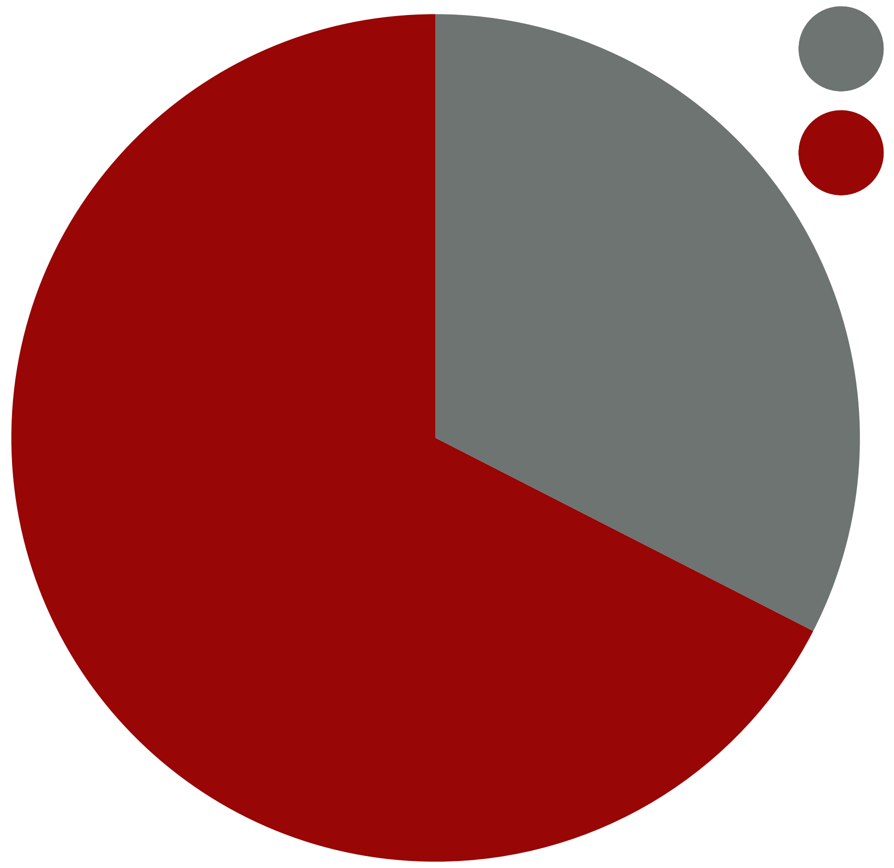
- Most precise measurement of W boson mass, m_W = 80,433.5 ± 9.4 MeV, performed at the CDF experiment at the Fermilab Tevatron, disagrees with expectation
  - And with other experiments… **new result needed!**

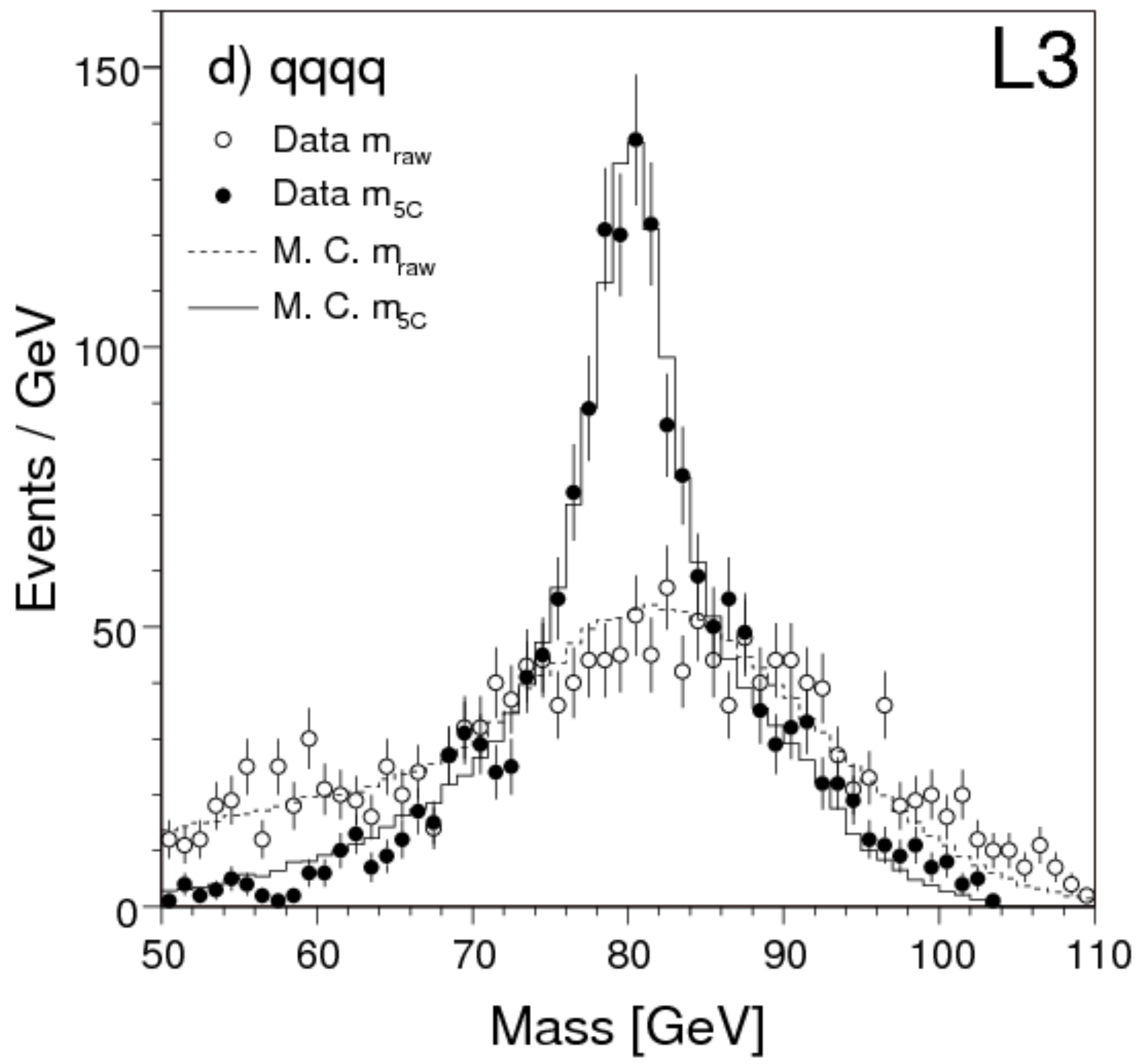


Reconstructing the W boson

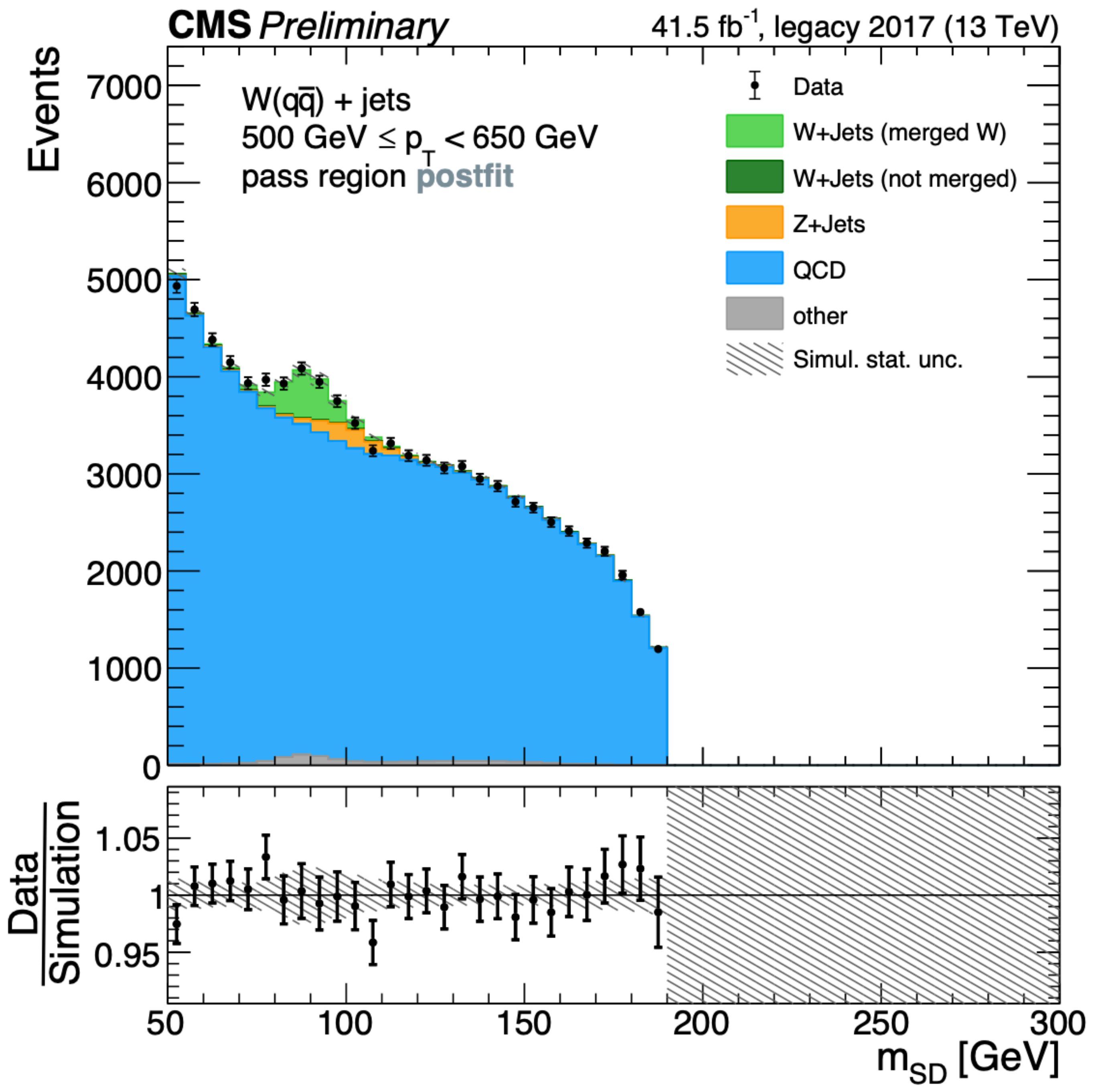
- If all decay products are measured, little dependence on W production
  - Direct reconstruction of W possible with hadronic decays
    - Precise measurement at LEP using ee→WW→qqqq (or qqℓν) events
    - Background/calibration of jet momentum more complex in hadron colliders
  - ➡ Only lepton+neutrino decay is practical
  - Introduces dependence on W production

W boson decays





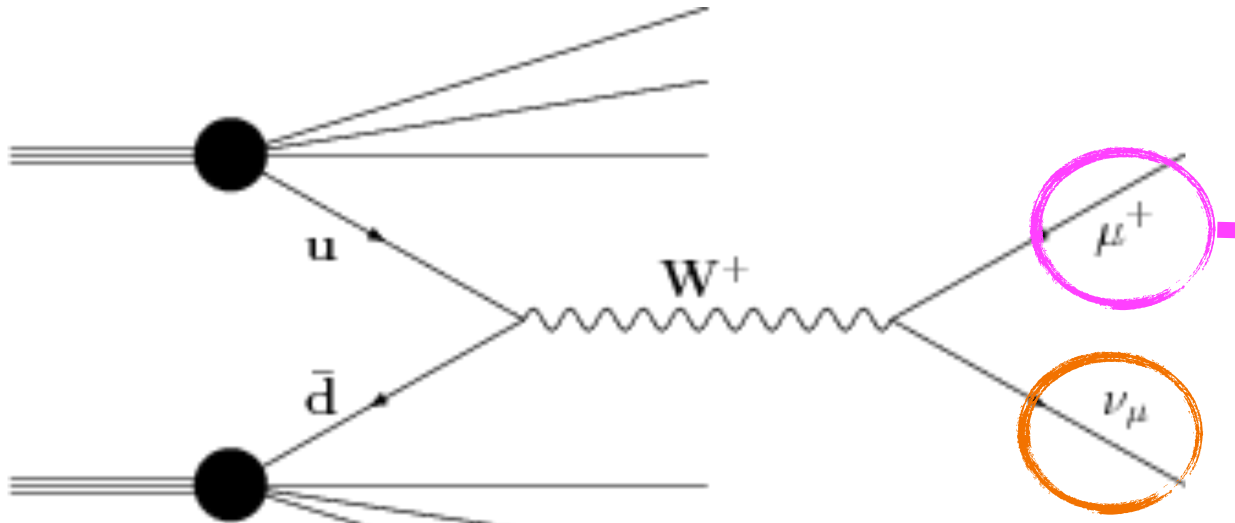
LEP (L3)
vs.
LHC (CMS)



https://cds.cern.ch/record/2865845

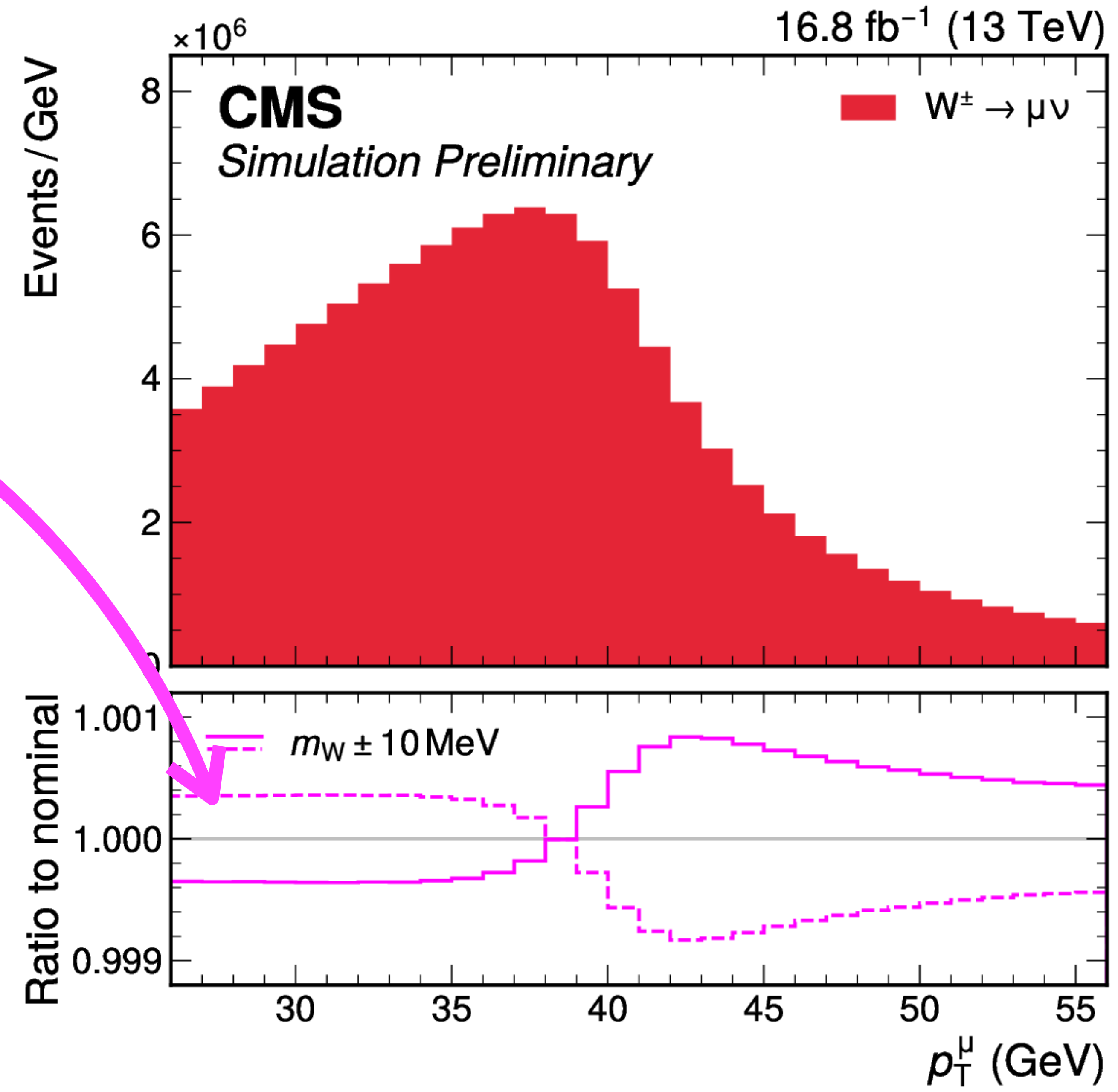
Measuring m_W at hadron colliders

- Rely on observable(s) sensitive to m_W built from measurable objects

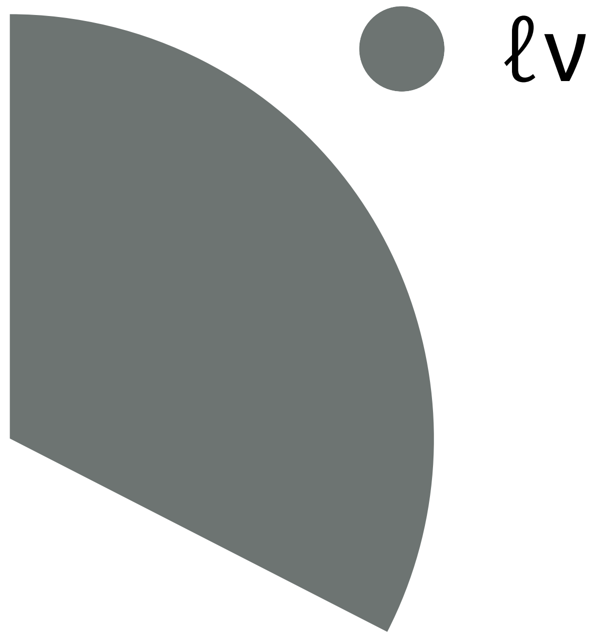


< per mille precision

Escapes detection
⇒Missing transverse momentum



W boson decays



- Mass is equally divided between μ and ν
  - In rest frame, $p^\nu \sim p^\ell \sim m_W/2$
  - In lab frame, smeared by p^W

➡ Knowledge of W momentum required

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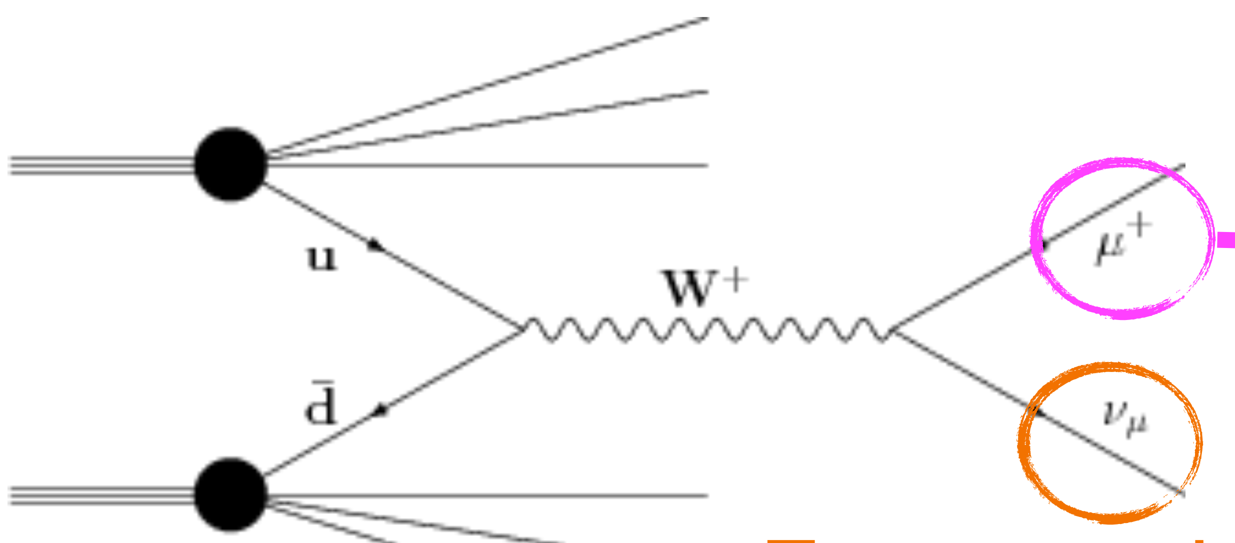

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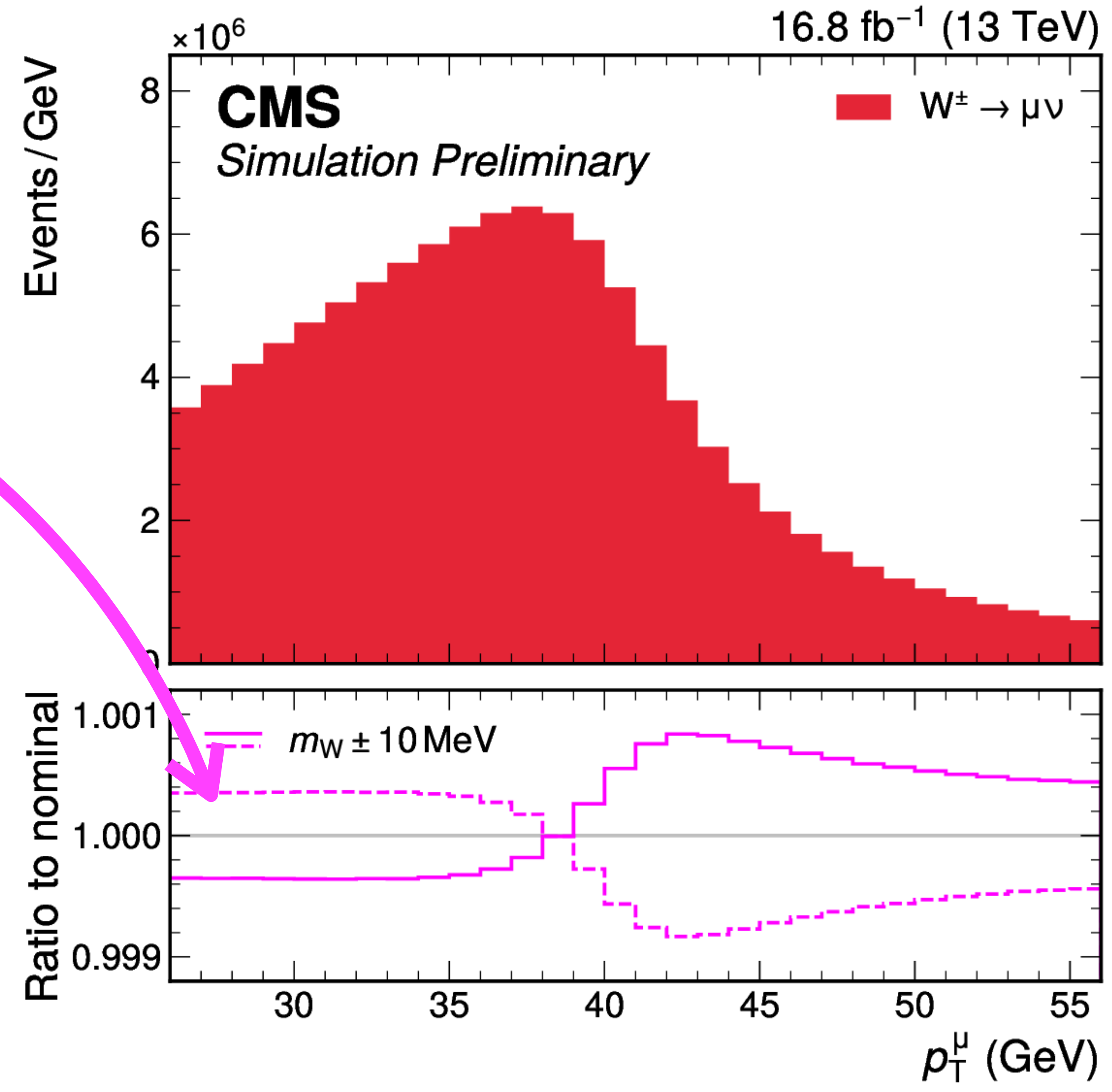

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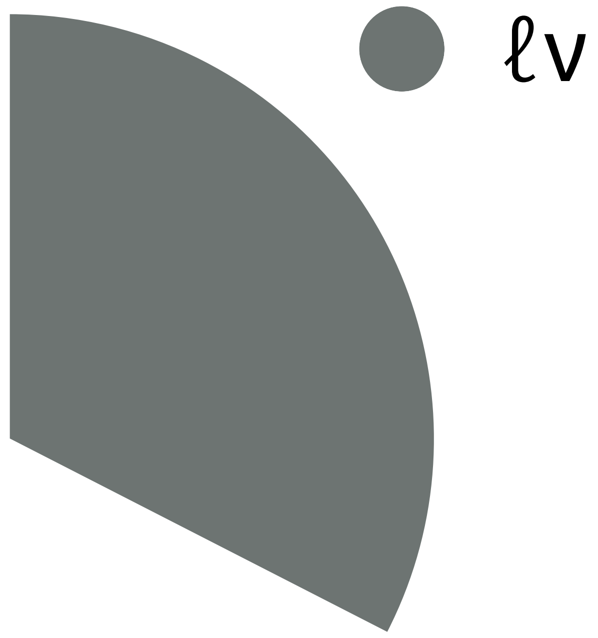

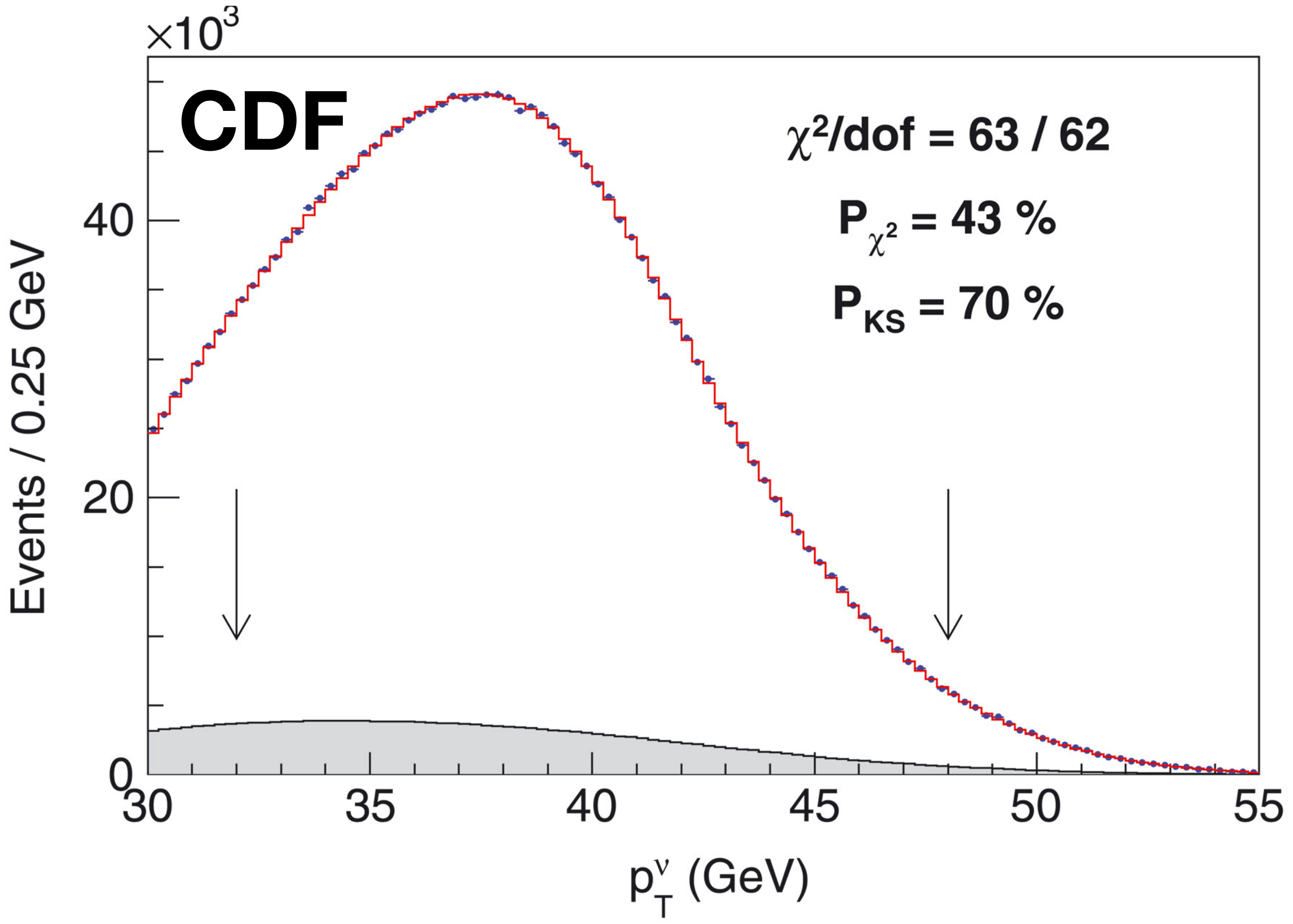

- p_T^{miss} estimates p_T^{ν}
- Precise p_T^{miss} reco. very difficult at LHC

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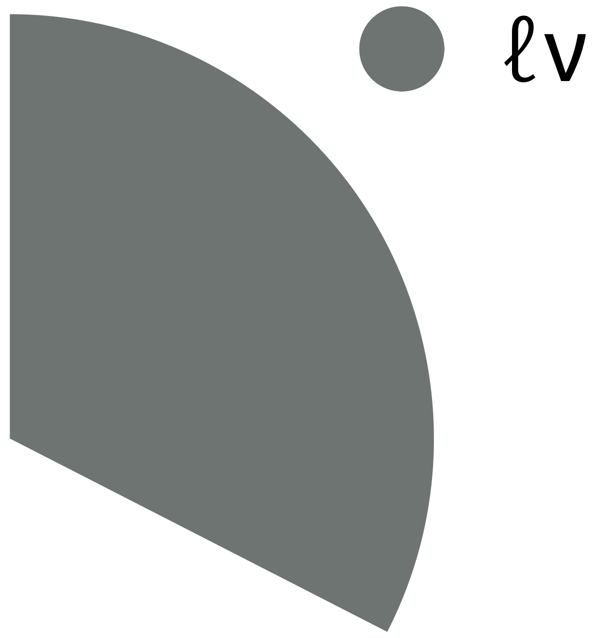

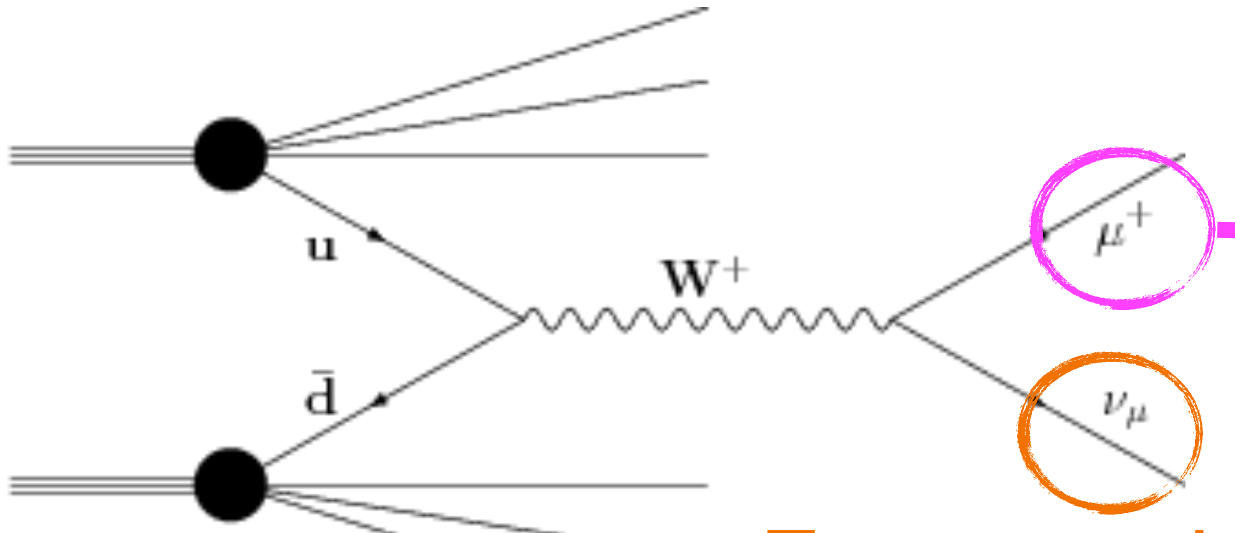

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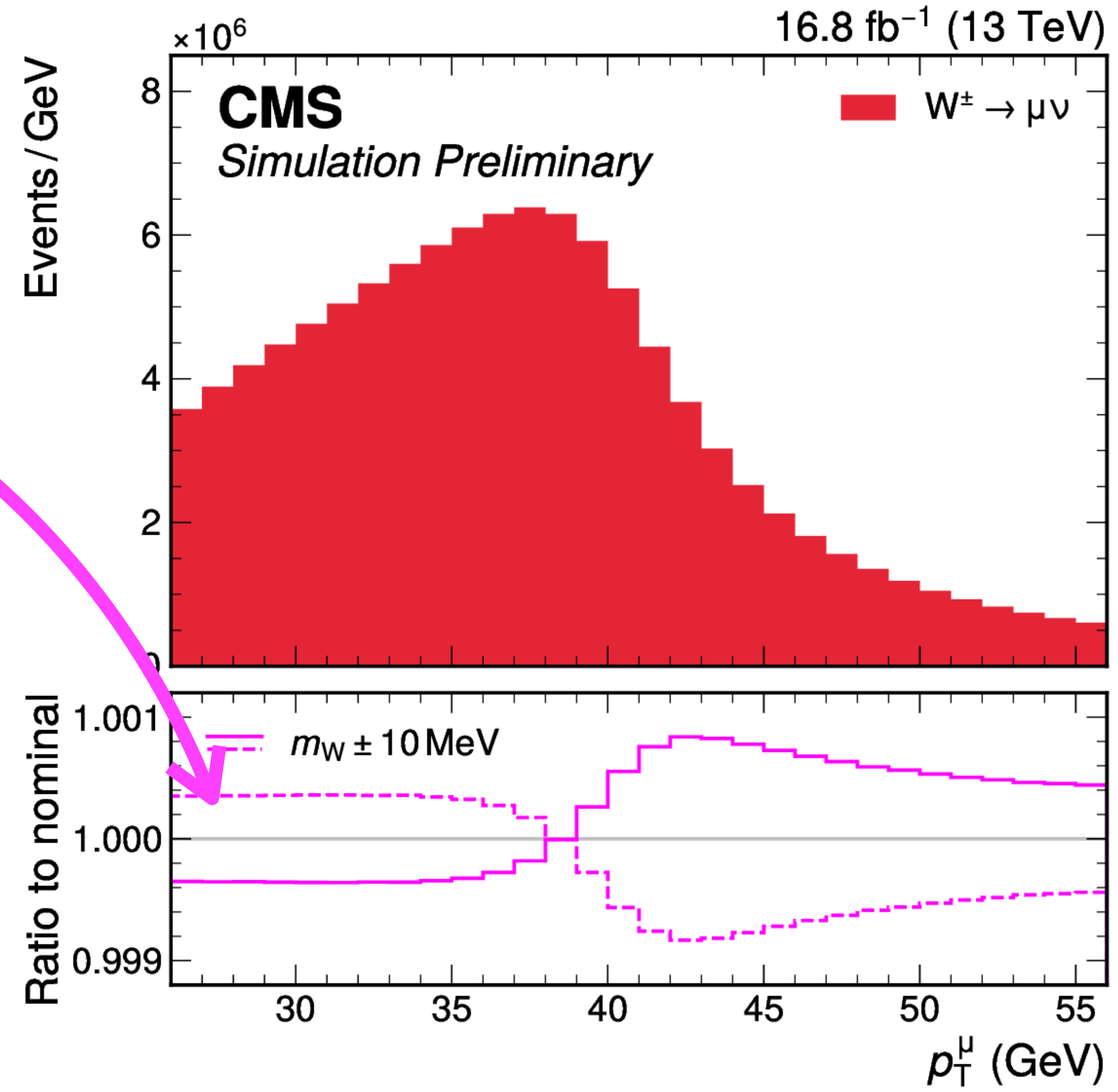

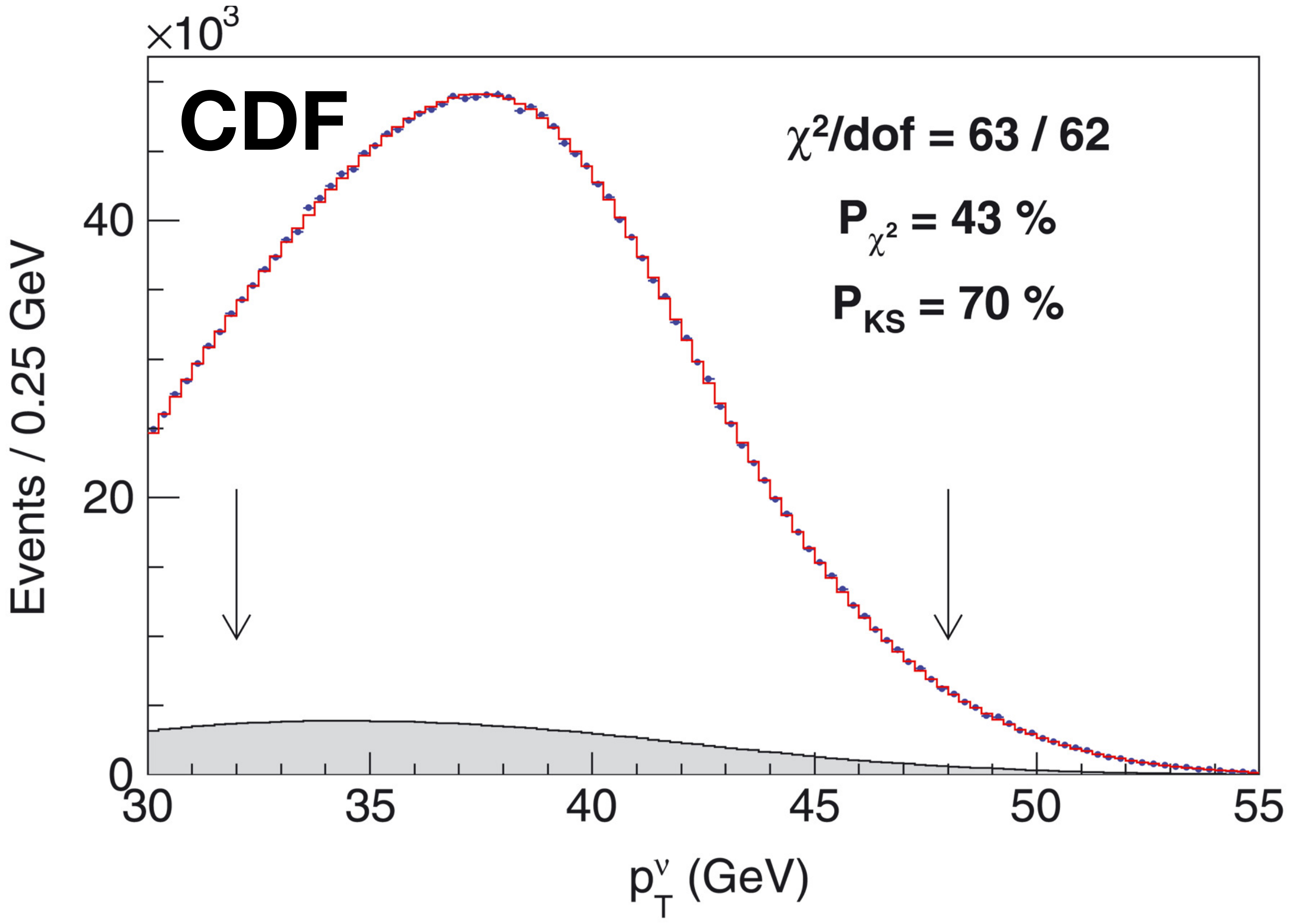

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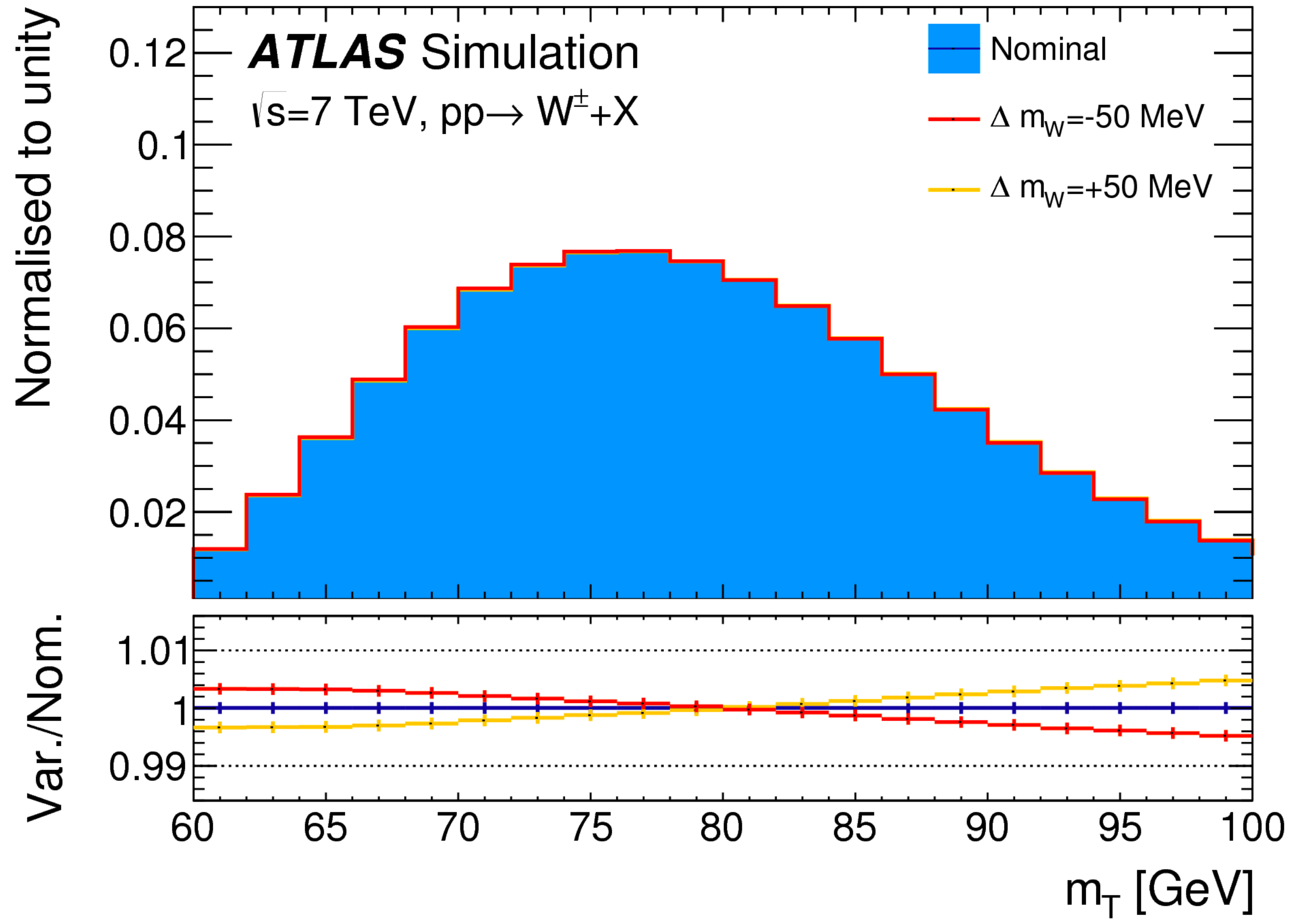
➡ Knowledge of W momentum required

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

- Jakobian peak at m_W
- Reduced dependence on W production



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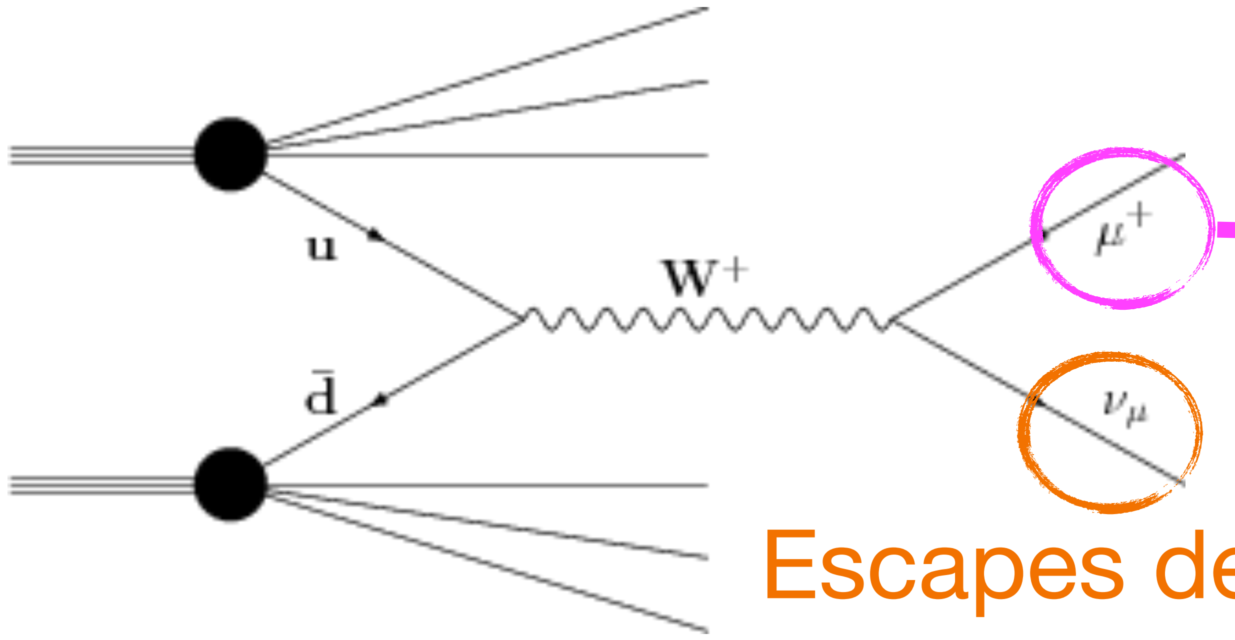

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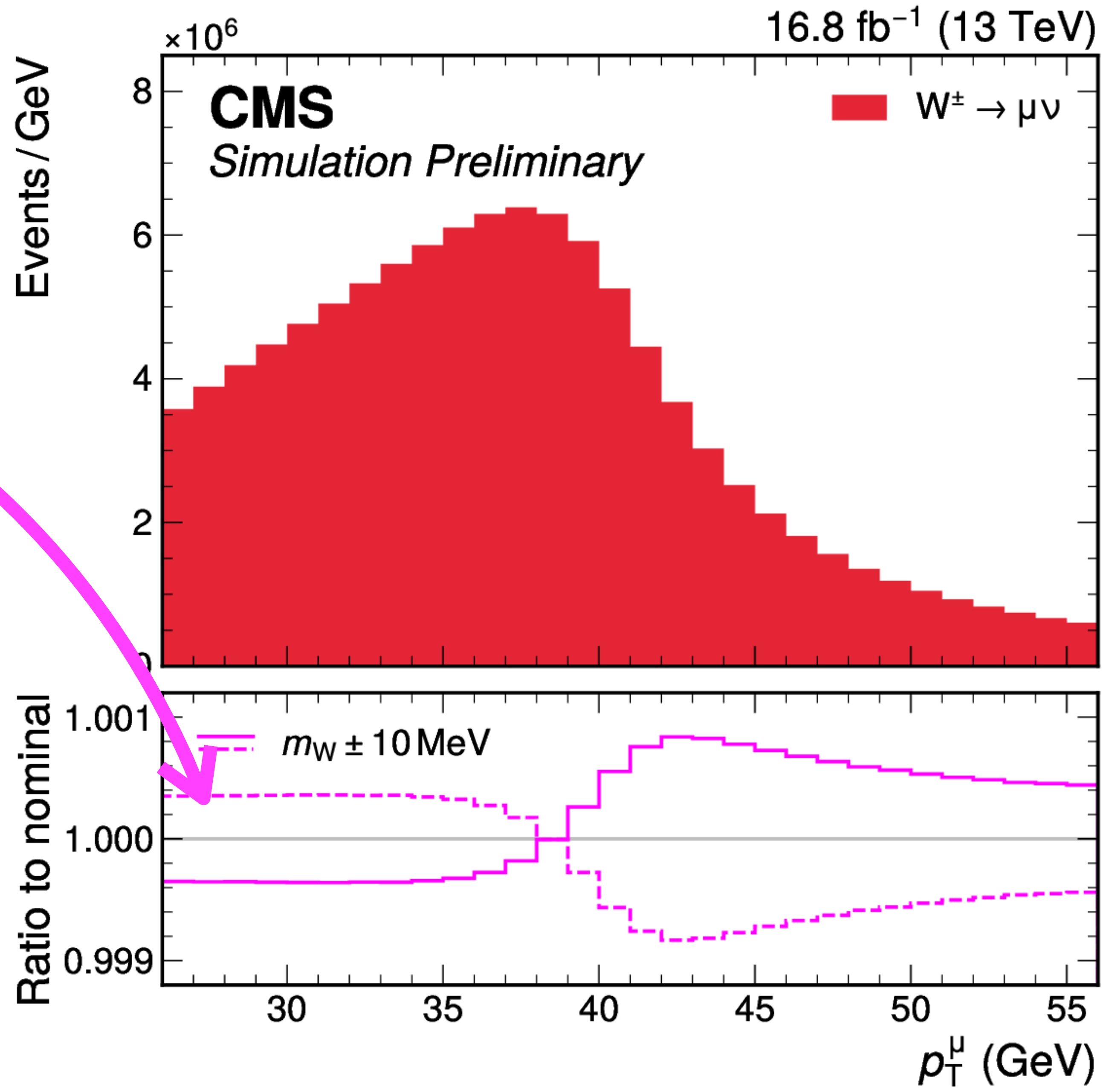
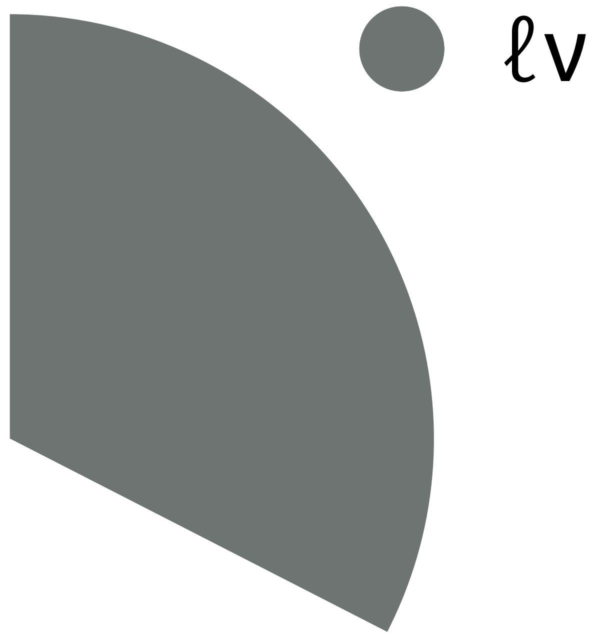


W boson decays



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➡ Knowledge of W momentum required

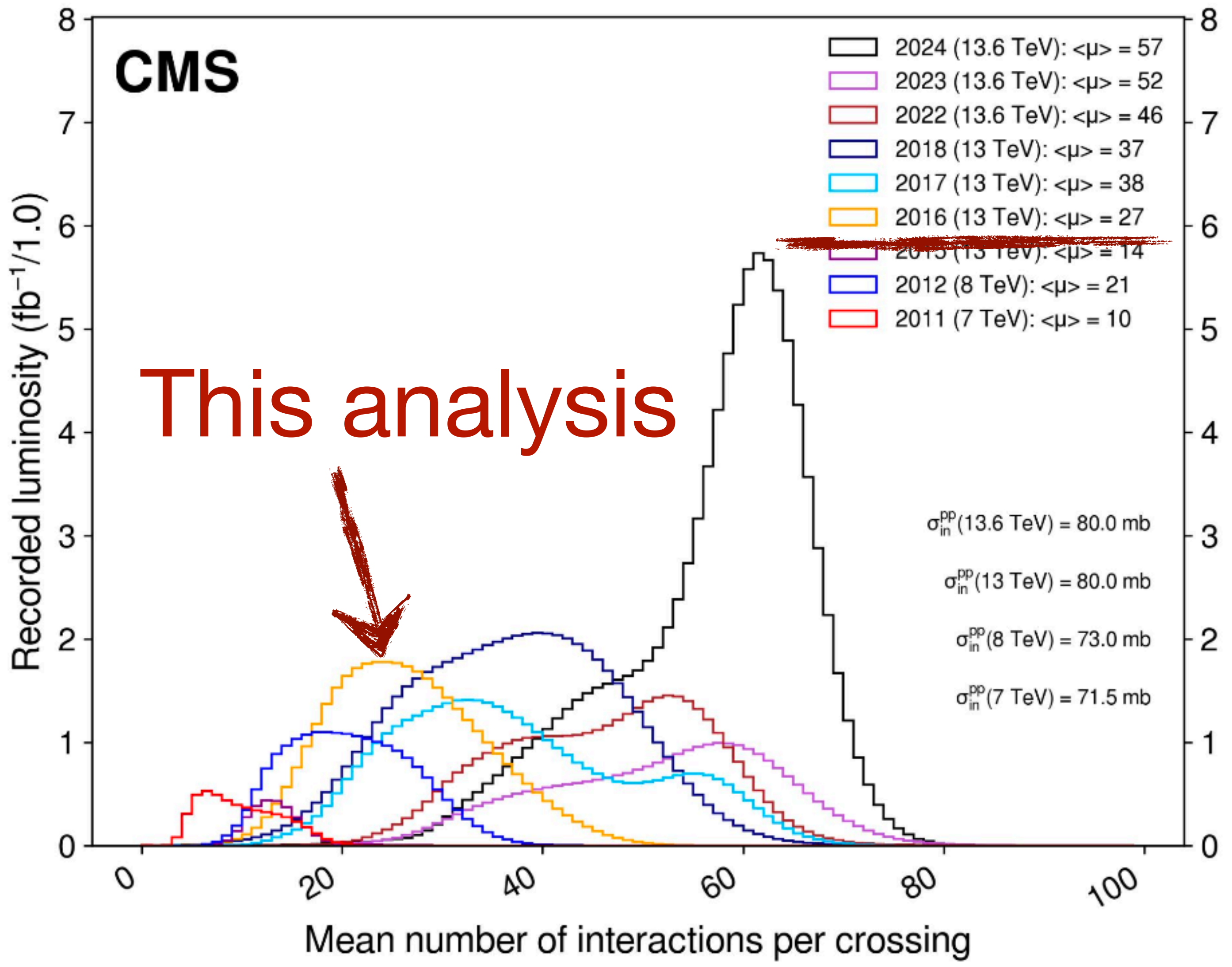
- Primarily due to high energy and high pileup, p_T^{ℓ} (ℓ = electron or muon, μ), is by far the most experimental favourable channel at the LHC
  - CMS momentum measurement of muons is an order of magnitude better than electrons

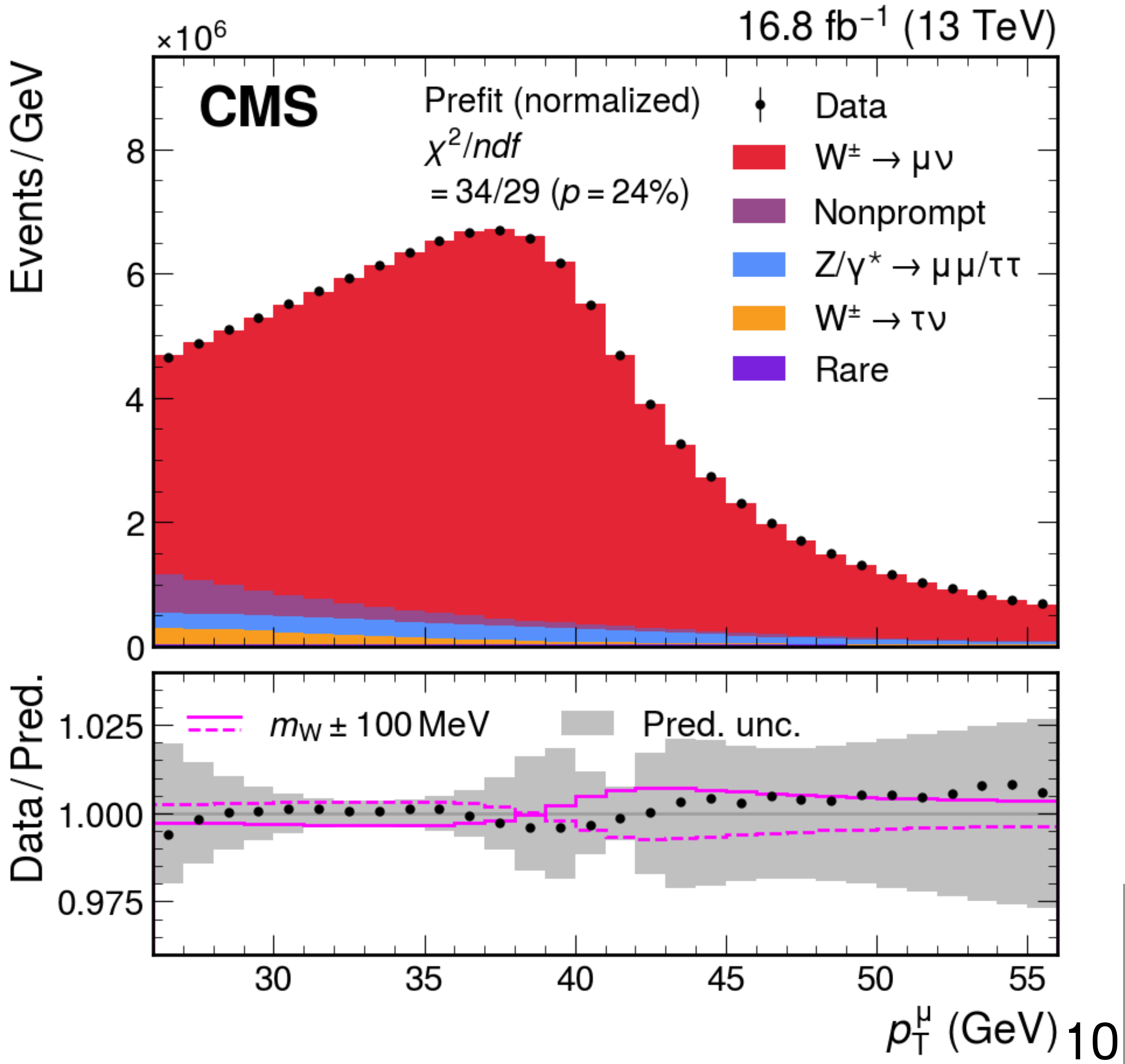
Dataset and selection

- 16.8 fb^{-1} of 13 TeV data collected in 2016
  - Small fraction of LHC data but largest-ever for m_W analysis
  - Also highest pileup ever used (~25)
    - Especially challenging for p_T^{miss} measurement
  - ★ Focus measurement on p_T^μ channel

- Select events with exactly one muon
  - $26 < p_T^\mu < 56$ GeV
  - Good track+muon system track, isolated from hadronic energy
  - $m_T > 40$ GeV
  - ~100 M selected $W \rightarrow \mu\nu$ events

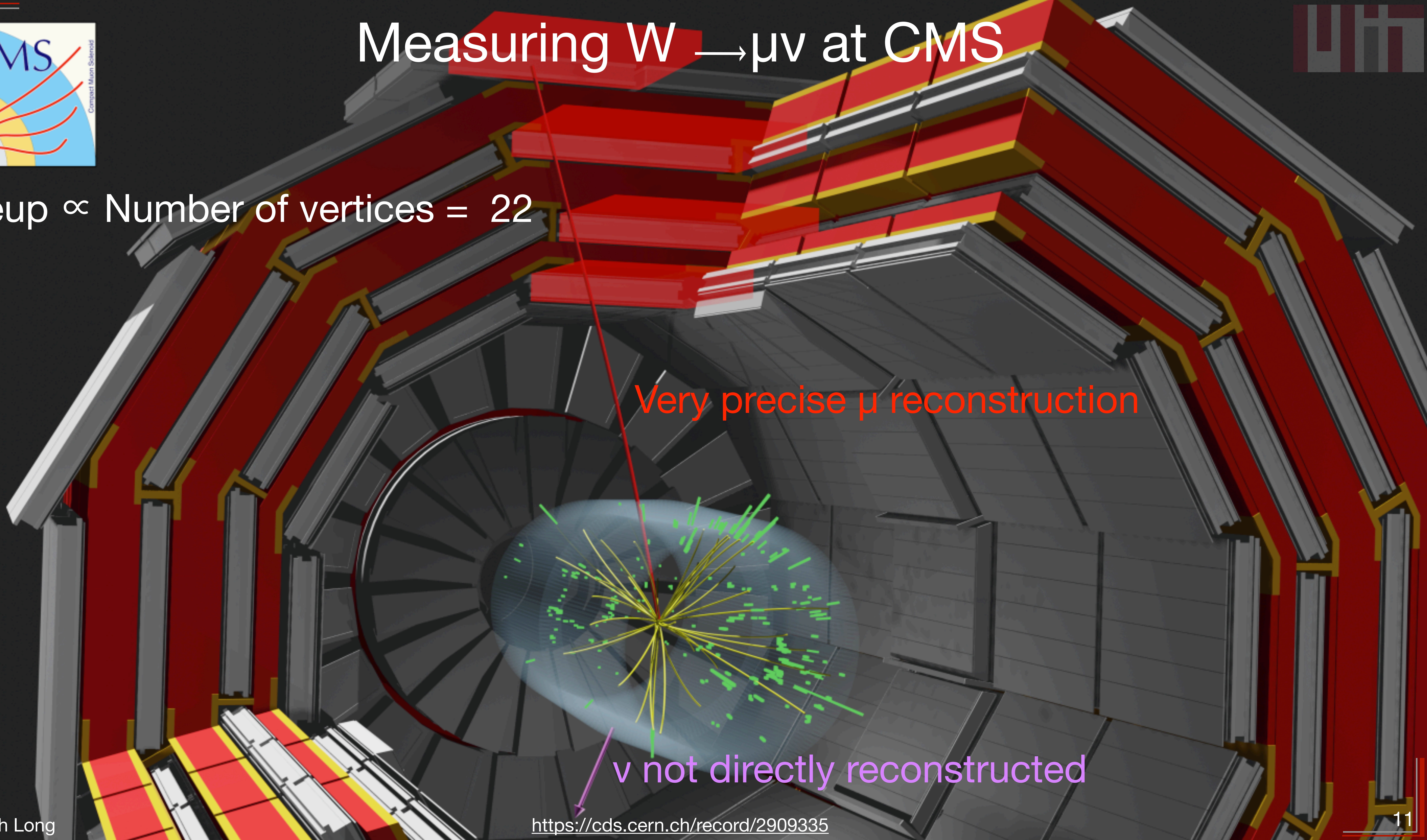
- Prompt backgrounds from simulation
  - $Z \rightarrow \mu\mu$ (mainly with 1 out-of-acceptance μ)
  - $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$, with τ decays into μ
  - Rare: top quark, boson pair production, photon-induced
- Nonprompt background estimated from data
  - Mainly QCD multijet events with B/D decays in flight
  - Suppressed by m_T cut





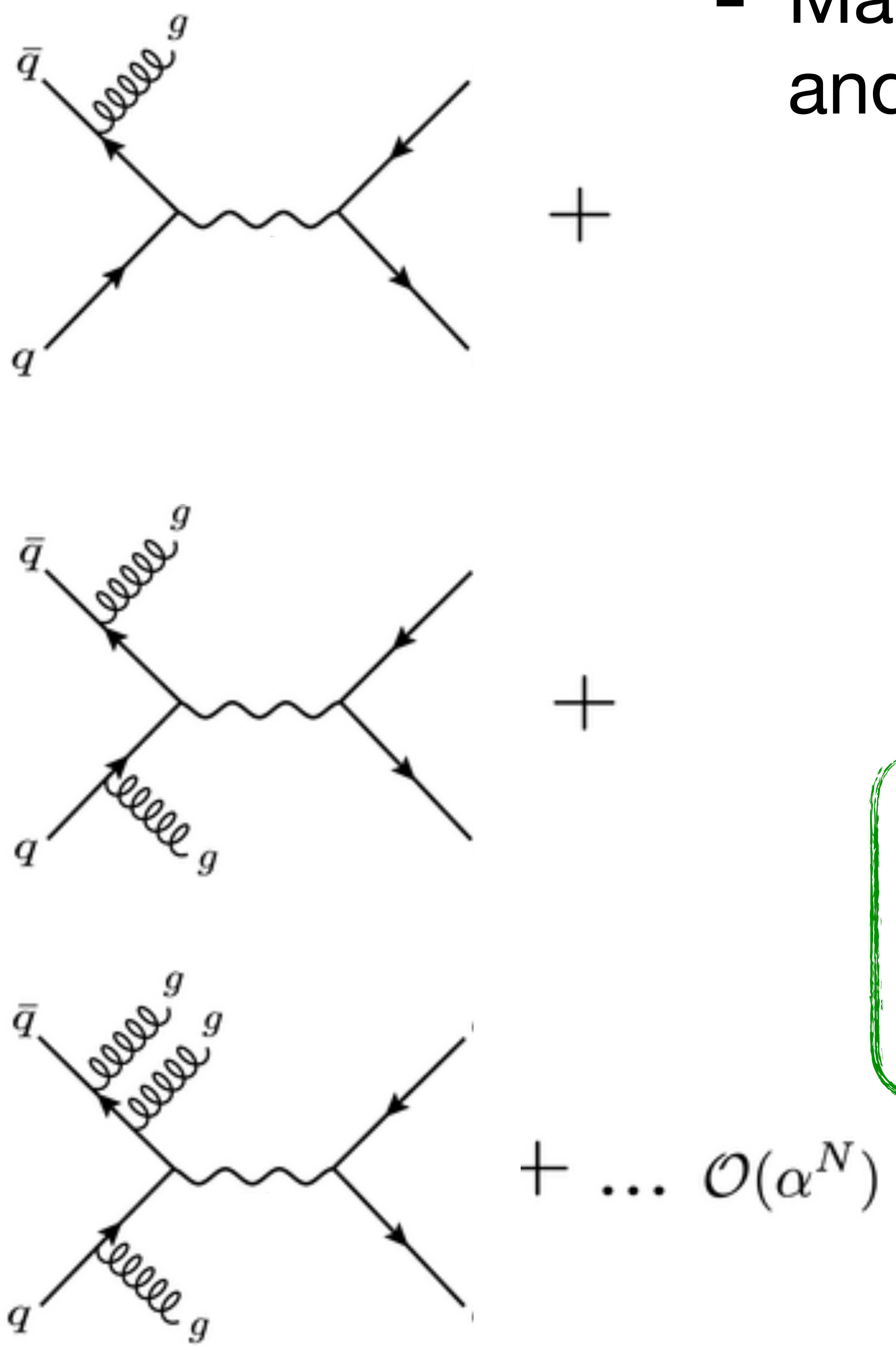
Measuring W $\longrightarrow \mu\nu$ at CMS

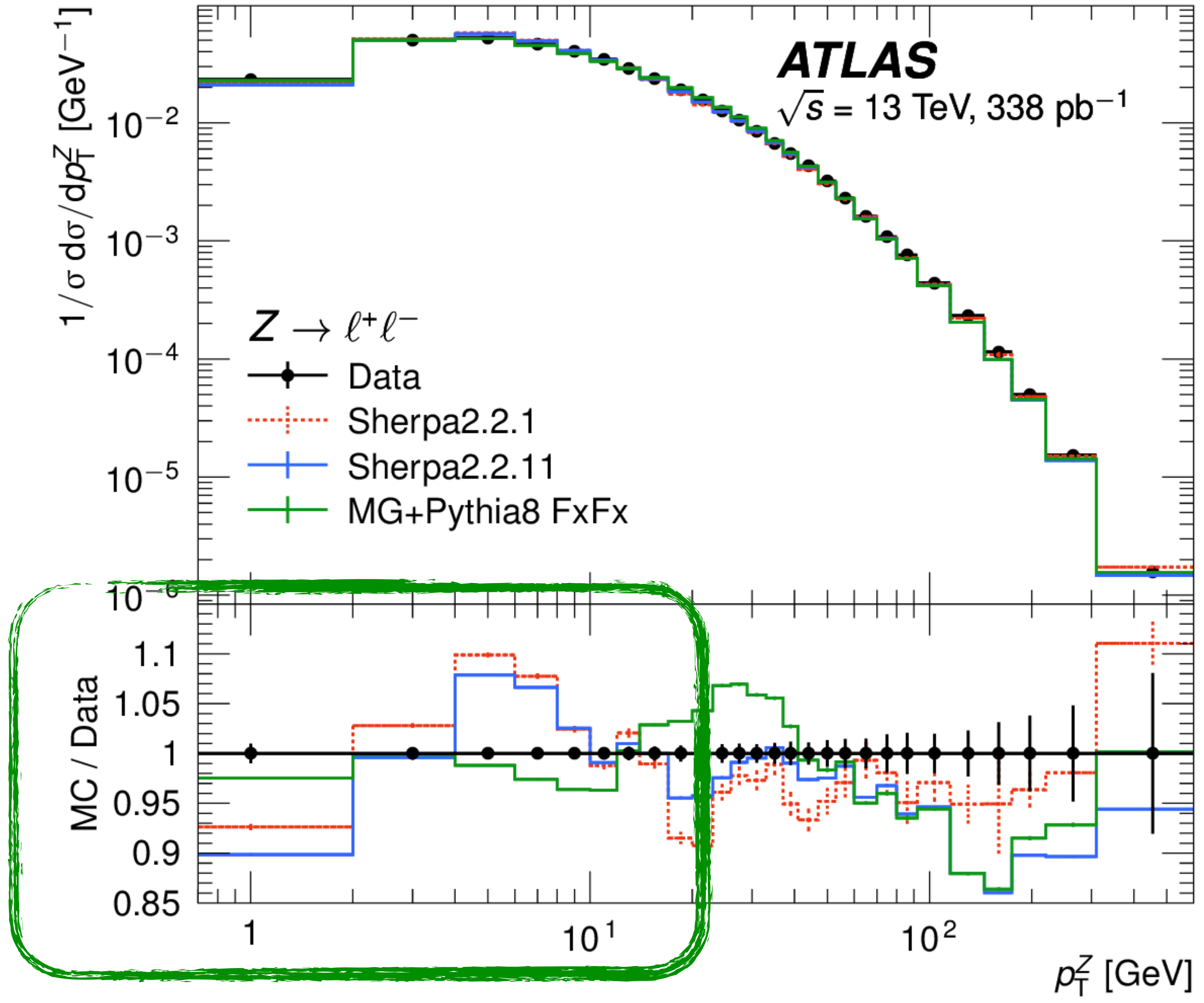
Pileup ∝ Number of vertices = 22

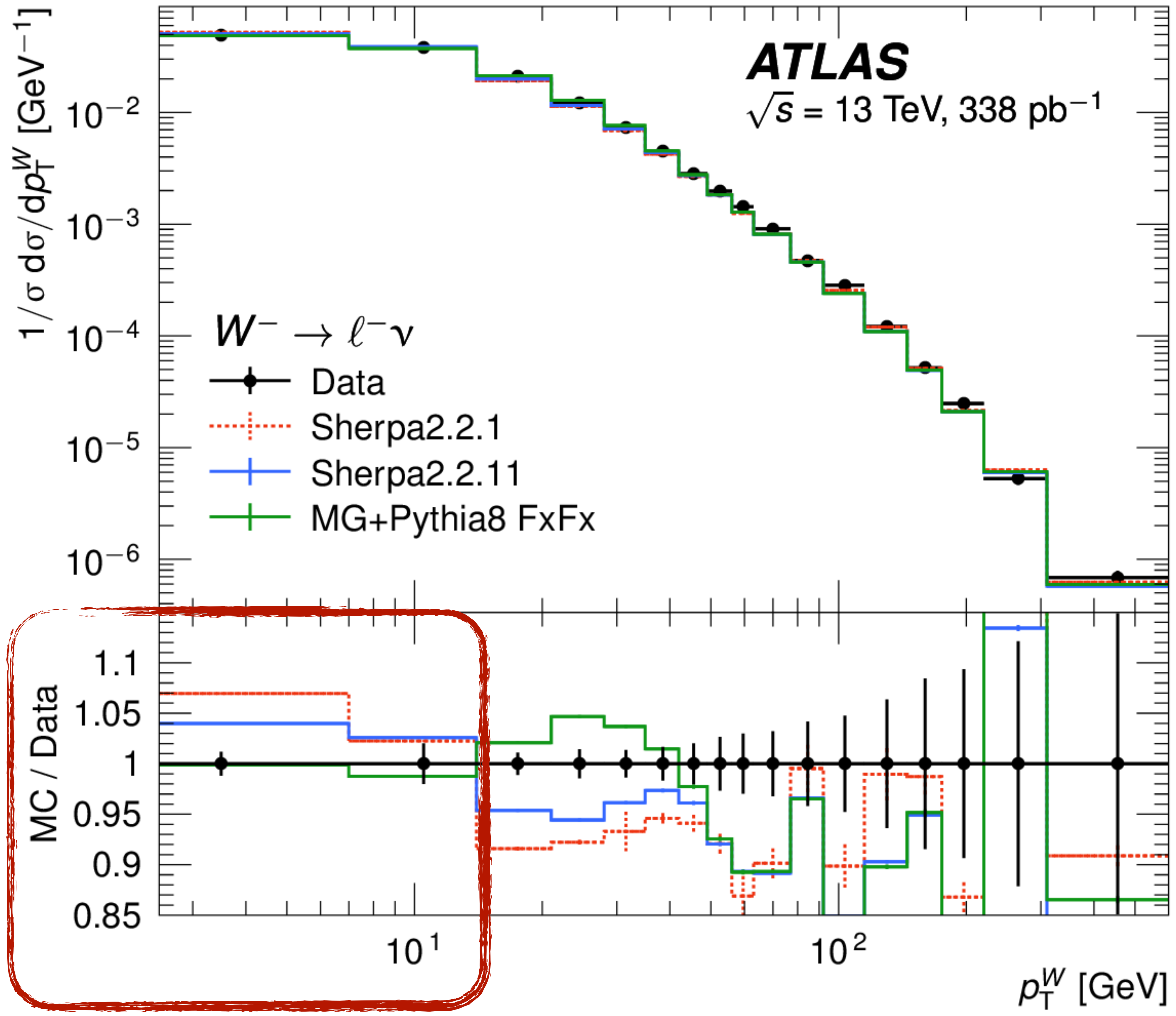


W and Z boson production at the LHC

- p_T^ℓ is not Lorentz invariant $\Longrightarrow$ sensitive to W production
    - W typically produced with some momentum transverse to the beam direction (p_T^W)
    - p_T^W not directly measurable w/high precision at LHC
        - p_T^V due to radiation of gluons from colliding quarks
    - **Many similarities (but some important differences) between W and Z production**







Precision, resolution of p_T^W not sufficient for m_W measurement

W and Z boson production at the LHC

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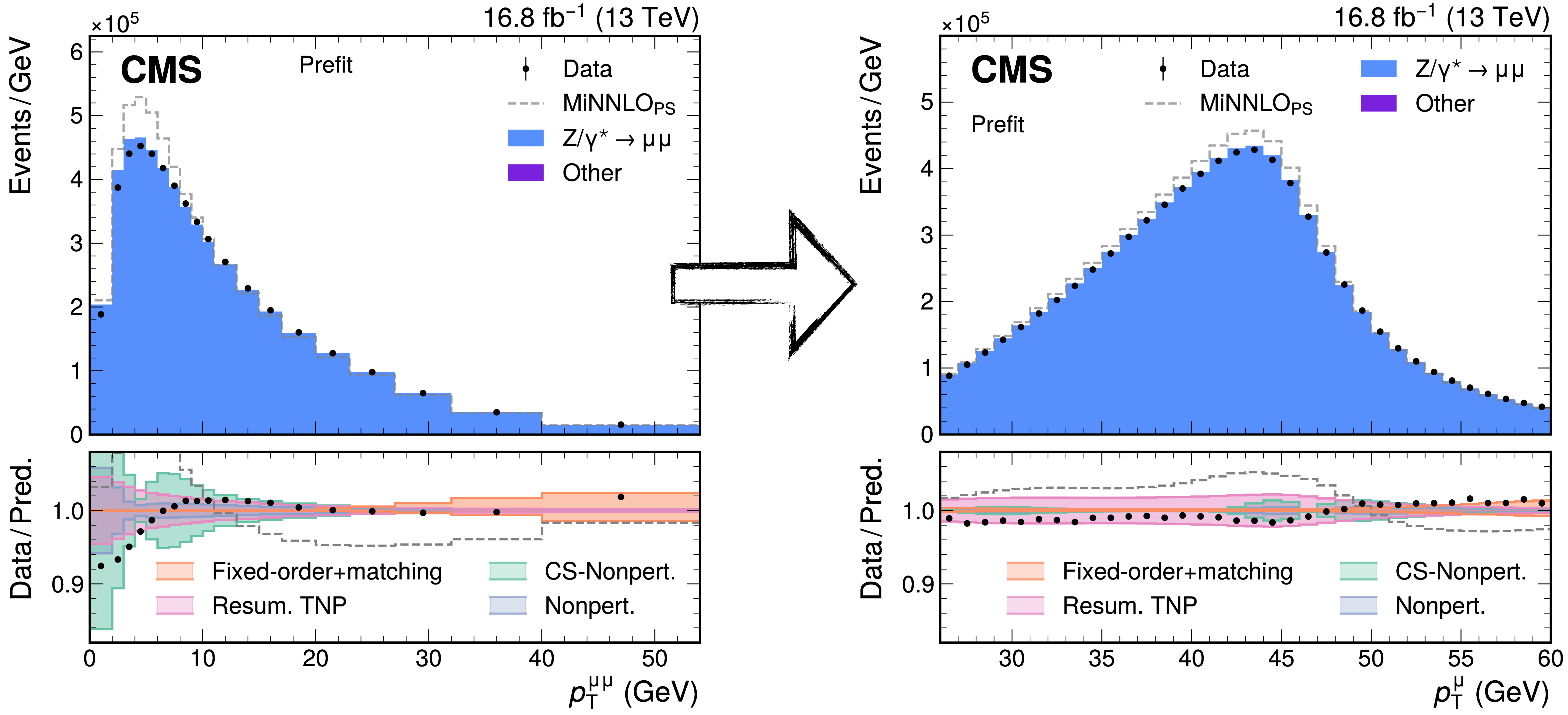
➡ Rely on theoretical predictions to describe p_T^W
  - Validate with measurements of Z boson production



Z production

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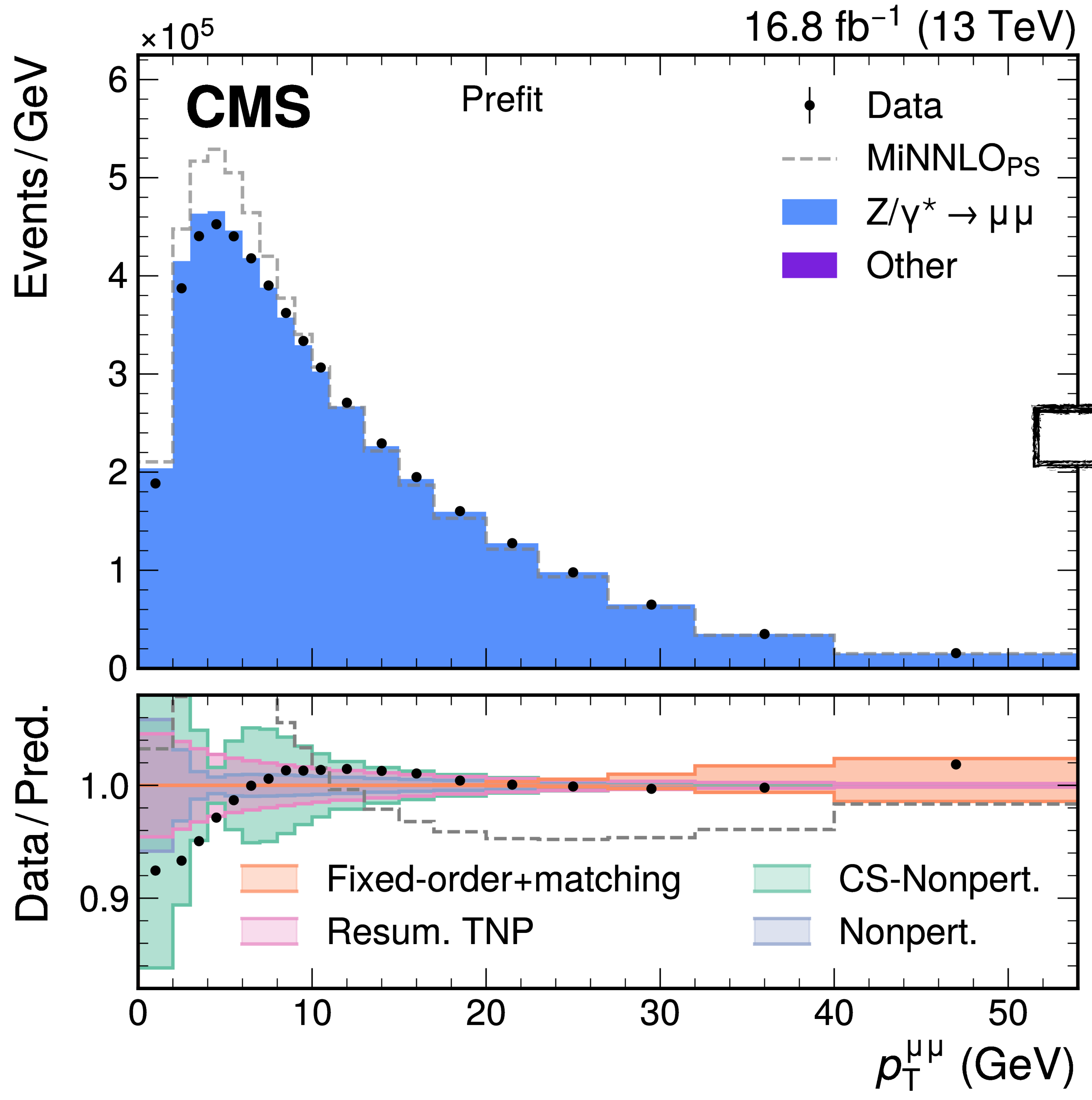
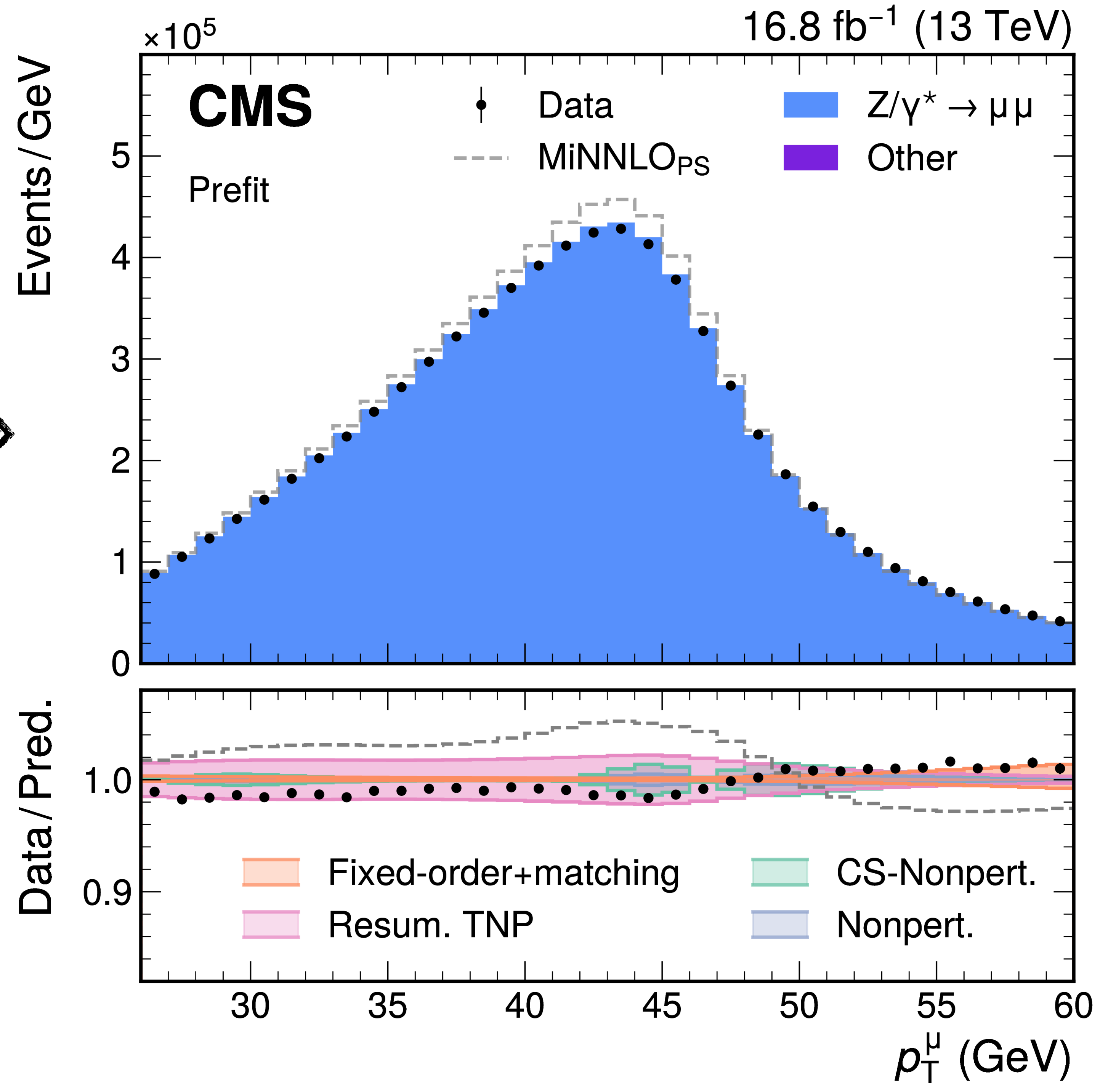
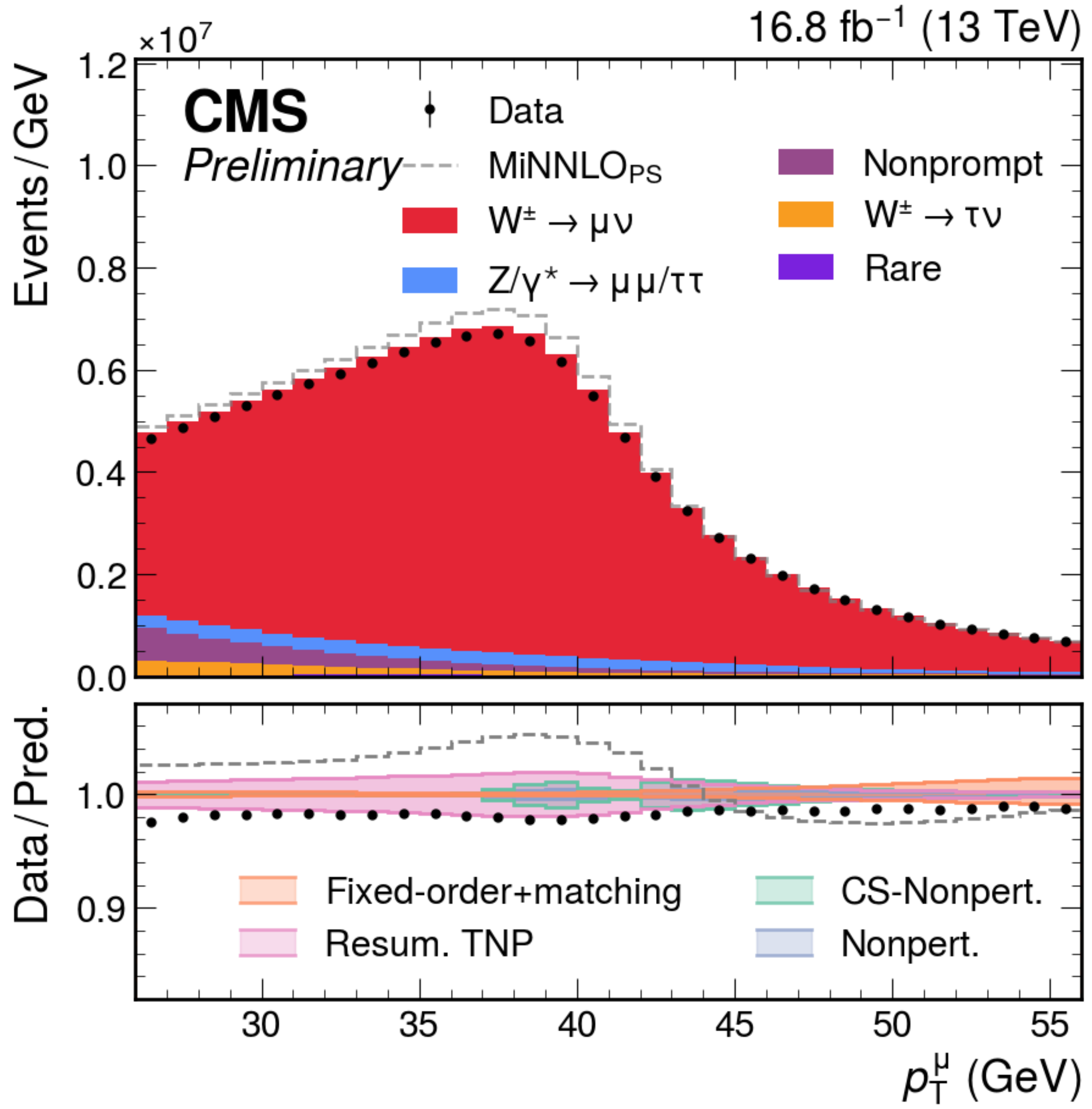




vs.



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W and Z boson production at the LHC

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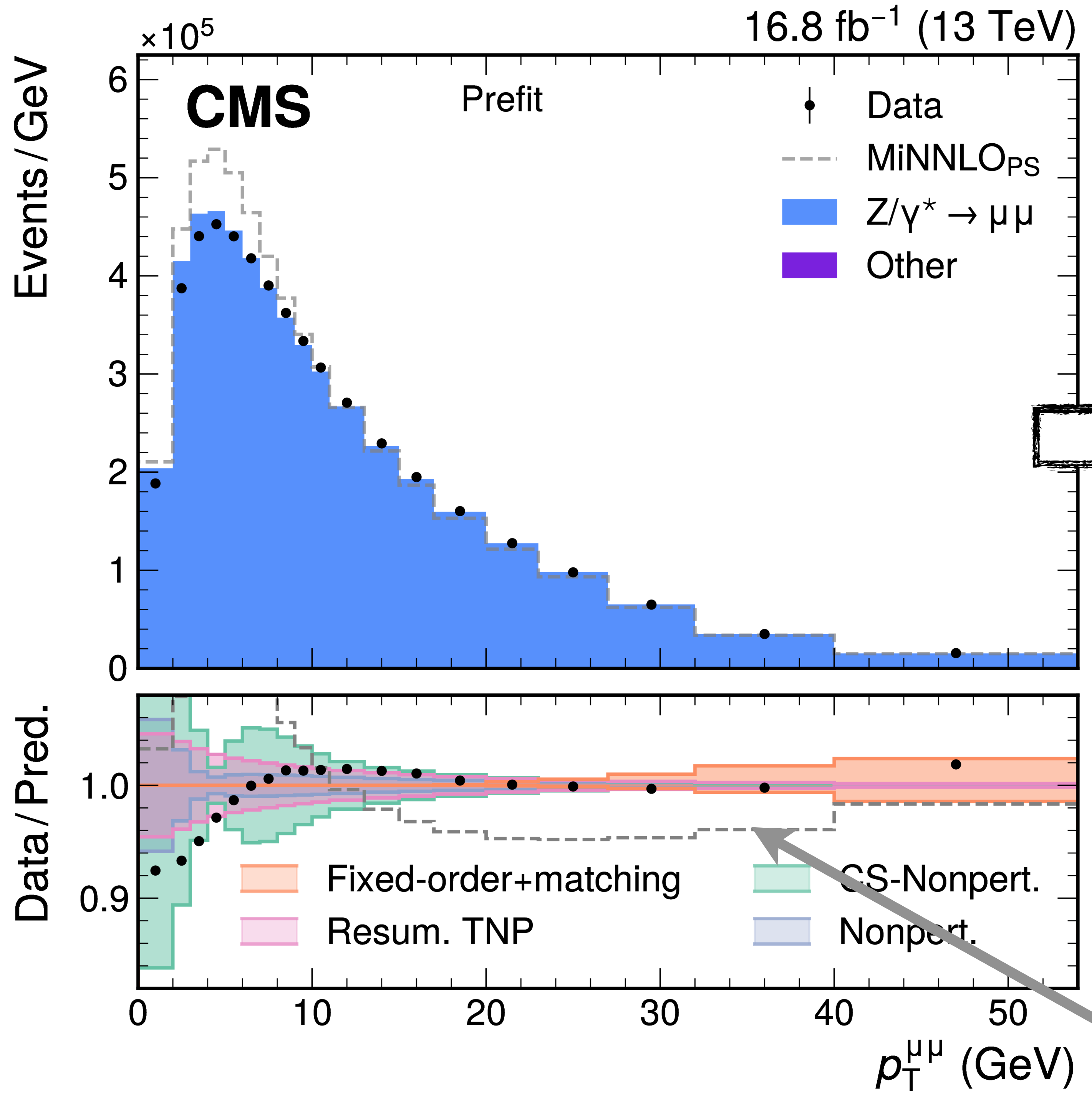
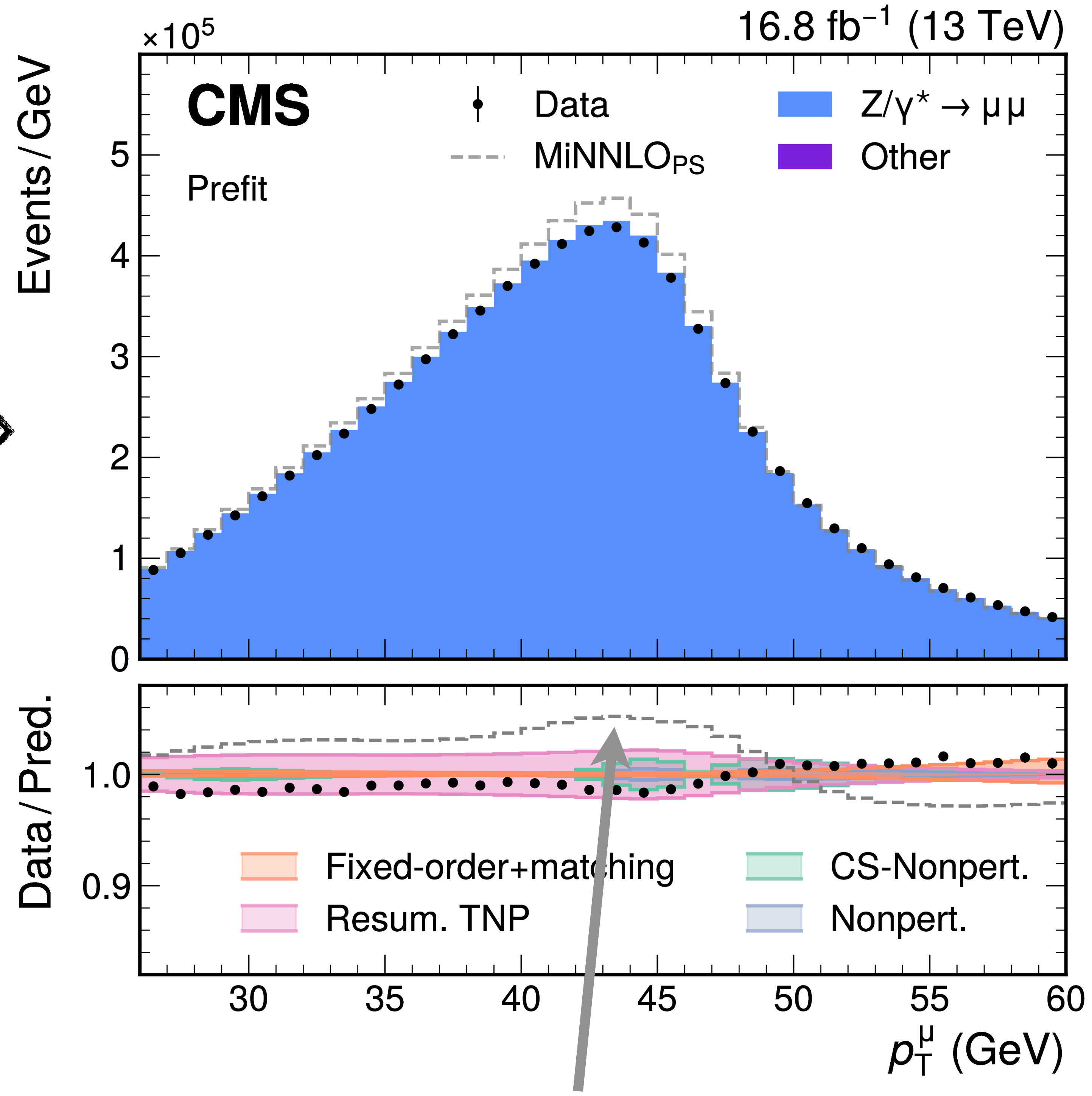
CMS analysis: do not "tune" predictions: rely on accurate predictions + uncertainty profiling





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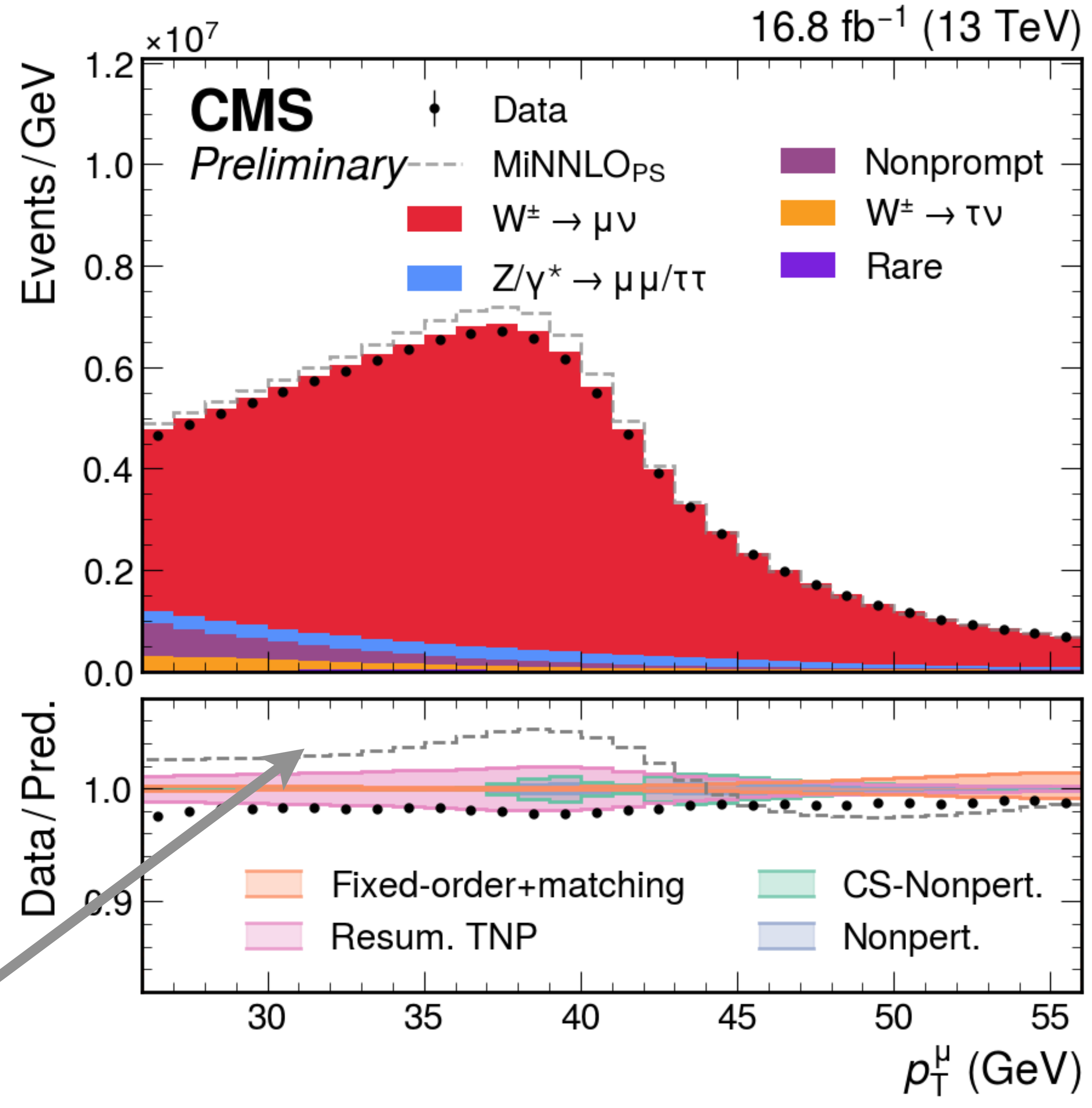
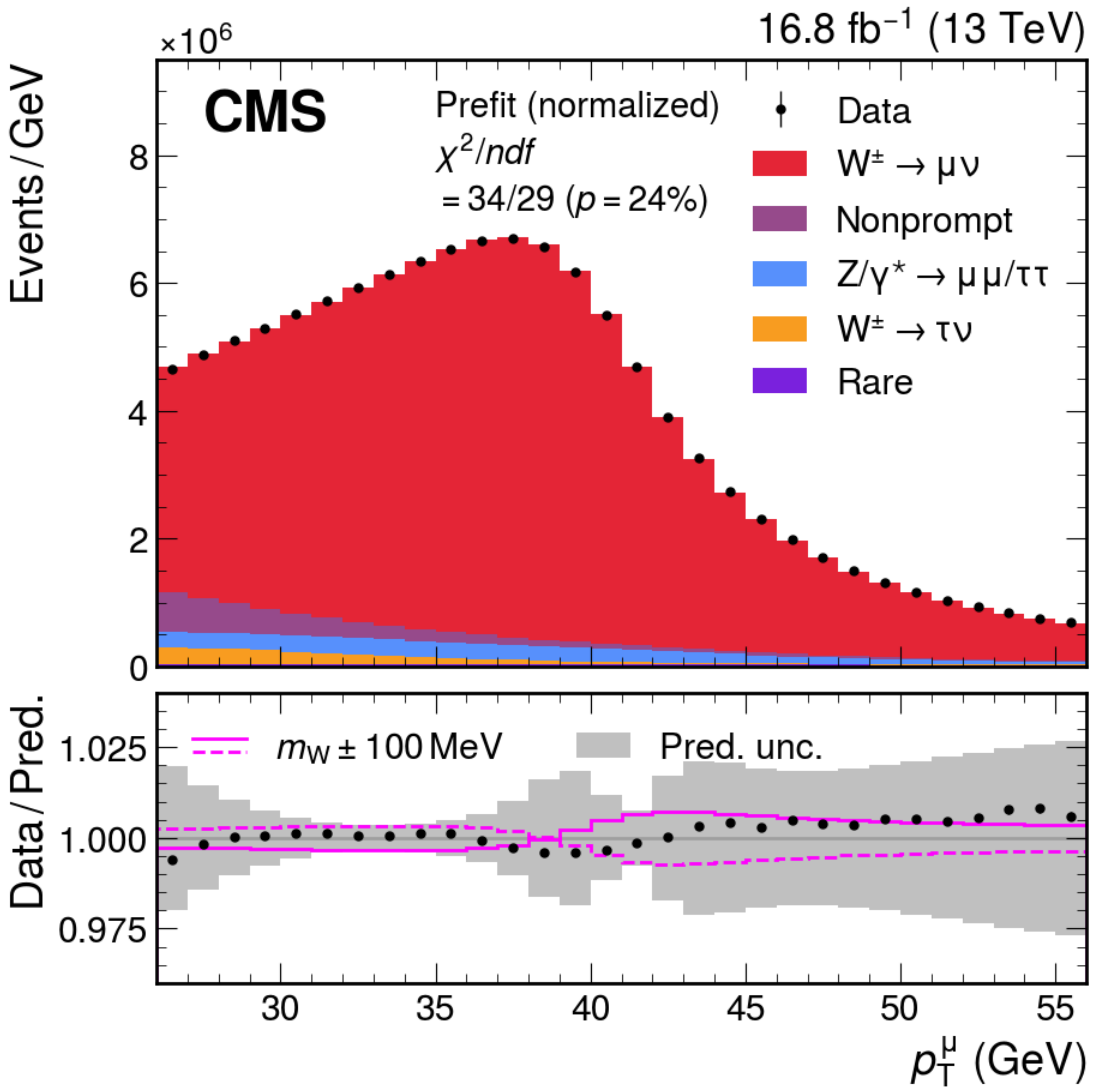


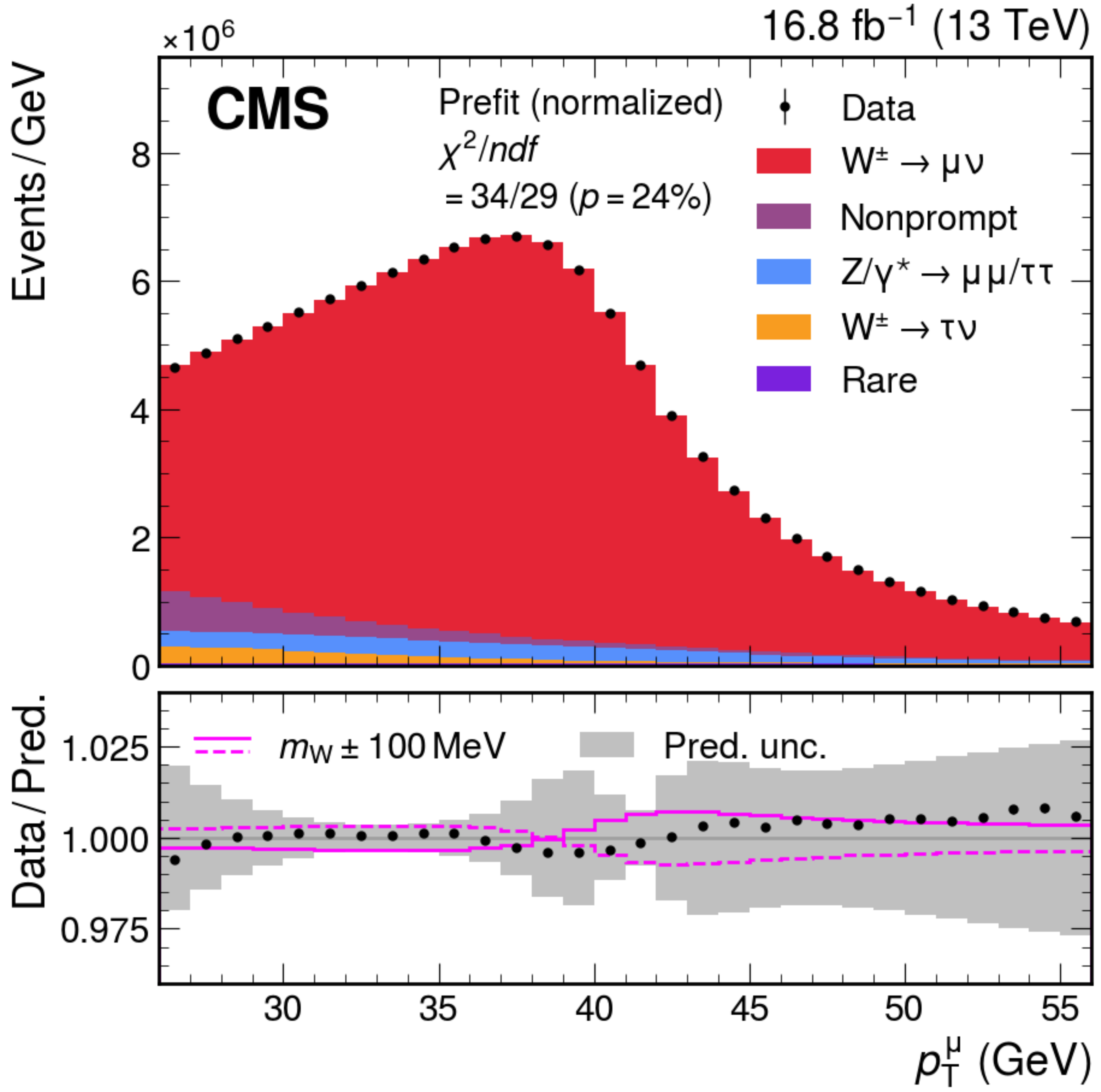
Uncertainties, corrections can be much larger than m_W variation!

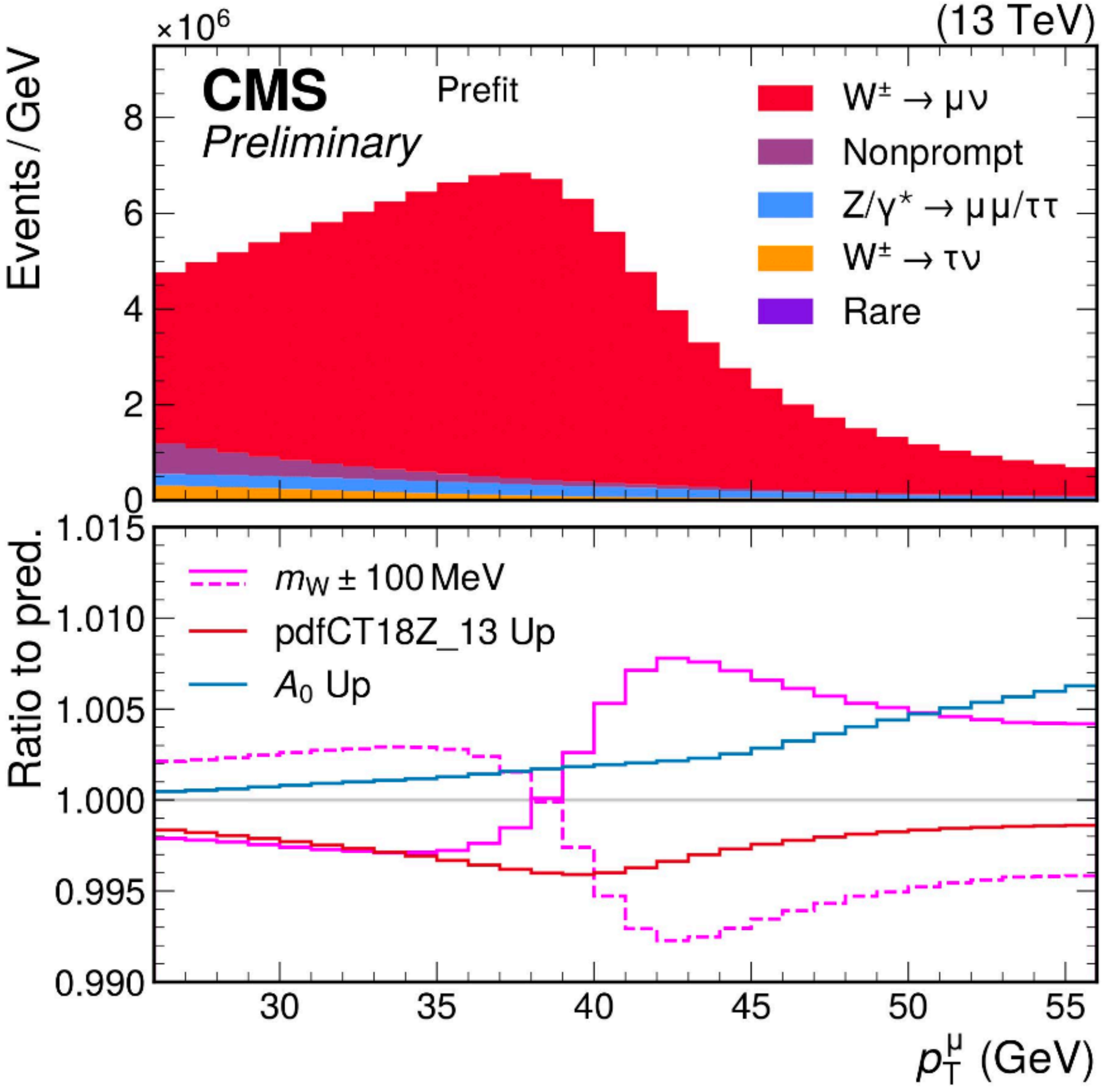
m_W measurement at a glance



- Binned maximum likelihood fit: test consistency of data with different m_W hypotheses
- Measurement performed ***blinded***

m_W measurement at a (closer) glance



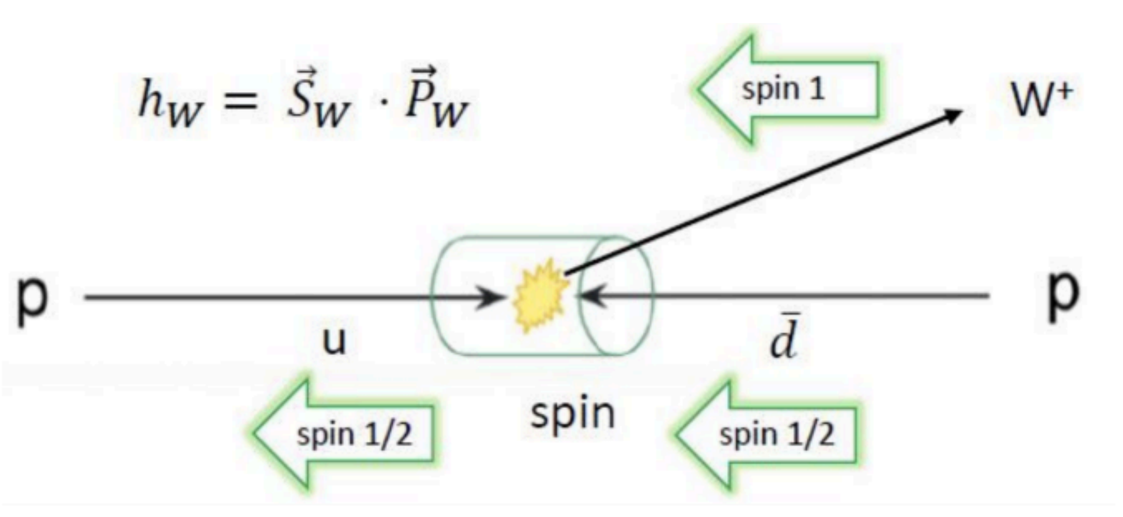


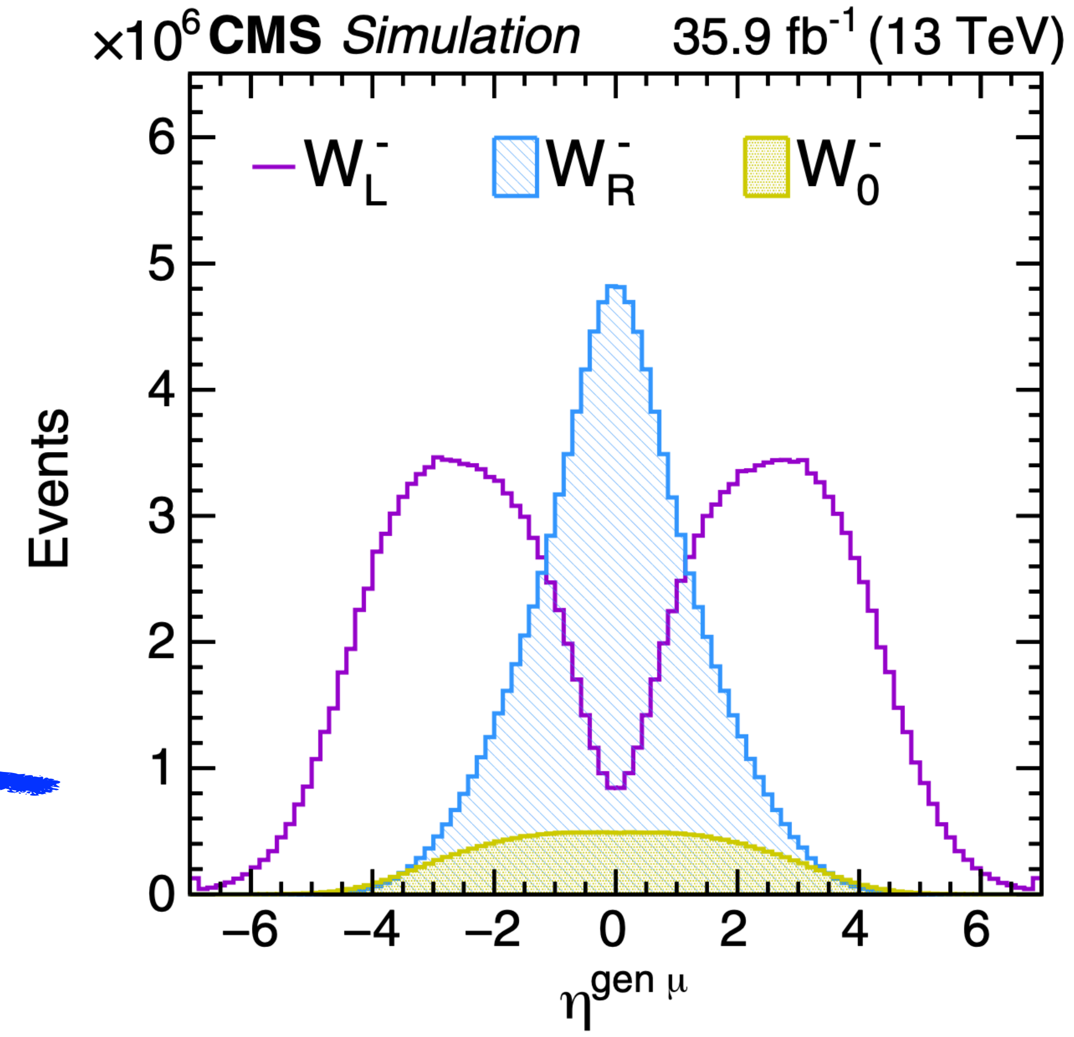
- Subpercent-level accuracy required

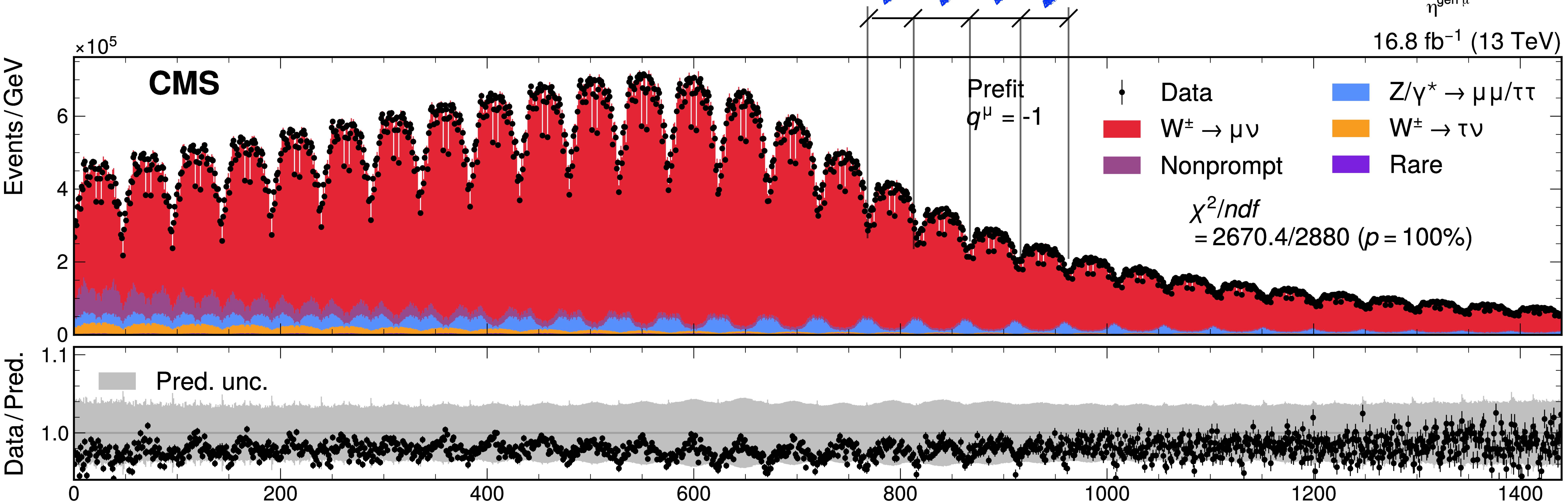
➡Requires detailed understanding of how theoretical and experimental uncertainty sources impact the distributions of interest

The m_W measurement at CMS

- y^W (η^μ), is dependent on W helicity, driven by PDFs
  - Sensitivity to PDF from η^μ
  - ➡ **Extract mass from fit to (q^μ, η^μ, p_T^μ) distribution**
  - ~2000 bins and 4000 nuisance parameters
  - Major computational challenge (CERN IT seminar)



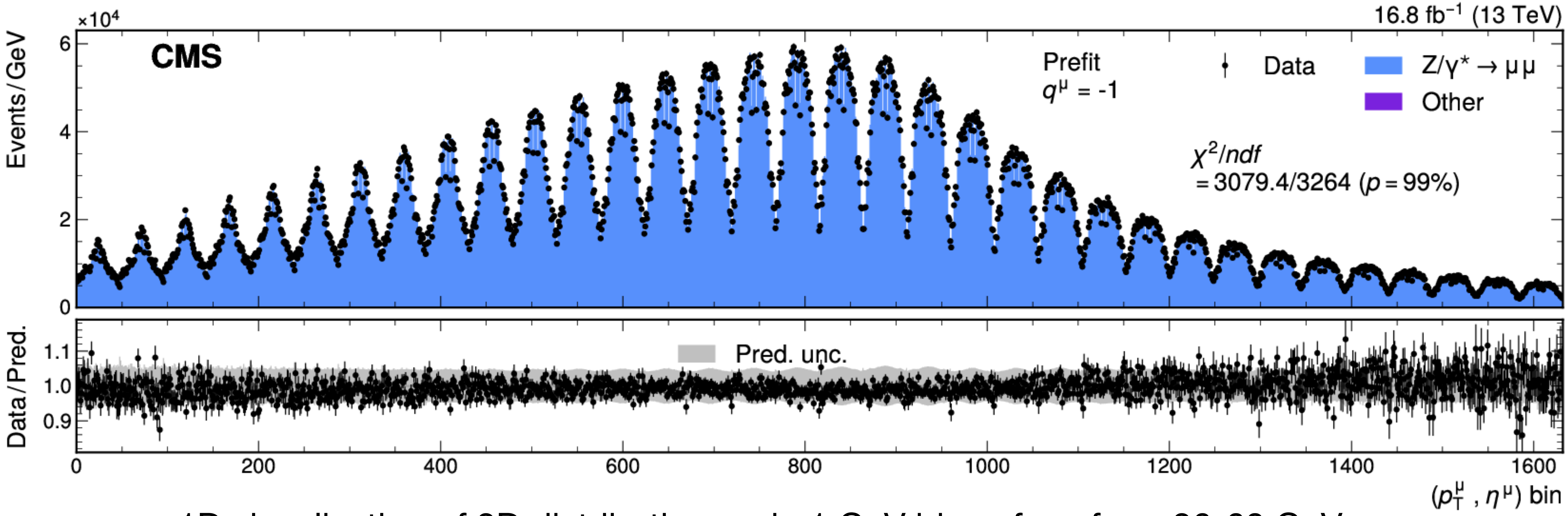




1D visualisation of 2D distribution: η^μ in 1 GeV bins of p_T^μ from 26-56 GeV

Validation with m_Z measurements

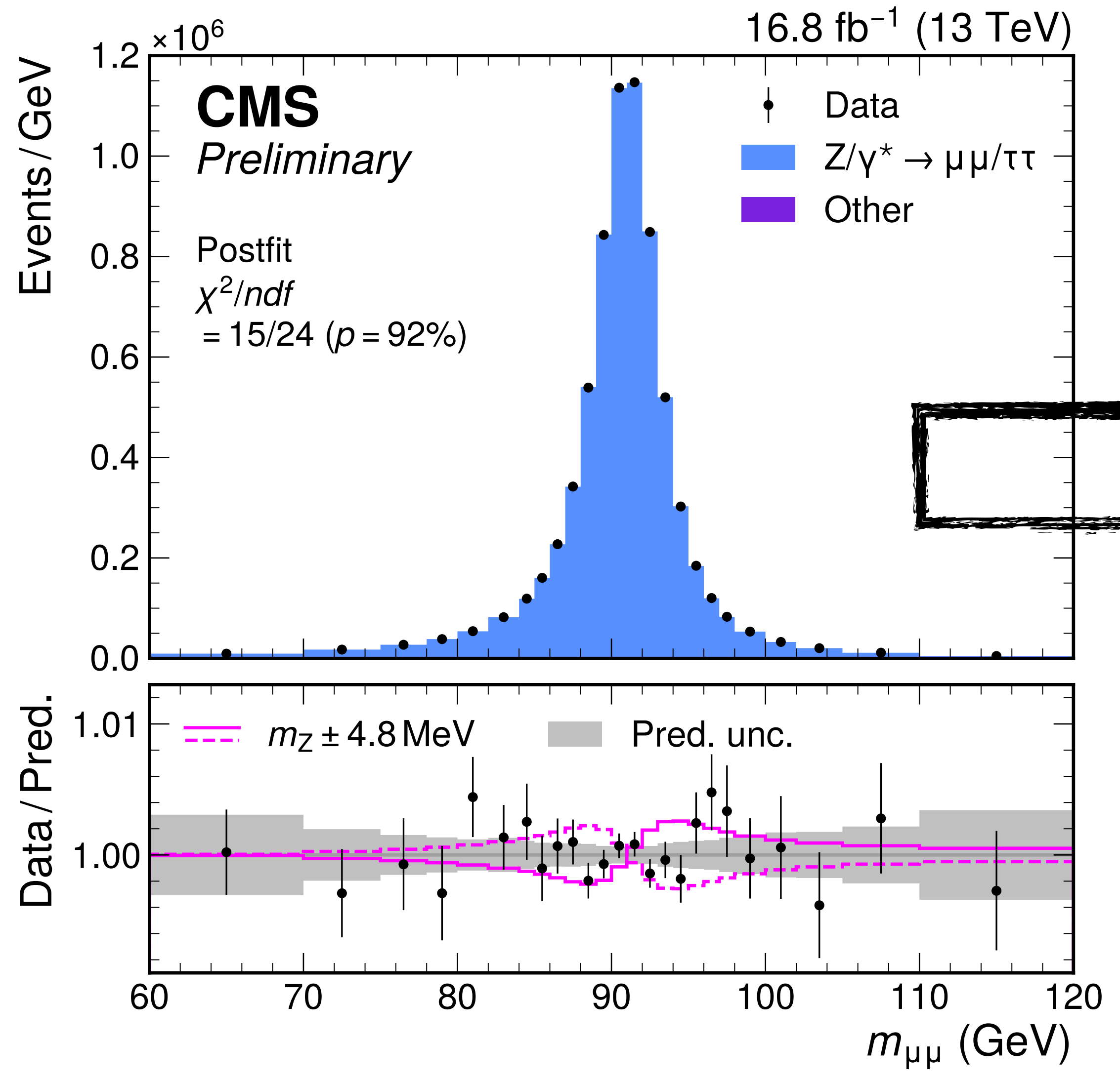
- Crucial tool to validate m_W extraction
  - Select Z events; discard one lepton (add to p_T^{miss})
  - Measure m_Z with single-lepton kinematics
  - Cross-check with direct measurement of m_Z (and m_Z world average)
- Selection maximally consistent with W analysis
  - Take ℓ^+ (ℓ^-) in even (odd) events; "selected" ℓ must trigger event



1D visualisation of 2D distribution: η^μ in 1 GeV bins of p_T^μ from 26-60 GeV

Measurement challenges and sequencing

★ m_Z measurement from $m_{\mu\mu}$



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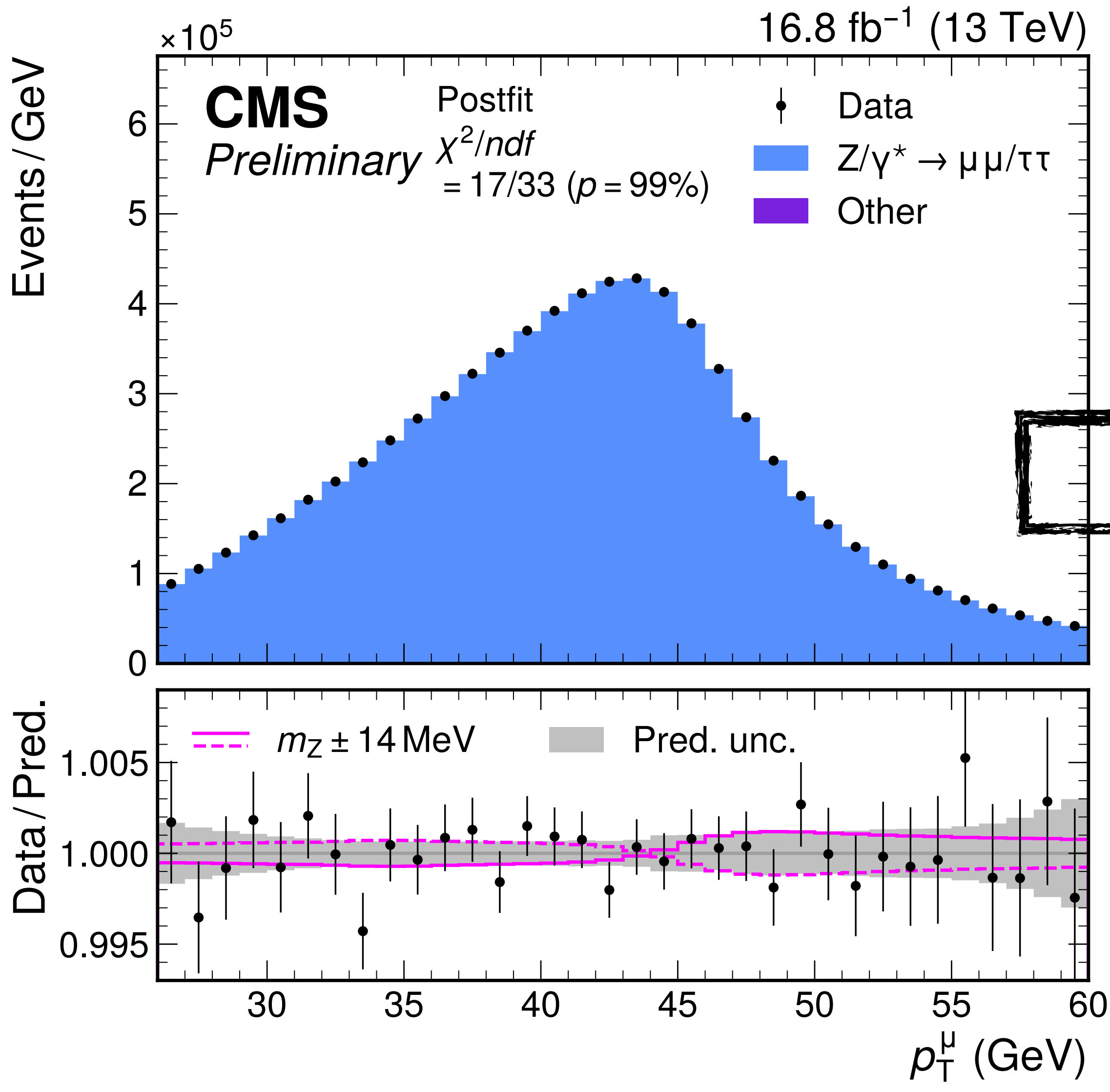

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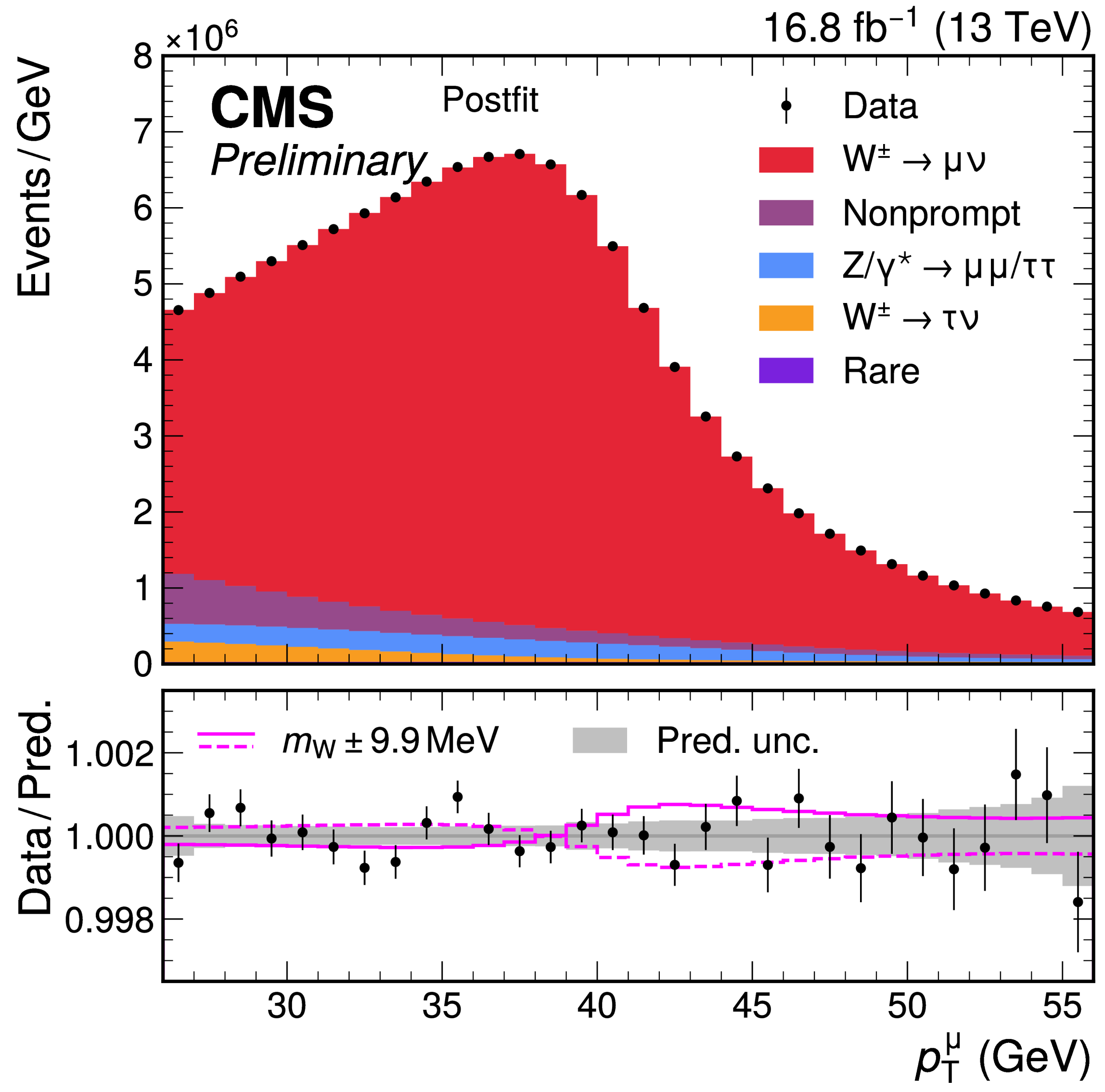

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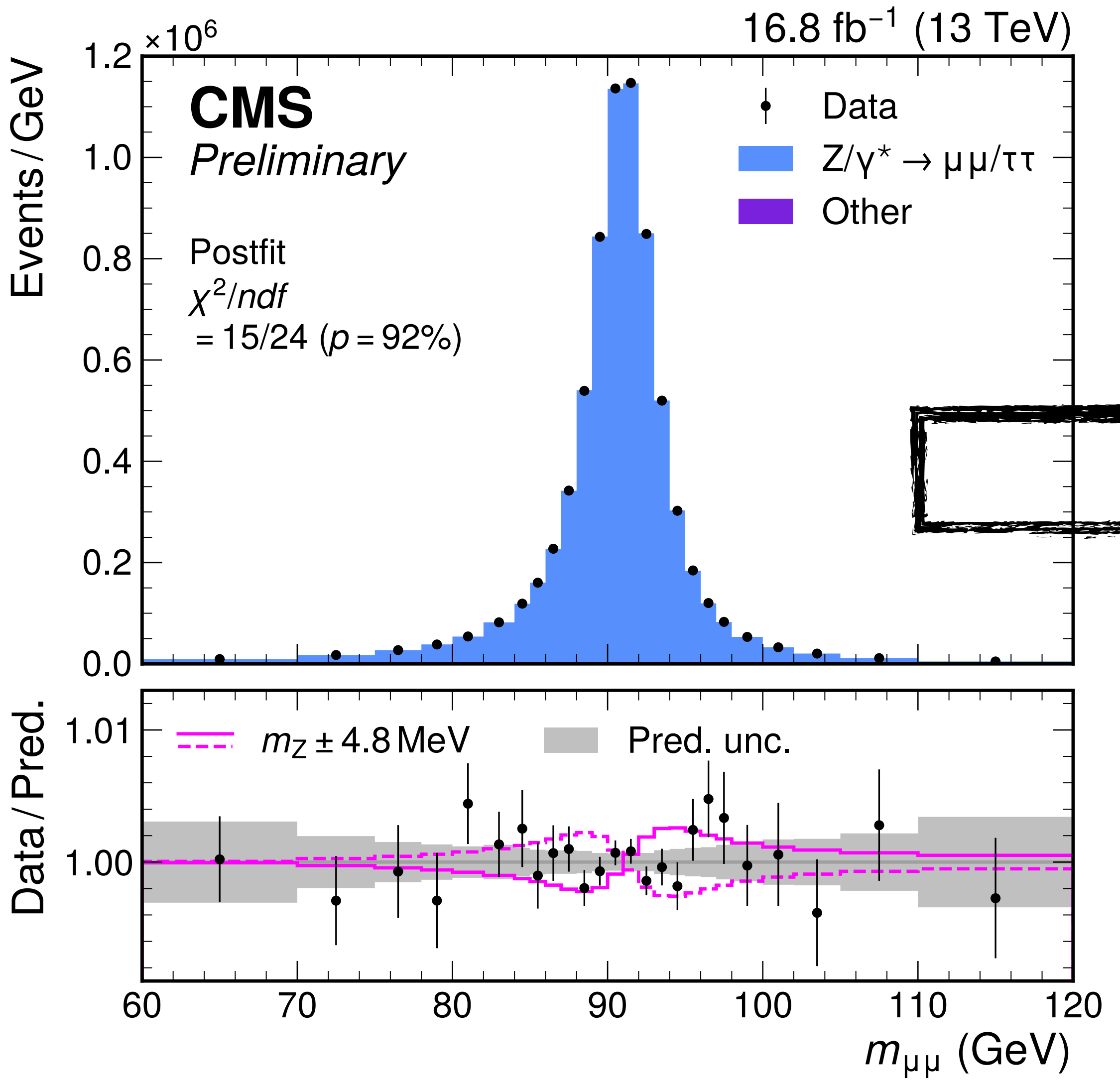

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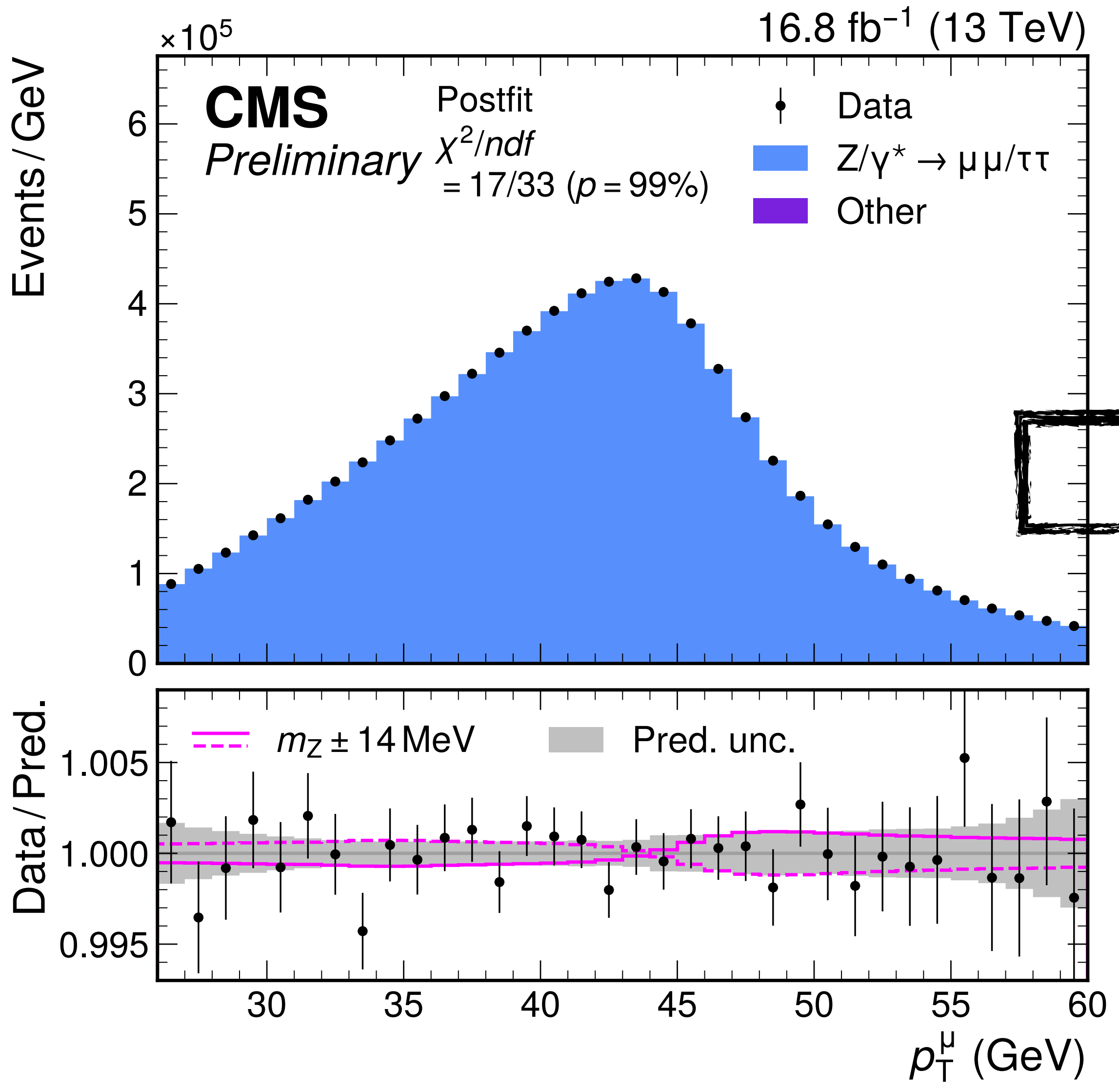

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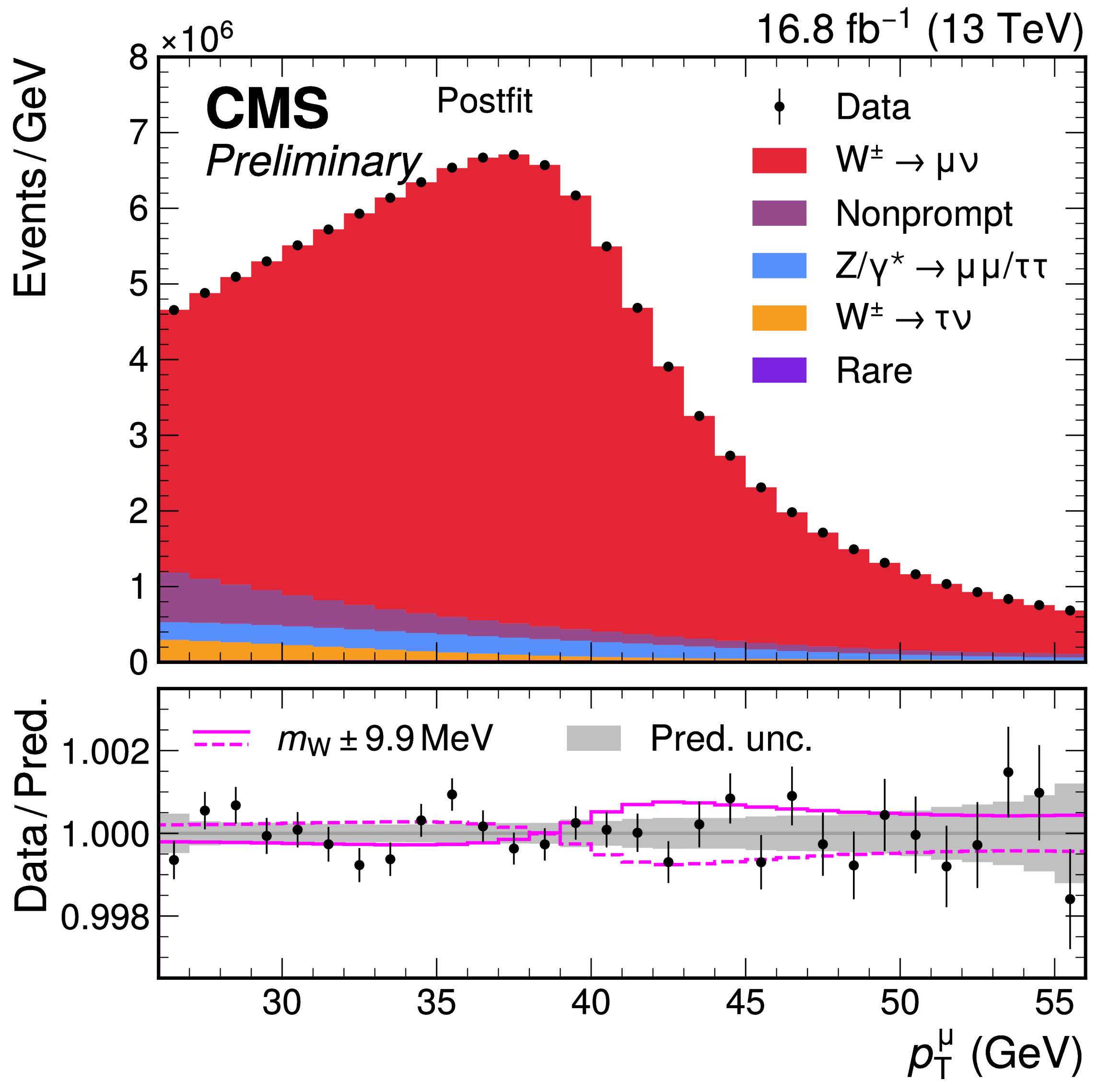
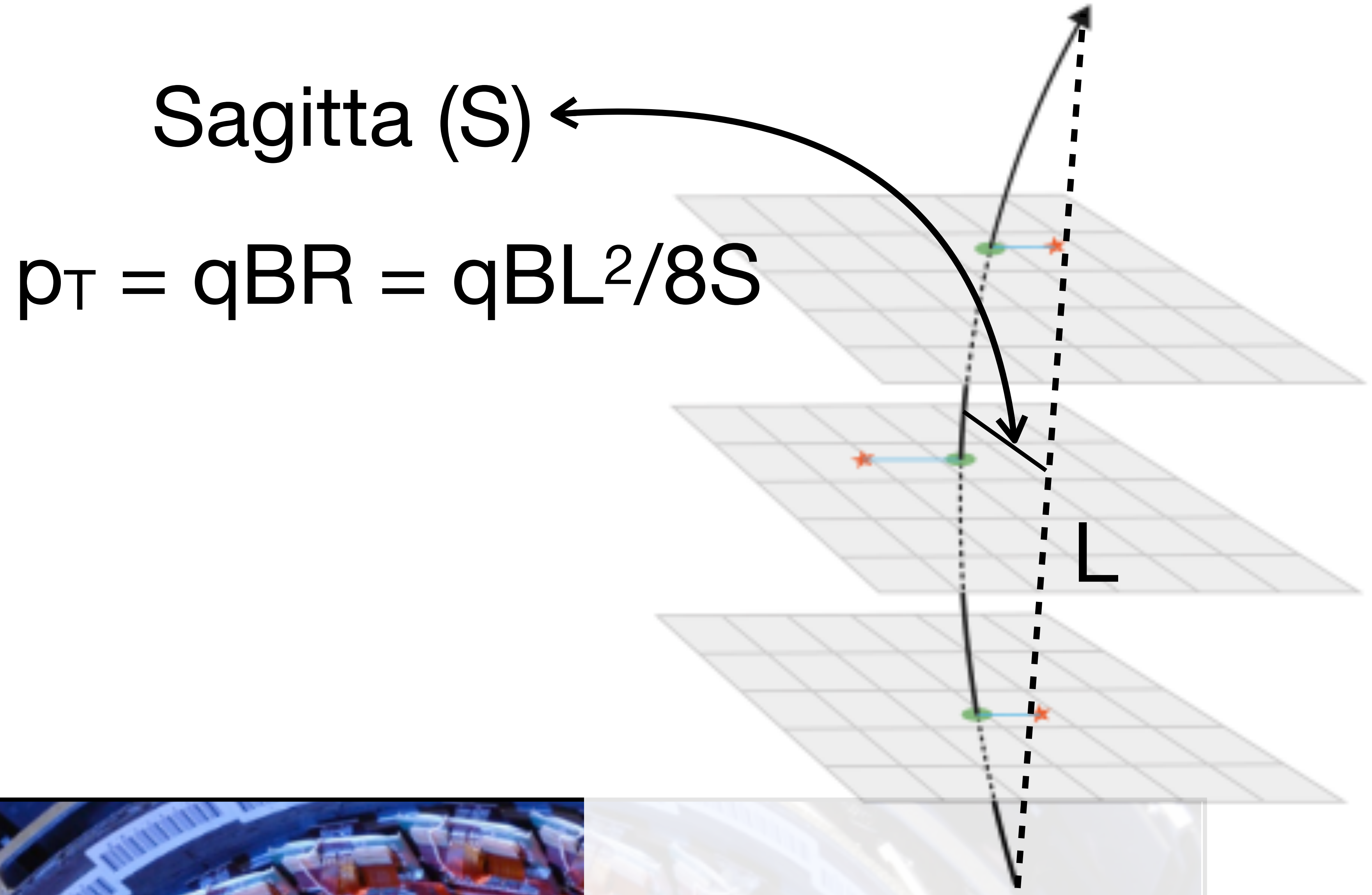
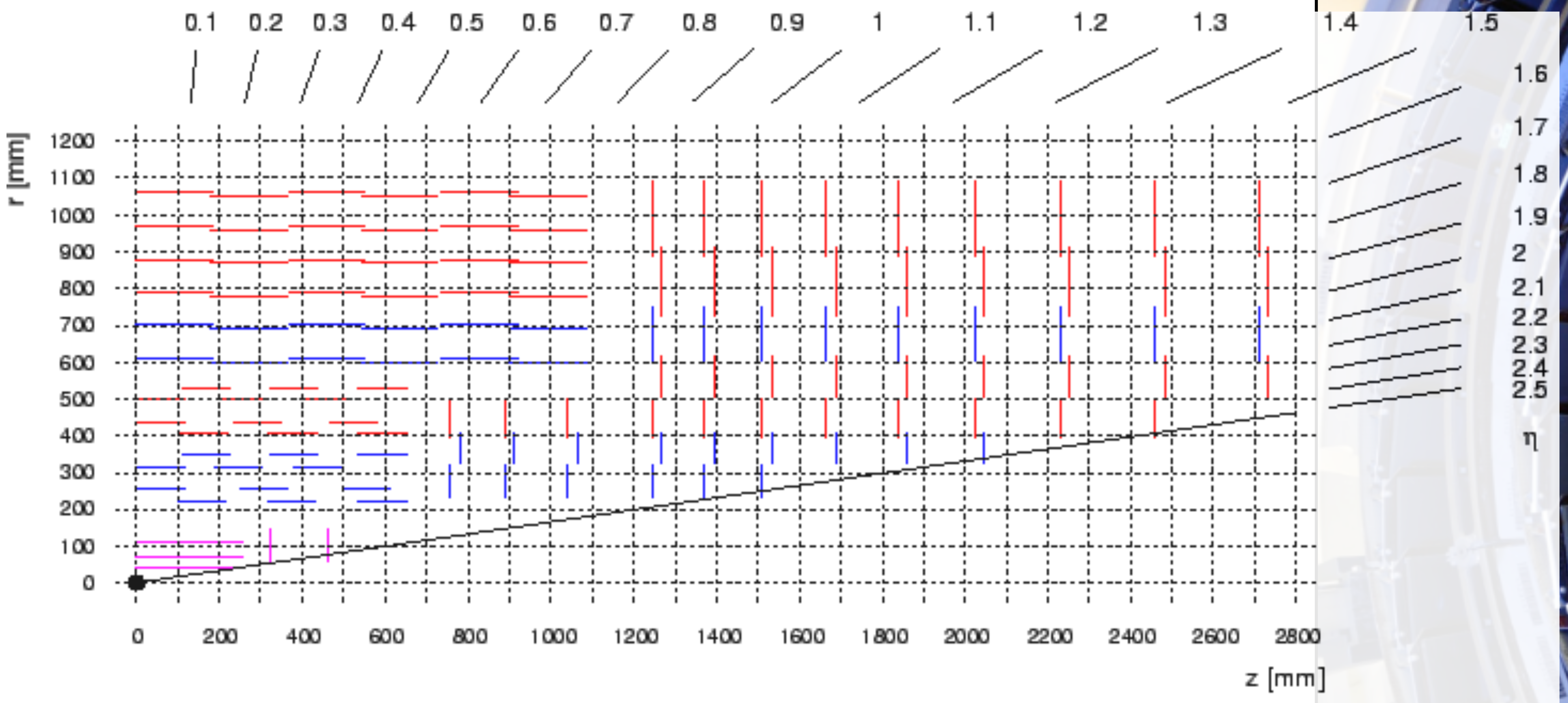


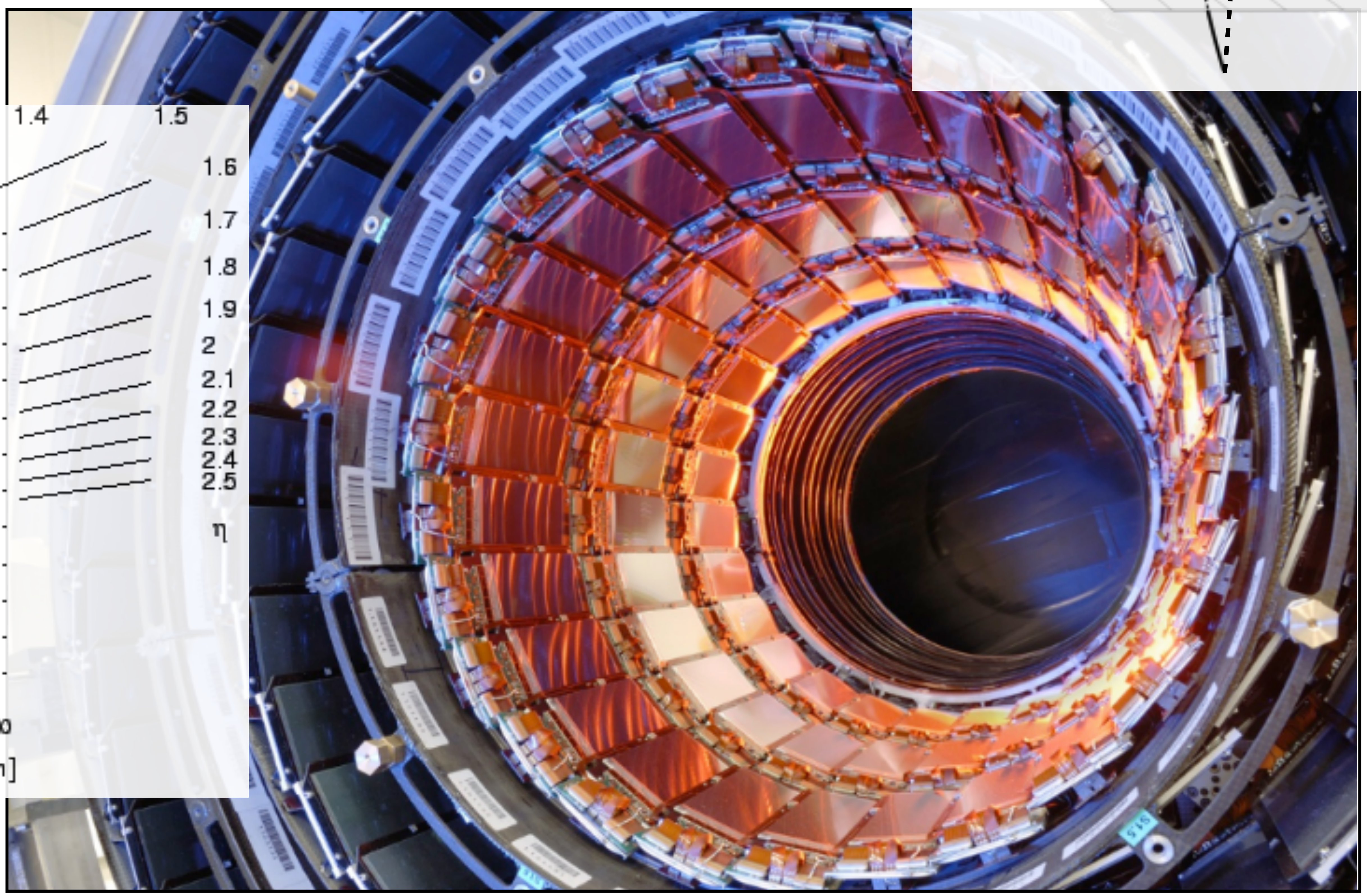
- ★★★ Highly granular and precise estimation of μ reconstruction efficiency
- ★★★ Calibration of absolute p_T^μ scale ($\delta p_T^\ell \sim 10^{-4} \Longrightarrow \delta m_W \sim 8$ MeV)
  - ➡ > x10 better than typical CMS analysis
- ★★ Accurate modeling and uncertainty estimation for W/Z production
- ★★ Calibration of the p_T^{miss}
- ★ Estimation of backgrounds: primarily heavy flavour decays in jets mis-ID'd as leptons


Tracker layers
Calorimeter layers
Particles
Tracker hits

- Momentum measured from track curvature (using tracker only)
  - ~17 hits per track: single-hit resolution of 9-50 μm
  - Typical sagitta ~ 6 mm (p_T^ℓ = 40 GeV)
  - **Target $\delta p_T^\ell \sim 10^{-4} \Rightarrow \delta S \sim 0.6$ μm**







Muon momentum calibration: overview

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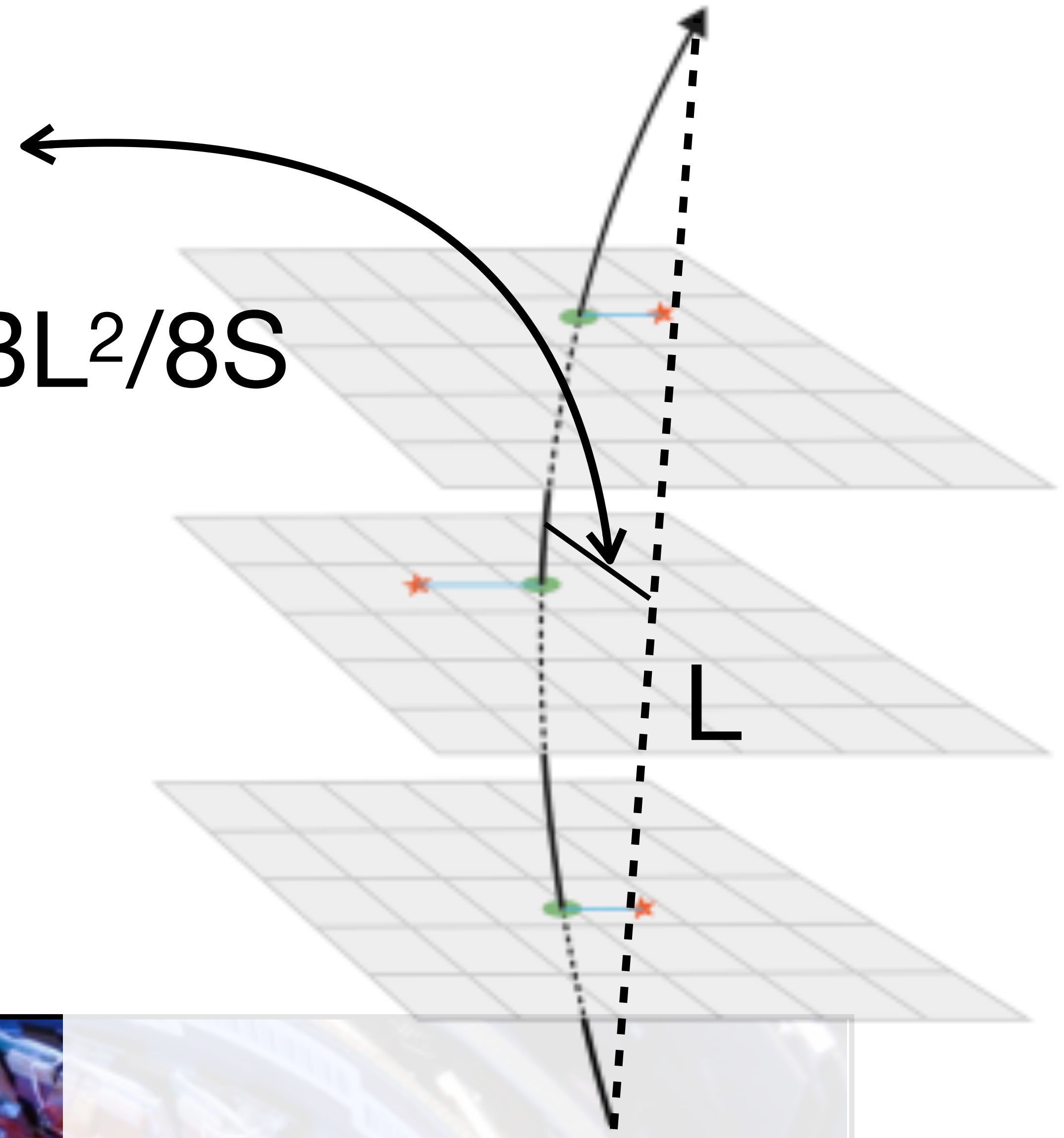
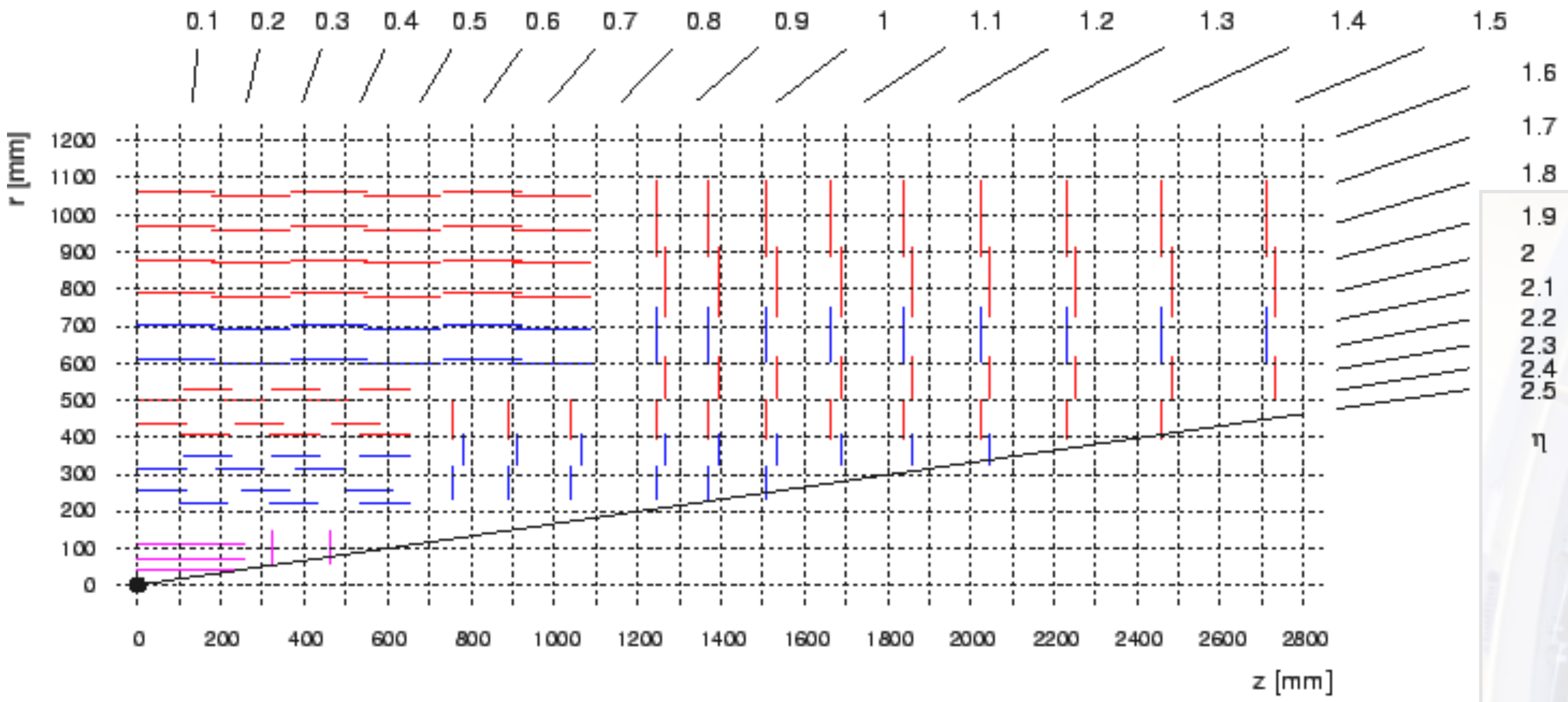
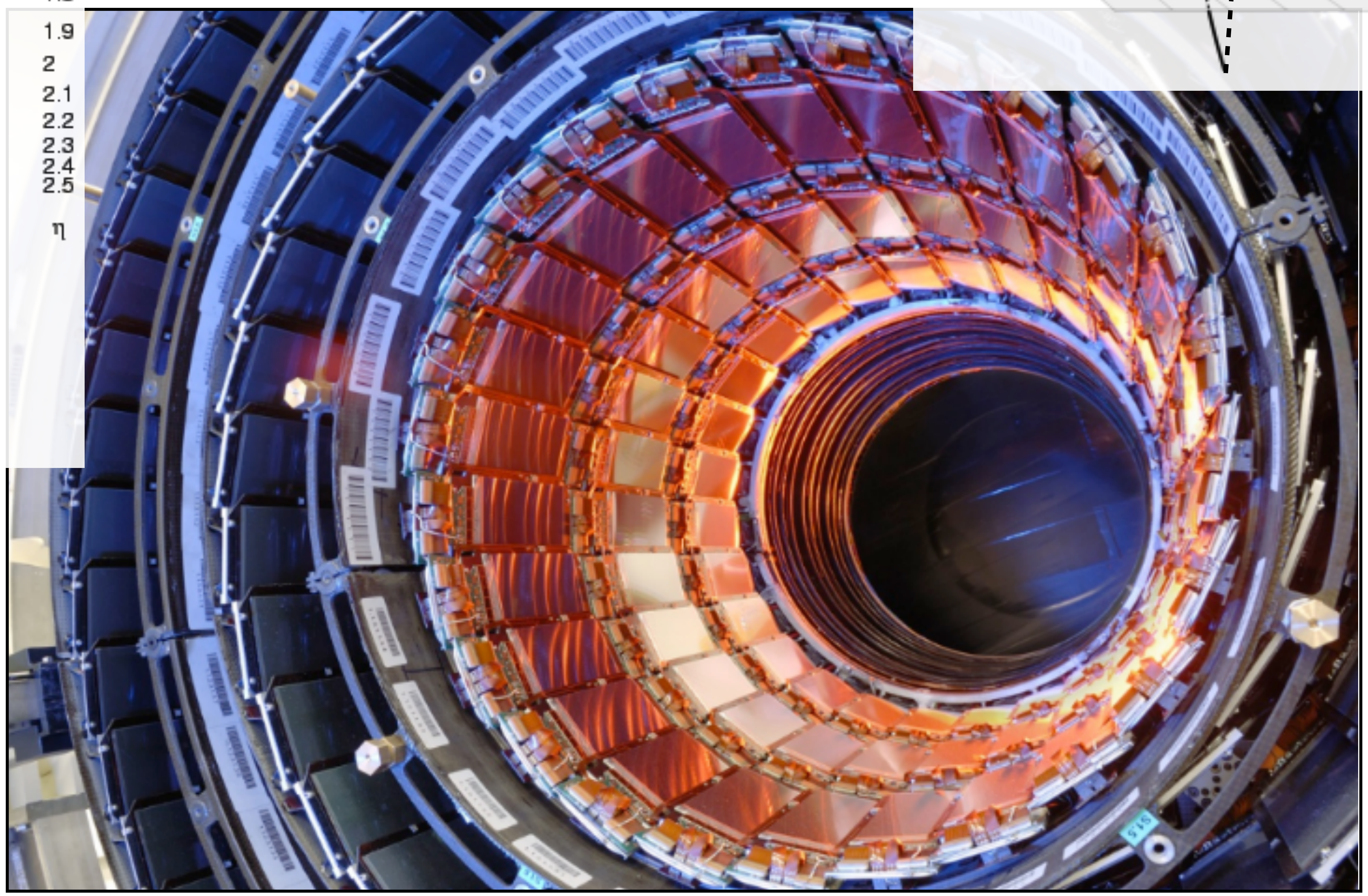
Sagitta (S)

$$p_T = qBR = qBL^2/8S$$

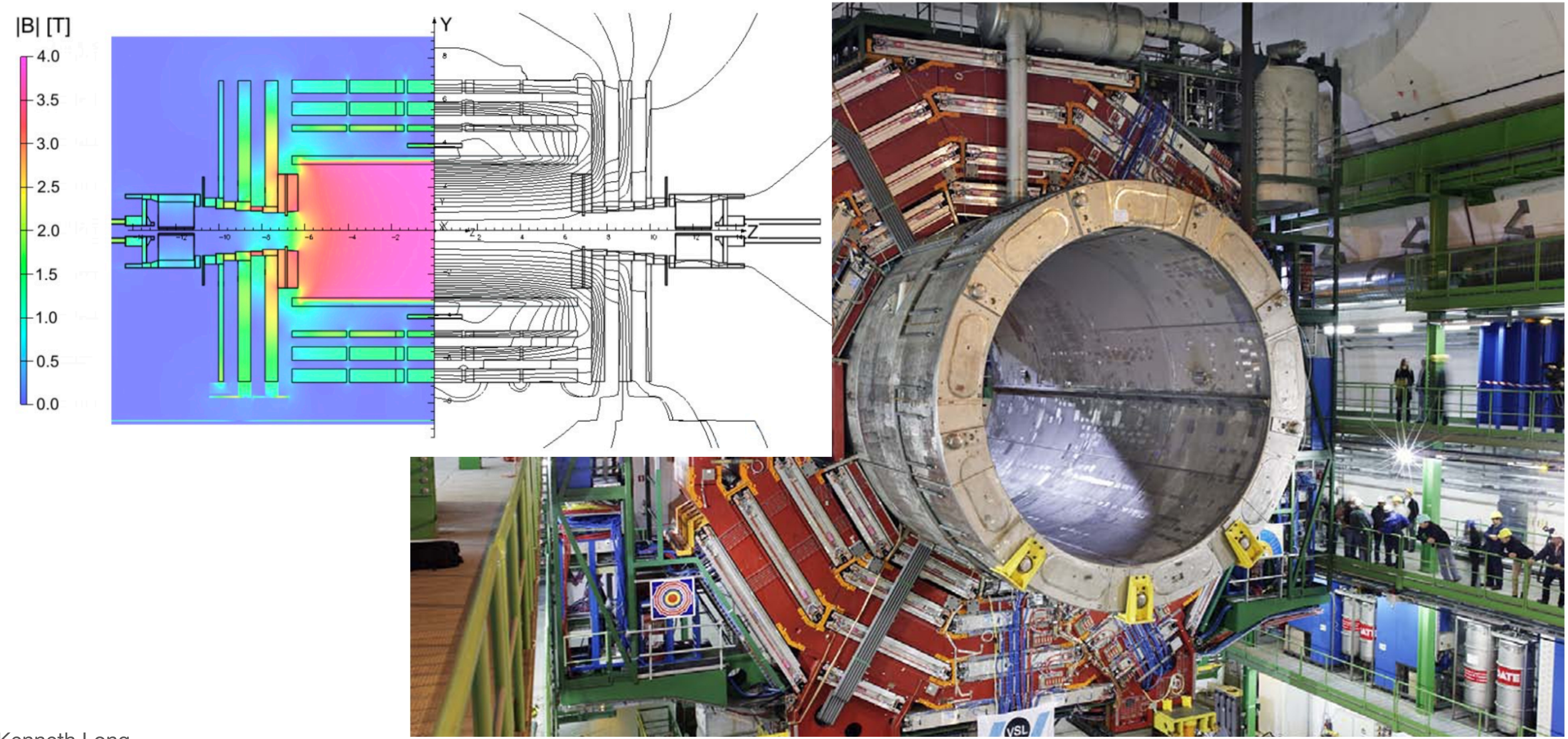






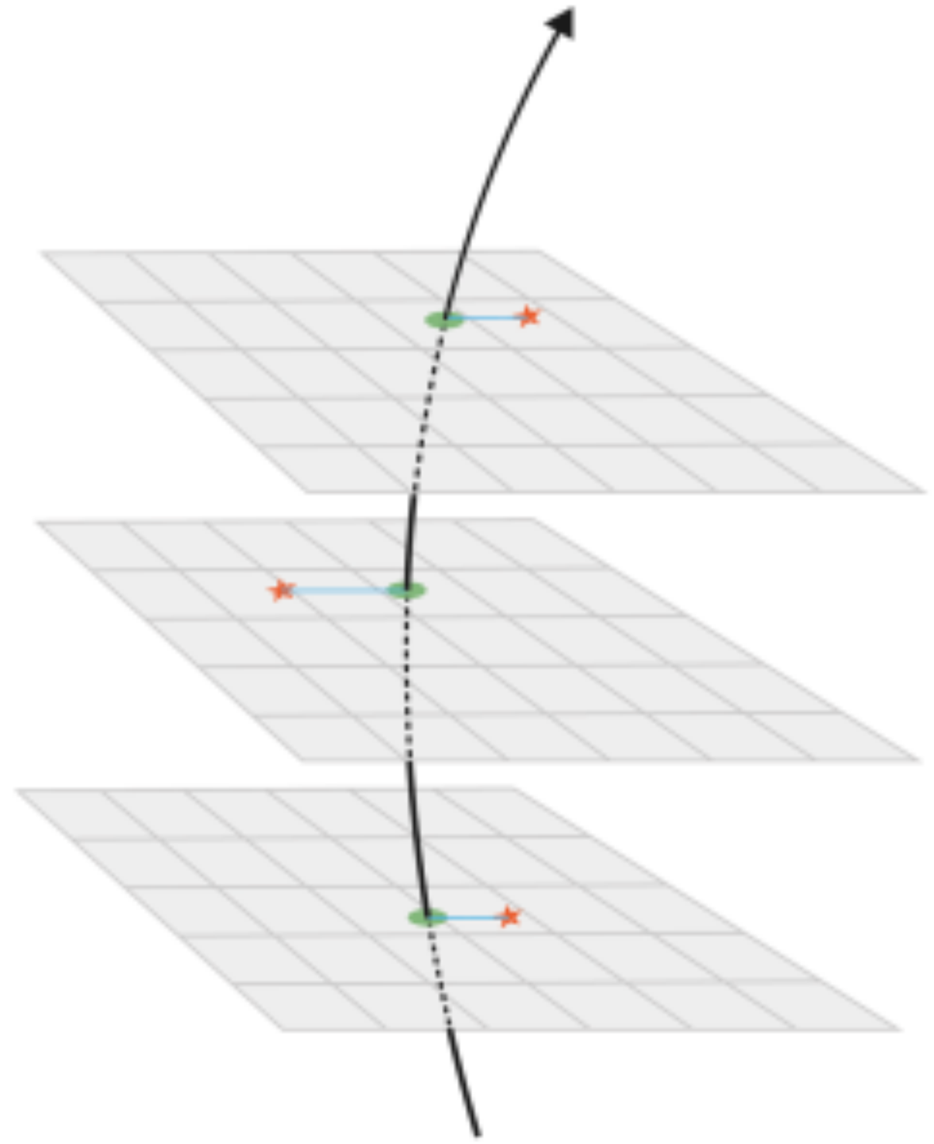
Muon momentum calibration: Magnetic field

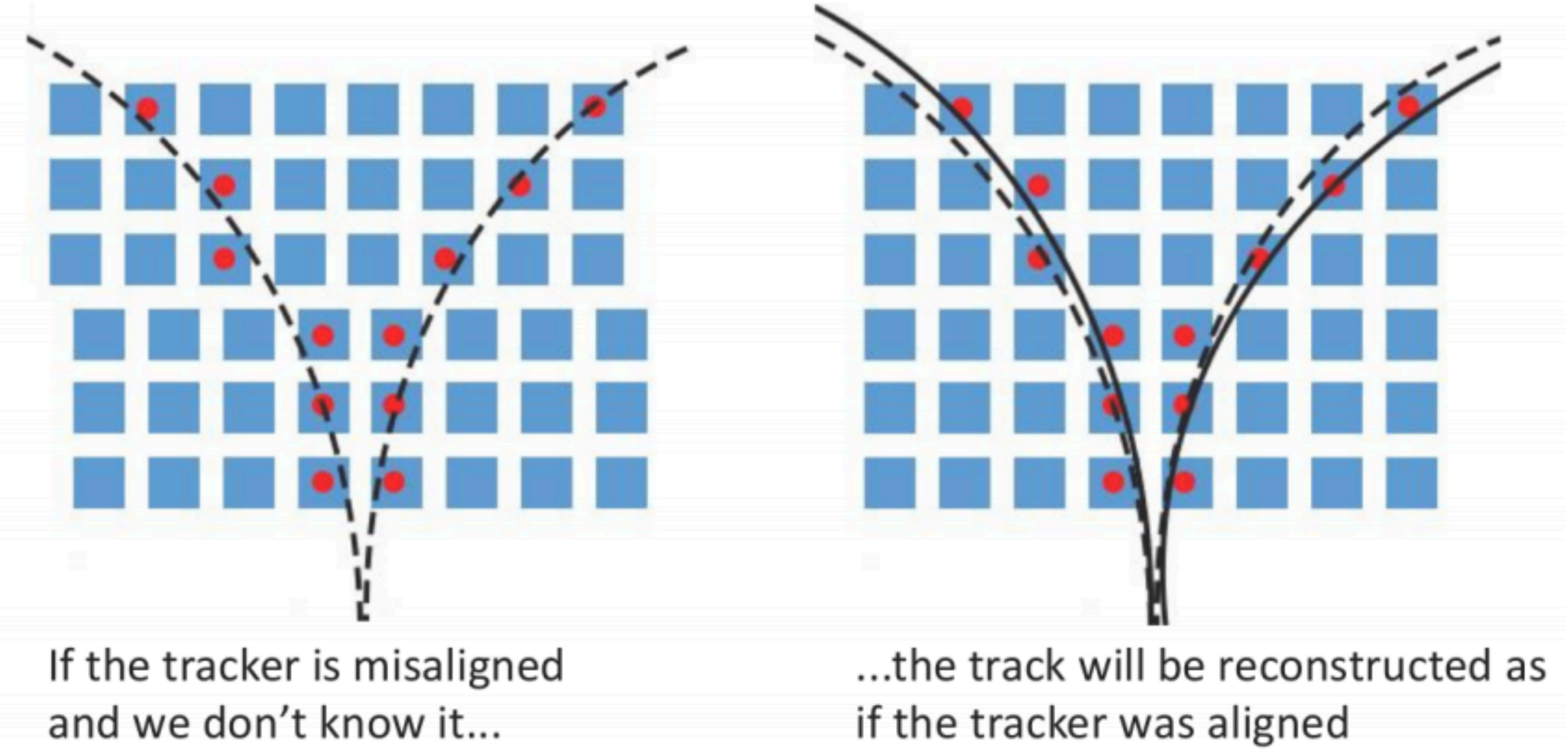
- CMS magnetic field was precisely mapped before being inserted into the detector
  - Differences from precise mapping and true B-field of ~0.003 T is ~100 MeV bias in m_W

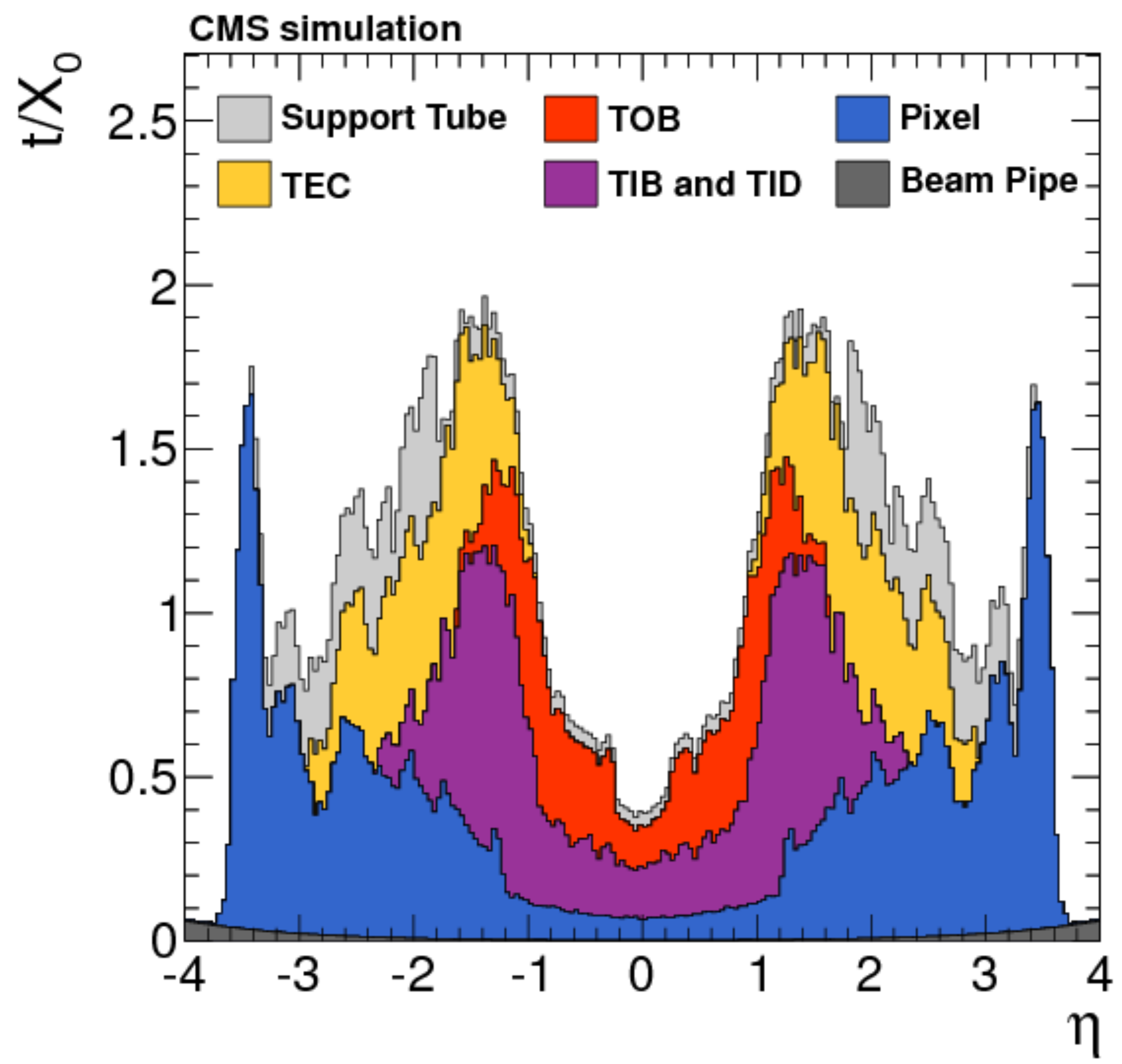


Muon momentum calibration: Alignment and material loss

- Knowing location, material, and relative alignment of 12k tracker modules crucial
  - Need to know material traversed—not just silicon, but electronics, cables, support structure…
    ➡**5 MeV of bias equivalent to ~Δ5 mm of iron in the tracker volume**
  - Relative shifts from gravity, opening of the detector, modify alignment
    ➡**5 MeV uncertainty is a ~0.4 μm misalignment**







Muon momentum calibration: procedure

★Calibrate in data using a known reference: J/ψ

- Mass known precisely

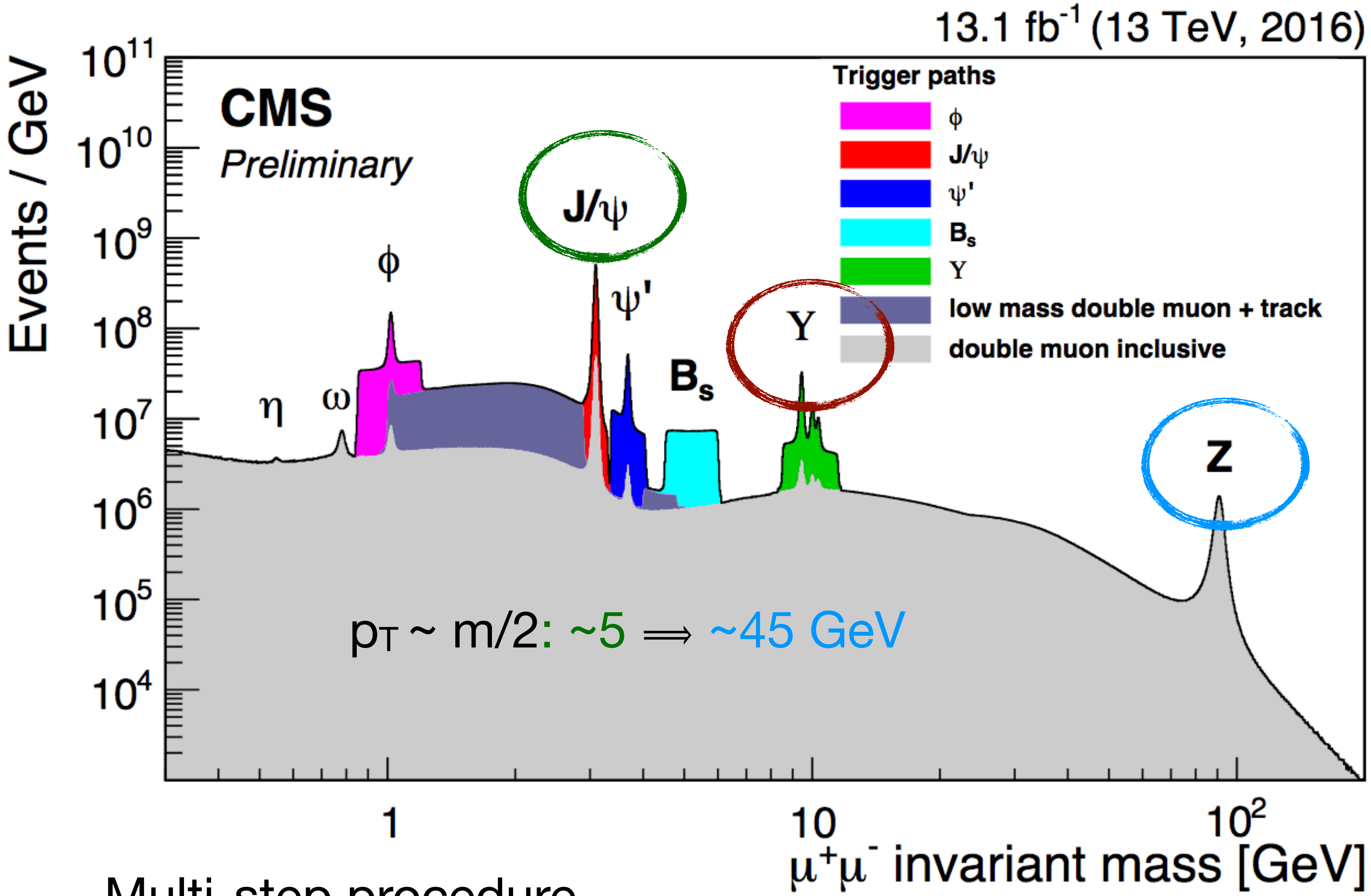
➡ Requires robust extrapolation across momentum scales

$$k_{corr} = Ak + qM + \frac{k}{1+ek}$$

$$\delta k/k \approx A + qM/k - ek$$

Parameterize by small differences in

- B-field
- Alignment
- Energy loss (material)

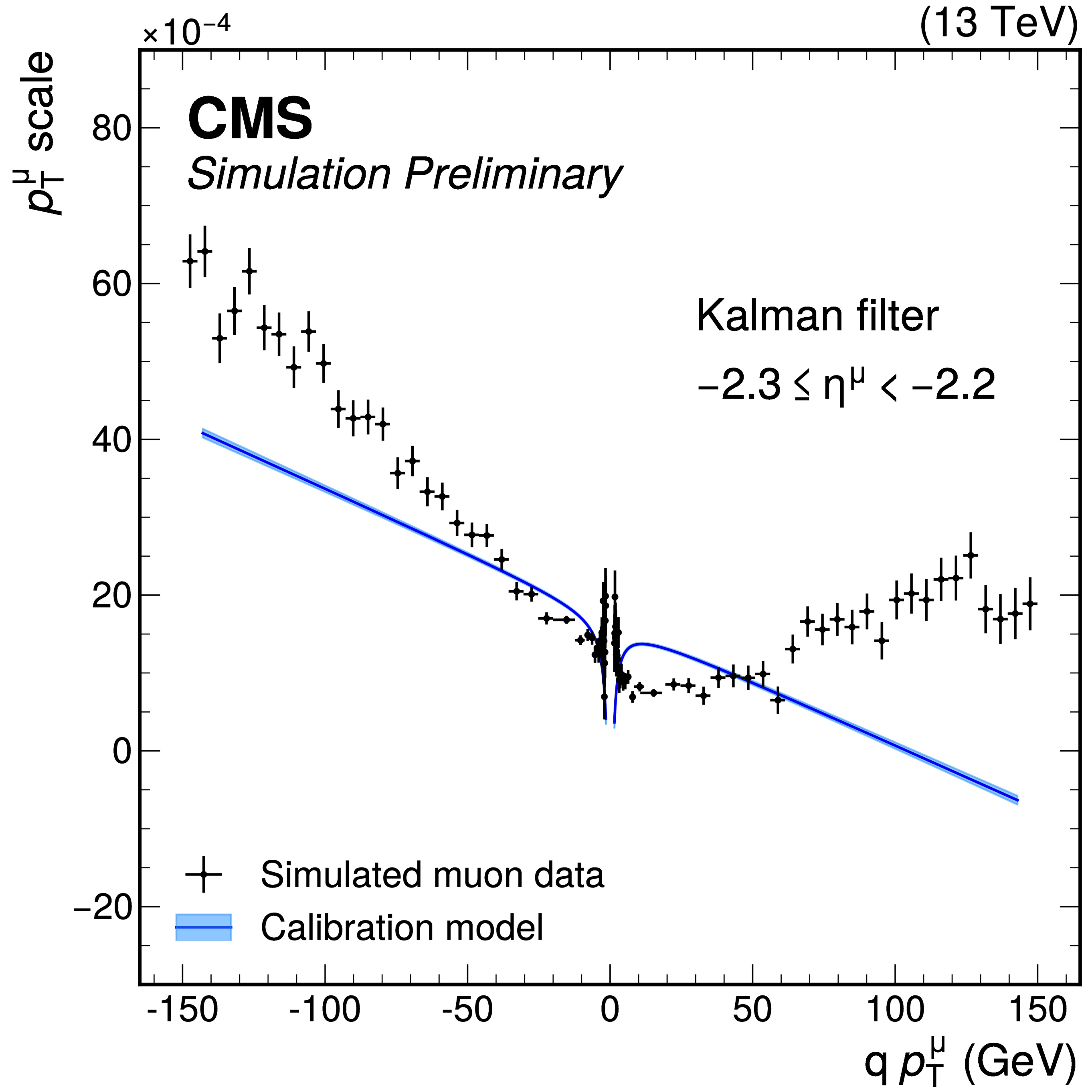


- Multi-step procedure
  1. Improved, custom refit of track to muon hits
  2. Apply module-by-module corrections from track refit
  3. Parameterised corrections (binned in η^{μ}) from fit to J/ψ →μμ events

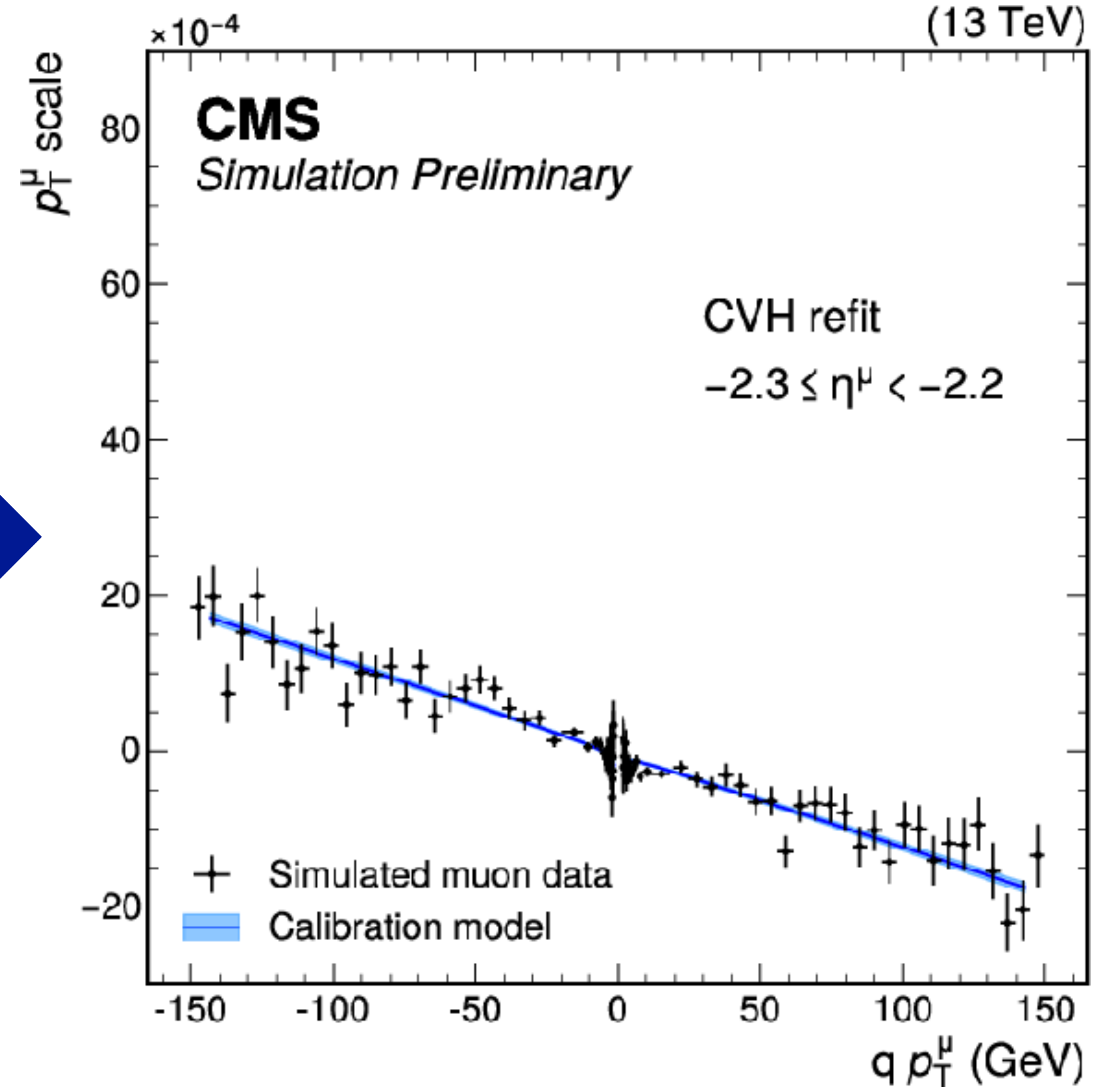
➡Validate J/ψ-based calibration with Υ(1S) and Z

- Fit muon hits with custom “Continuous Variable Helix”
- **Model material in helix fit with Geant4**+additional params for B-field
  - Increase Geant precision wrt standard CMS reco.
- **Use of high-precision B-field map** (lower speed wrt standard reco.)

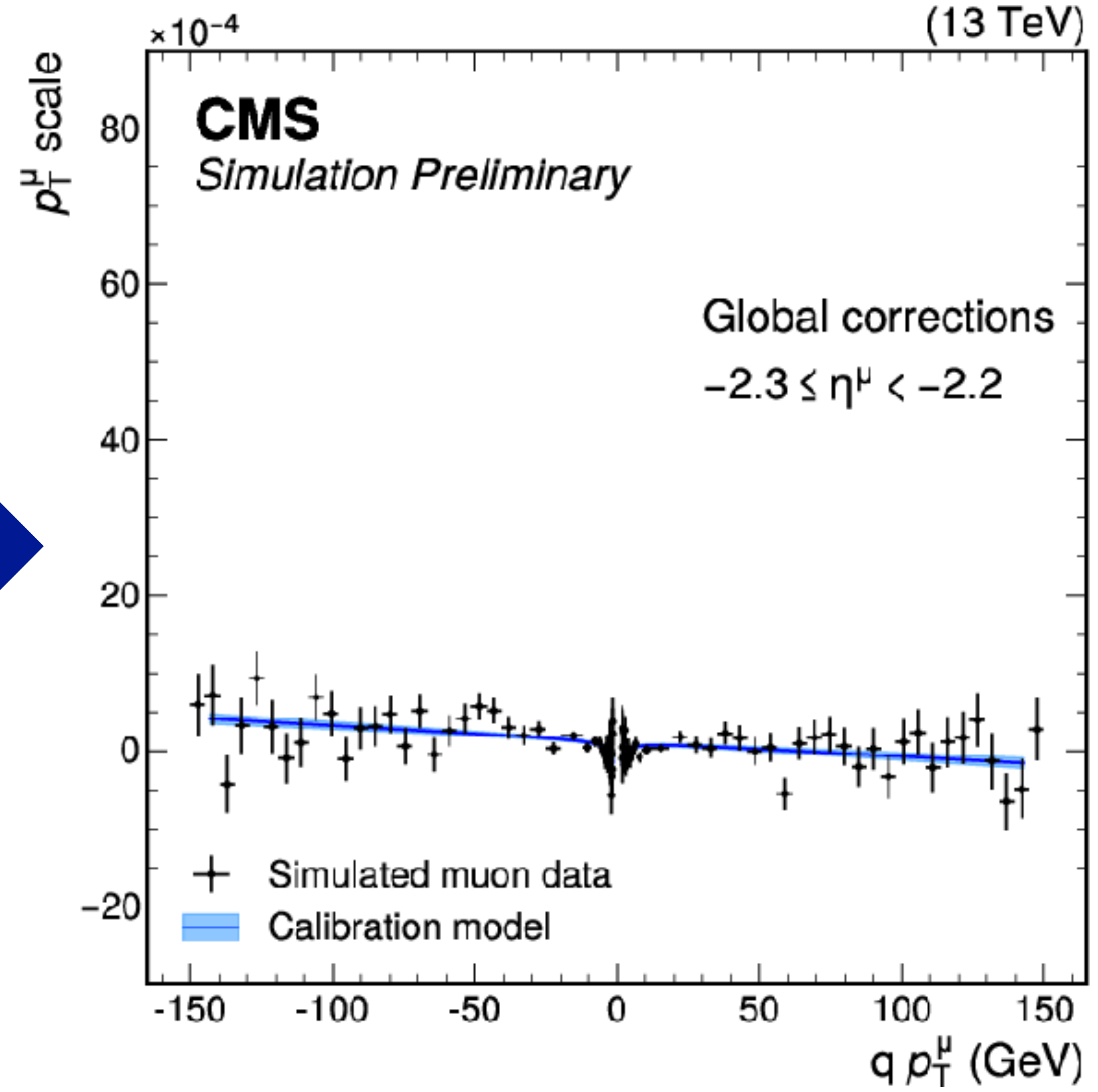
➡Extract and apply ~100,000 corrections params (B-field, material, alignment)



CMS standard reco.



CVH refit

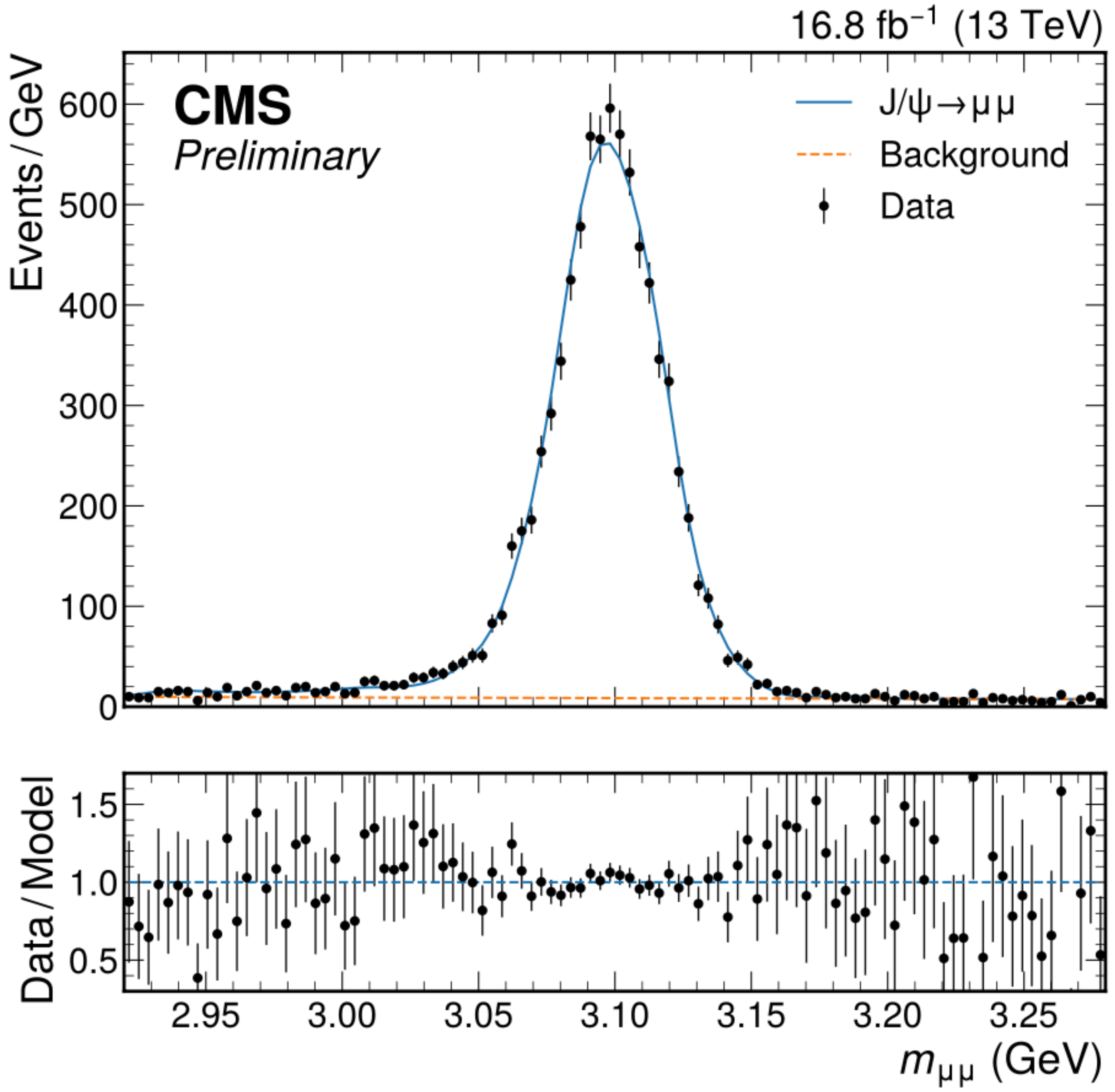


CVH refit+corr.

Fit of parameterisation function to single muon simulation vs. ground truth

Physics-model corrections from resonant mass fits

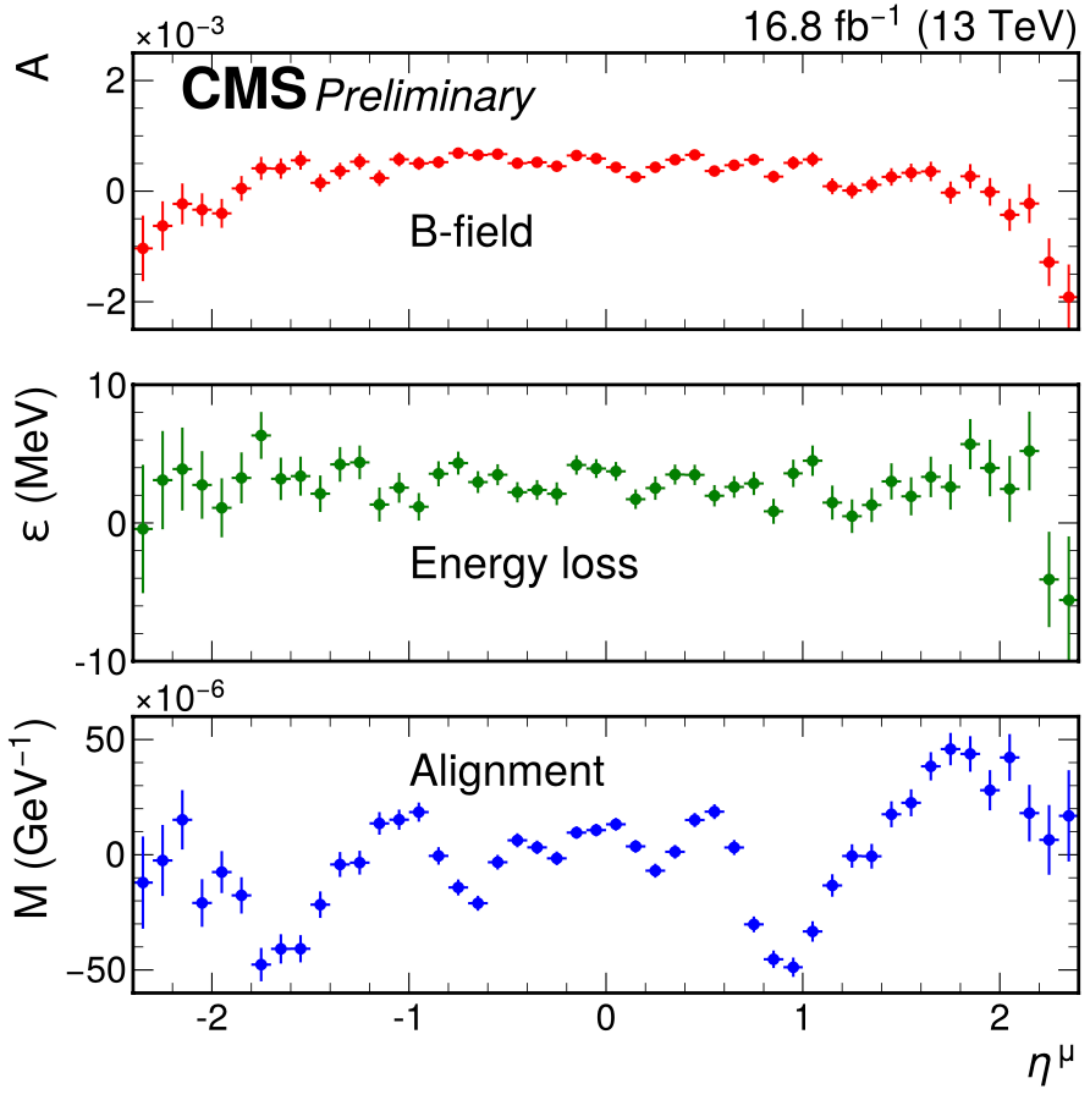
- Parameter extraction procedure
  1. **Derive scale from fit to J/ψ mass** in a binned 4D space of ($p_T^{\mu+}$, $p_T^{\mu-}$, $\eta^{\mu+}$, $\eta^{\mu-}$)
  2. Using χ^2 minimization, **extract η-binned calibration parameters** per muon
  3. Closure test: **perform same procedure on Y(1S) and Z to assess consistency**



$$\delta k/k \approx A + qM/k - ek$$

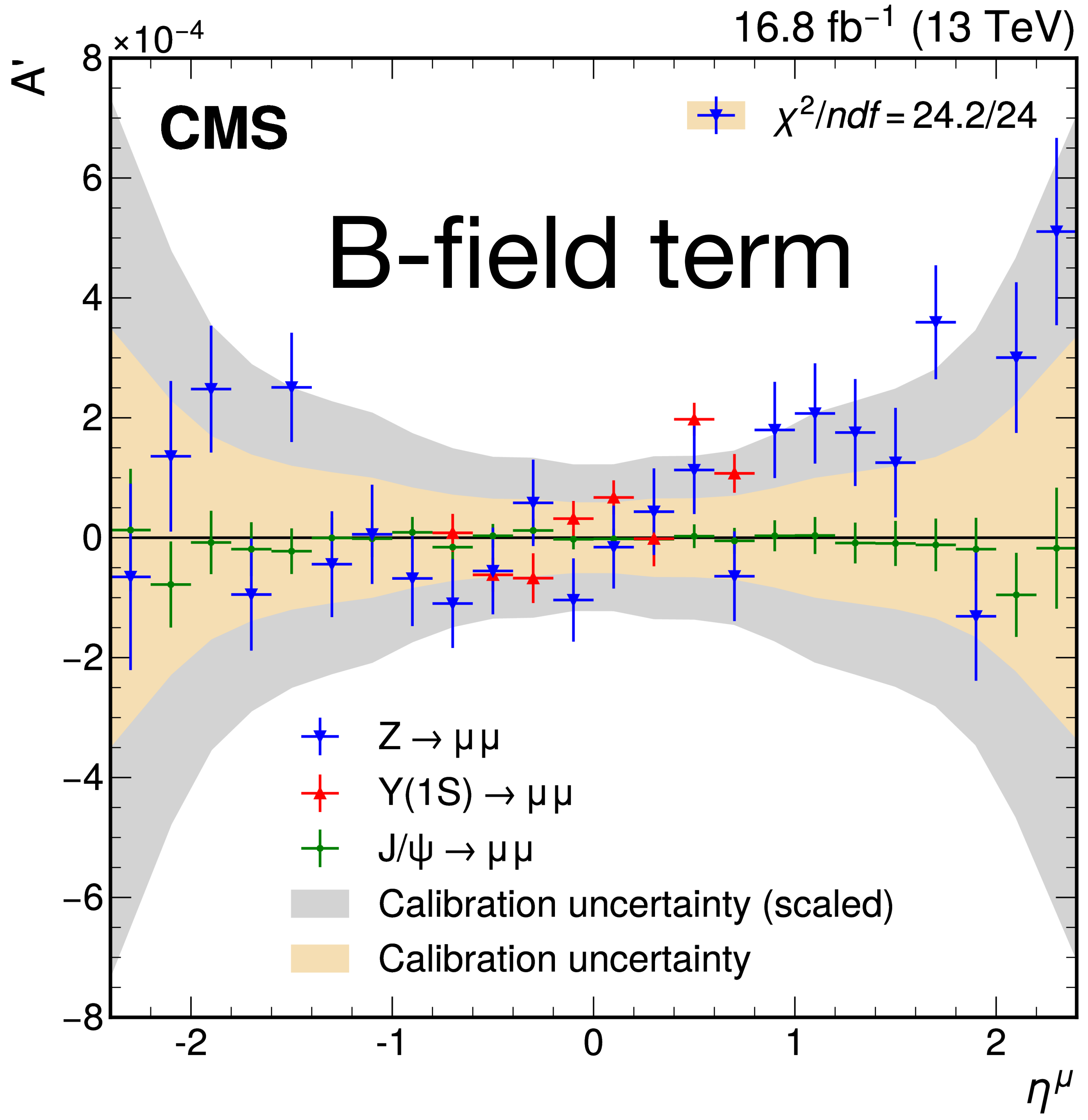
Left: example fit to J/ψ in central η bin

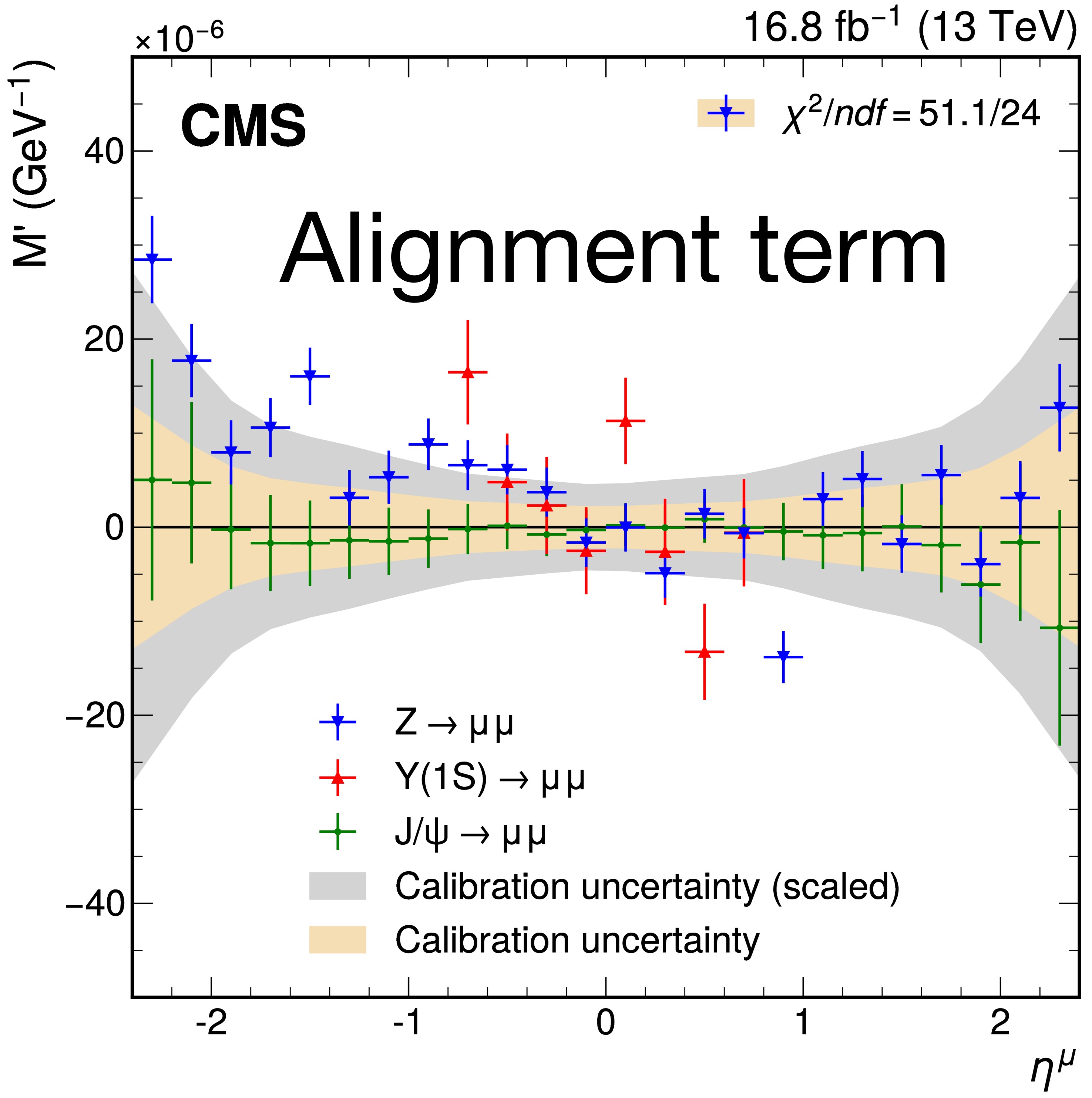
Right: Extracted parameters per η bin, (on top of module-level corrs.)



Calibration uncertainty and consistency between J/ψ, Υ, and Z

- Closure tests: apply mass-fit procedure to Υ(1S) and Z
    1. Correct by binned (A, e, M) parameters from J/ψ
    2. Fit for residual correction parameters





- Stat. unc. in parameters from J/ψ used as basis for systematic unc.
    - Scaled up by 2.1 for full coverage

➡Uncertainty in m_W 4.8 MeV

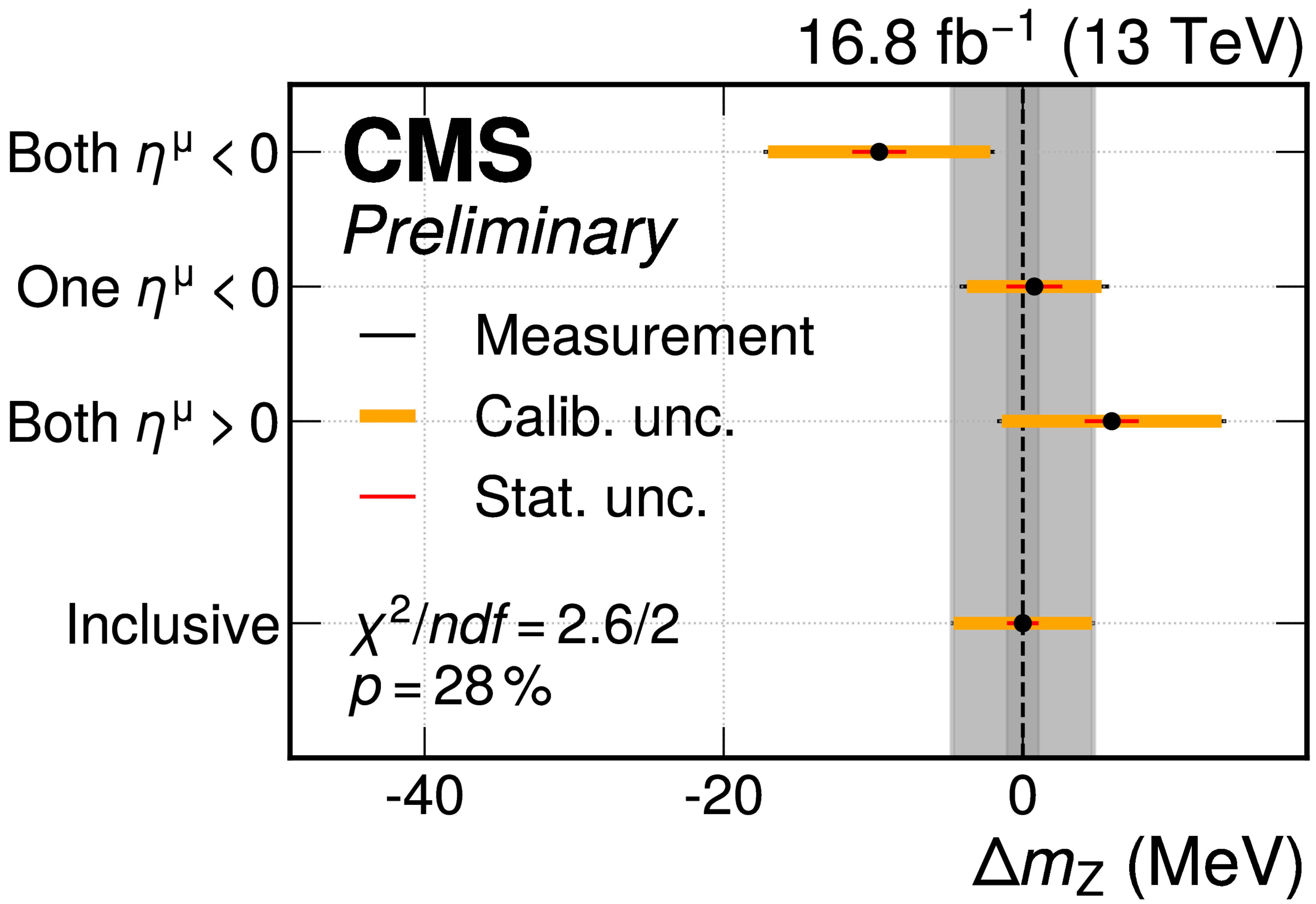
ATLAS: calibration on Z (~7 MeV unc.)
CDF: Combination of J/ψ, Υ, and Z (3 MeV unc.)

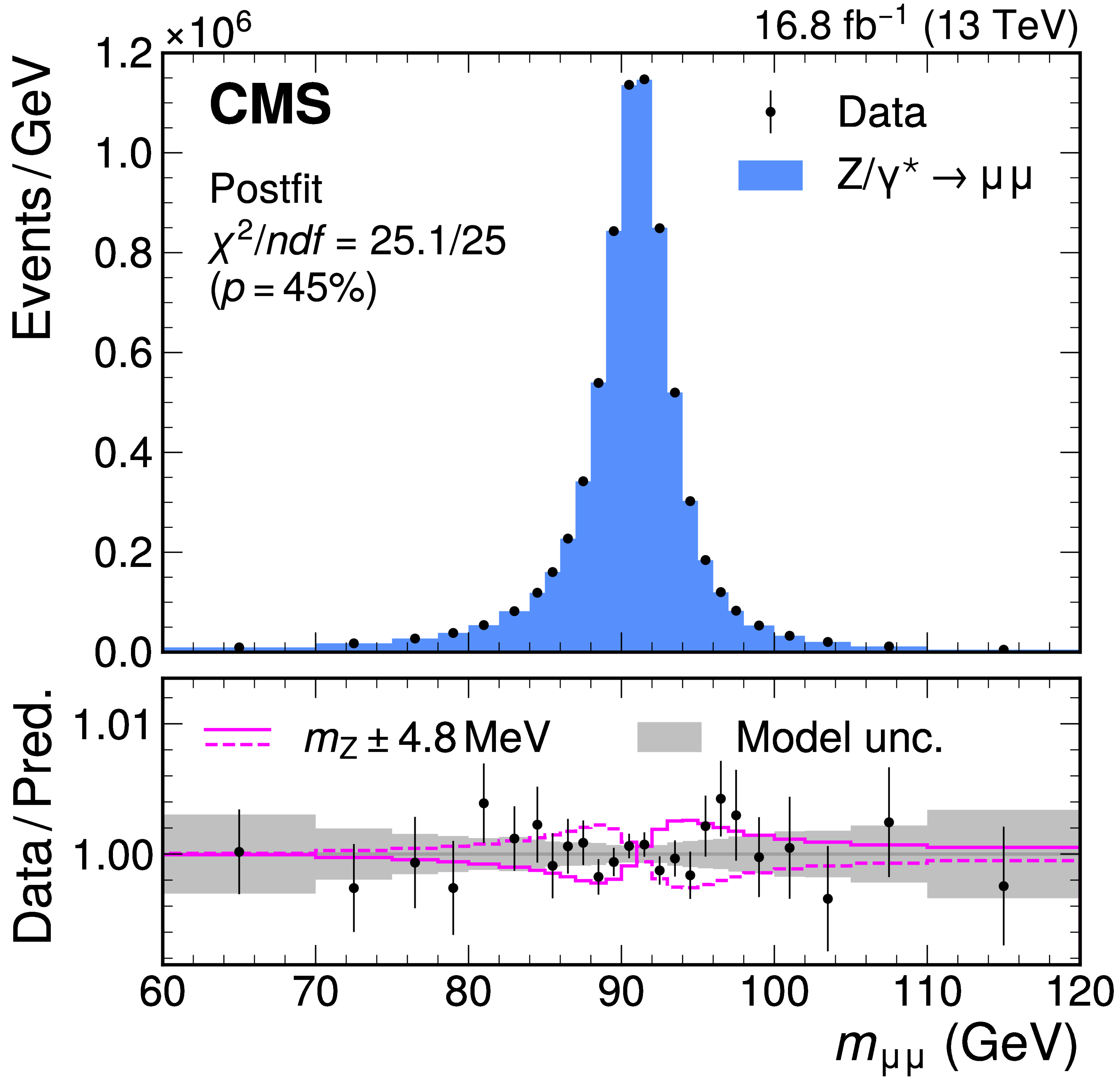
★ Extracting m_Z from fit to $m_{\mu\mu}$

- Extract m_Z from binned likelihood fit to $m_{\mu\mu}$ in bins of signed η^μ of most forward muon
  - Validate experimental techniques

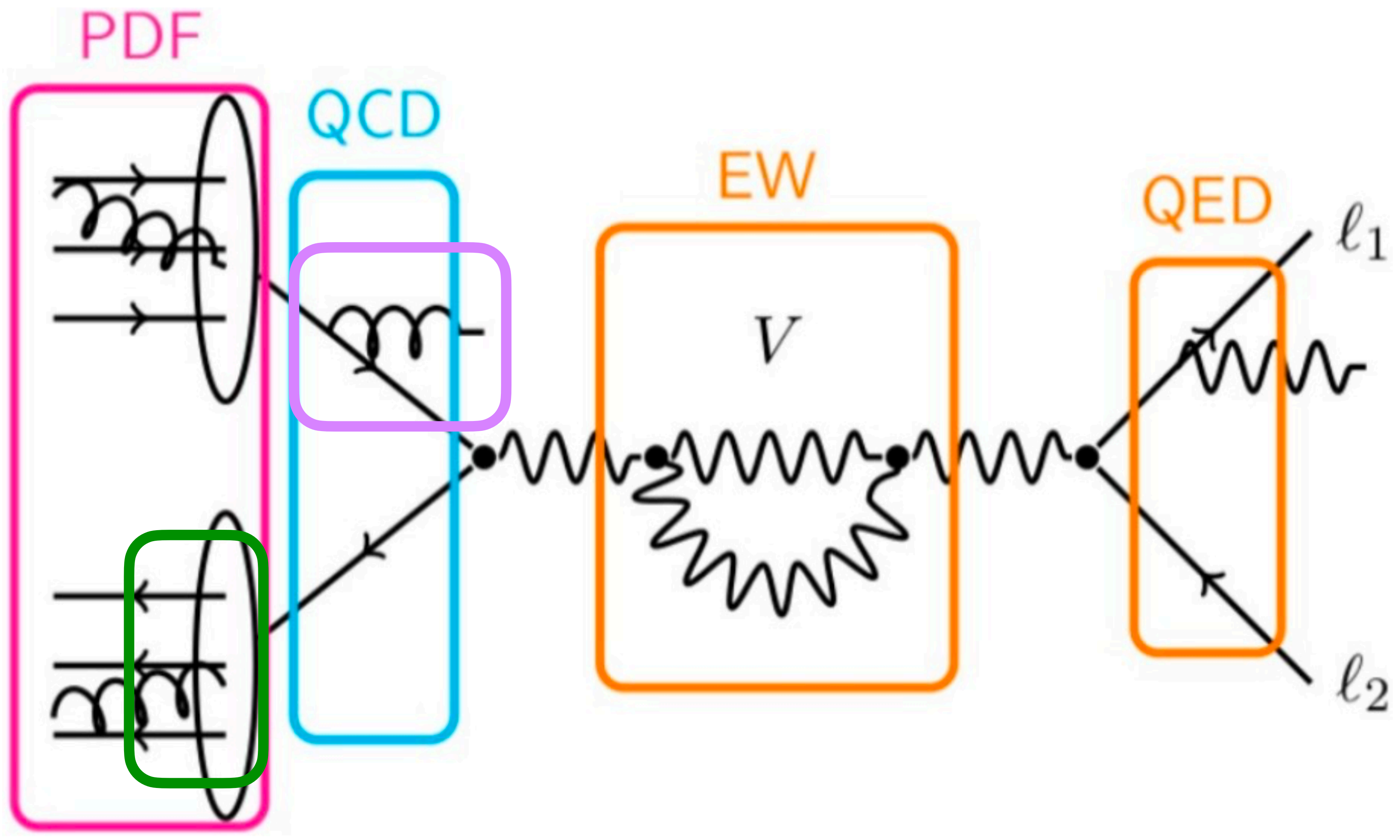
$$\mathbf{m_Z - m_Z^{PDG} = -2.2 \pm 4.8\ MeV} = -2.2 \pm 1.0\ (\text{stat}) \pm 4.7\ (\text{syst})\ \text{MeV}$$

- Not (yet) an independent measurement of m_Z
- Stability of result (calibration) validated across η^μ

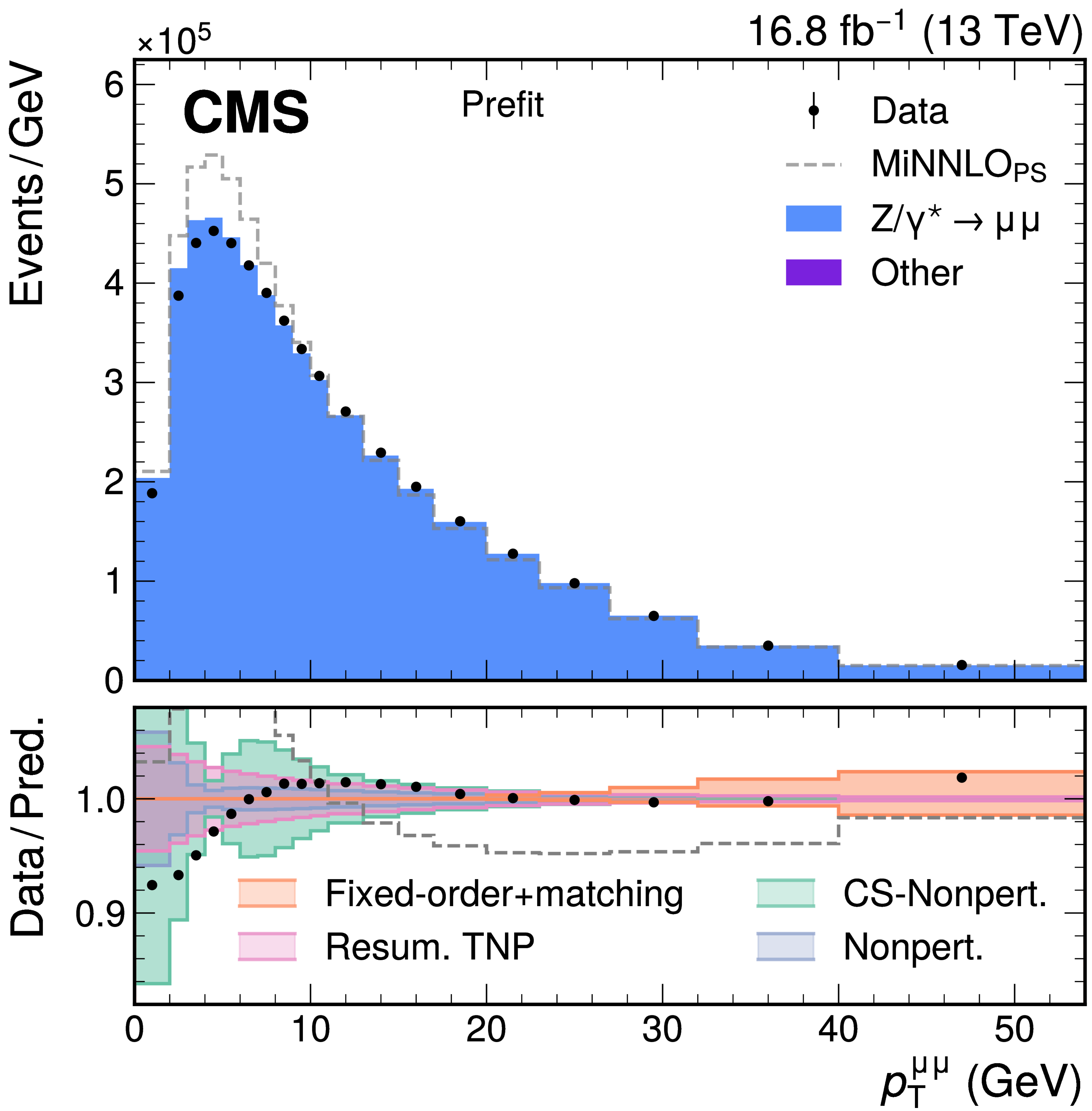




- Measurement requires percent-level control of predictions
- **Predictions for W and Z production combine complex calculations with many sources of uncertainty**

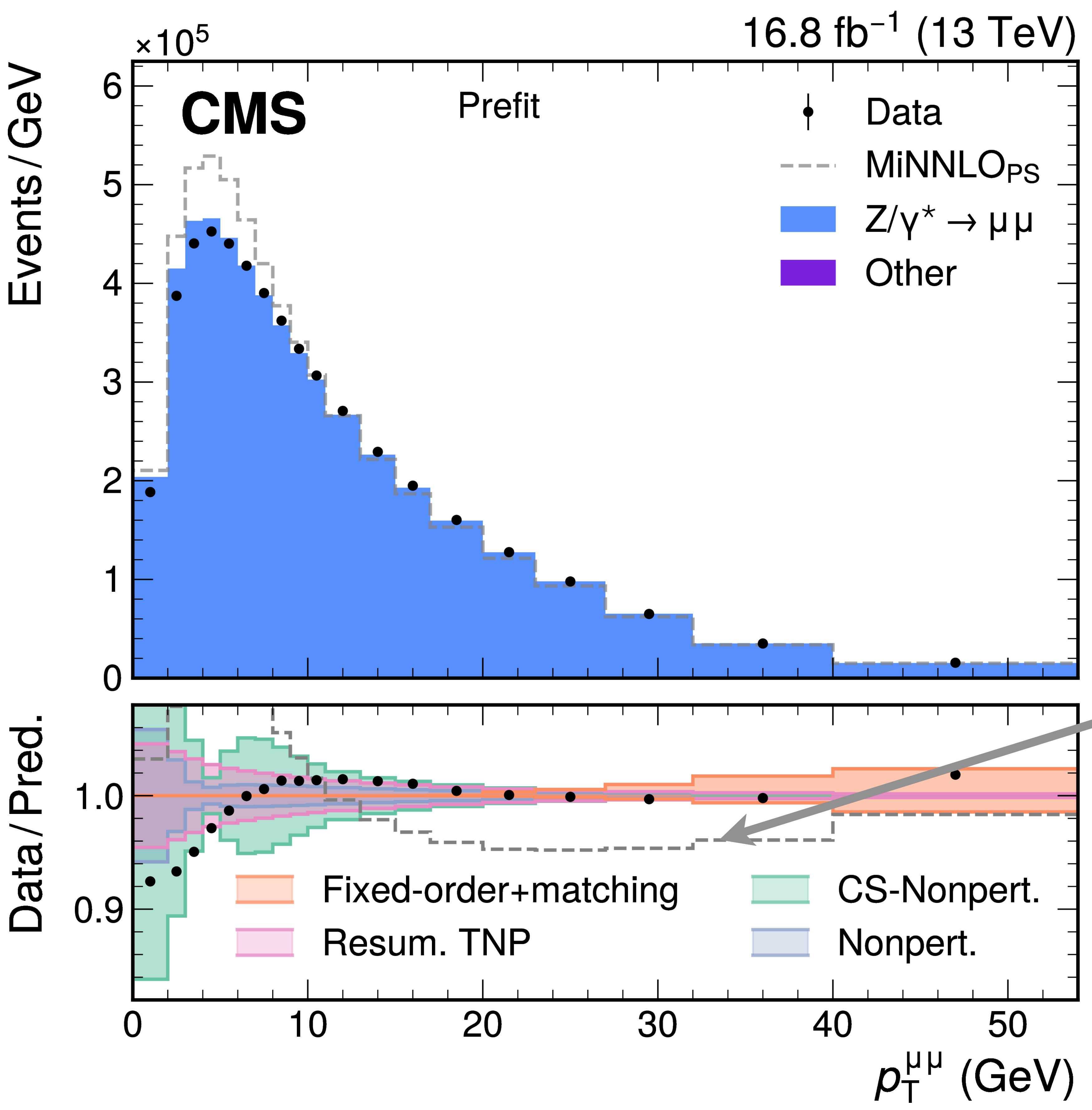


- PDF determines quark flavour and momentum
  - Non-perturbative motion of quarks important at low p_T^V
- Resum soft gluons for low/intermediate region
- pQCD accurate at high p_T^V
- Electroweak corrections small, but relevant

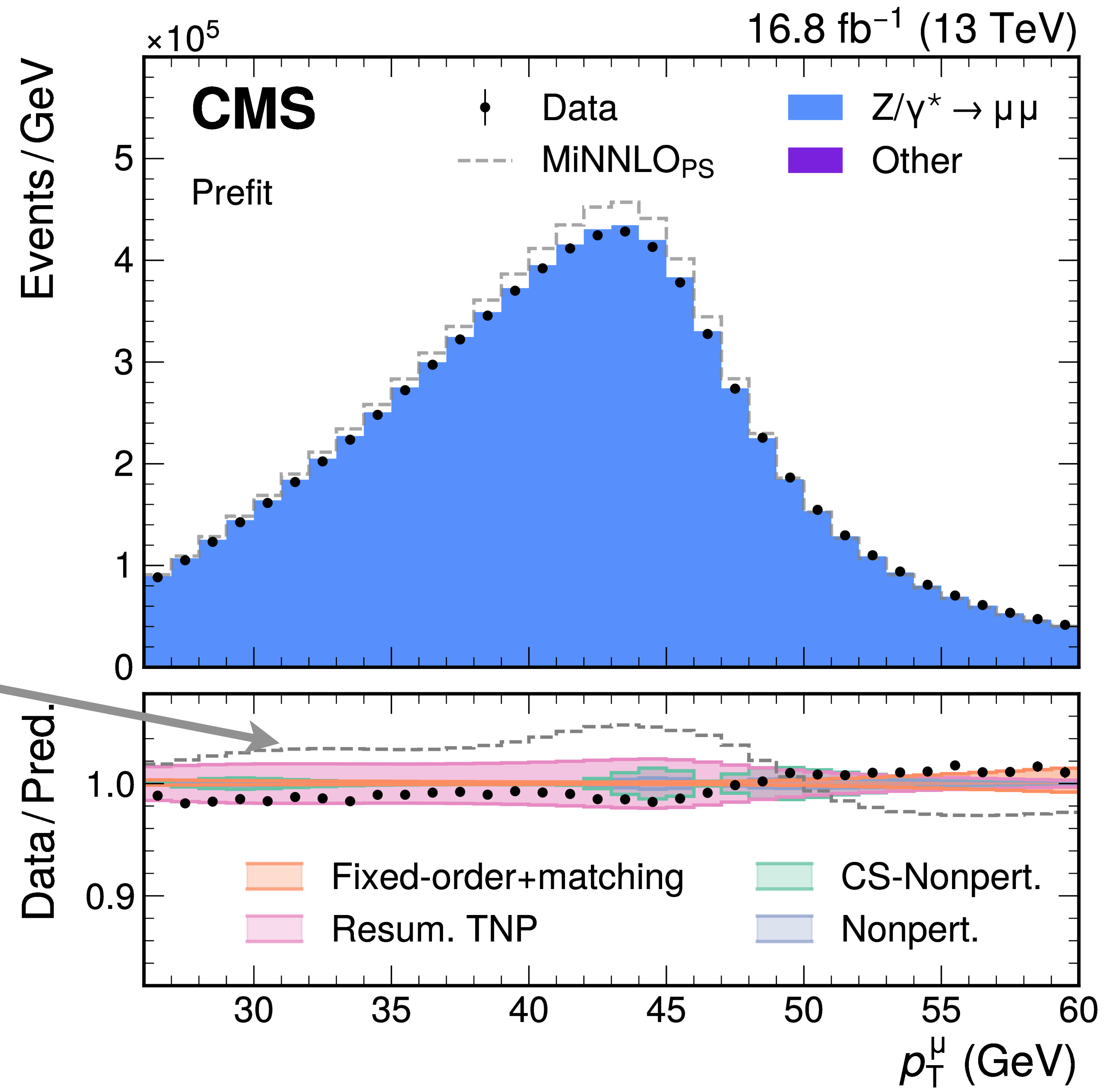


W boson production modeling and uncertainties: overview

- Huge Monte Carlo samples with full detector simulation (4 B events) from MiNNLO$_{PS}$+Pythia+Photos
  - Low-p_T^V dominated by non-perturbative effects, radiation of soft gluons (modelled by Pythia)
    - Improved accuracy from high-order calculation in resummation theory
    - Apply granular, high-stat. 2D **binned corrections to MiNNLO from SCETlib (N^{3}LL+NNLO)**

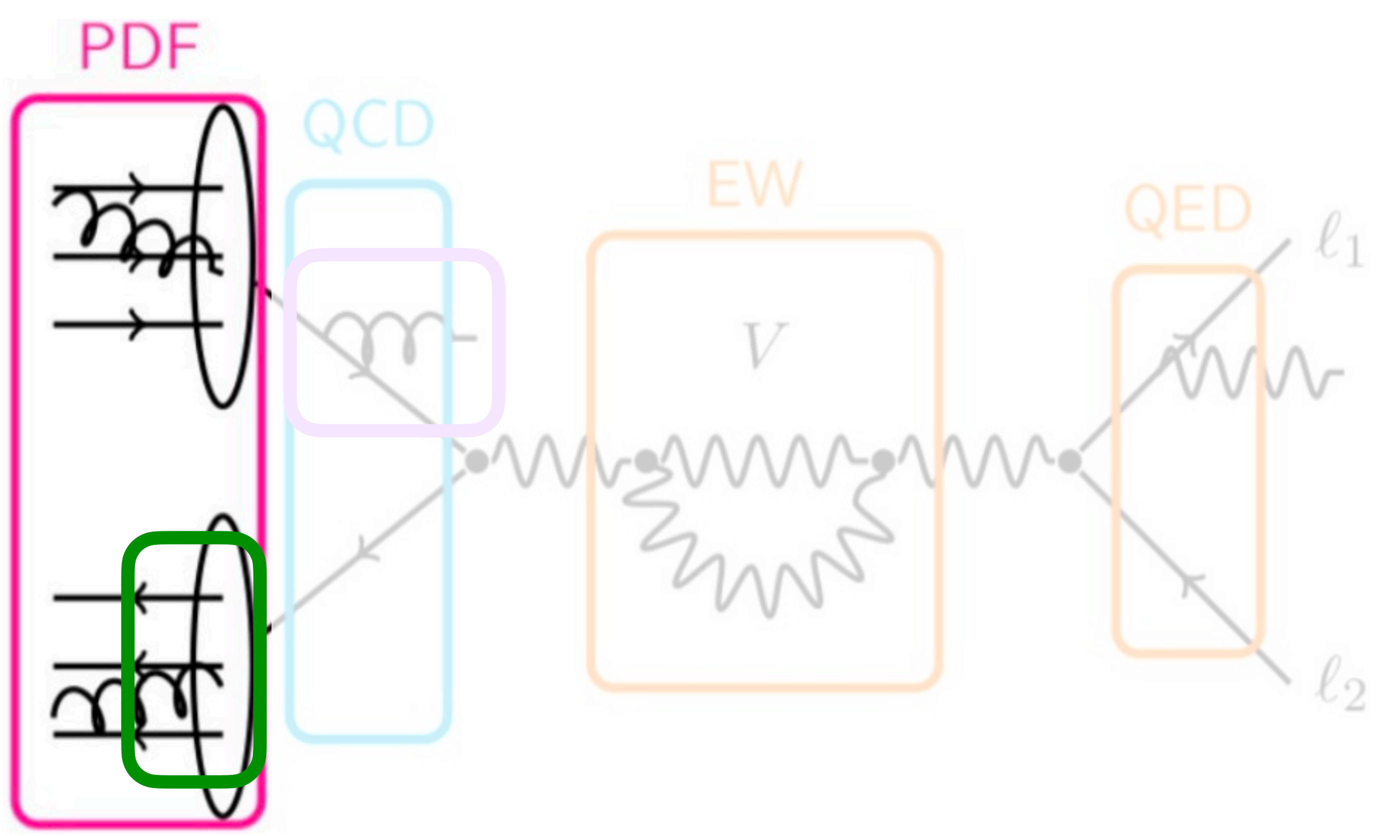


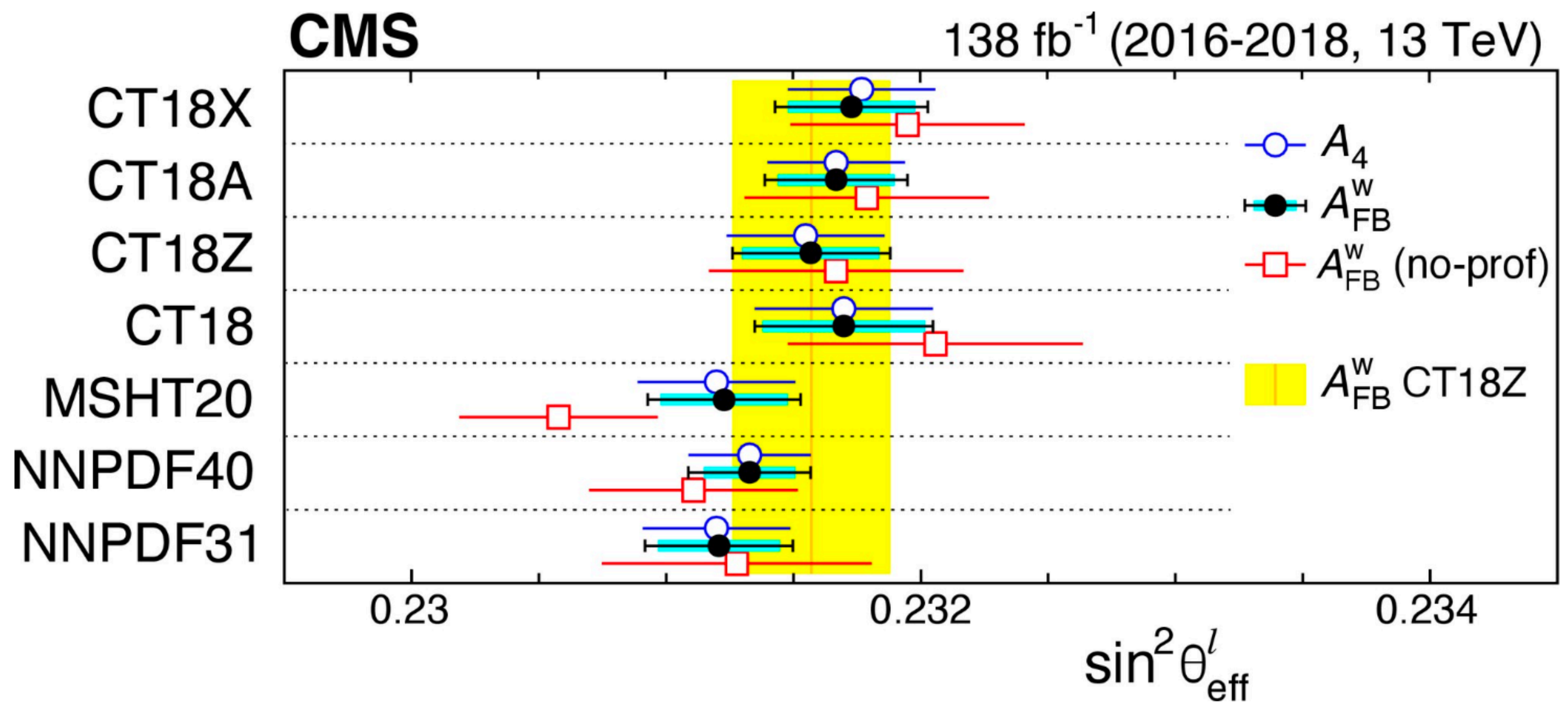
MiNNLO$_{PS}$+Pythia
Uncorrected

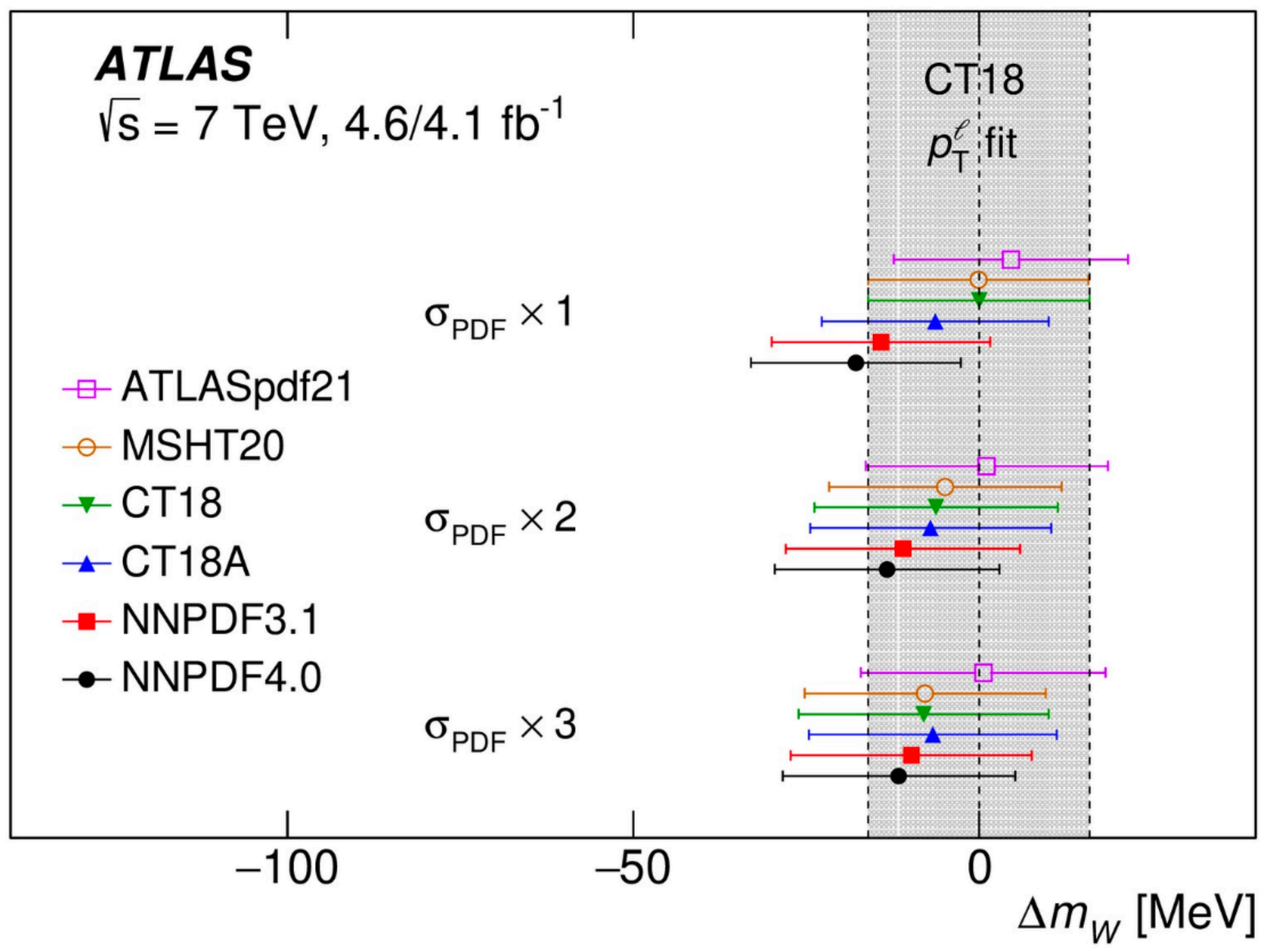


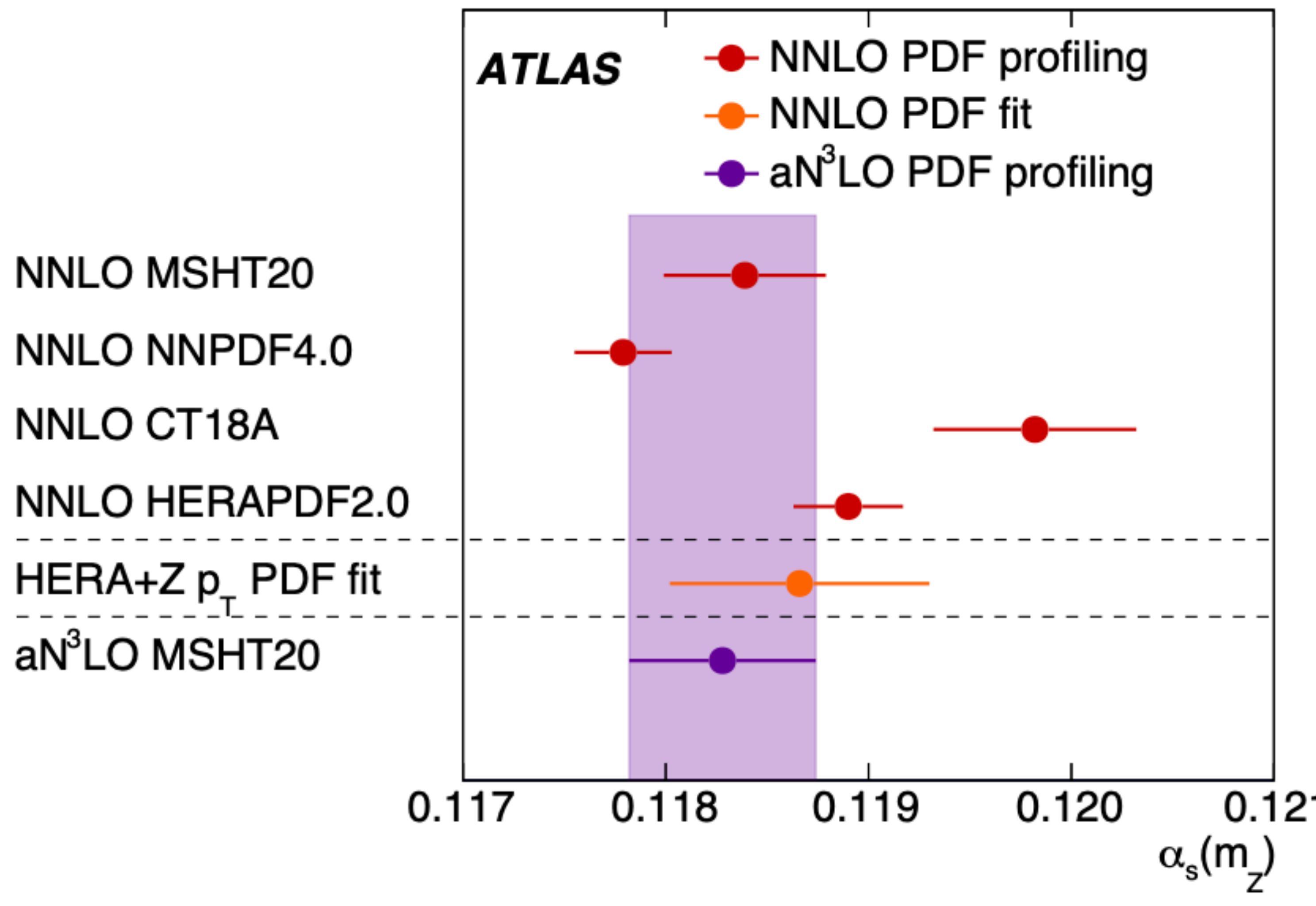
Theoretical modeling: PDF

- **PDF uncertainty impacts W production (and decay)**
- Derived from the fitted experimental data (with tolerance)
  - Well defined statistical treatment
  - But… different parameterisations are not necessarily covered by unc.
    - ➡ Seen in wide range of precision measurements
  - **No PDFs include theory unc.** (approx. in special MSHT20, NNPDF)

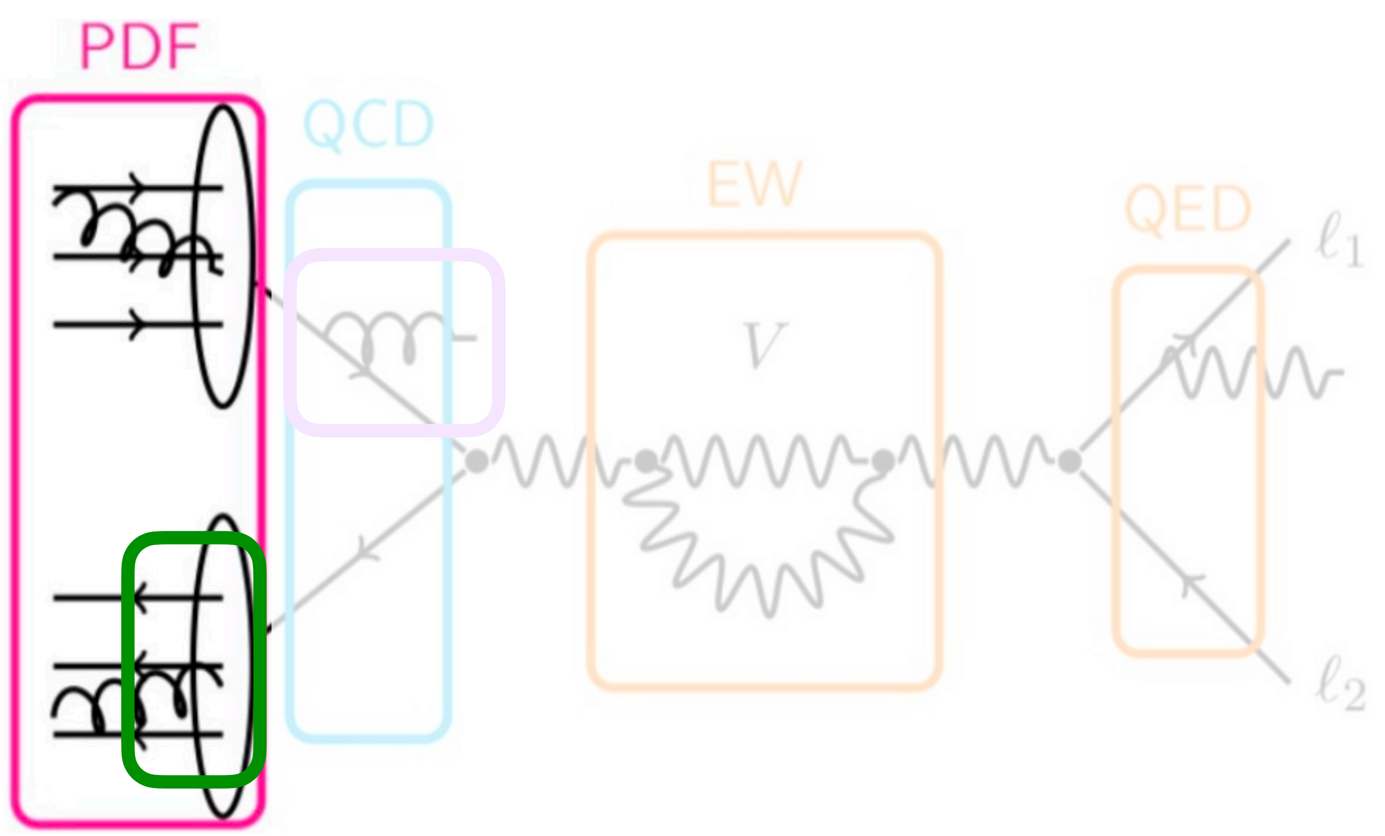




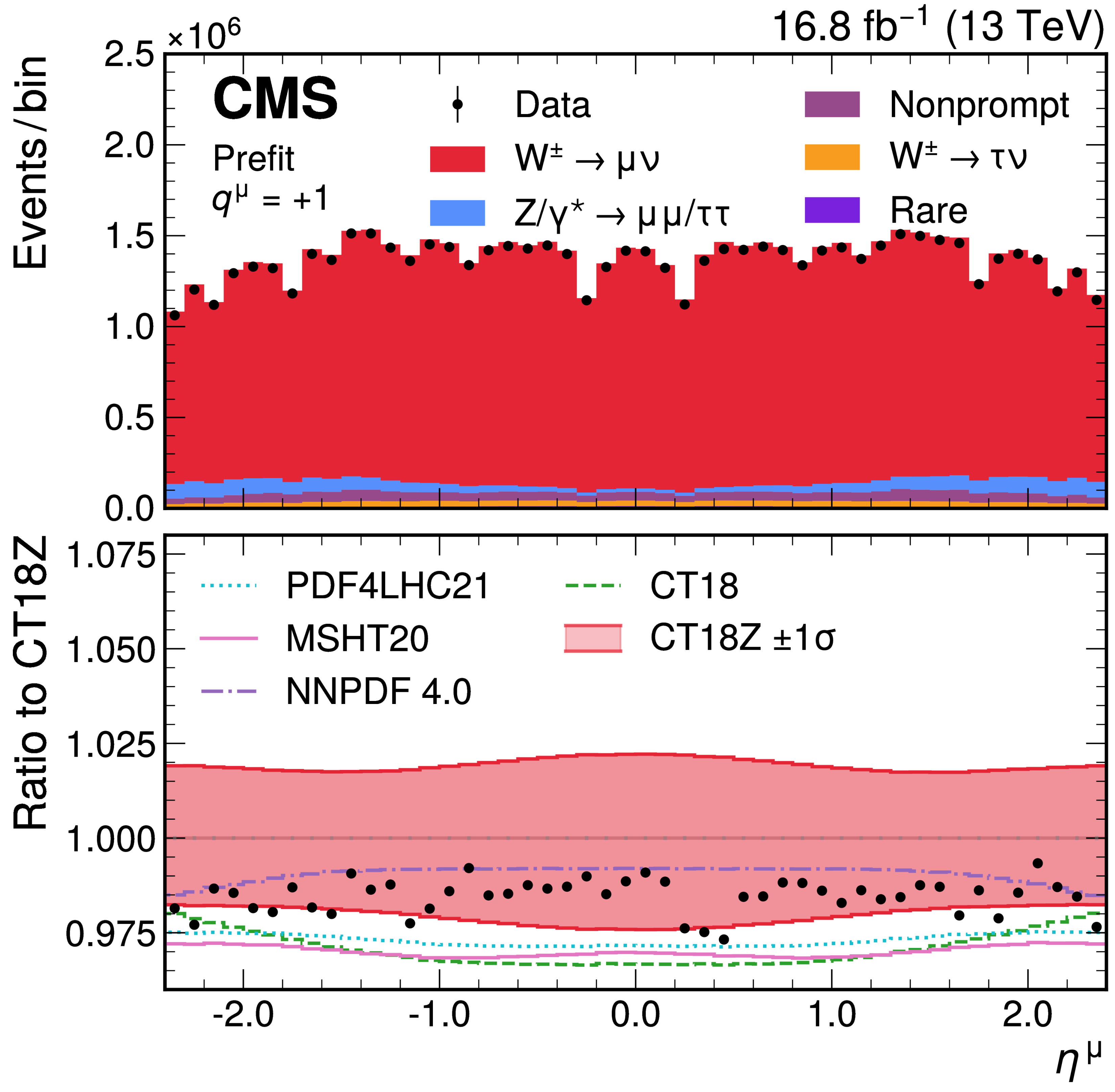




- Studied the impact of 8 modern PDF sets in our analysis
  - Compare consistency of sets with bias tests:
    - Consider one as MC prediction and others as pseudo data
    - Derive scaling factors per PDF set from bias studies
  - ➡ Results for m_W with derived scaling and unscaled
- **Select CT18Z as nominal set** because of coverage of other sets and consistency with our data
  - ➡4.4 MeV in m_W

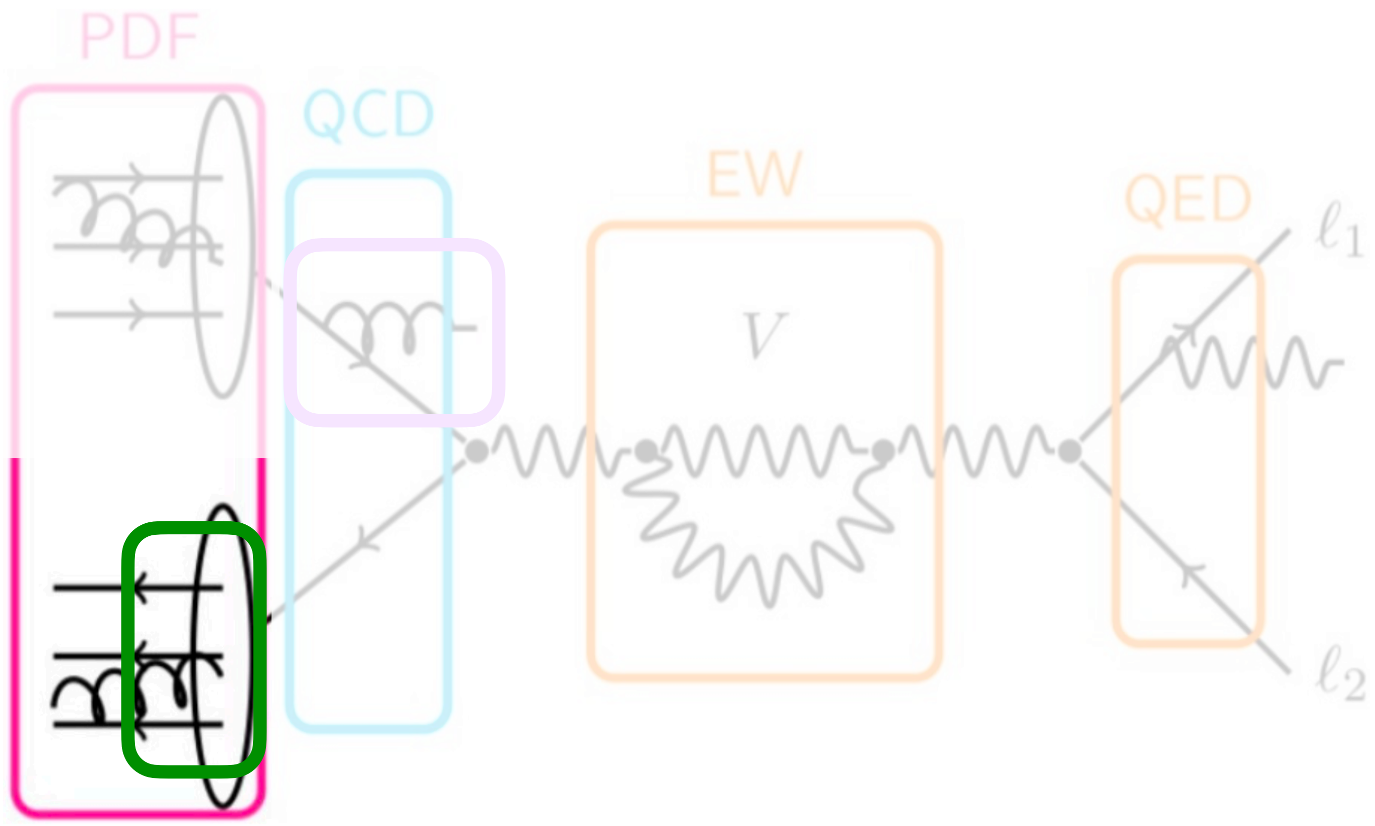


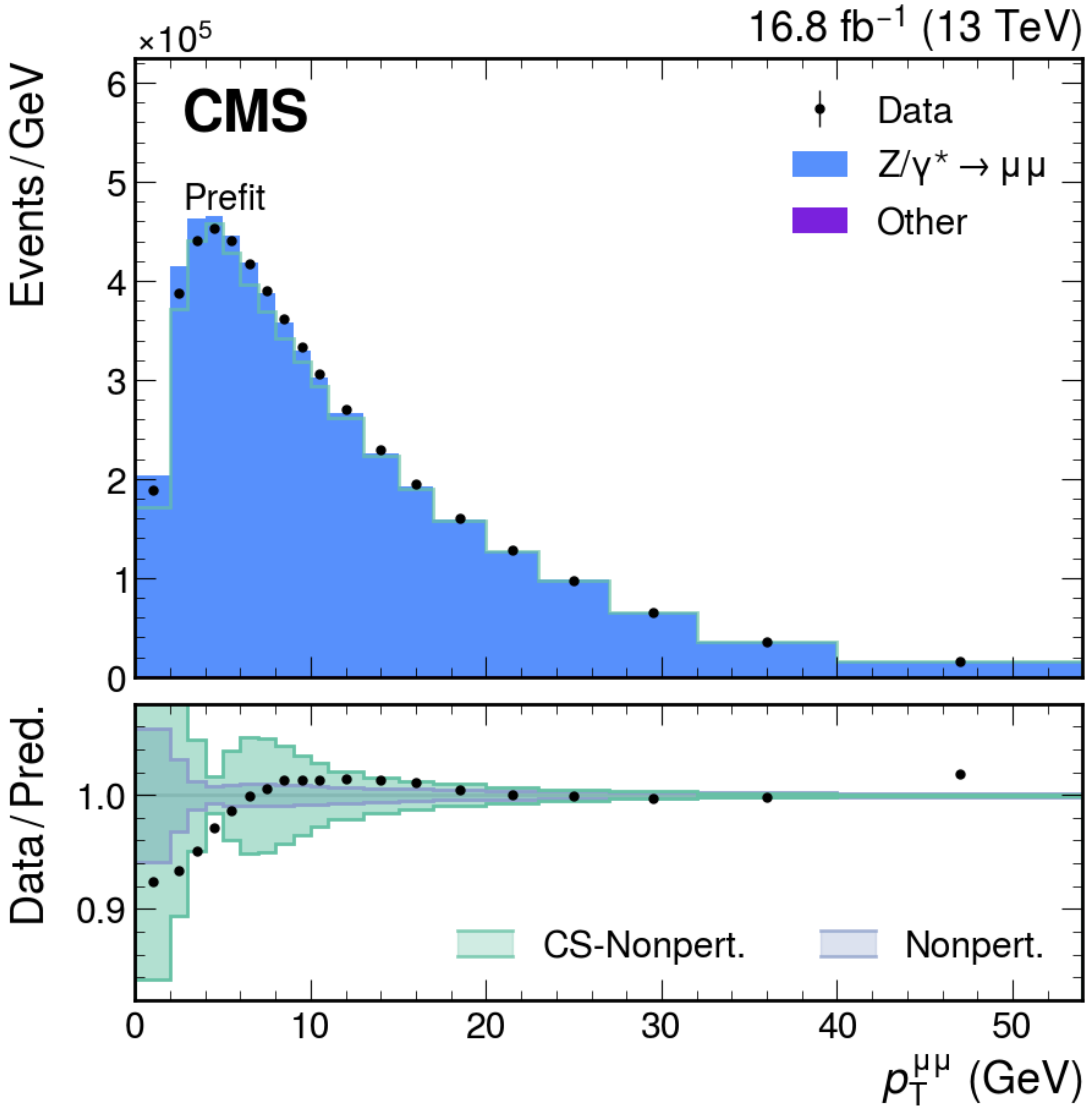
PDF set	Scaling factor	Impact on m_W Original σ_{PDF}	Impact on m_W Scaled σ_{PDF}
CT18Z	1.0	4.4	
CT18	1.0	4.6	
PDF4LHC21	1.0	4.1	
MSHT20	1.5	4.3	5.1
MSHT20an3lo	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0

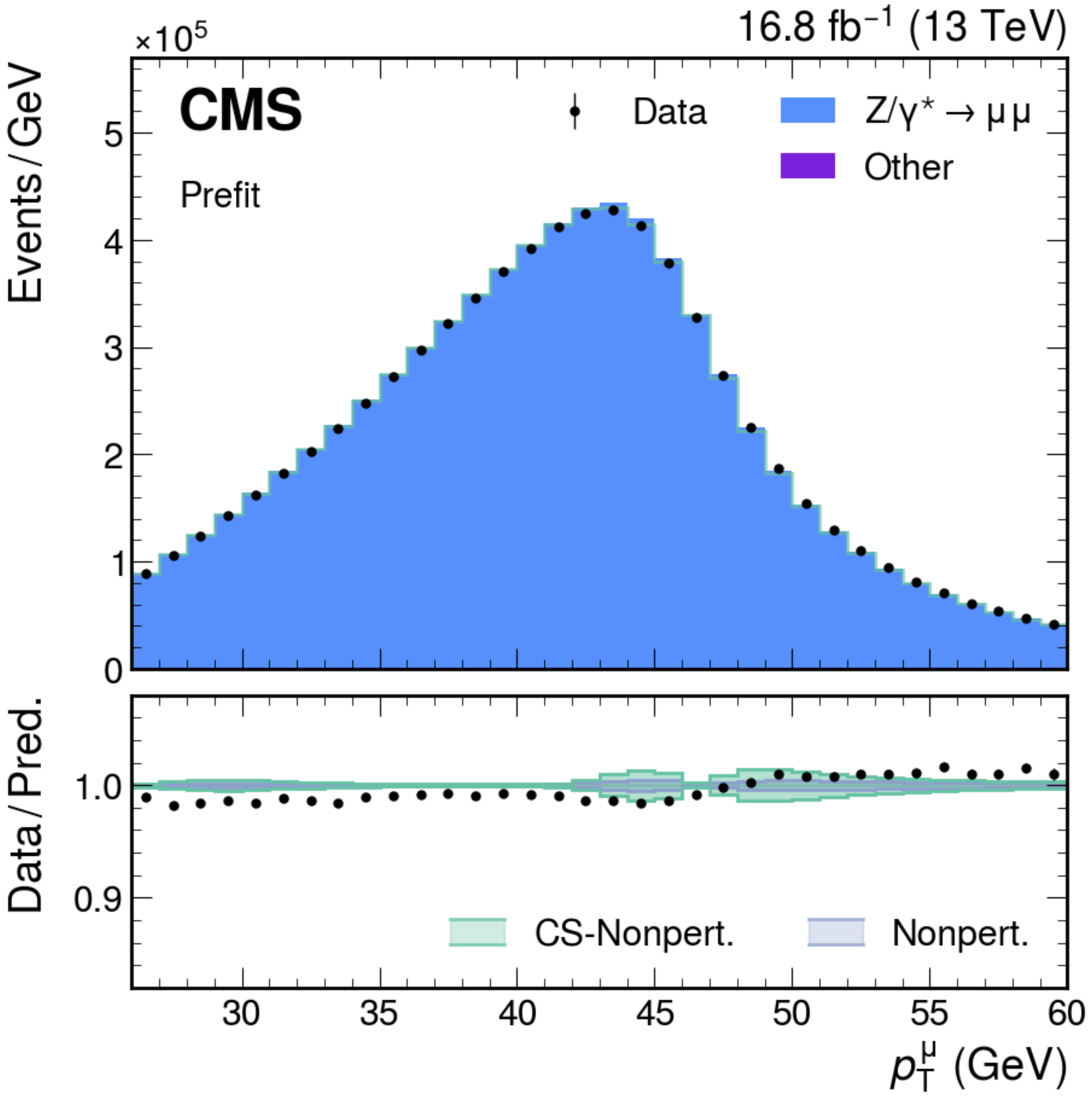


Nonperturbative effects and uncertainty

- PDF assumes parton momentum is entirely aligned with the proton motion
  - Residual motion in the proton: **low energy ⟹ nonperturbative (NP)**
- Use **phenomenological NP model in SCETlib** inspired by lattice QCD







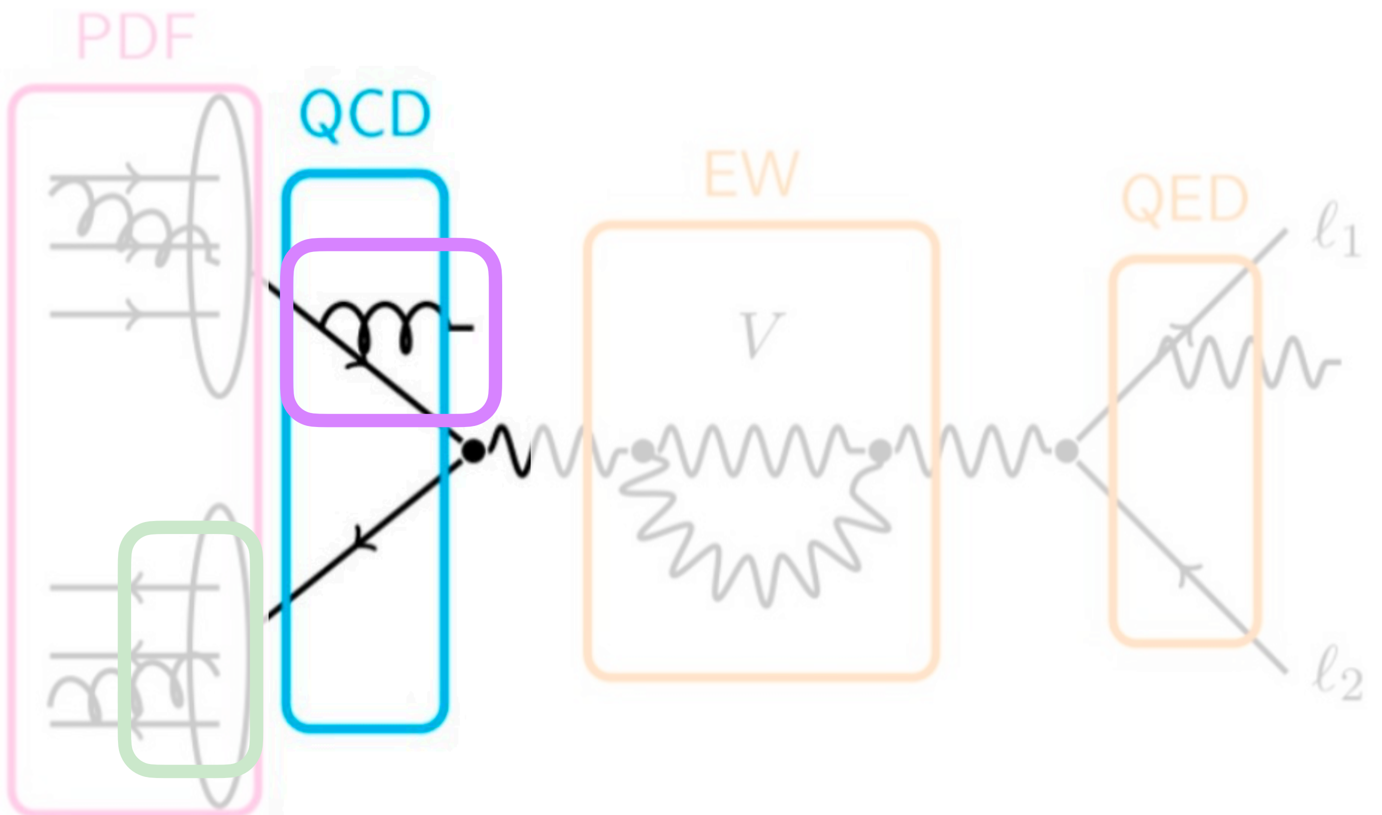
- Collins–Soper (CS) kernel universal (correlated for W and Z)
- Others (Gaussian intrinsic momentum) not correlated

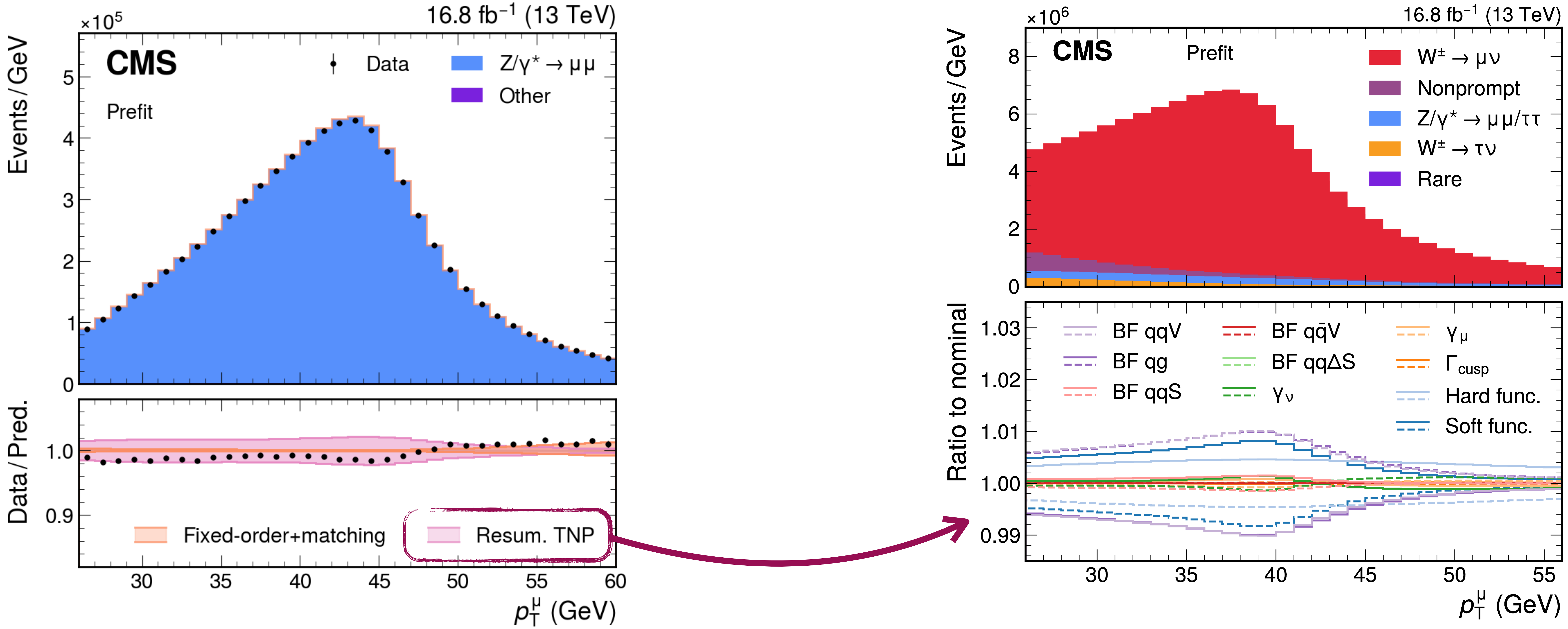
$$\tilde{\sigma}^{\rm np}(Y) = \left[1 + \overline{\Lambda}^{(2)}(Y)\, b_T^2\right]^2 \exp(-2\Lambda^{(4)}\, b_T^4)\,,$$
$$\overline{\Lambda}^{(2)}(Y) = \overline{\Lambda}^{(2)} + Y^2 \Delta\overline{\Lambda}^{(2)}\,.$$

arxiv:2201.07237

Perturbative uncertainties

- “Theory nuisance parameters” calculated w/SCETlib at N^{3}LL
  - Structure of resummation is known, many corrections are (unknown) numerical constants
  - Uncertainties directly represent unknown terms
  - Meaningful shape variation **(critical!)** and meaningful constraints from data

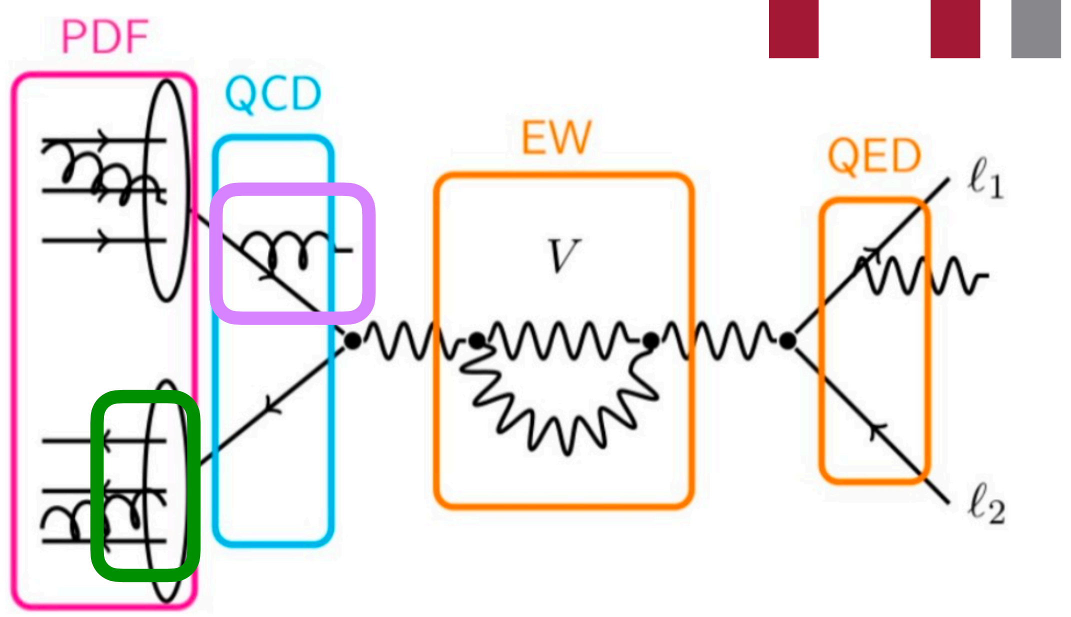


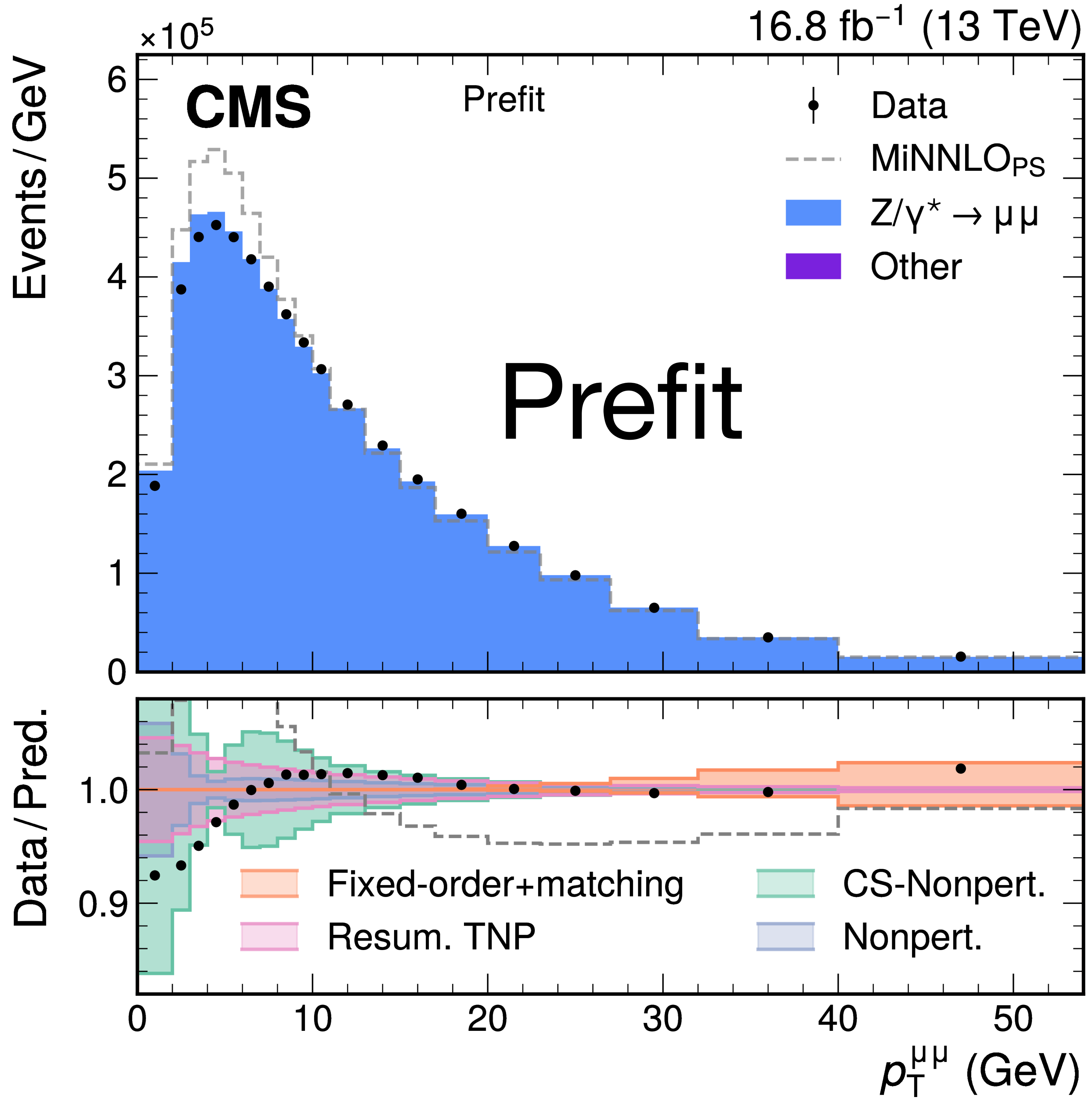


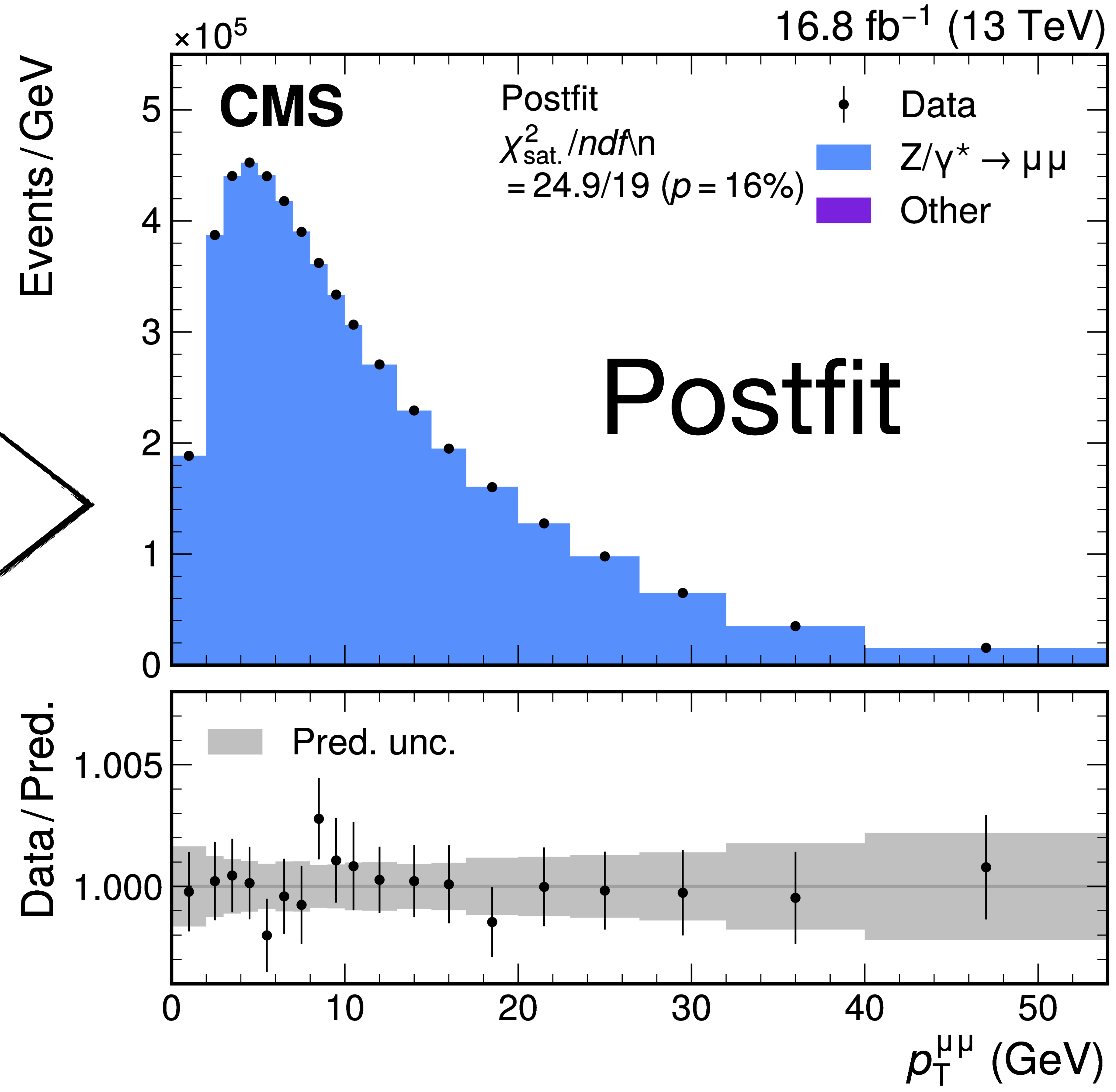
Sufficiency of the theoretical model

- General strategy: **do not tune parameters of the theoretical models**
  - Data corrections directly from maximum likelihood fit
- Direct fit to ($y^{\mu\mu}$, $p_T^{\mu\mu}$) is first test of sufficiency of this approach

➡**p-value of 16%; total unc. in m_W 2.0 MeV**





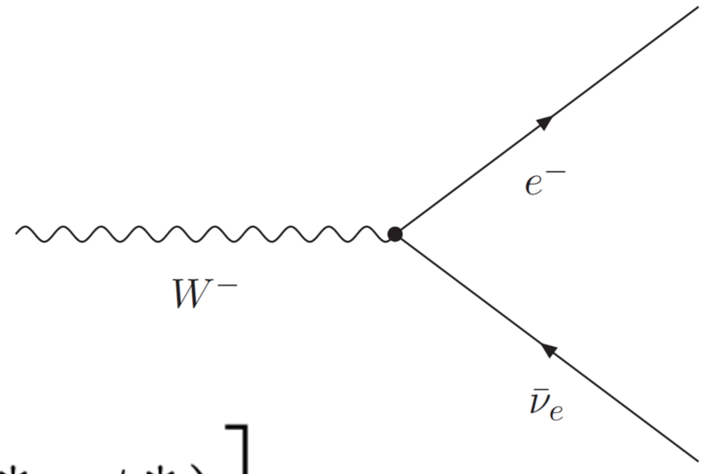


ATLAS: tune Pythia to p_T^Z (5 MeV unc.)

CDF: Tune Resbos+reduce unc. from data comparisons (2 MeV unc.)

W/Z helicity states and impact on lepton kinematics

- For a given helicity state, **relationship between V = W, Z and decaying leptons is known analytically** (up to small higher-order QED corrections)



$$\frac{d\sigma}{dp_T^2\, dm\, dy\, d\cos\theta^*\, d\phi^*} = \frac{3}{16\pi} \underbrace{\frac{d\sigma_{UL}}{dp_T^2\, dm\, dy}}_{\text{Kinematics of W/Z}} \left[(1+\cos^2\theta^*) + \sum_{i=0}^{7} \underbrace{A_i(p_T, m, y)}_{\text{Angular coefficients (Predicted by pQCD)}} \cdot \underbrace{P_i(\cos\theta^*, \phi^*)}_{\text{Spherical harmonics of decay angles in CS frame}}\right]$$

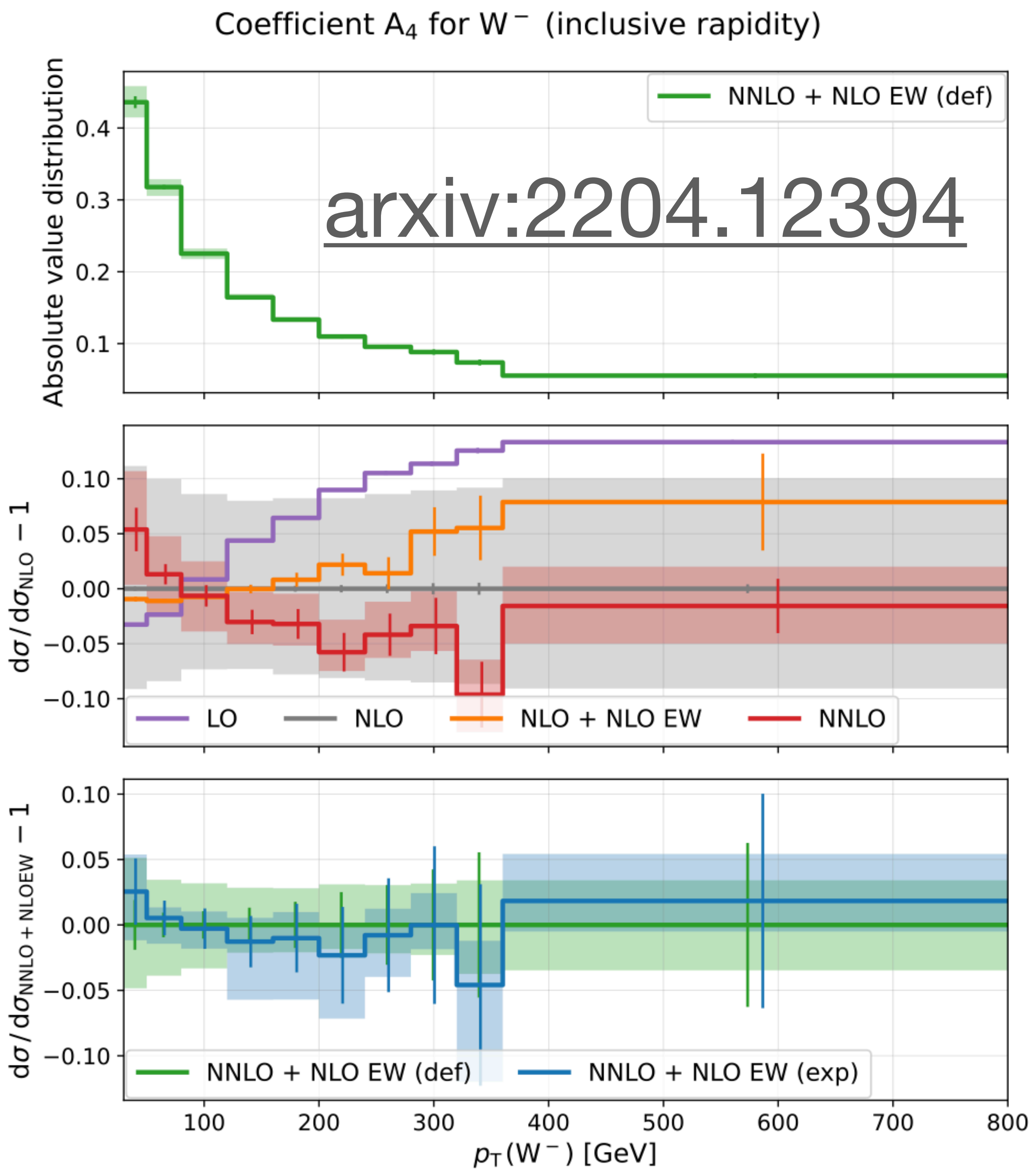
Kinematics of W/Z

Angular coefficients (Predicted by pQCD)

Spherical harmonics of decay angles in CS frame

- Modifications of A_i **change relationship between p_T^V and p_T^μ**
  - Estimated at NNLO with MiNNLO, verified consistency with fixed-order NNLO
  - Uncertainty from scale variations, uncorrelated across 10 bins of p_T^V

➡3.3 MeV unc. in mW



W/Z helicity states and impact on lepton kinematics

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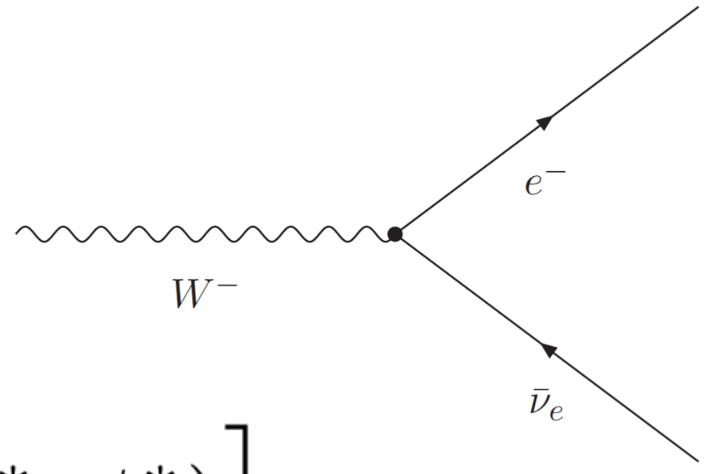
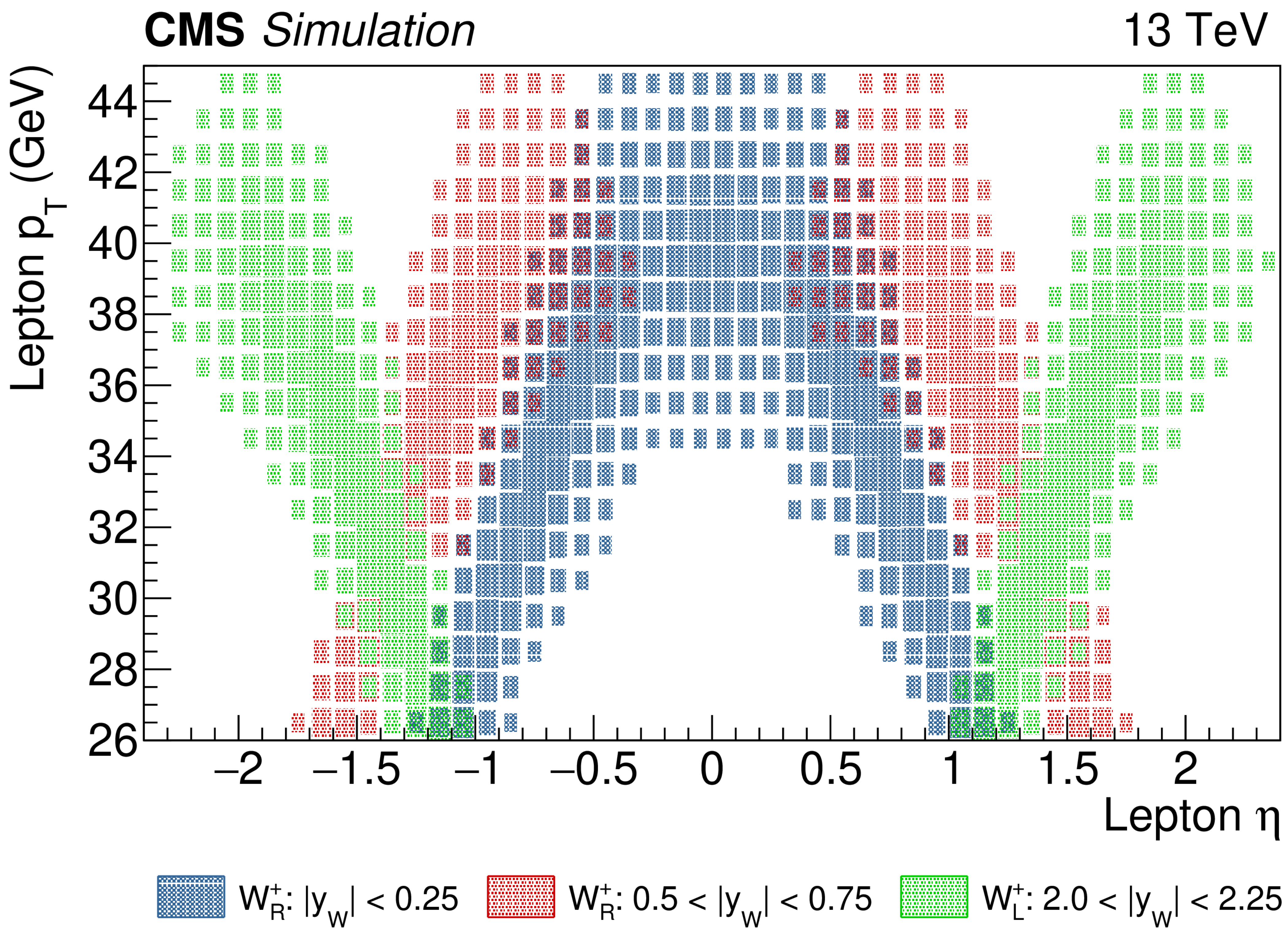


$$\frac{d\sigma}{dp_T^2\, dm\, dy\, d\cos\theta^*\, d\phi^*} = \frac{3}{16\pi} \underbrace{\frac{d\sigma_{UL}}{dp_T^2\, dm\, dy}} \left[(1+\cos^2\theta^*) + \sum_{i=0}^{7} \underbrace{A_i(p_T, m, y)} \cdot \underbrace{P_i(\cos\theta^*, \phi^*)} \right]$$

- Exploit this relationship for **alternative theory-reduced measurement (helicity cross-section fit)**
  - Measure (y^V, p_T^V): divide (η^V, p_T^μ) templates by A_i
  - ~600 parameters, binned in (y^V, p_T^V) per A_i, loosely constrained around theory
    - Uncertainty in σ_{UL} (σ_4) of 50% (100%), others constrained by envelope of theory unc (e.g., different PDFs)

➡Larger stat. uncertainty but reduced theory dependence



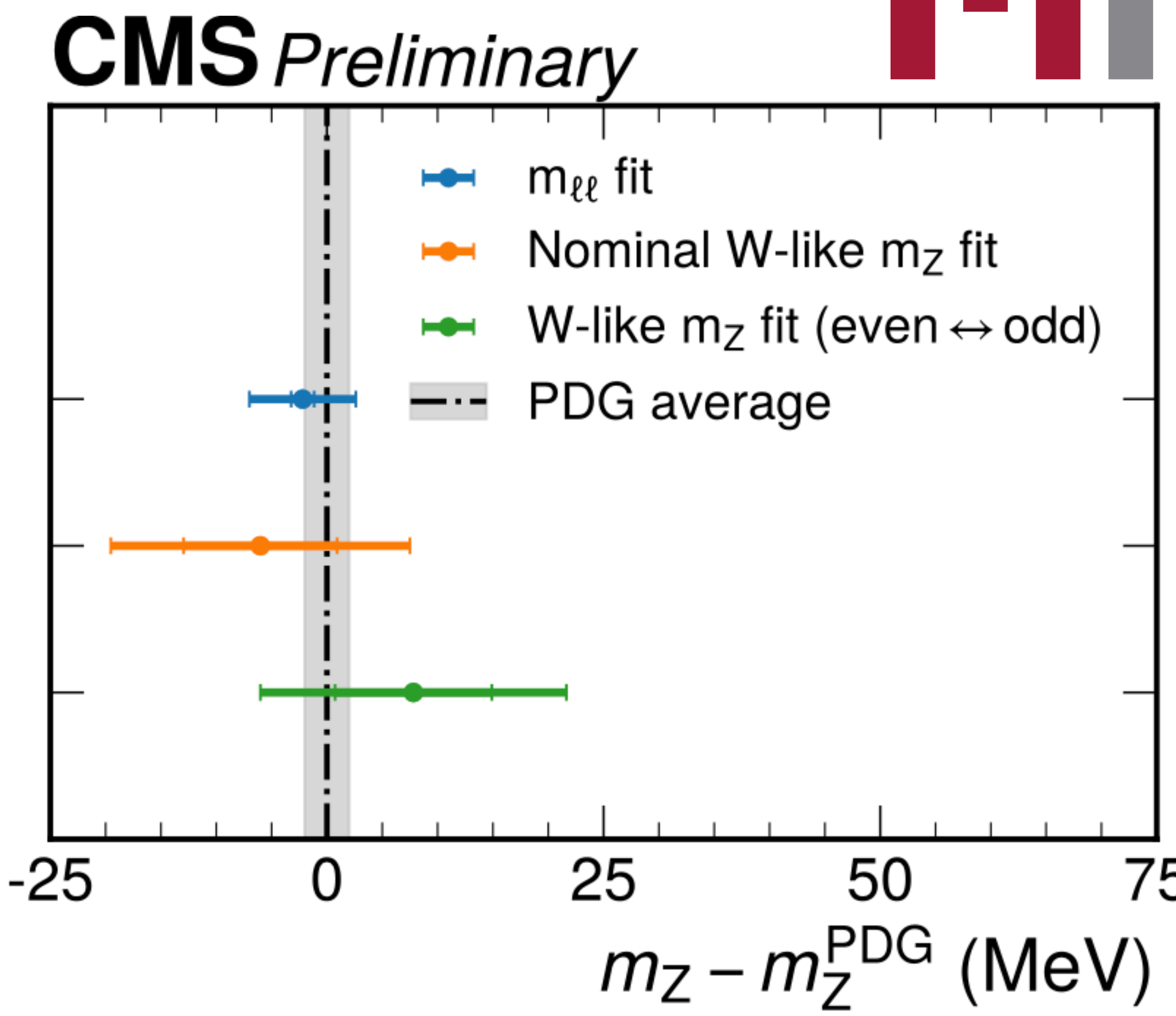
(R,L related to A_4)

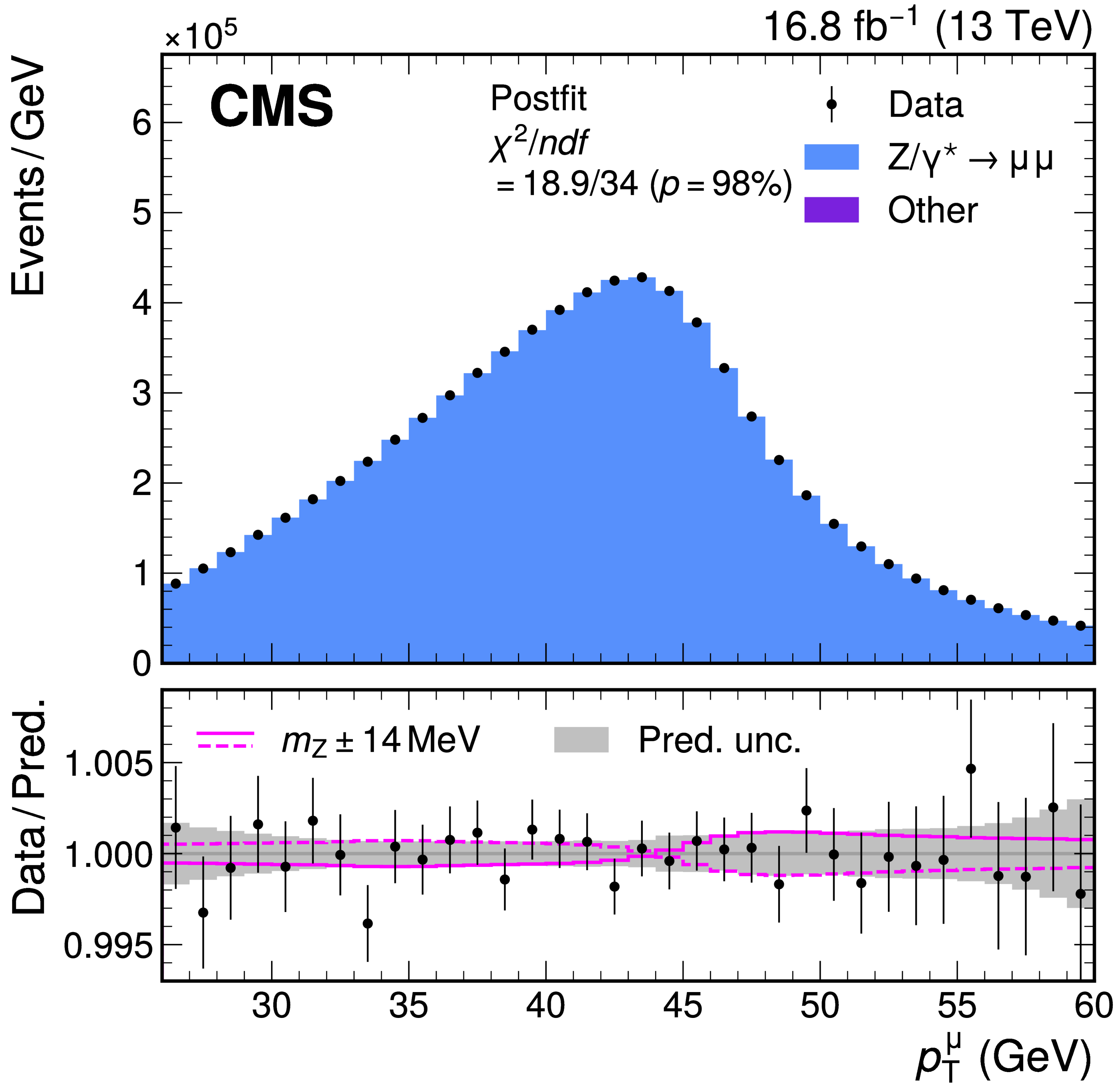
★ Extracting m_Z from fit to (η^μ, p_T^μ)

- W-like measurement of m_Z using approach developed for m_W
  - Split into two data samples to avoid need for evaluating correlations within events
  - Both results highly consistent with PDG (LEP)

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

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





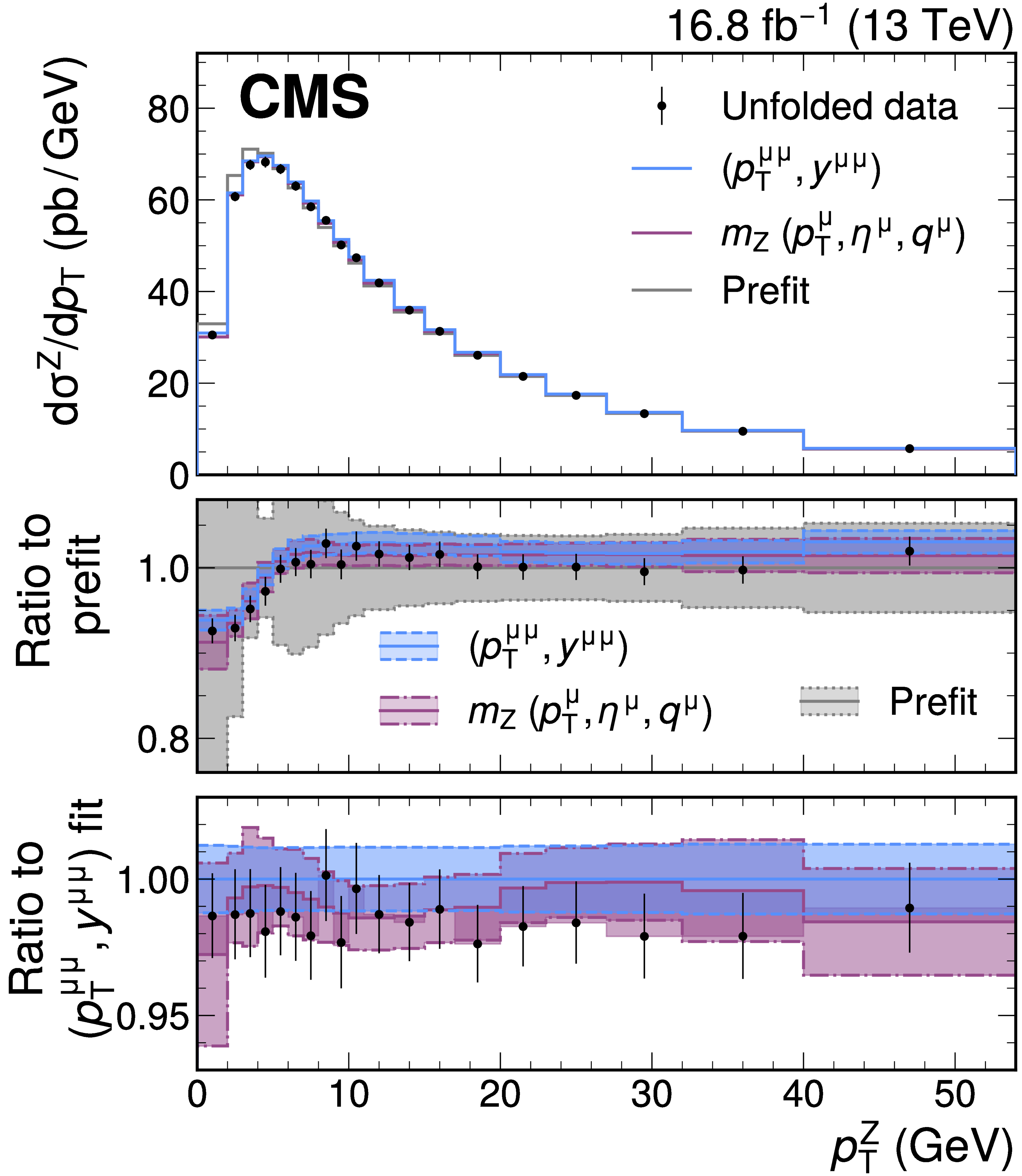
Validation of the theoretical model

- Propagate postfit pulls and constraints of theory uncertainties to generator-level distributions
  - In situ corrections from data
- Compare
  - **Unfolded $p_T^{\mu\mu}$ data**
  - **Direct fit to $p_T^{\mu\mu}$**
  - **W-like m_Z (η^μ, p_T^μ) fit**

➡ **Strong and consistent constraints between direct fit to and $p_T^{\mu\mu}$ to p_T^μ**

- (η^μ, p_T^μ) distribution able to simultaneously correct $p_T^{\mu\mu}$ and extract m_Z without bias

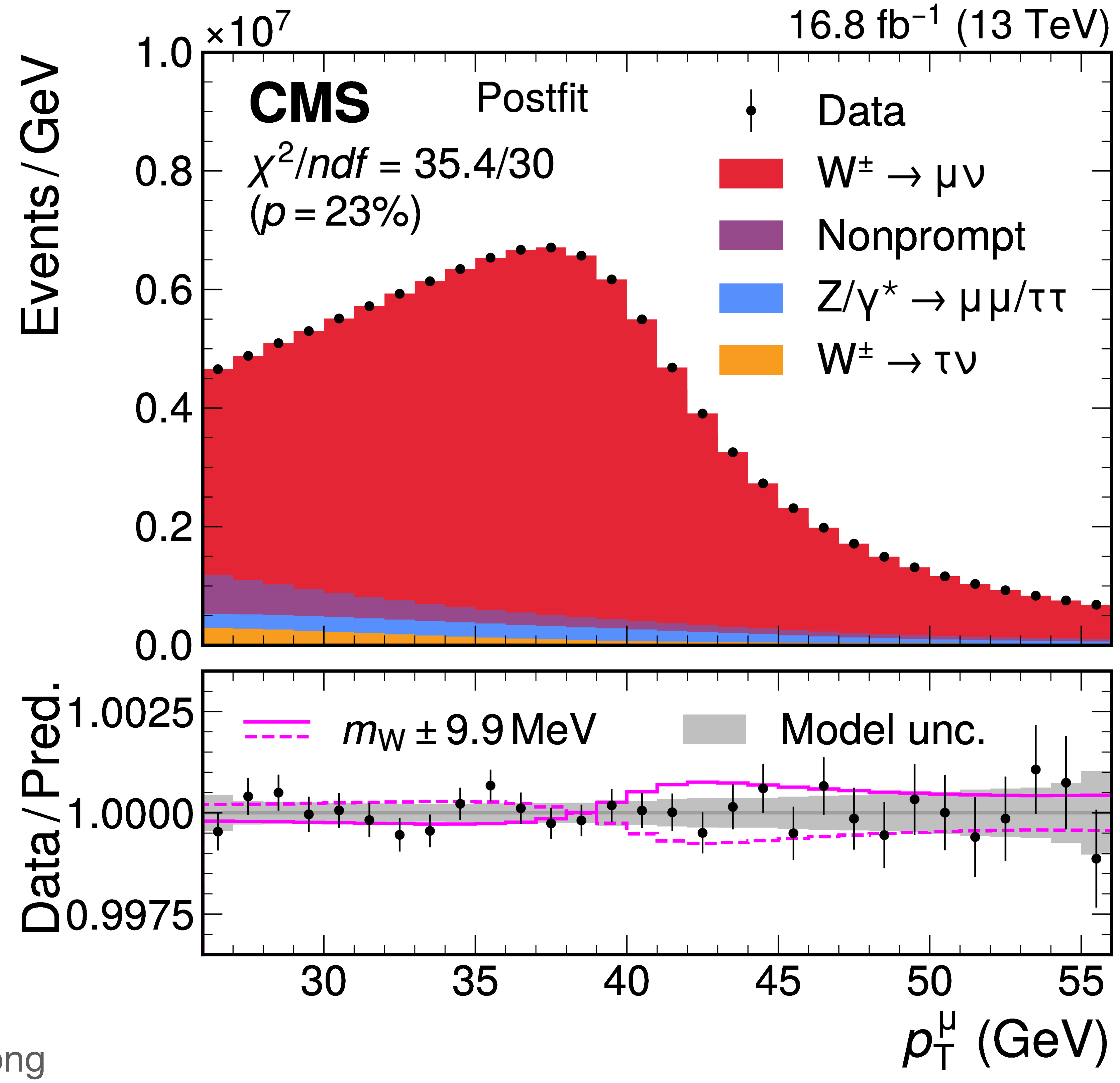
➡ **Justifies performing m_W measurement without corrections from $p_T^{\mu\mu}$**



★ Extracting m_W from fit to (η^μ, p_T^μ)

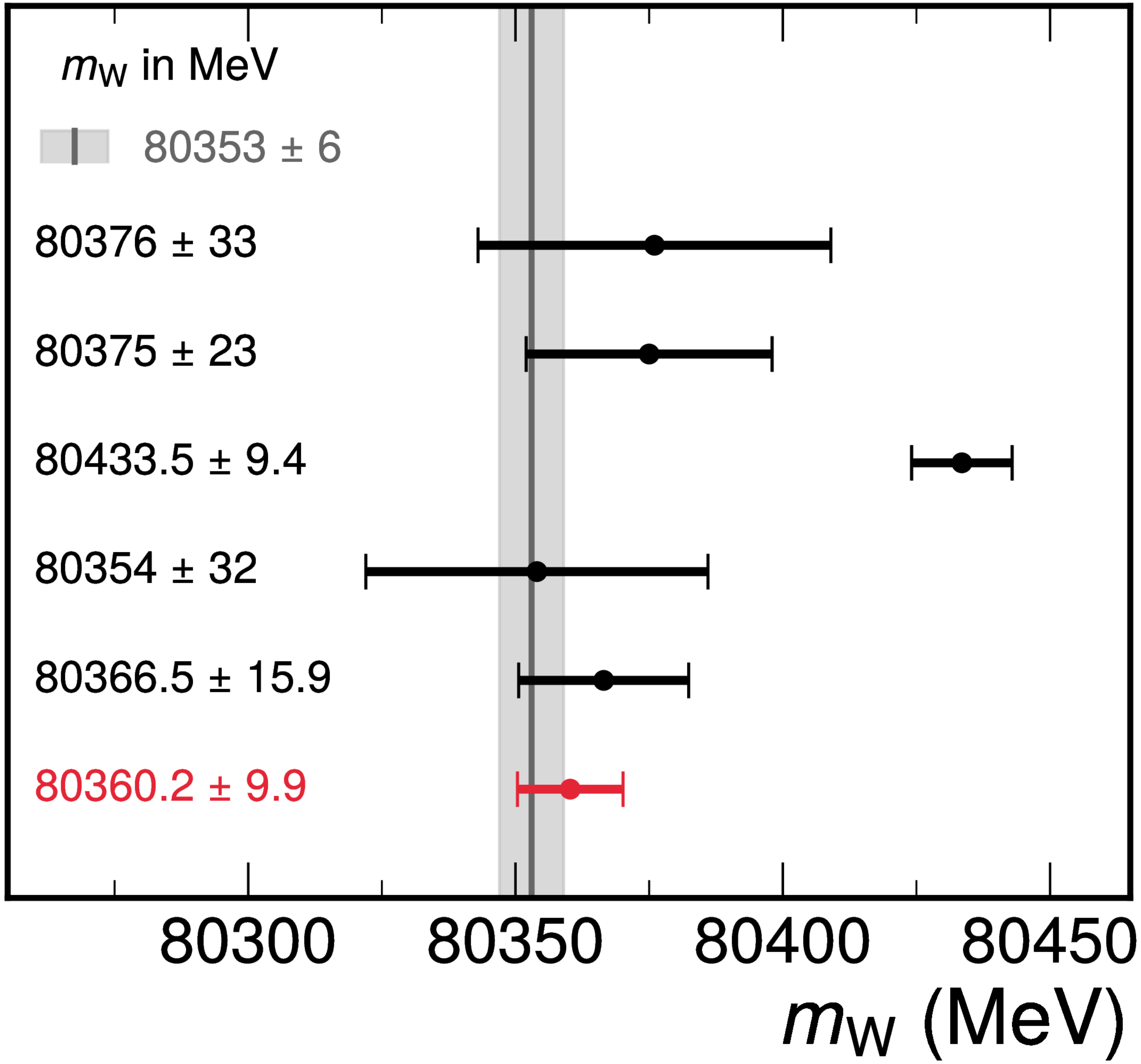
- Total uncertainty of 9.9 MeV
  - Muon momentum scale and PDF dominant unc.

$$m_W = 80360.2 \pm 9.9\,\mathrm{MeV}$$



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

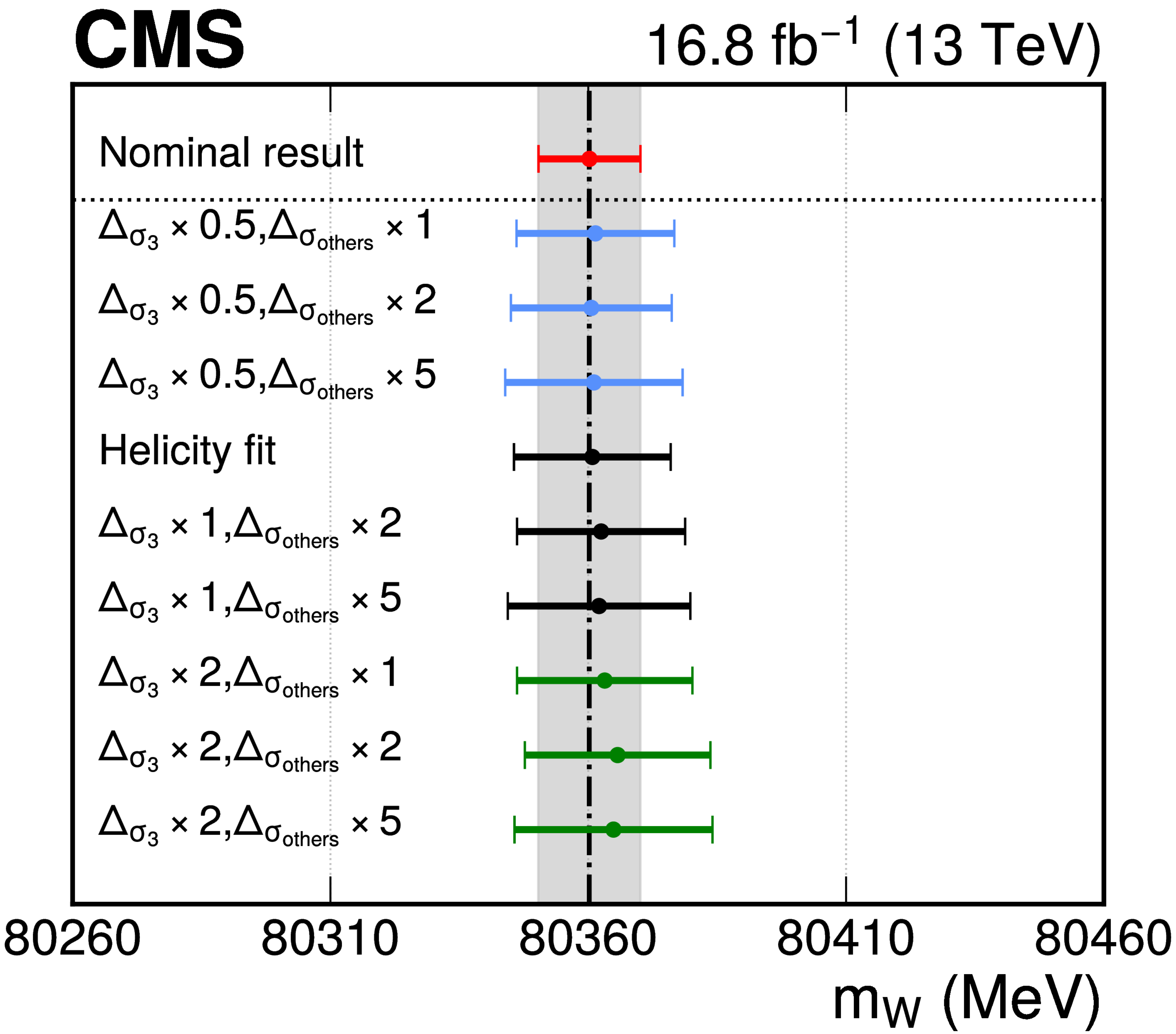
Electroweak fit
PRD 110 (2024) 030001
LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arXiv:2403.15085
CMS
This work



Helicity cross section fit result

$$m_W = 80360.8 \pm 15.2 \text{MeV}$$

- Helicity cross section fit result very compatible with the nominal
  - Larger uncertainties by design
- Result istable wrt looser or tighter initial constraints on the helicity cross sections

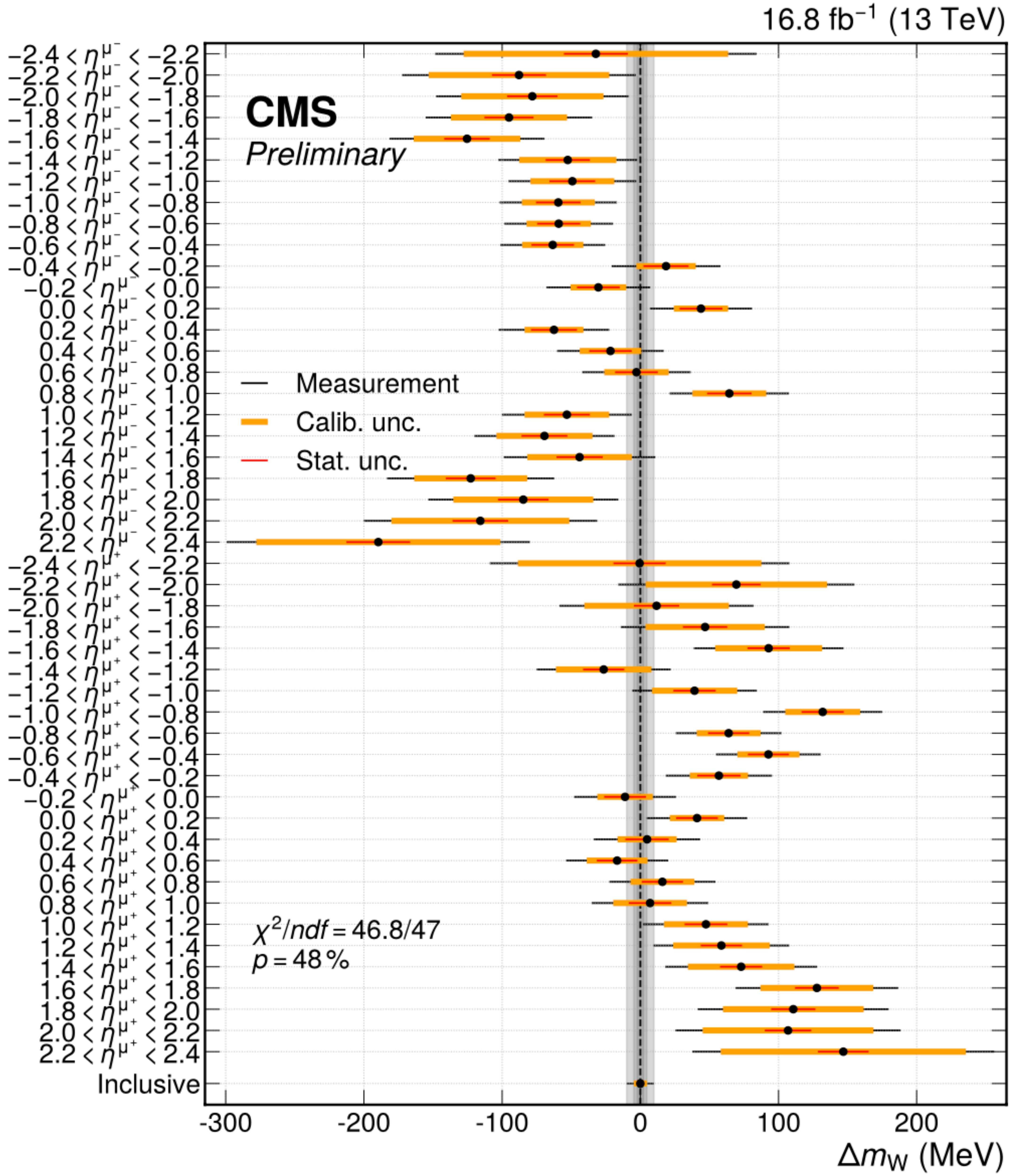


Experimental validation

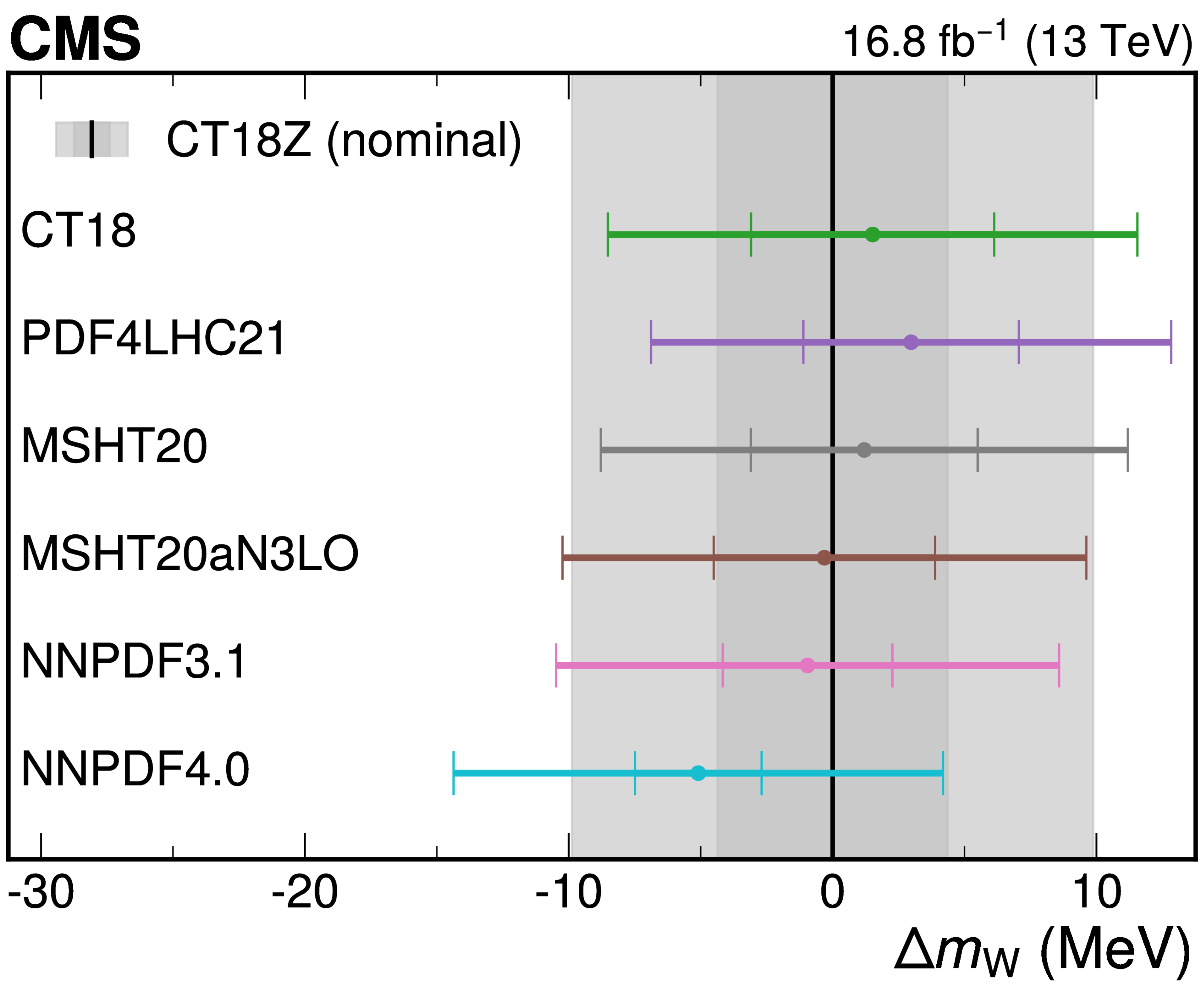
- Compatibility tested when allowing different m_W parameters per η/charge regions
- Mass difference between
  - η < 0 and η > 0: 5.8 ± 12.4 MeV
  - Barrel vs. endcap: 15.3 ± 14.7 MeV
  - W^+ and W^-: 57± 30 MeV
- Charge difference studied extensively, no issues found
  - m_{W^+} and m_{W^-} are highly anti-correlated (-40%)
  - Only 2% correlation between m_{W^+} and m_{W^-}

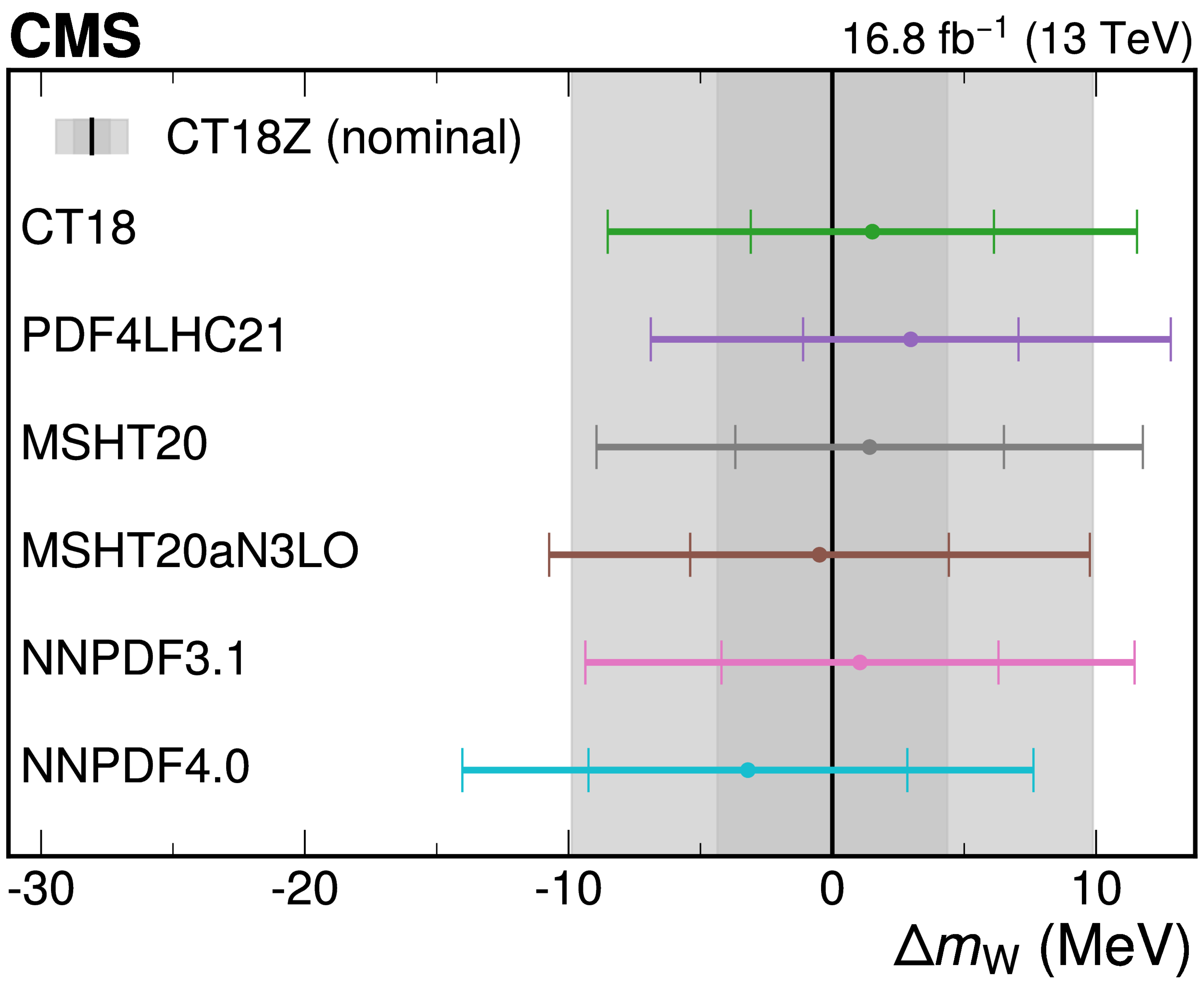
➡Even if some small charge-dependent correction is underestimated, impact in m_W is very small

  - At 1.9σ from the expectation, it is also not particularly unlikely



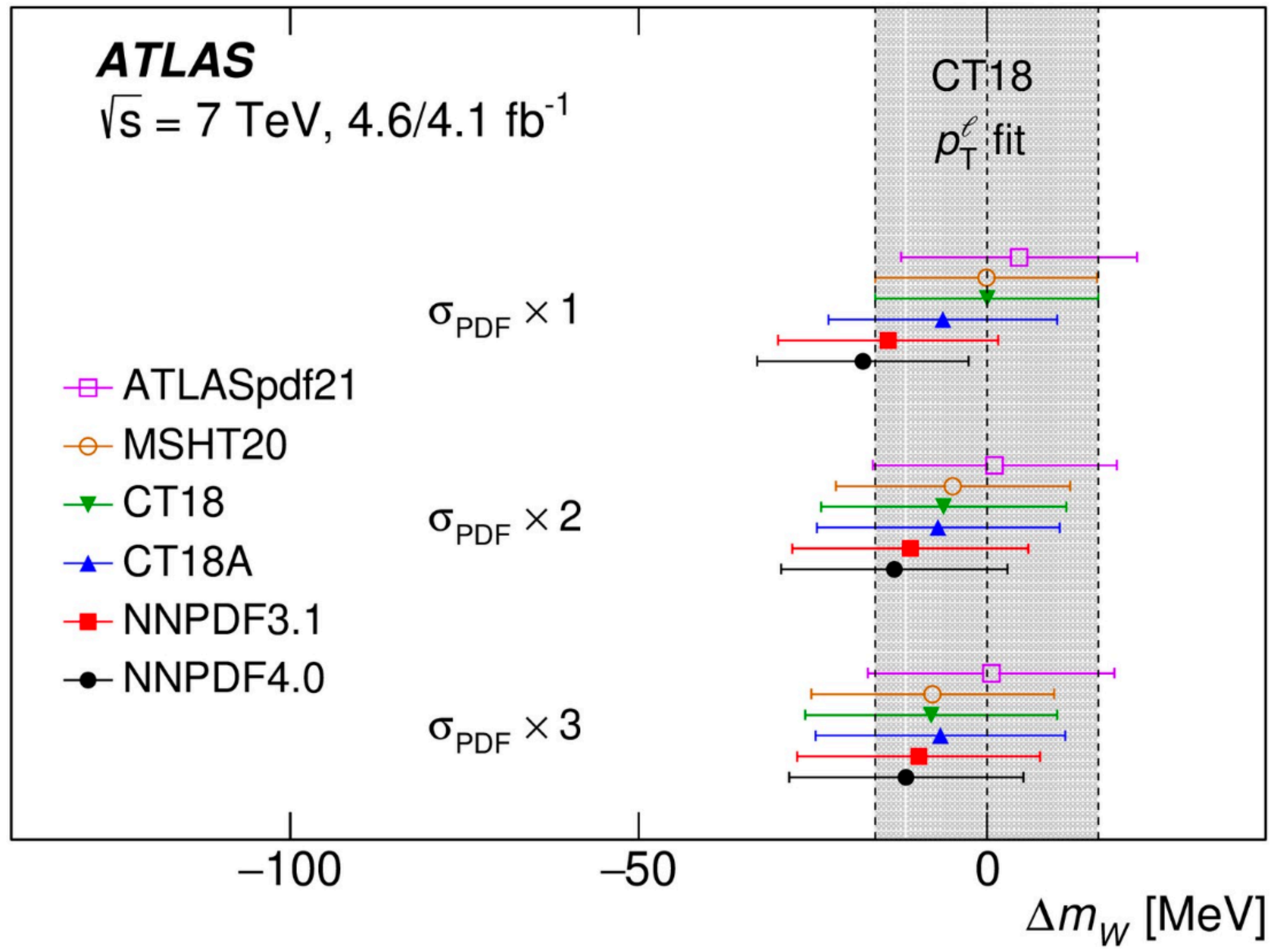
Results with alternative PDF sets





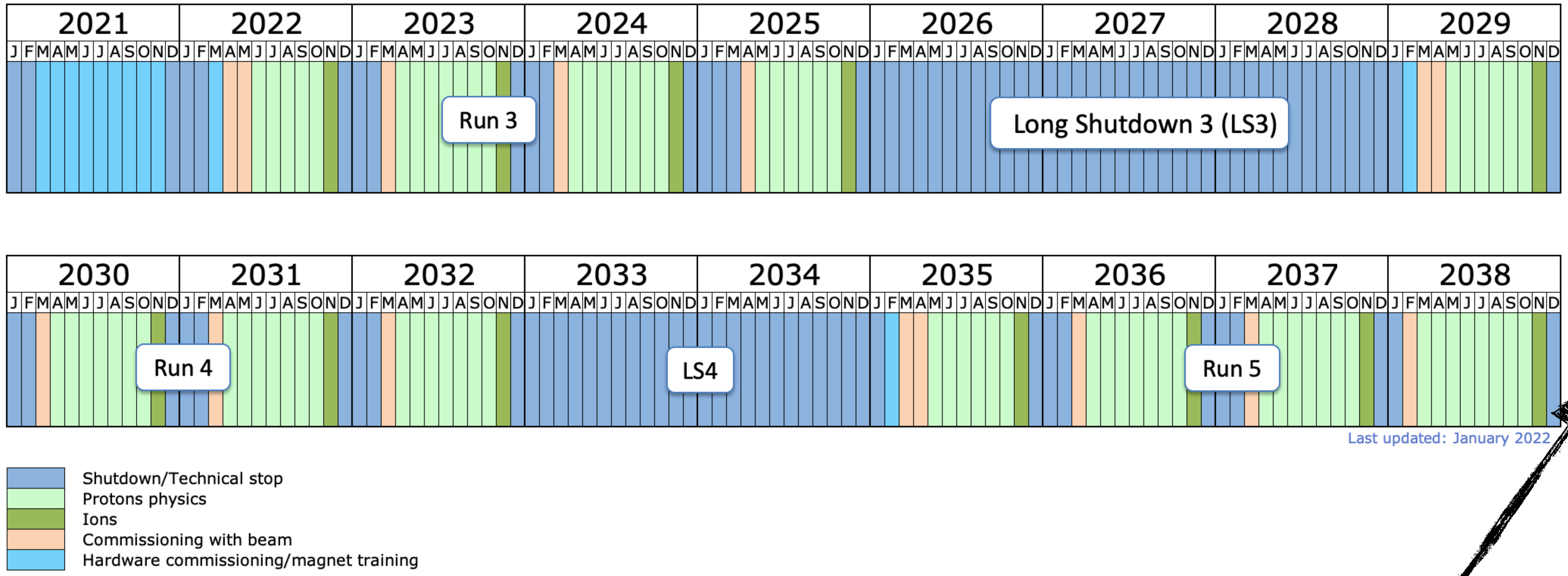
Unscaled (left) vs. scaled (right) uncertainty

- PDF uncertainty scaling reduces spread of results, brings all central values within nominal PDF uncertainty
  - Smaller spread than in similar ATLAS study due to constraining power of analysis strategy



Looking forward

- In the near (and not so near) future, **hadron colliders are our main probe of m_W**
  - Envision huge theoretical progress
  - Enormous data set, but increased challenges: high-pileup and detector aging
  - Mitigate with special runs, detector upgrades, reconstruction advancements

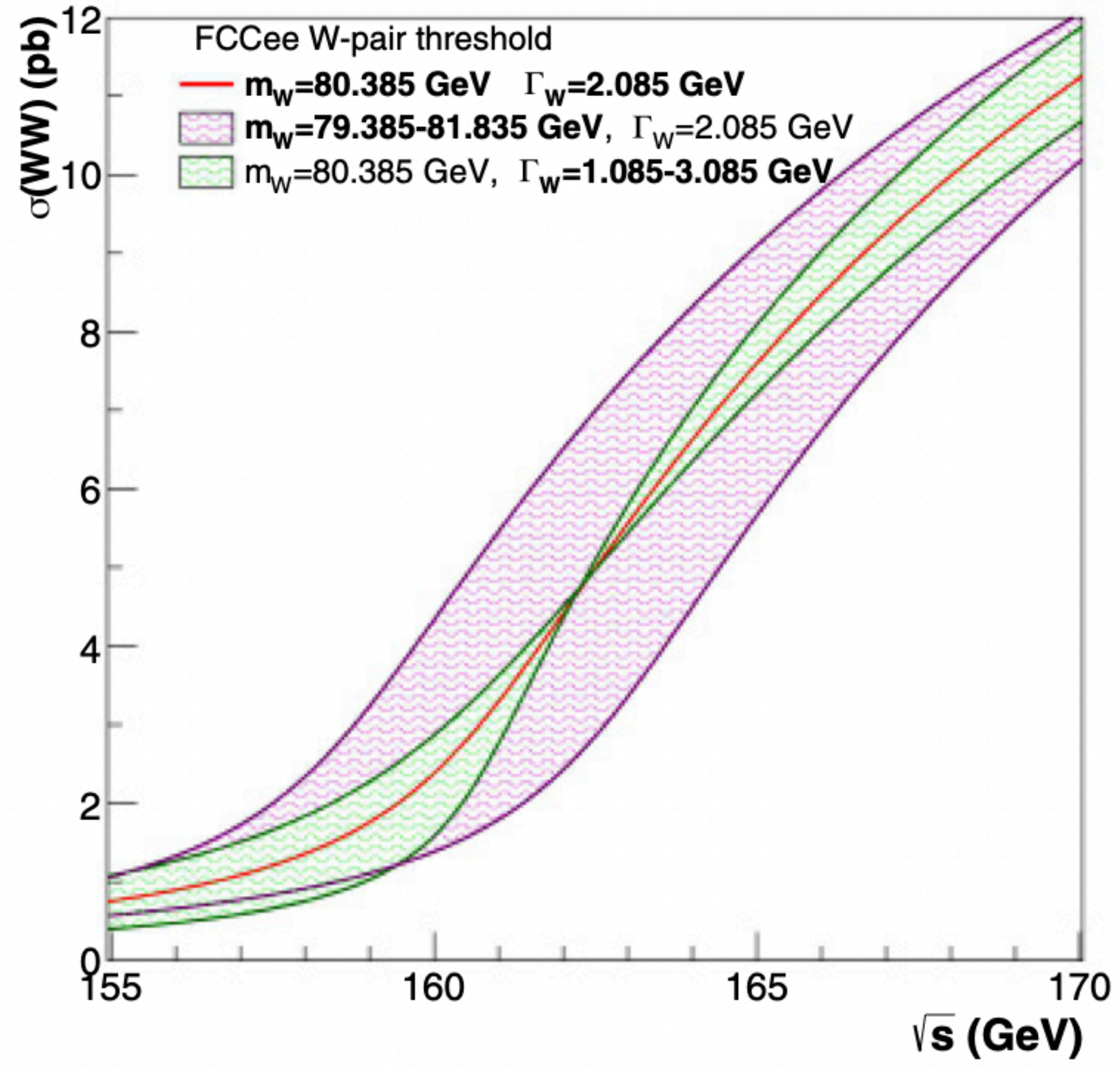


- Future e^+e^- collider provides more direct, less theory-dependent measurement from threshold scans
  - FCC-ee anticipates < 1 MeV unc. in m_W

- Experimental+theory hadron collider communities must meet the challenge of providing results that stand the test of time
- Publish/maintain analyses that can be reinterpreted with improved theory

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

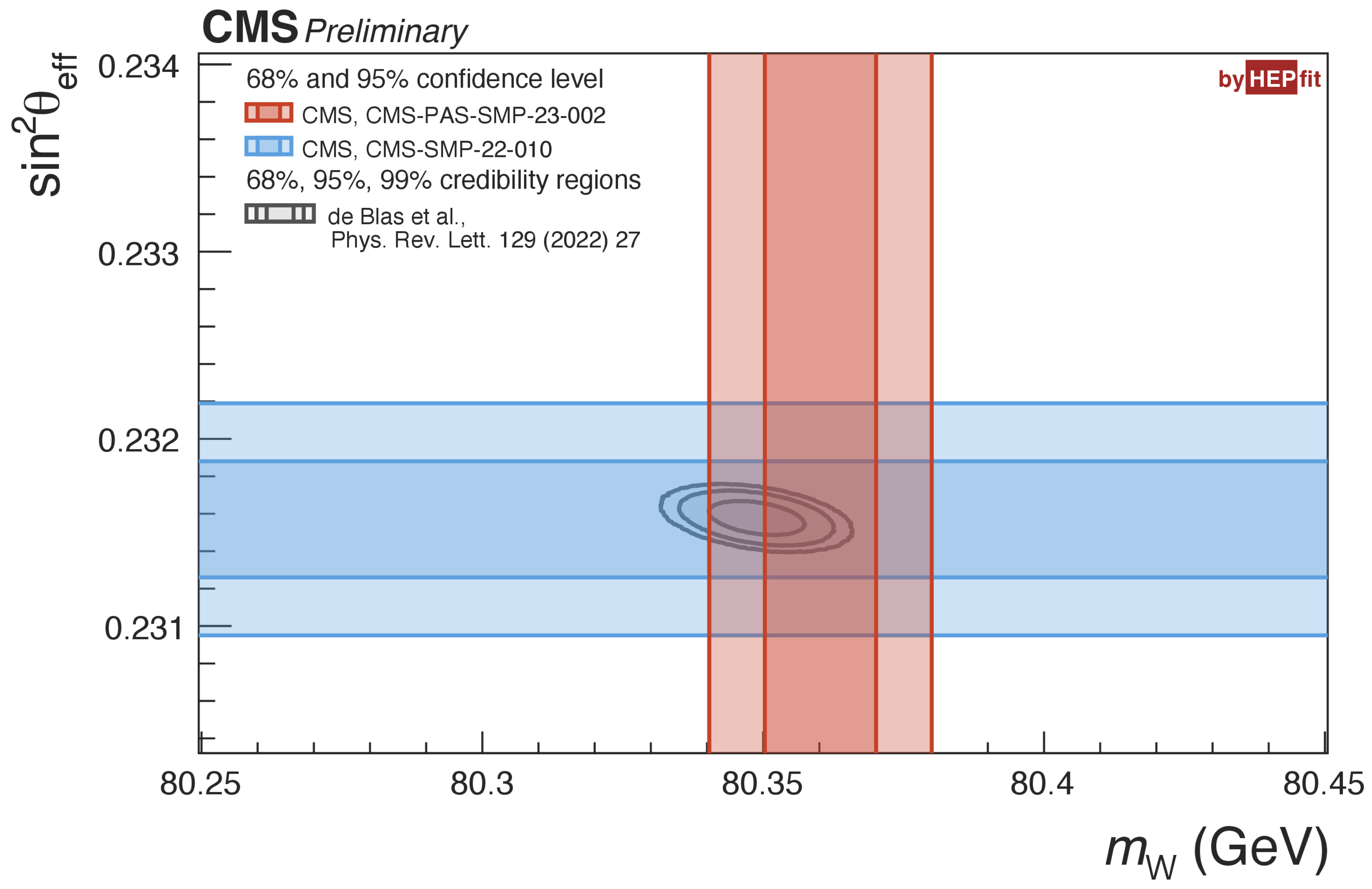
FCC-ee?



https://doi.org/10.1140/epjst/e2019-900045-4

Summary and conclusions

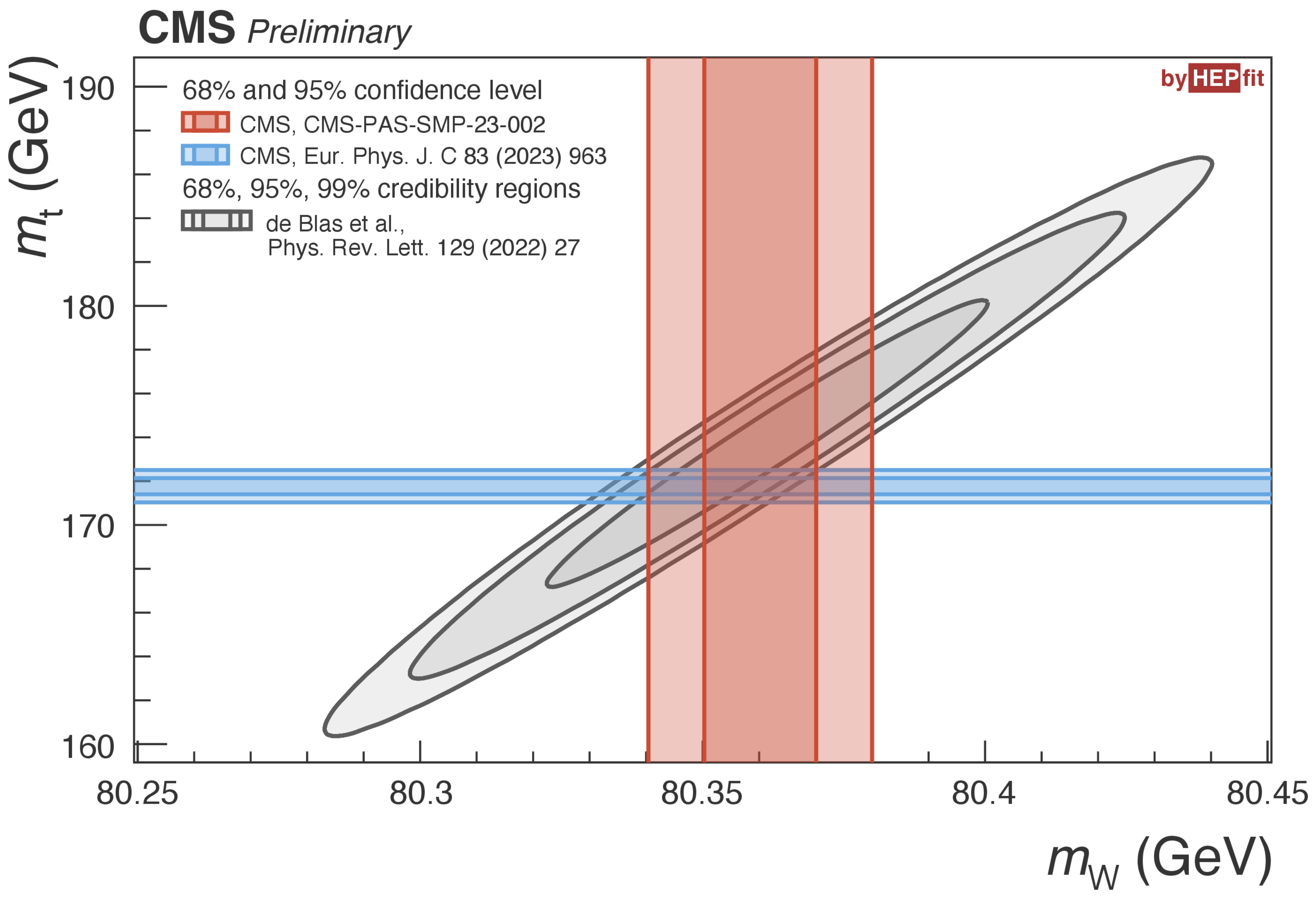
- The first m_W measurement at CMS is a long-awaited milestone for precision physics at the LHC
  - Most precise measurement at the LHC
  - In disagreement with CDF measurement
  - Documented in CMS-SMP-23-002, submitted to *Nature*
- The CMS detector and the LHC are instruments for precision measurements of fundamental parameters




nature

By Elizabeth Gibney

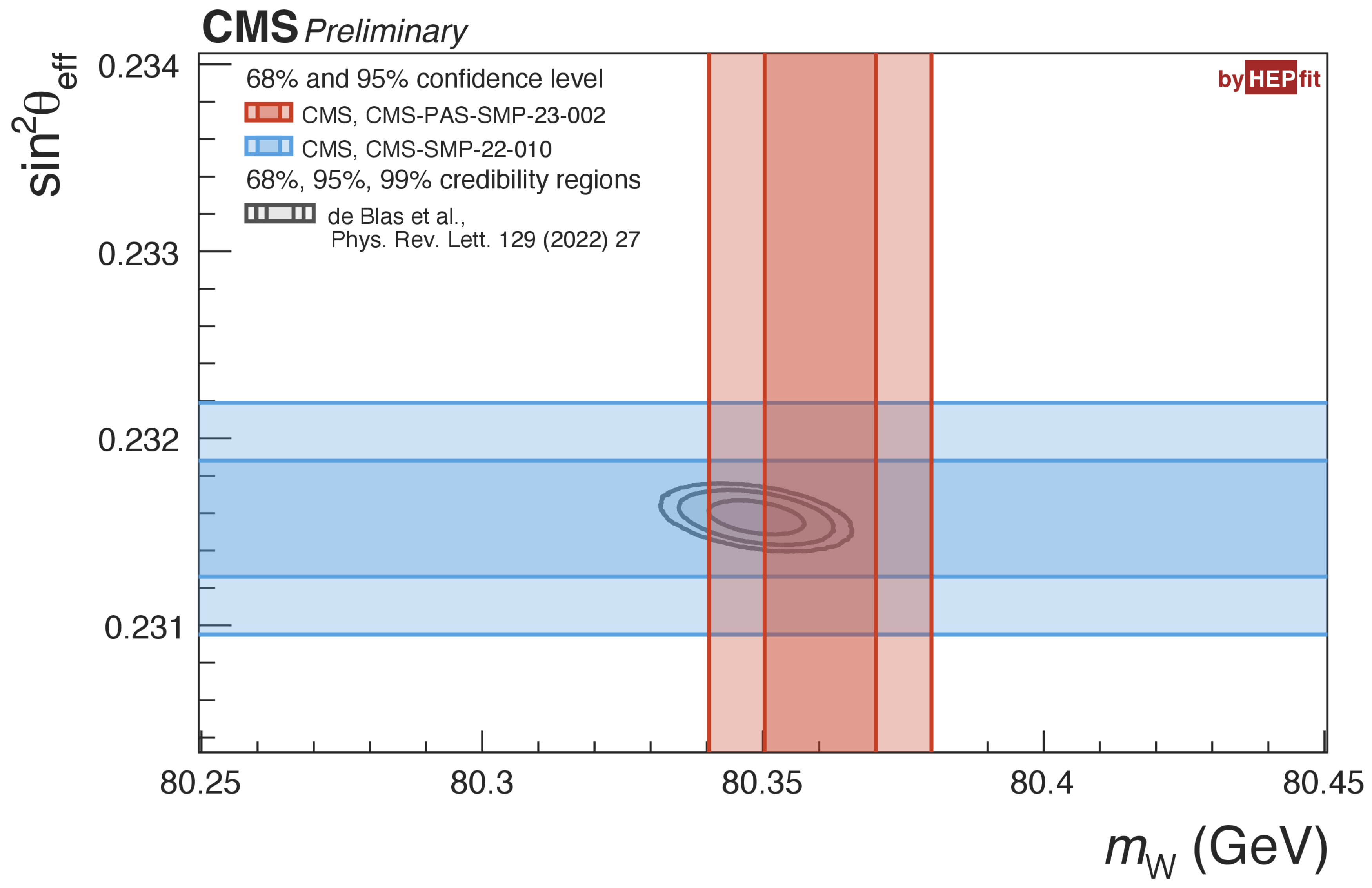
'The standard model is not dead': ultra-precise particle measurement thrills physicists

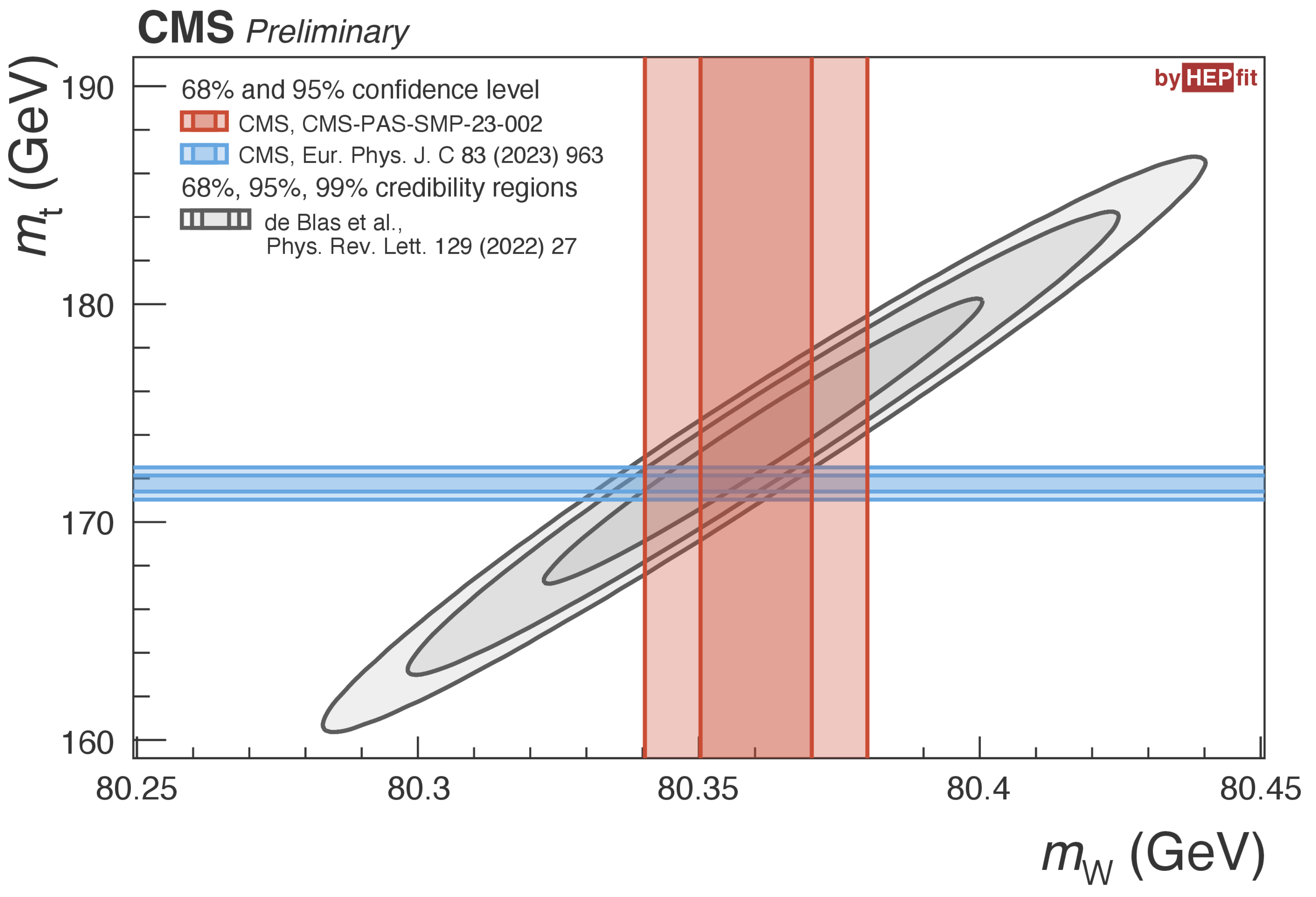


Summary and conclusions

- The first m_W measurement at CMS is a long-awaited milestone for precision physics at the LHC
  - Most precise measurement at the LHC
  - In disagreement with CDF measurement
  - Documented in CMS-SMP-23-002, submitted to *Nature*
- The CMS detector and the LHC are instruments for precision measurements of fundamental parameters

  ➡**Exciting future ahead**





Backup

Comparison with other measurements

- Only "global" uncertainty breakdown (arxiv:2307.04007) comparable to 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

ATLAS

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

CDF

Compared to ATLAS

- Leverage larger data set while managing comparable exp. uncertainties in high PU
- Stronger constraints on PDFs
- Reduced impact of other theory
  - ATLAS EW unc. due to use of older Photos++
- Total calibration + muon eff. only 10% better
  - but Z-independent, model-based

CDF has advantages from p$\bar{\text{p}}$, lower E, PU

- PDFs better understood (valence quarks)
- Less hadronic activity (simpler recoil calibration)
- Low tracking material aids lepton calibration

➡Much larger data set is the CMS saving grace

Source of uncertainty	Impact (MeV) Nominal	Impact (MeV) Global
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CMS

Mass difference vs. average uncertainties

- m_{W+} - $m_{W,avg}$ = 30 ± 20 MeV
- m_{W-} $m_{W,avg}$ = -19 ± 19 MeV
- Correlation coefficient ρ_{+-} = -0.4

Compare sum and difference of correlated observables

- https://en.wikipedia.org/wiki/Propagation_of_uncertainty#Example_formulae

Function	Variance	Standard deviation
$f = aA$	$\sigma_f^2 = a^2\sigma_A^2$	$\sigma_f = \|a\|\sigma_A$
$f = A + B$	$\sigma_f^2 = \sigma_A^2 + \sigma_B^2 + 2\sigma_{AB}$	$\sigma_f = \sqrt{\sigma_A^2 + \sigma_B^2 + 2\sigma_{AB}}$
$f = A - B$	$\sigma_f^2 = \sigma_A^2 + \sigma_B^2 - 2\sigma_{AB}$	$\sigma_f = \sqrt{\sigma_A^2 + \sigma_B^2 - 2\sigma_{AB}}$

$$\sigma_{AB} = \rho_{AB}\sigma_A\sigma_B$$

- Compare uncertainty on average to uncertainty on difference (assume $\sigma_+ \sim \sigma_+ \coloneqq \sigma_C \approx 19$ MeV):

$$\sigma^2_{m_+-m_-} = 2\sigma_c^2 - 2\sigma_c^2\rho_{+-}$$

$$\sigma_{m_+-m_-} = \sqrt{2.8}\sigma_c$$

$$\sigma^2_{m_++m_-} = 2\sigma_c^2 - 2\sigma_c^2\rho_{+-}$$

$$\sigma_{m_++m_-} = \sqrt{1.2}\sigma_c$$

$$\sigma_{avg} = \frac{1}{2}\sigma_{m_++m_-} = \frac{\sqrt{1.2}}{2}\sigma_c$$

$$\frac{\sigma_{avg}}{\sigma_{m_+-m_-}} = \frac{1}{2}\sqrt{\frac{1.2}{2.8}} \approx \frac{1}{3}$$

Compare 30 MeV uncertainty in difference to 10 MeV uncertainty in average

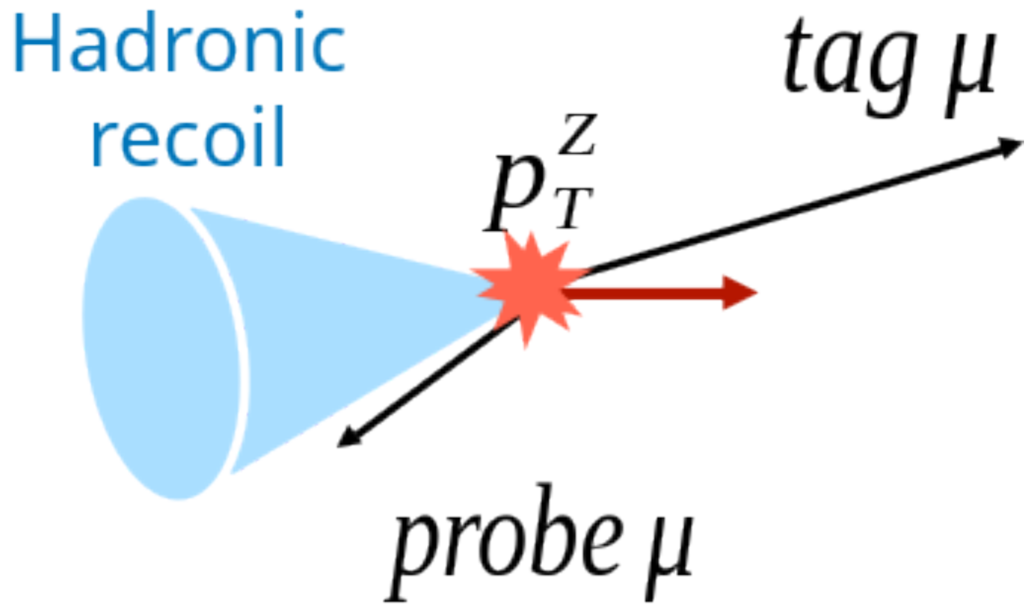
Muon reconstruction efficiency

- First step of analysis is reconstructing muons very precisely
  - *in situ* measurement of reconstruction rate from $Z \longrightarrow \mu\mu$ sample (tag-and-probe)
    - ε binned very finely in (p_T^μ, η^μ) and divided by into steps:
      - tracking, track+muon system match, ID, trigger, isolation
    - Smoothed in p_T^μ to reduce stat. fluctuations
  - ~2400 nuisance parameters in final signal extraction

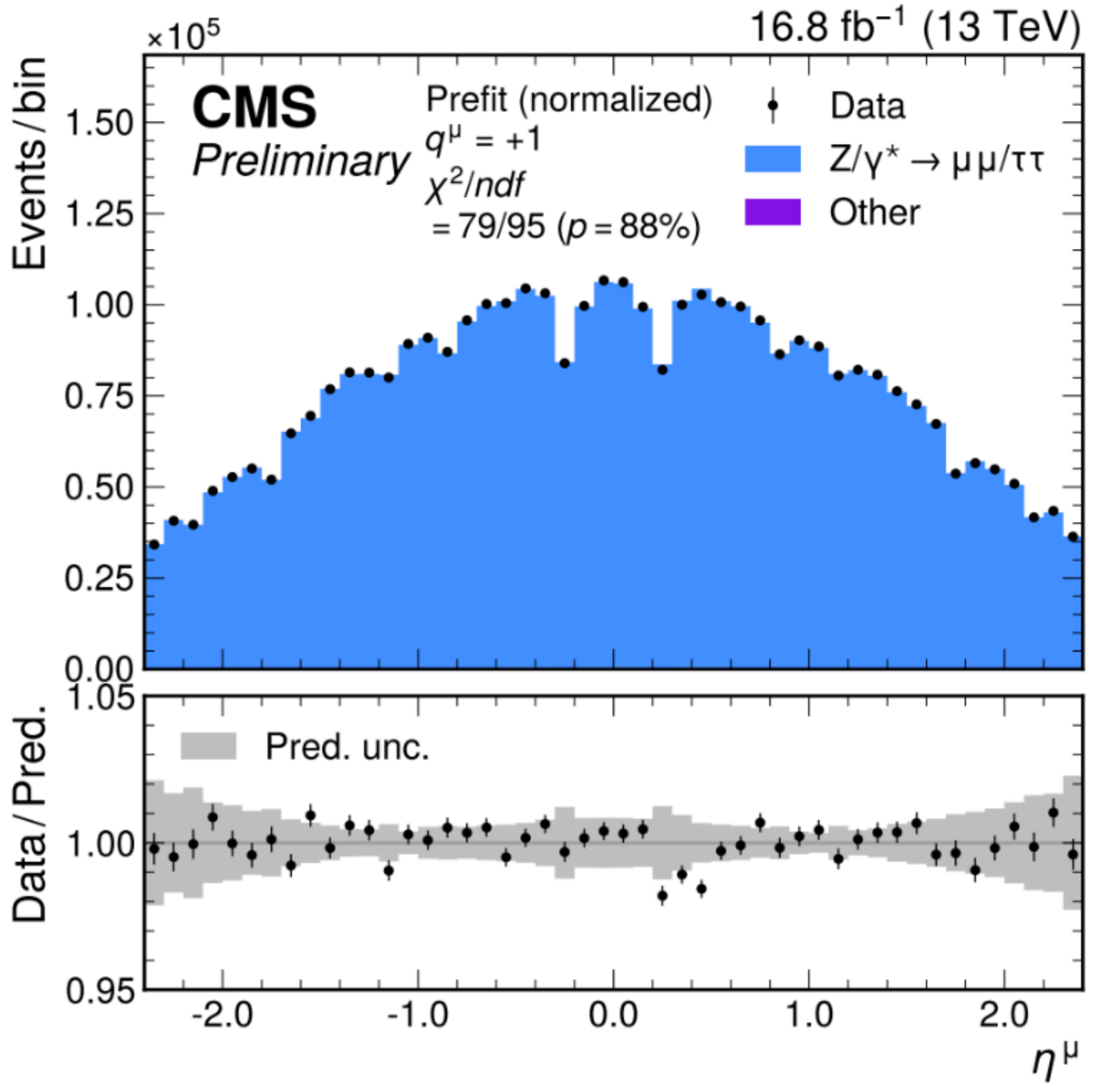
➡3.0 MeV unc. in m_W

$$\varepsilon = \frac{passing\ probes}{passing\ probes + failling\ probes}$$

- Note: tag-and-probe cannot capture loss of events before the trigger, or differences between W and Z
  - Account for W/Z recoil differences
  - Custom vertex selection for W/Z consistency
  - Trigger "pre-firing" estimated independently



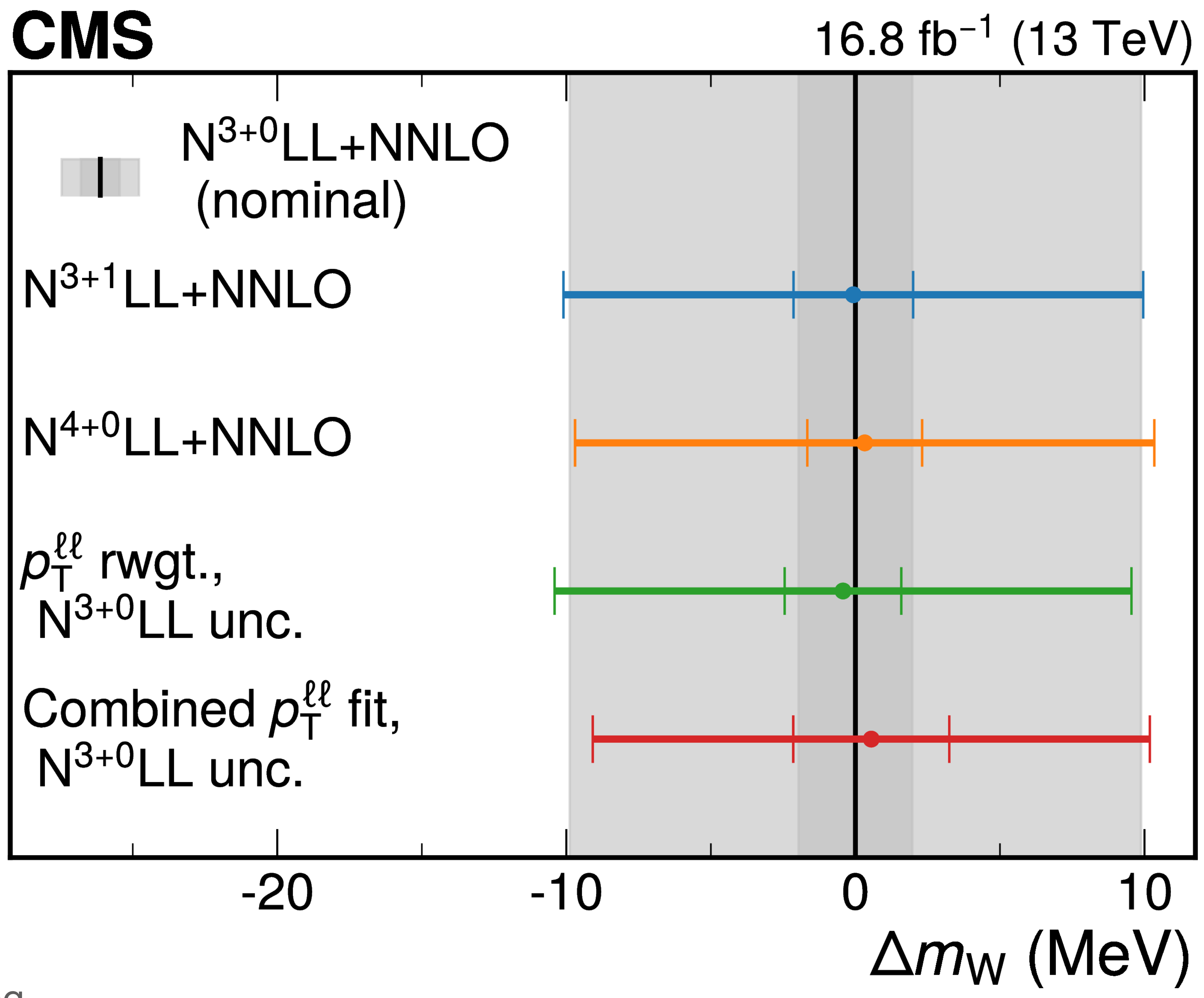
$$u_T = \frac{\vec{p}_T^{\mu} \cdot \vec{p}_T^{V}}{p_T^{\mu}}$$

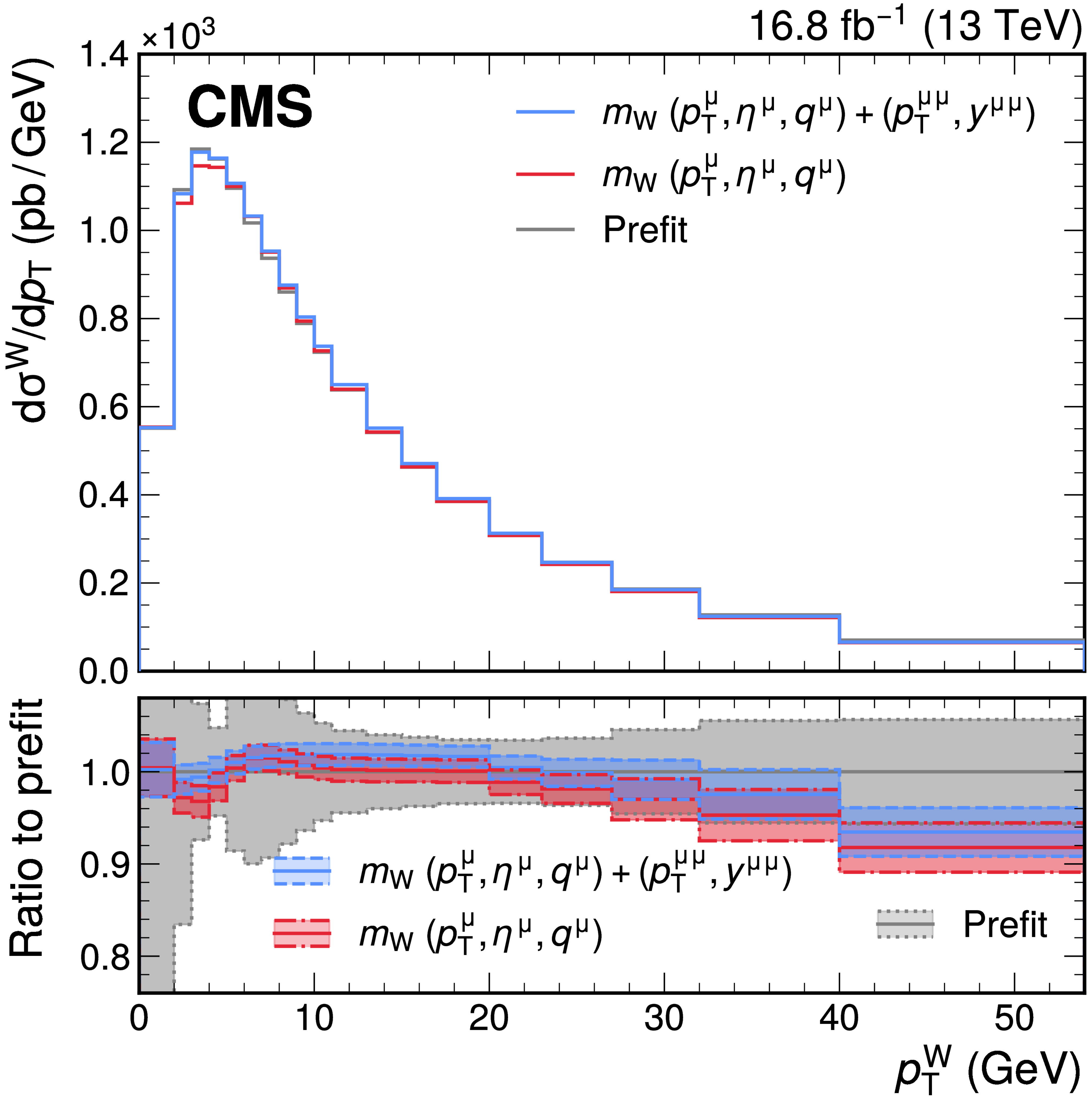


Impact of modeling and validation

- Tested effect of varying treatment of theoretical uncertainties
  - Partial high-order resummation + theory nuisance parameters
  - Explicit reweighing of p_T^W by measured p_T^Z correction
  - Combined m_W + $p_T^{\mu\mu}$ fit

➡All results consistent with nominal approach

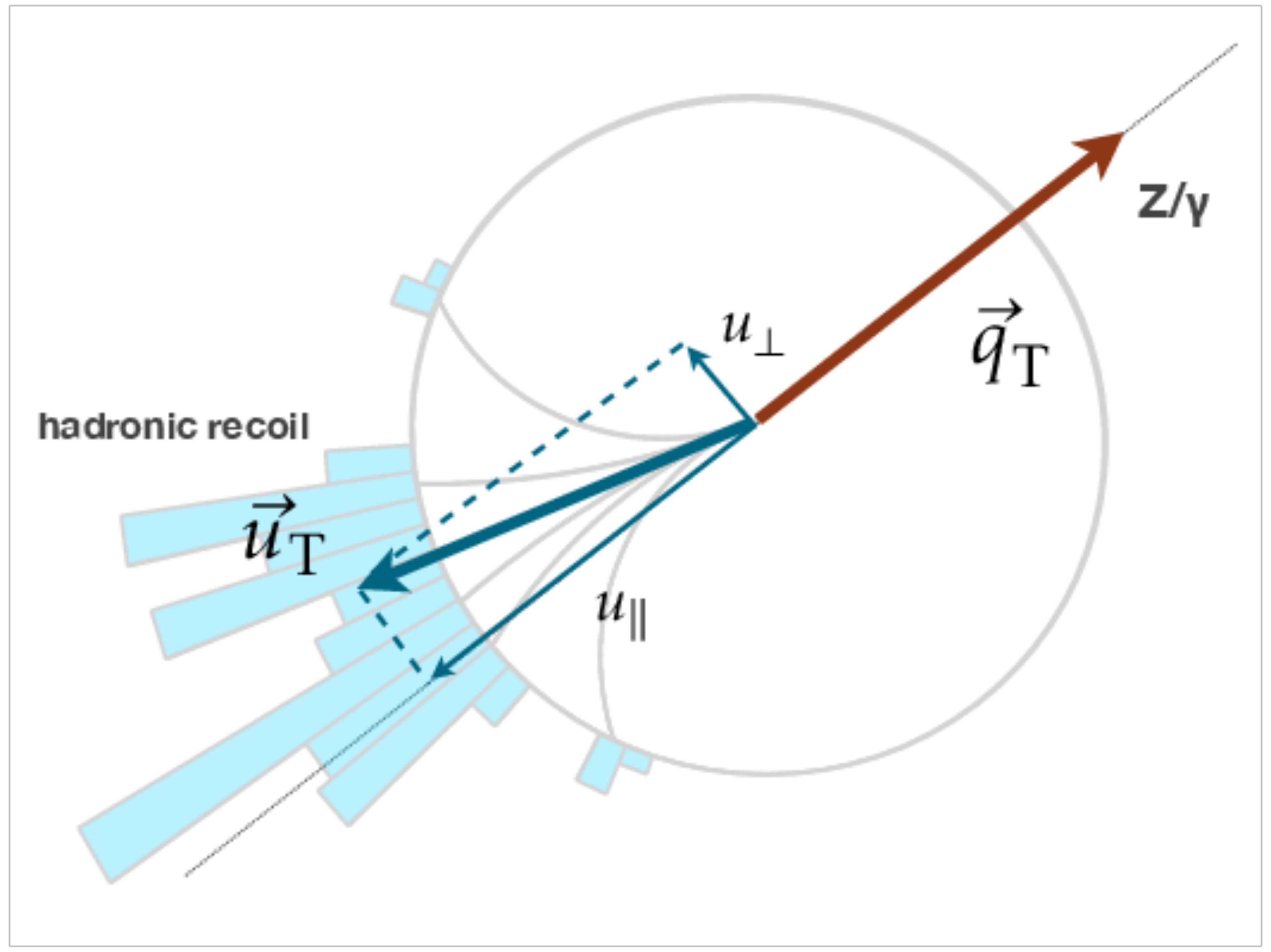


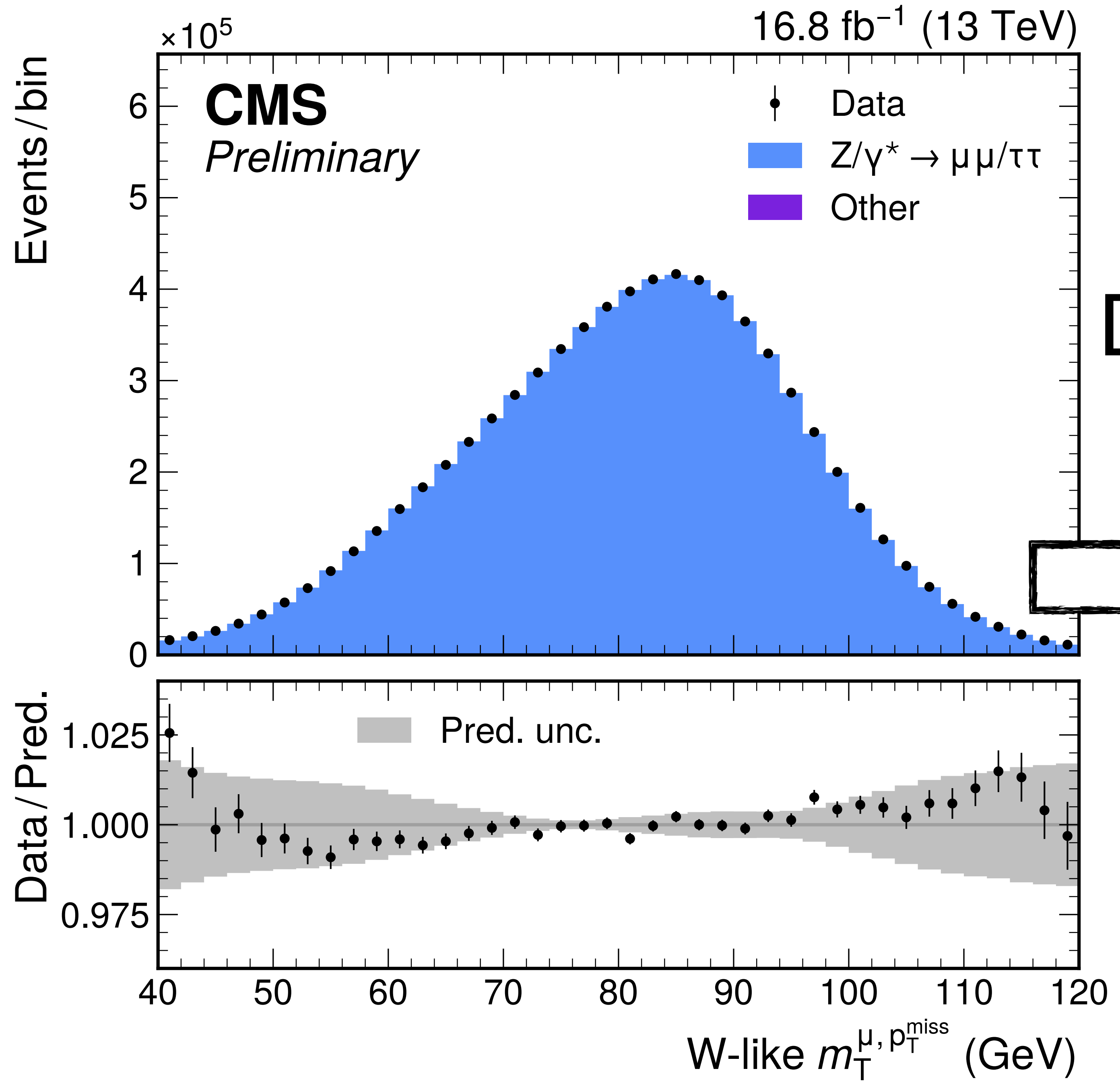


Comparison of generator-level postfit distributions from nominal and combined m_W + $p_T^{\mu\mu}$ fits

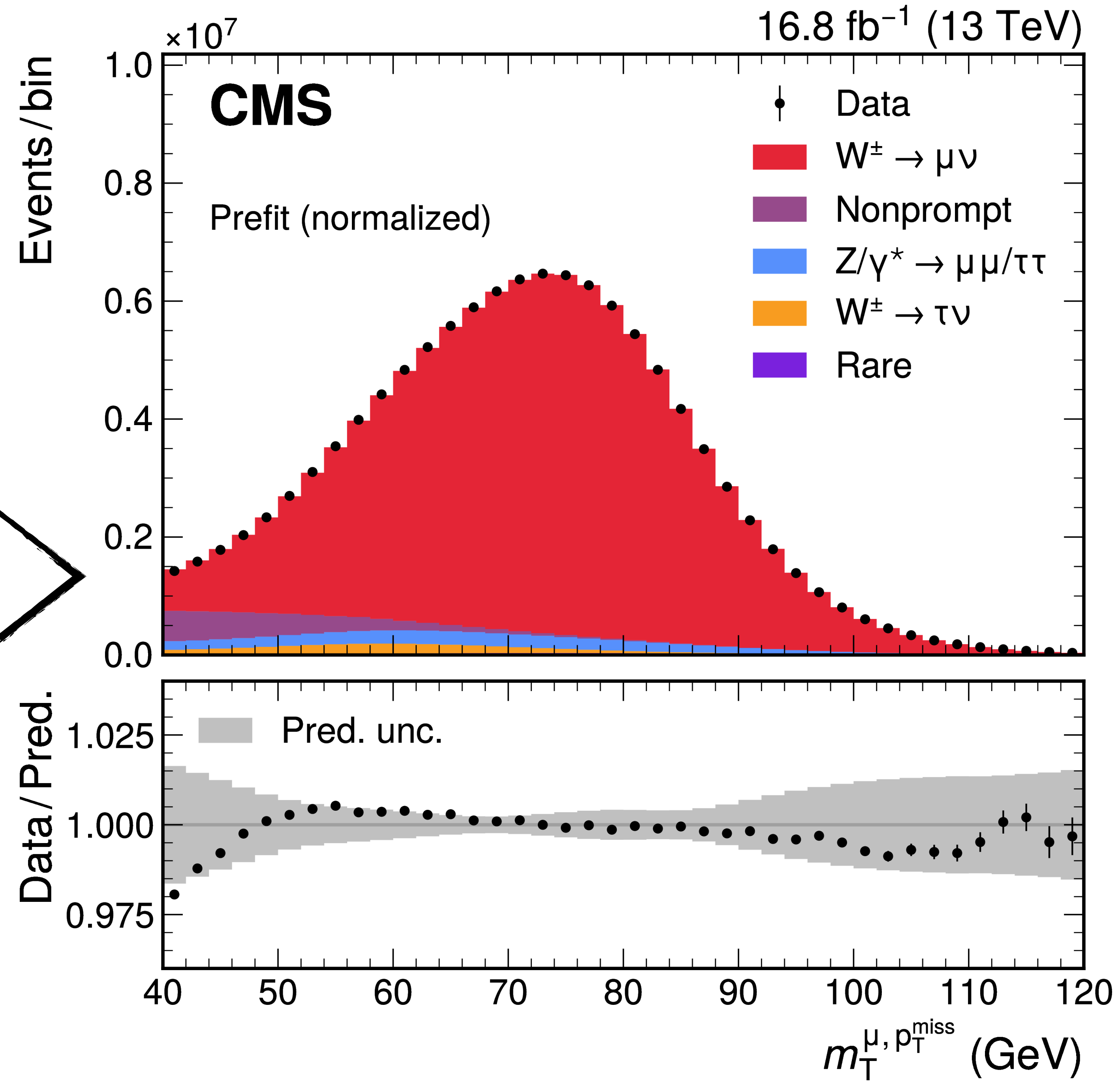
p_T^{miss} calibration

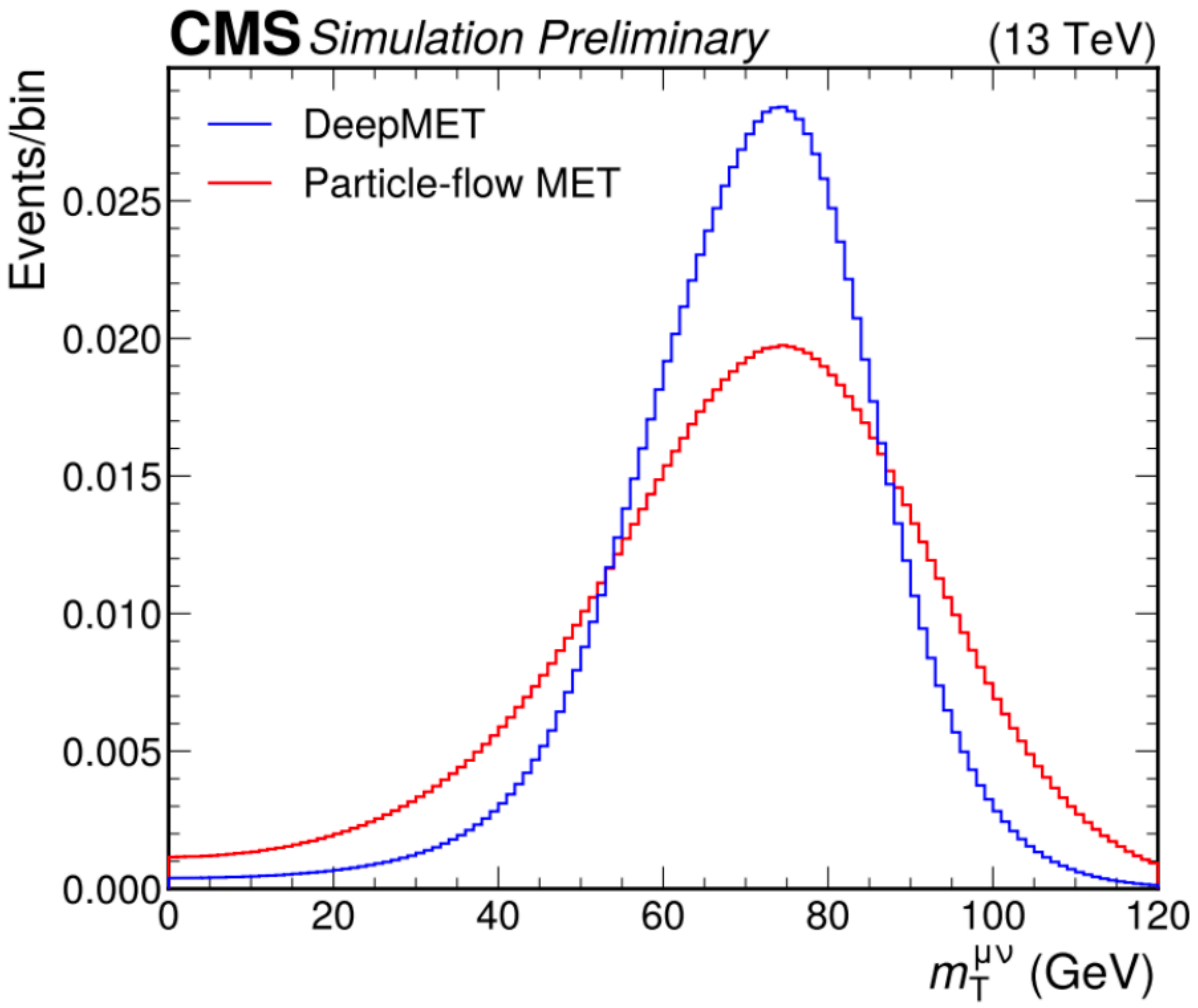
- p_T^{miss} enters the analysis via the signal ($m_T > 40$ GeV)
  - DeepMET gives improved resolution, better signal vs. background
- Calibrate p_T^{miss} in dimuon data
  - Hadronic activity must balance $p_T^{\ell\ell}$
  - Parameterised corrections in bins of boson p_T
  - Applied to Z (validation) and W MC using generator-level p_T^W





Derived from Z applied to W



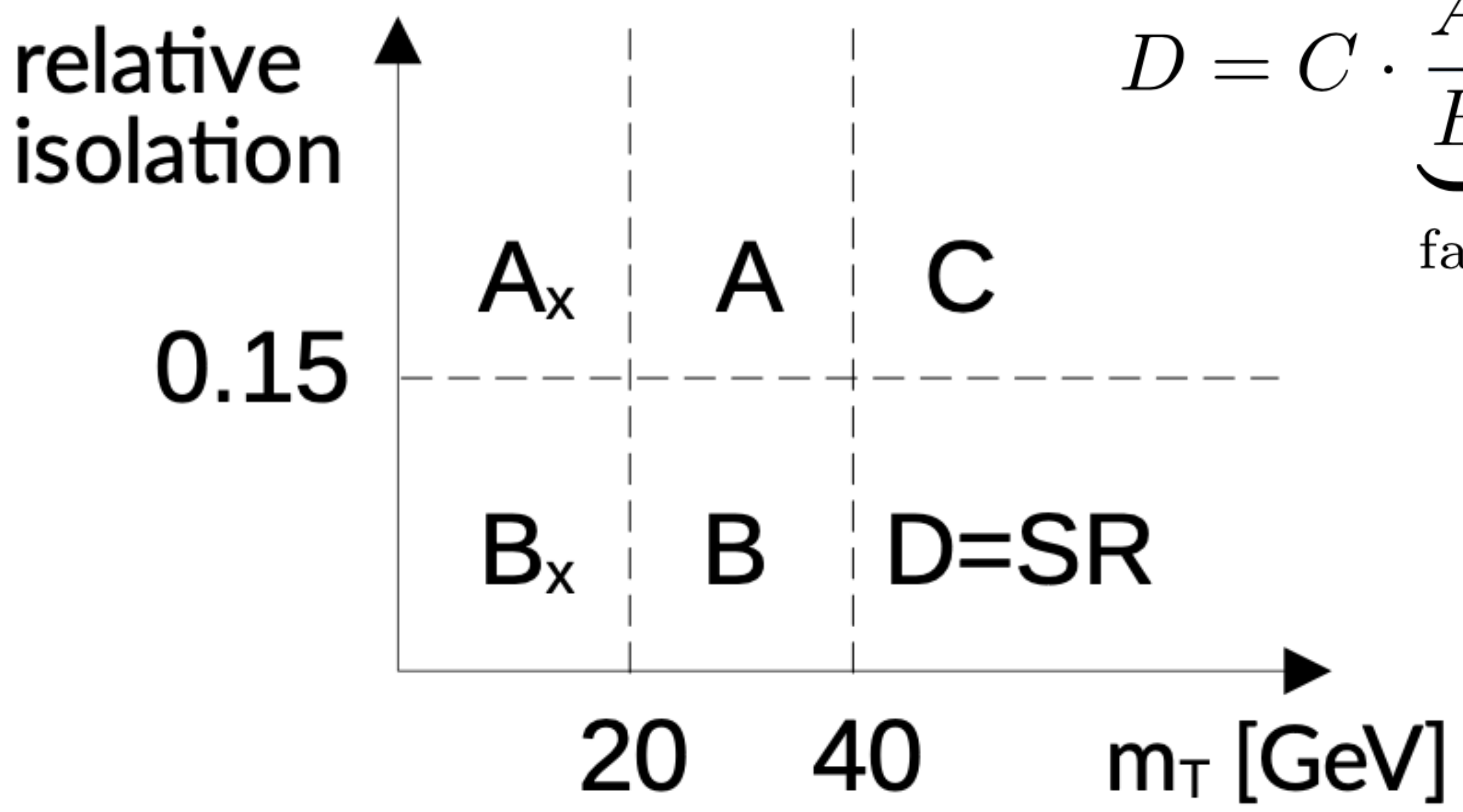


Nonprompt background estimation

- Data driven estimate with "extended ABCD method"
  - 5 (+1 signal) regions of isolation/m_T to correct for correlations
  - Smoothing to reduce stat. fluctuations

➡3.2 MeV unc. in m_W

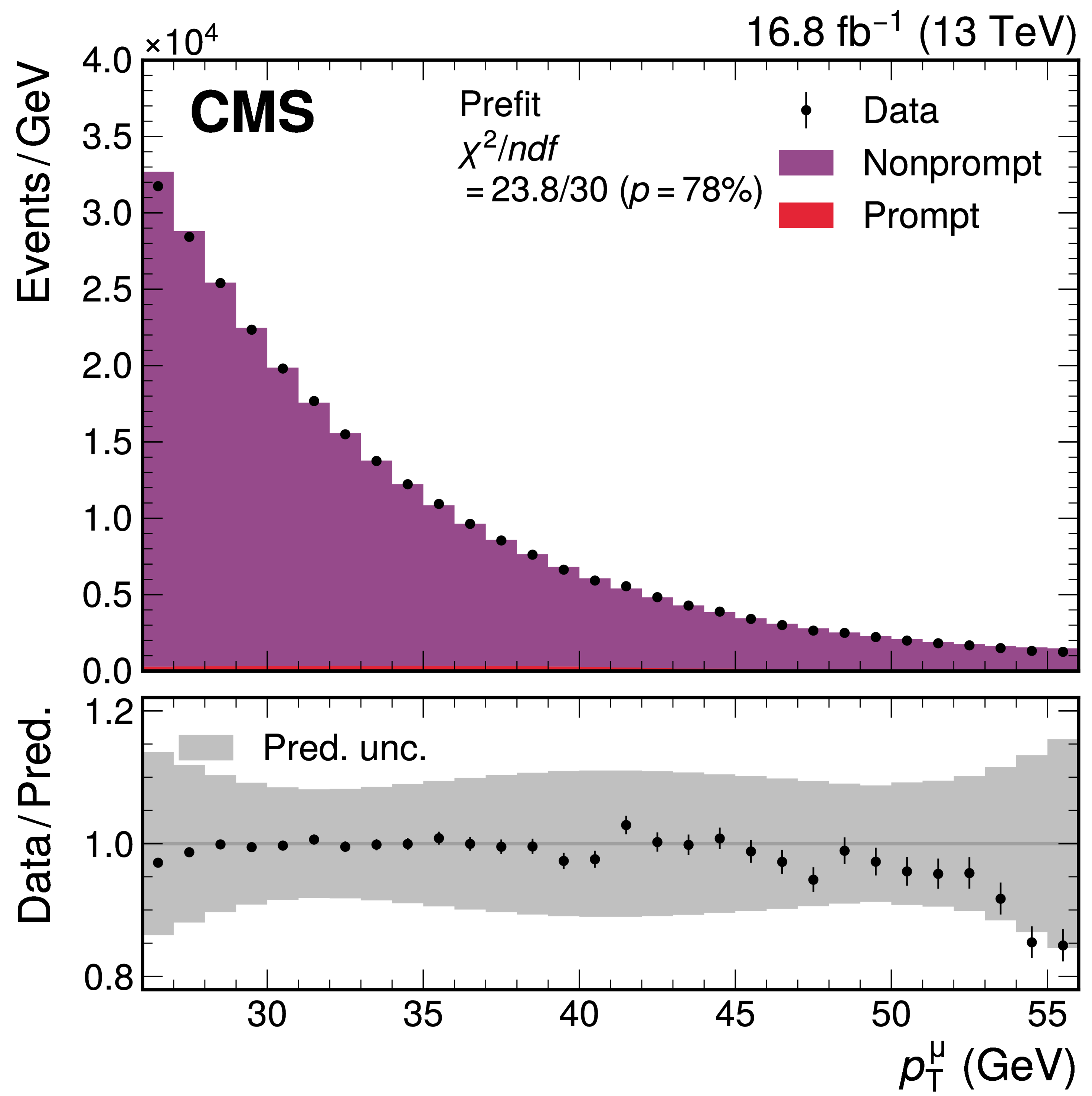
- Full **uncertainties of prompt subtraction propagated to 5 regions**
  - Dedicated efficiency measurement for iso-failing muons

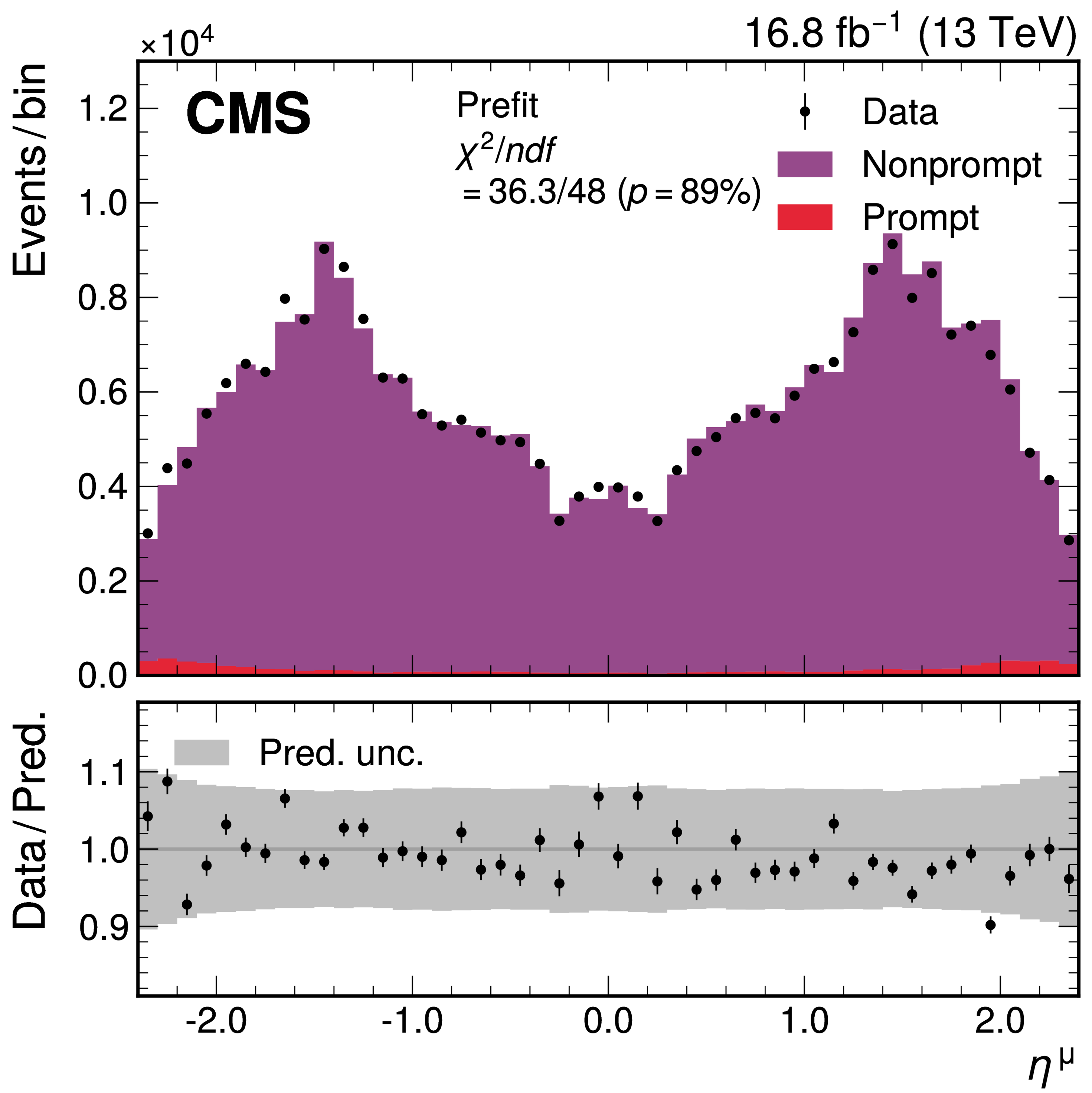


$$D = C \cdot \underbrace{\frac{A_x B^2}{B_x A^2}}_{\text{fakerate}}$$

- Primarily heavy flavour decays to leptons in jets

➡Validated in secondary vertex control region

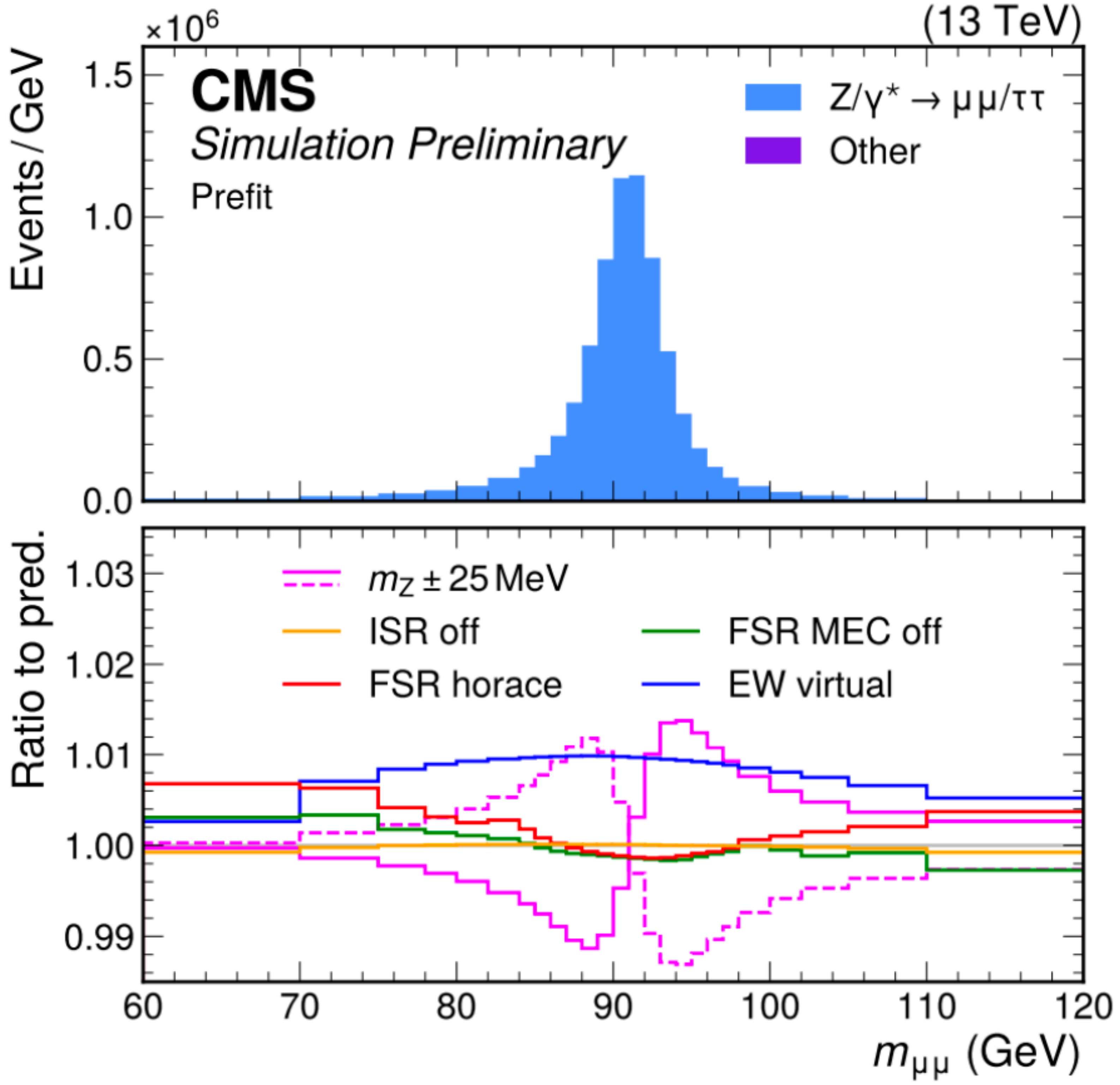


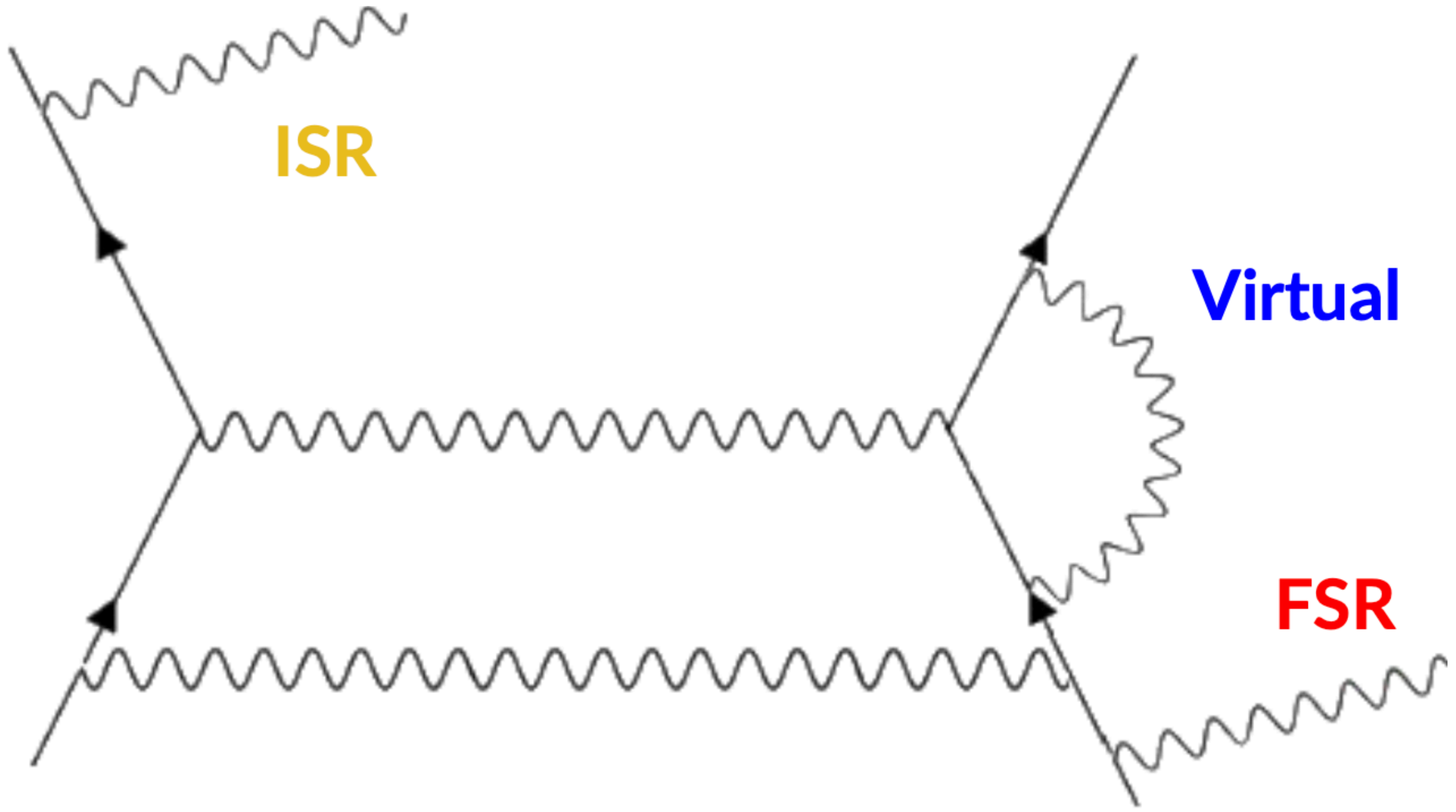


Higher-order EW uncertainties

- Main impact of EW corrections captured by Photos++
  - Includes QED @leading-log γ➞ee/μμ pair production and matrix element corrections (MEC) ~NLO QED

- Impact of higher-order EW evaluated by comparisons of full NLO EW calculation to MiNNLO+photos prediction. Factorized
  - FSR ~ **0.3 MeV in m_W**
    - Horace QED FSR
    - Photos++ MEC off
  - ISR < **0.1 MeV**
    - Switching on/off QED ISR in pythia
  - Virtual ~**1.9 MeV**
    - Z: Powheg NLO+HO EW
    - W: ReneSANCe NLO+HO EW





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

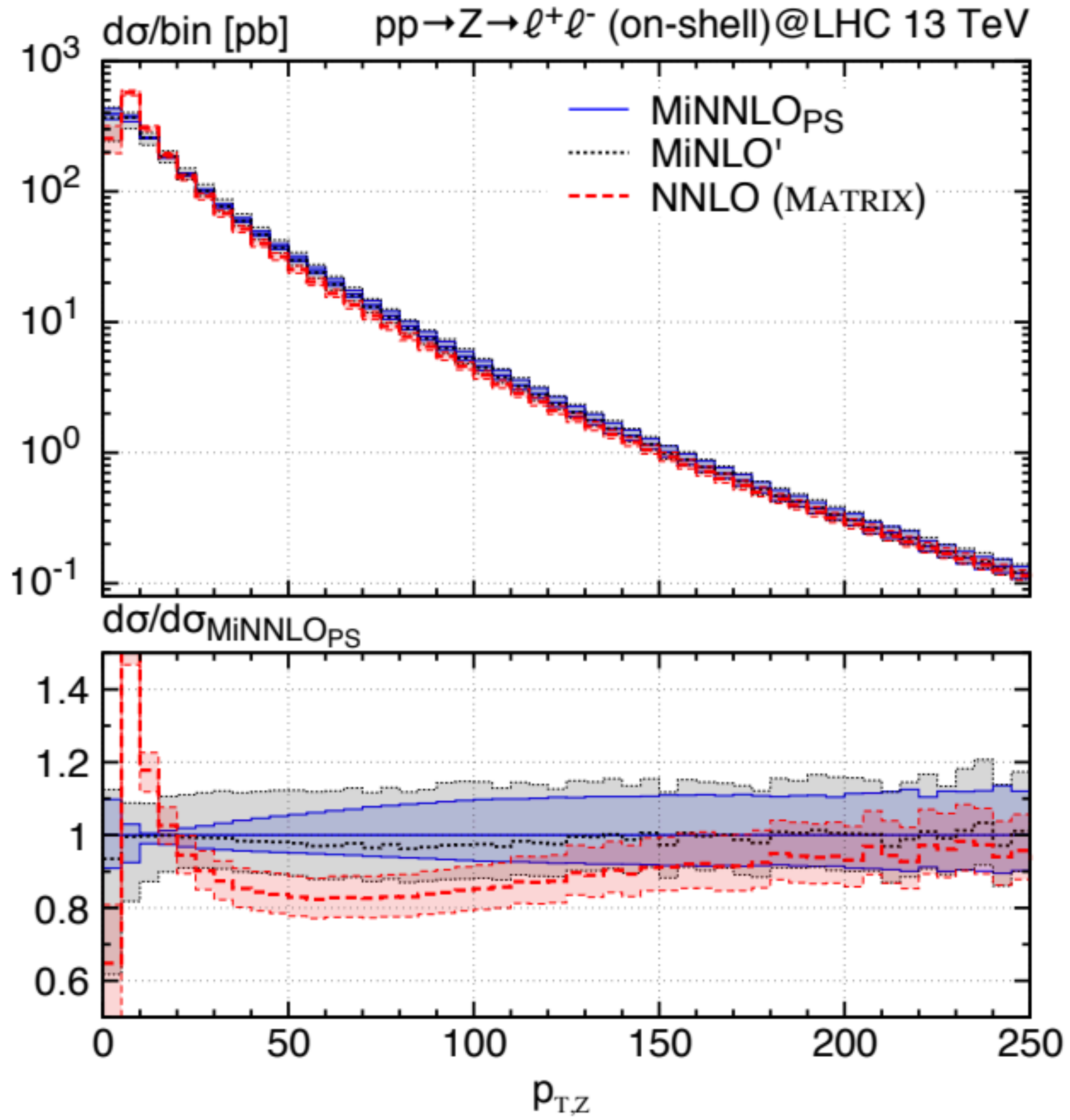
Monte Carlo simulation for the m_W measurement

Requirements

- Not limited by MC stats: ~1-to-1 data/MC events
- Considering negative weight fraction of MC, **> 1 billion events** (W, Z muon, tau decays)
- Full consistency with fixed-order NNLO essential for PDF constraints

➡ Use MiNNLO (2019-2020): [arXiv:1908.06987](https://arxiv.org/abs/1908.06987)

  - **NNLO accuracy** by merging jet multiplicities w/ custom scale choice
  - More efficient than NNLOPS, not limited by stat. unc of NNLO grids
  - Smaller fraction of negative weights, based on POWHEG ⇒ relatively easy integration into CMSSW



- Obviously **needs to be extensively validated**
  - Use of MC for an experimental analysis is much more intense than usual tests by authors
    - "Surprises" should be expected
  - Historically, issues in simulation discovered after production for 7 TeV samples, and MiNLO samples for 13 TeV, were major setbacks in out m_W effort

Theory nuisance parameters: more detail

Consider a series expansion in a small parameter α:

$$f(\alpha) = f_0 + \alpha f_1 + \alpha^2 f_2 + \alpha^3 f_3 + \alpha^4 f_4 + \mathcal{O}(\alpha^5)$$

$$\text{LO}: \; f(\alpha) = \hat{f}_0 \pm \Delta f$$

$$\text{NLO}: \; f(\alpha) = \hat{f}_0 + \alpha \hat{f}_1 \pm \Delta f$$

$$\text{NNLO}: \; f(\alpha) = \hat{f}_0 + \alpha \hat{f}_1 + \alpha^2 \hat{f}_2 \pm \Delta f$$

Δf is due to the series of the unknown true values $\hat{f}_n$ $\longrightarrow$ missing higher orders (MHOs)

$$\text{N}^{1+1}\text{LO}: \quad f(\alpha, \theta_2) = \hat{f}_0 + \hat{f}_1\,\alpha + f_2(\theta_2)\,\alpha^2\,,$$

$$\text{N}^{1+2}\text{LO}: \quad f(\alpha, \theta_2, \theta_3) = \hat{f}_0 + \hat{f}_1\,\alpha + f_2(\theta_2)\,\alpha^2 + f_3(\theta_3)\,\alpha^3$$

$$\text{N}^{2+1}\text{LO}: \quad f(\alpha, \theta_3) = \hat{f}_0 + \hat{f}_1\,\alpha + \hat{f}_2\,\alpha^2 + f_3(\theta_3)\,\alpha^3\,.$$

Uncertainty estimate defined by how unknown piece is parameterised

$$\text{N}^{1+0}\text{LO}: \quad f(\alpha, \theta_2) = \hat{f}_0 + \left[\hat{f}_1 + \alpha_0 f_2(\theta_2)\right]\alpha\,,$$

$$\text{N}^{2+0}\text{LO}: \quad f(\alpha, \theta_3) = \hat{f}_0 + \hat{f}_1\,\alpha + \left[\hat{f}_2 + \alpha_0 f_3(\theta_3)\right]\alpha^2\,.$$

https://arxiv.org/abs/2411.18606
G. Marinelli, SM@LHC 2025

Theory nuisance parameters: more detail

- Particularly favourable for resummation of p_T^V spectrum, where the leading power (in q_T/m_V) dependence is known to all orders
  - Ingredients of the calculation are often numerical constants (except for beam functions)
  - This is the dominant source of uncertainty (low p_T^V) for the m_W analysis

$$q_T \frac{d\sigma}{dq_T} = \left[H \times B_a \otimes B_b \otimes S \right] (\alpha_S, L \equiv \ln q_T/m_Z) + \mathcal{O}\left(\frac{q_T^2}{m_Z^2}\right)$$

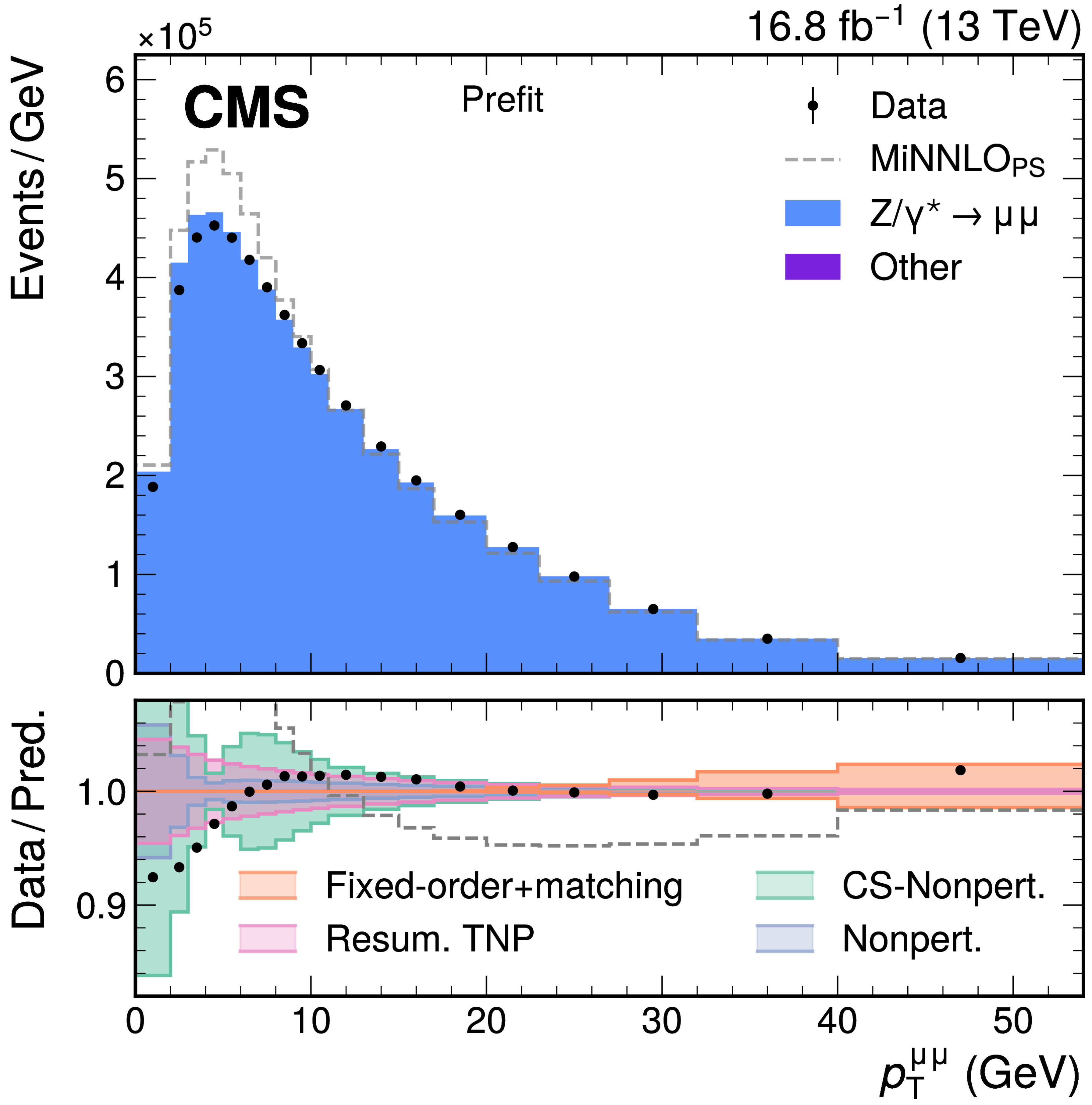
$F = \{H, B, S\}$ solution to RGE equations

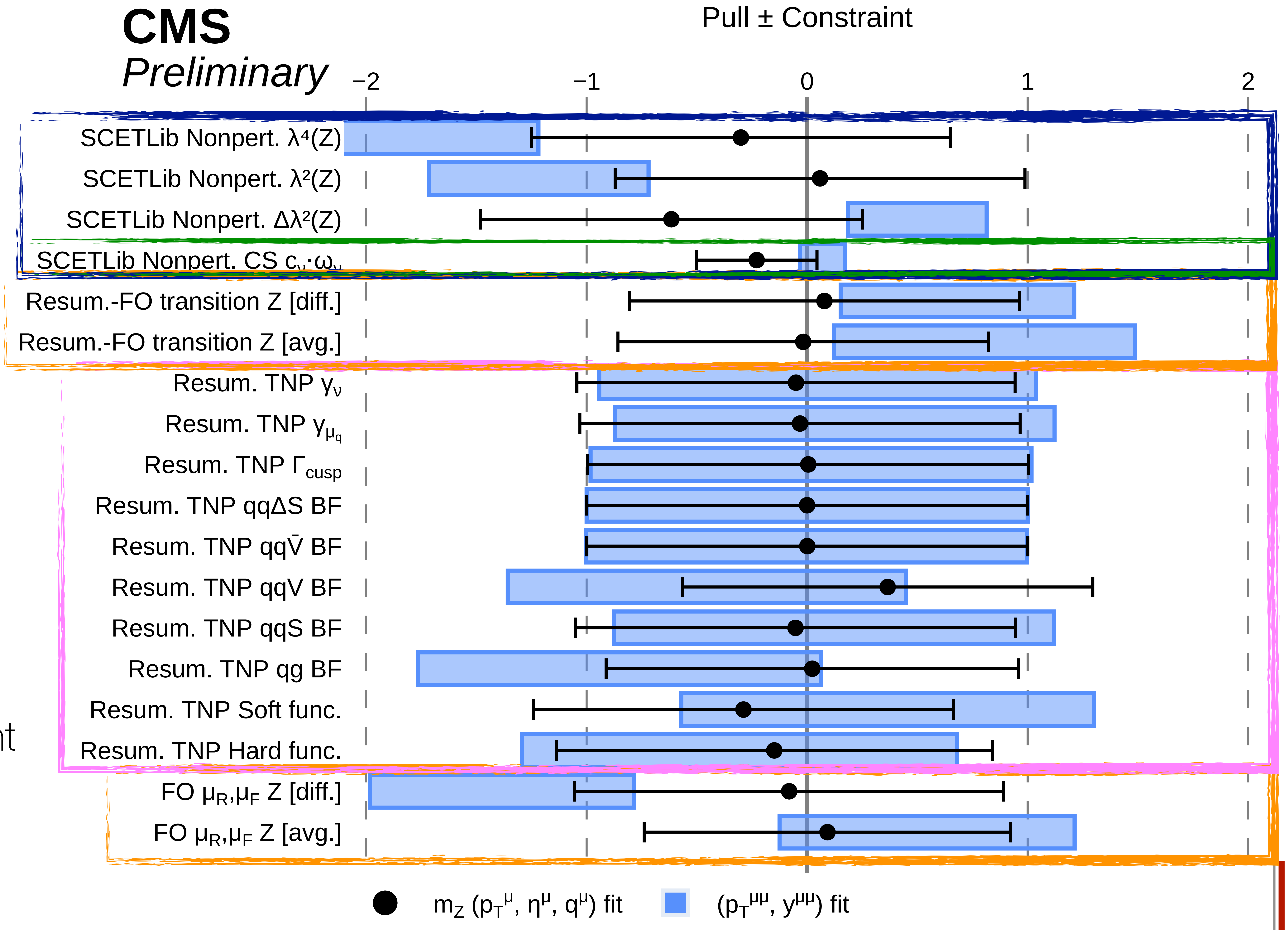
$$F(\alpha_S, L) = F(\alpha_S) \exp \int_0^L dL' \{ \Gamma[\alpha_S(L')] L' + \gamma_F [\alpha_S(L')] \}$$

boundary conditions   anomalous dimensions

- For more complex processes (e.g., ttbar), the resummation is more complicated
- For fixed order calculations, the "structure" of the calculation is not known in the same way
  - In principal, same idea can be applied by guessing a parameterisation (e.g., Chebyshev polynomials) and using known corrections (e.g., NLO -> NNLO)
  - Lim, Poncelet, 2412.14910; SM@LHC2025

Parameter level view of the theory model





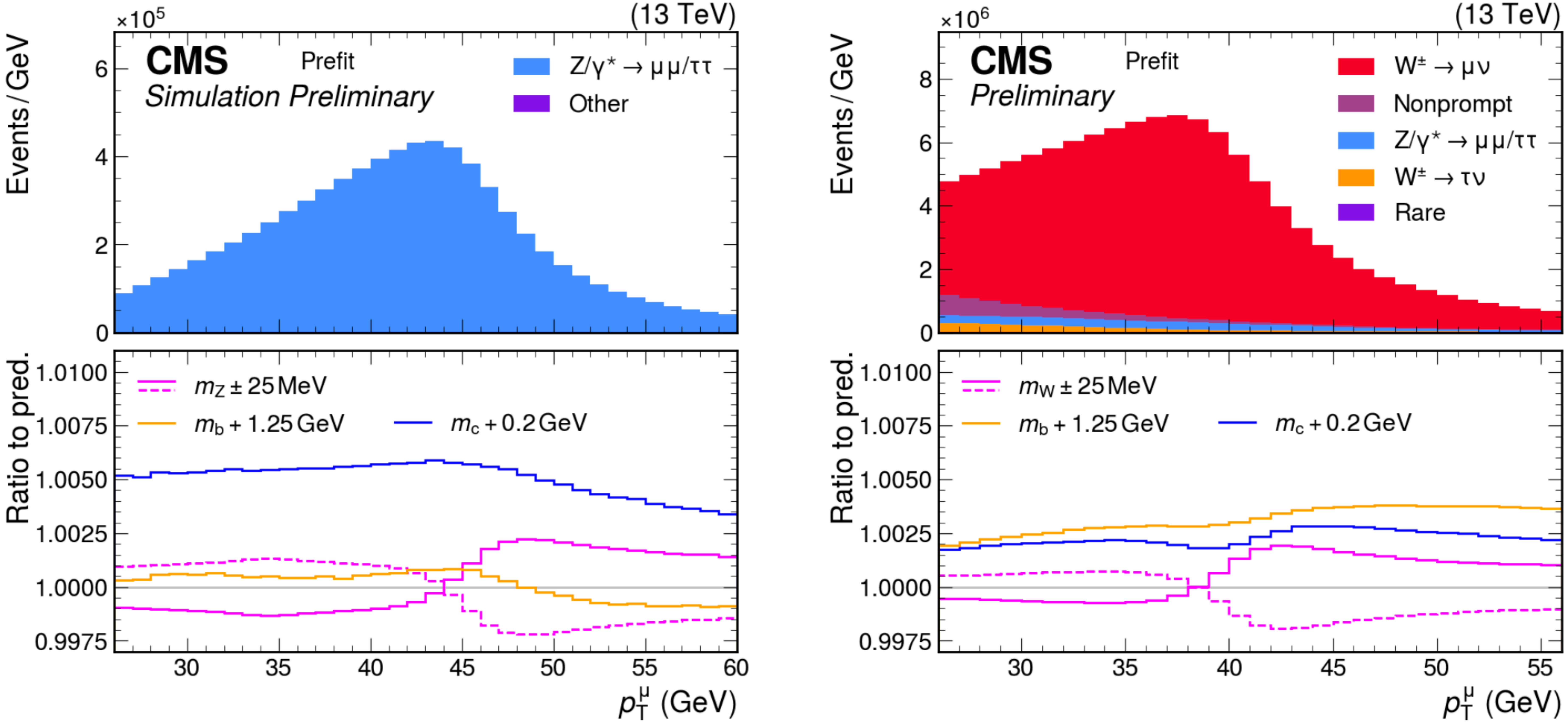
- Small pulls/constraints on TNPs
- Nonperturbative terms most important
  - Different behaviour of $\Lambda^{(2)}$ and CS terms due to degeneracy
- **Consistent impact on p_T^Z**

Heavy quark masses

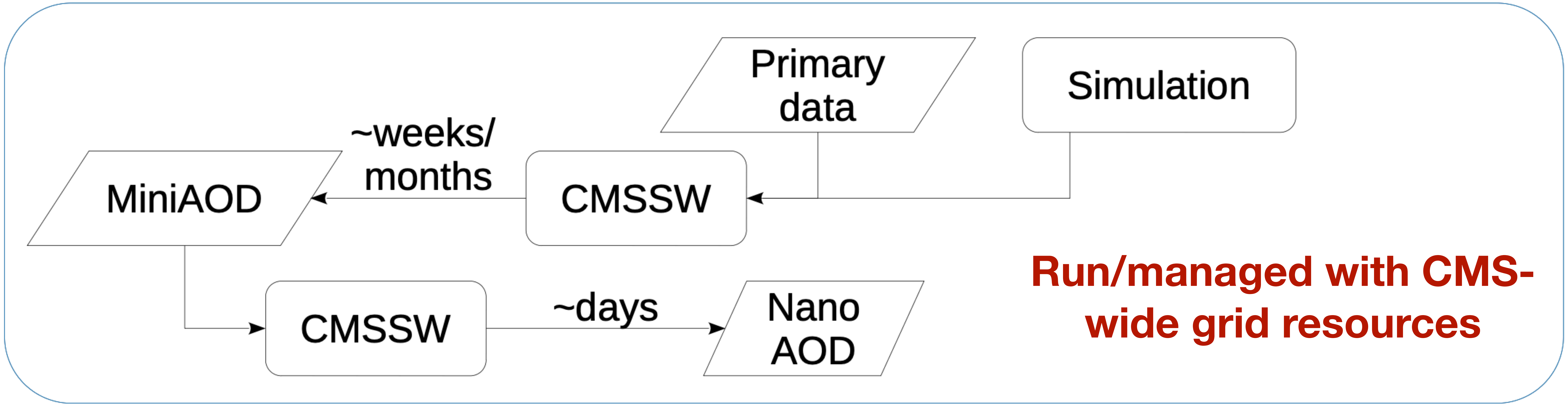
- SCETlib calculation assumes massless quarks
  - Full calculation at comparable accuracy not known

➡ Estimate impact by varying quark mass thresholds in PDF (dedicated MSHT20 PDF sets)

  - **Impact ~0.7 MeV**



Outline of the data processing workflow



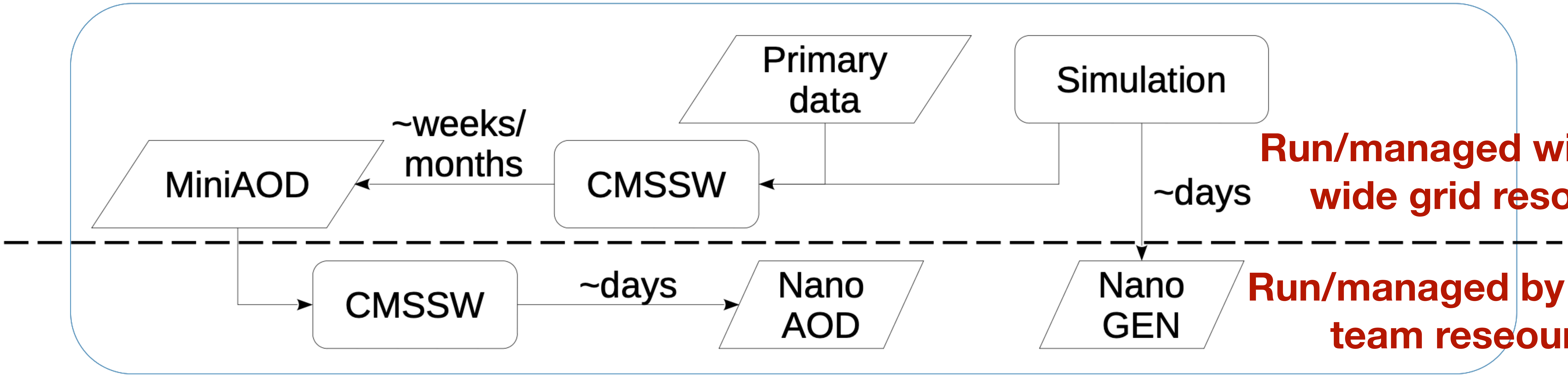
- Raw data (and simulation) processed with the standard CMS reconstruction chain (EDM format instantiates C++ objects)

➡Final, lightweight **NanoAOD** produced with collaboration wide resources in standard processing chain[0,1]

- Flat ROOT TTree with only data primitive types
- Independent of experiment specific software (e.g., no custom C++ objects)
- High level physics objects (p_T, η, ϕ, ID, … of muons, electrons, jets, …)
- ~2kB per event
- Good for ~50% of analyses

Data tier	**Size (kB)**
RAW	1000
Gen	<50
SIM	1000
DIGI	3000
RECO(SIM)	3000
AOD(SIM)	400
MiniAOD(SIM)	50
NanoAOD(SIM)	2

Outline of the data processing workflow



Run/managed with CMS-wide grid resources

Run/managed by analysis team reseources

(Ran ~10 times over 3 years)

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- Independent of experiment specific software (e.g., no custom C++ objects)
- High level physics objects (p_T, η, ϕ, ID, … of muons, electrons, jets, …)
- ~2kB per event

- **Easily customisable for this analysis**
  - Refit muon tracks, store low-level fit information, additional generator information (e.g., more PDF sets…)

Data tier	**Size (kB)**
RAW	1000
Gen	<50
SIM	1000
DIGI	3000
RECO(SIM)	3000
AOD(SIM)	400
MiniAOD(SIM)	50
NanoAOD(SIM)	2

The “analysis” steps of the processing workflow

- **Process ~1 B data events and 4B simulation events** in NanoAOD format (every time, no pre-filtering!)
- Output high dimensional histograms
- Store in hdf5 format, further processing for statistical analysis, publication-level plots…

Ran on daily basis (>1000 times)

Hardware and resources

- The "analysis" (data processed into histrograms) step is executed locally
  - No resubmission of failed jobs/ merging of jobs etc.
  - Direct feedback on progress
  - Heavily multithreaded

	CERN	MIT/Pisa
CPU	2 x EPYC	2 x EPYC
cores	128	192
threads	256	384
memory	1TB	1.5/2TB

- Necessitates high performance machine with high availability
  - High performance, high thread count machines (256/398/796 threads) at CERN, MIT, Pisa
  - Reading/writing on fast NVMe SSDs
  - Local or via network interface 100Gbit/s (e.g., from CERN eos via xrootd)

- Sounds like a luxury that cannot be widely adopted but…
  - Price/core is increasingly competitive with cluster built from many low-core machines
  - Can be seamlessly integrated into condor/slurm etc cluster
  - For future: DistRDF allows interactive-like running

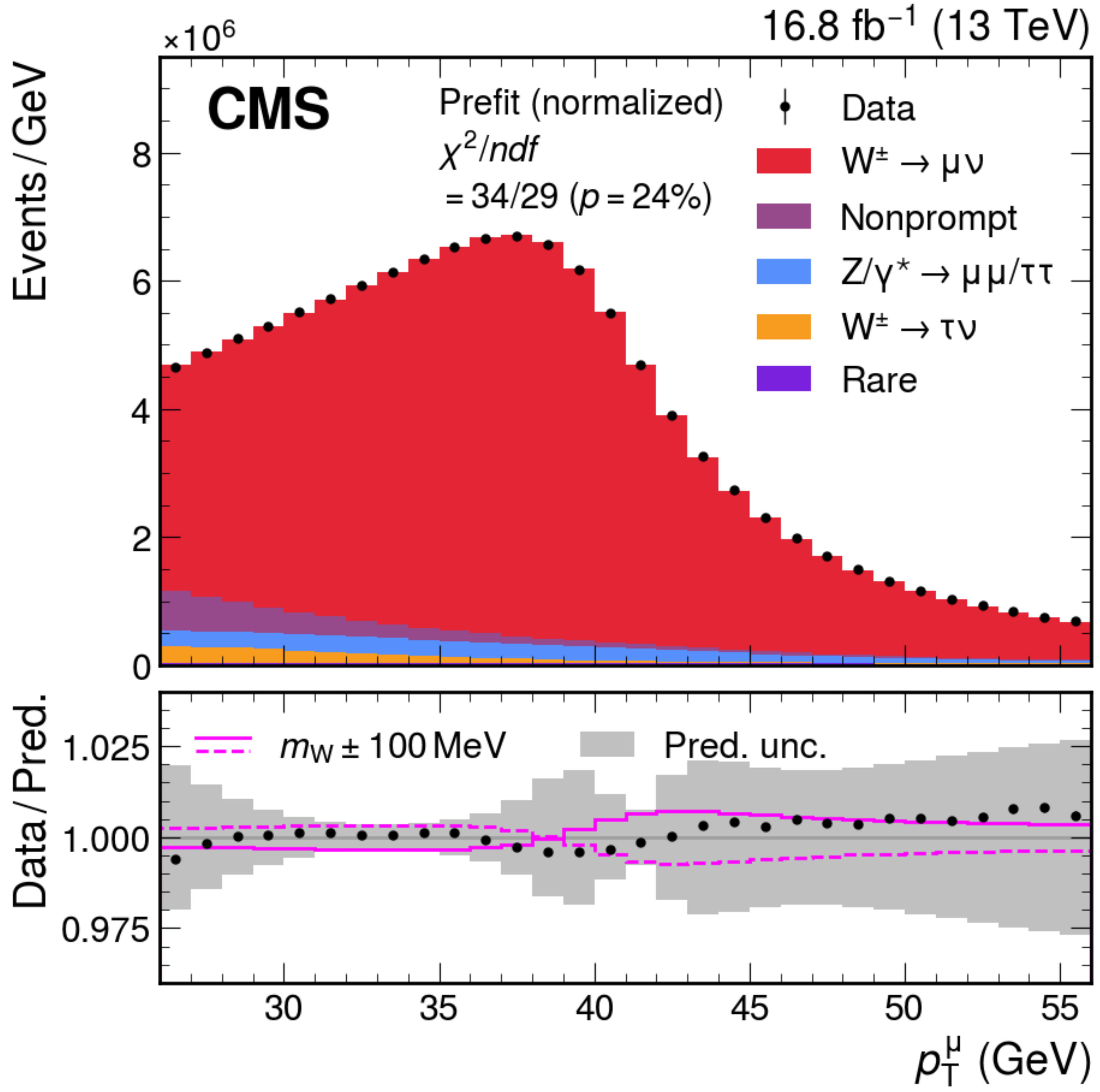
Statistical analysis

- Results from binned maximum likelihood fits to distributions sensitive to parameter-of-interest (m_W or m_Z)
  - **Using <u>tensorflow-based</u>** implementation of binned maximum likelihood fit
    - Avoid numerical instabilities due to fit complexities

- **O(3k) template bins in m_W fit and ~4000 nuisance parameters**

- **m_W (m_Z) uncertainty ± 100 MeV shift computed in simulation and propagated via event weights**
  - Unconstrained in fit
  - Extrapolation within range using log normal shape (validated to within < 0.1 MeV)
  - Consistent with typical χ^2 minimization

- **Measurement performed “blind”**
  - Likelihood fit with m_W only performed on data in final steps
  - m_Z and m_W values hidden, “unblinded” in sequence after finalising all inputs



Statistical analysis: technical details

- Analysis is based on determining the value of m_W that maximizes Likelihood (minimises -2ln *L*)

$$\ln L = \sum_{ibin} \left(-n_{ibin}^{obs} \ln n_{ibin}^{exp} + n_{ibin}^{exp} \right) + \frac{1}{2} \sum_{ksyst} \left(\theta_{ksyst} - \theta_{ksyst}^{0} \right)^2 \quad \text{where} \quad n_{ibin}^{exp} = \sum_{jproc} \mu_{jproc} \, n_{ibin,jproc}^{exp} \prod_{ksyst} \kappa_{ibin,jproc,ksyst}^{\theta_{ksyst}}$$

~2000 | Gaussian constraint nuisance parameters | ~10 | ~5000

- RooFit+Minuit workflow found to be insufficient for minimisation
  - Limited numerical precision/efficiency/run time

- Built custom implementation of likelihood and minimisation in tensorflow:

➡Combinetf (PyHEP talk)
  - Automatic differentiation for high-precision gradient calculation
  - Quasi Newton trust region based minimizer to reliably find global minimum
  - Fast, numerically accurate, stable
    - Extensively validated against CMS Combine package

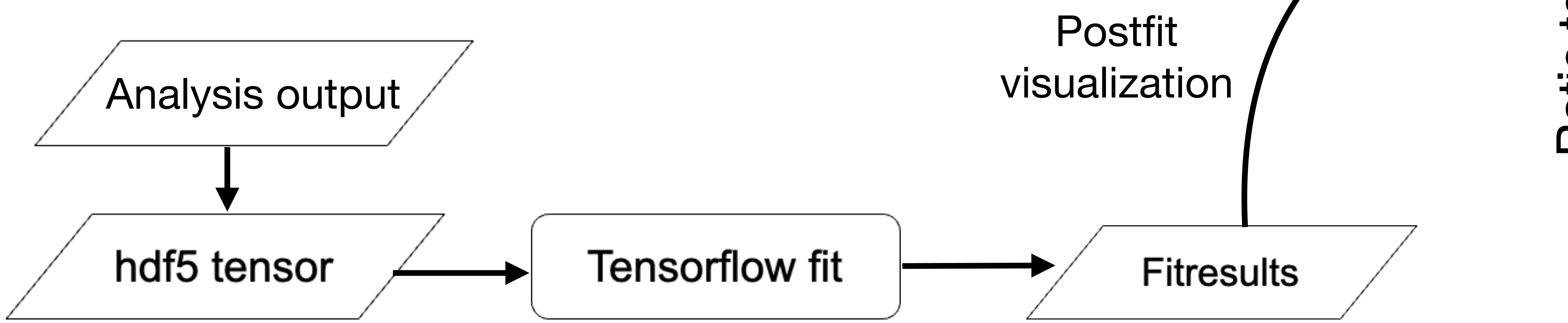
Statistical analysis

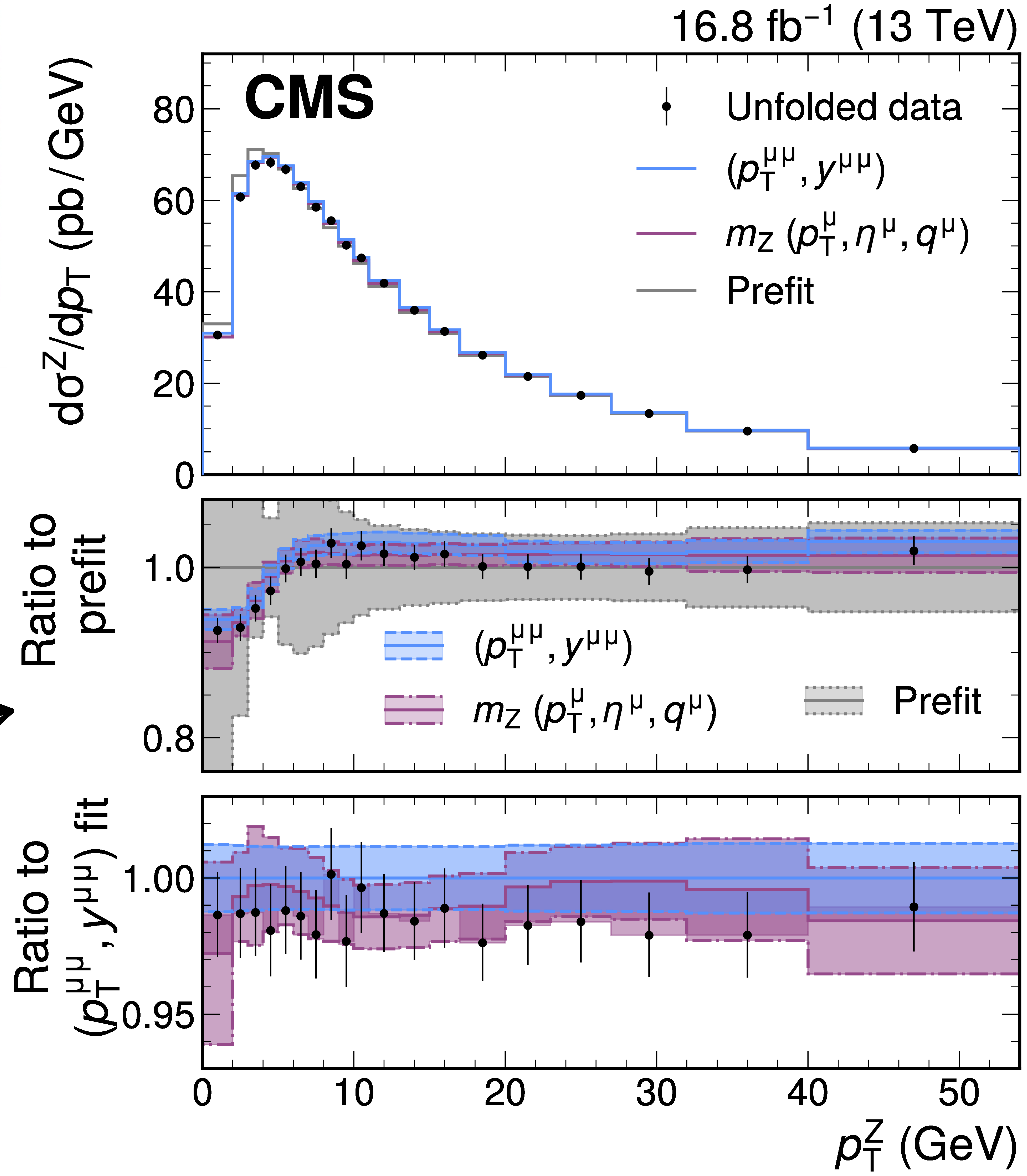
- Rewrite in tensorflow2 recently completed

➡**R**apid **A**utomatic **B**in **B**ased **I**nference **T**ool

  - New UI + More developer friendly
  - More efficient computatoin of hessian and hessian vector products
  - Native/improved support for plotting post-fit distributions
    - Including applying postfit nuisance pulls/ constraints from separate fit
    - Ex: postfit generator-level distribution from fit to reconstructed variables

RABBIT





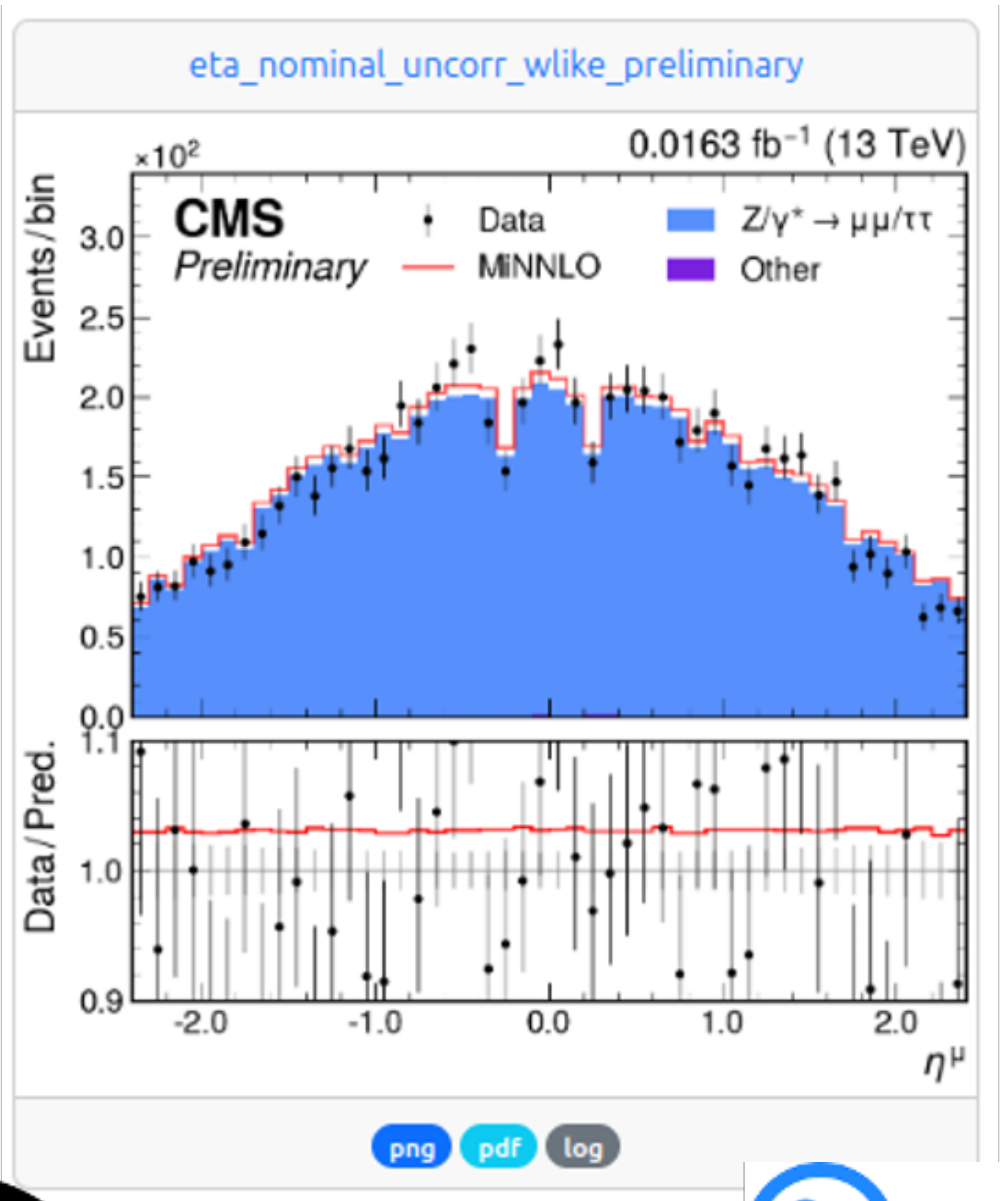
Continuous integration

- Common framework for multiple analysis interpretations
  - Reuse existing code, find/avoid bugs, save time
  - Rapid developement with O(10) contributors
    - >500 pull requests (PRs)

- Updates often unintentionally affected (or break) other parts
  - Not noticed immediately, difficult to trace down source
  - Harder to fix after the fact

- Solution ➞ GitHub actions: platform for automate developer workflows
  - Use continuous integration and deployment (CI/CD) pipeline
  - Slim and easily to set up and manage (compared to e.g. Jenkins)

- Locally hosted on dedicated machine at CERN
  - Executed on subset of data for each PR
  - Full stats run 3/week over night




```
on:
  pull_request:
    branches: [ main ]
  schedule:
    - cron: '30 5 * * 1-5'
    - cron: '0 1 * * 2,4,6'
  workflow_dispatch:
```

Continuous integration pileline

- Execute full graph of analysis workflows and dependencies for every PR
- independent steps run in parallel, error stop further processing
- Linters (Black, Flake, isort) check code quality and basic errors in first step

Continuous integration and self-documentation: summary pages

- Full result produced on interactive web pages
  - Plots for all analysis
  - Log files with yields
  - Uncertainty Impacts, pulls/constraints
- Allows precise validation of changes to physics results

/eos/home-i04/c/cmsmwbot/www/WMassAnalysis/PRValidation/PR598/2025_06_20

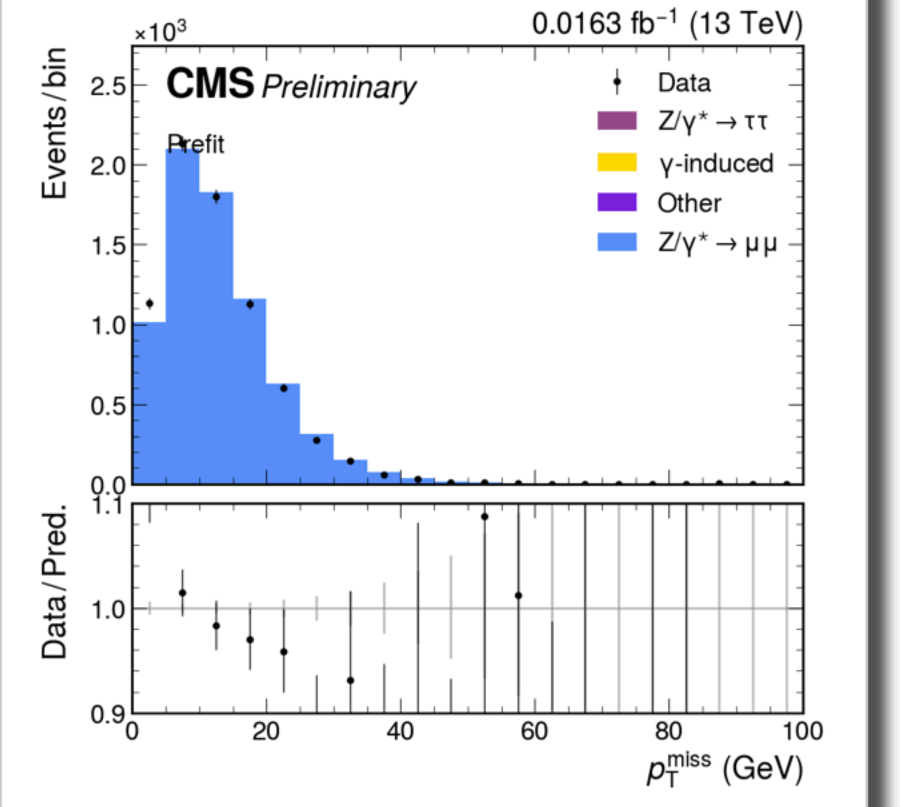
Directories

[parent] [lowPU] [unfolding_dilepton] [unfolding_mw]

Plots

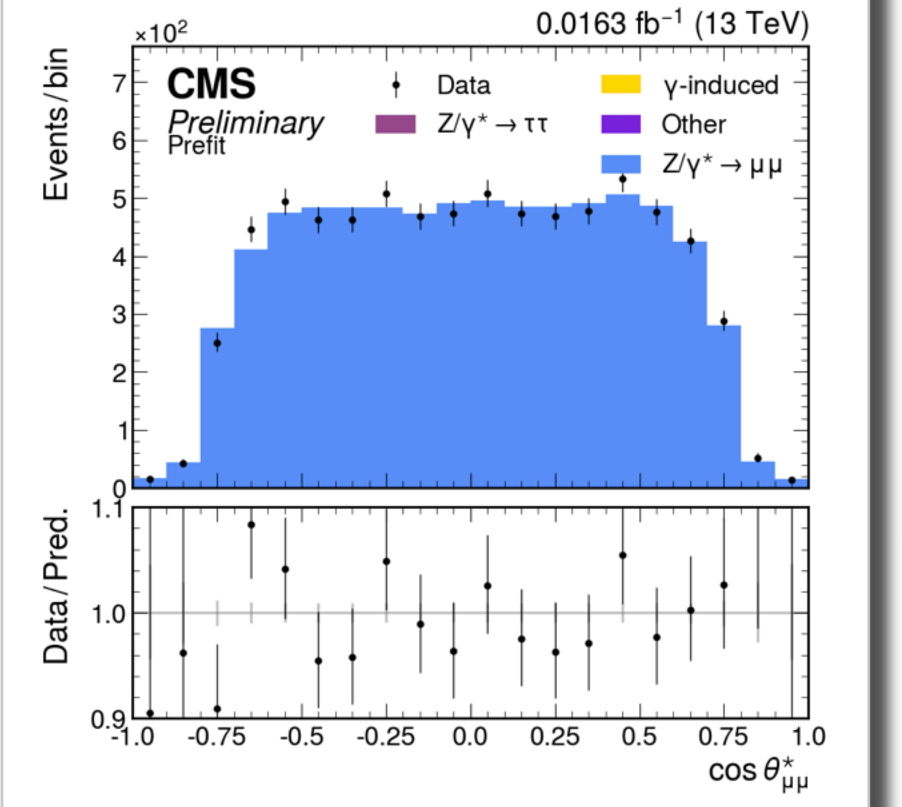
Filter: Go RegExp

MET_wlike_preliminary.png



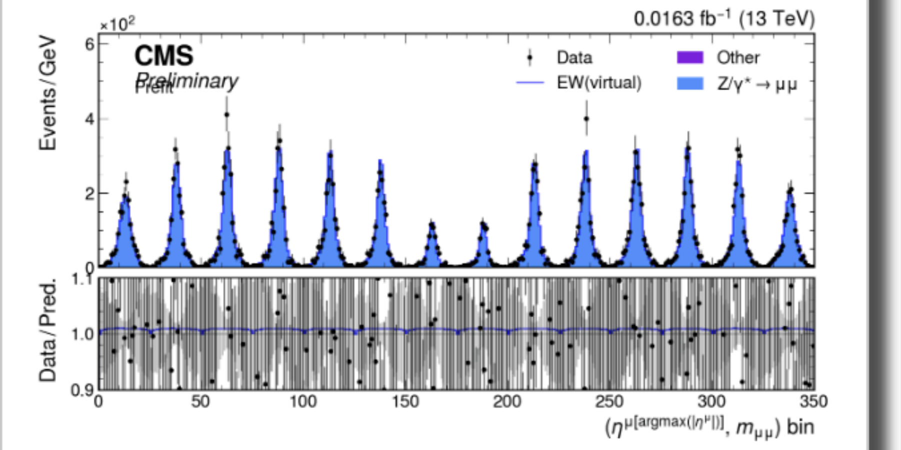
Also as [.pdf], [.log]

cosThetaStarll_z_preliminary.png



Also as [.pdf], [.log]

etaAbsEta_mll_weak_default_z_-preliminary.png



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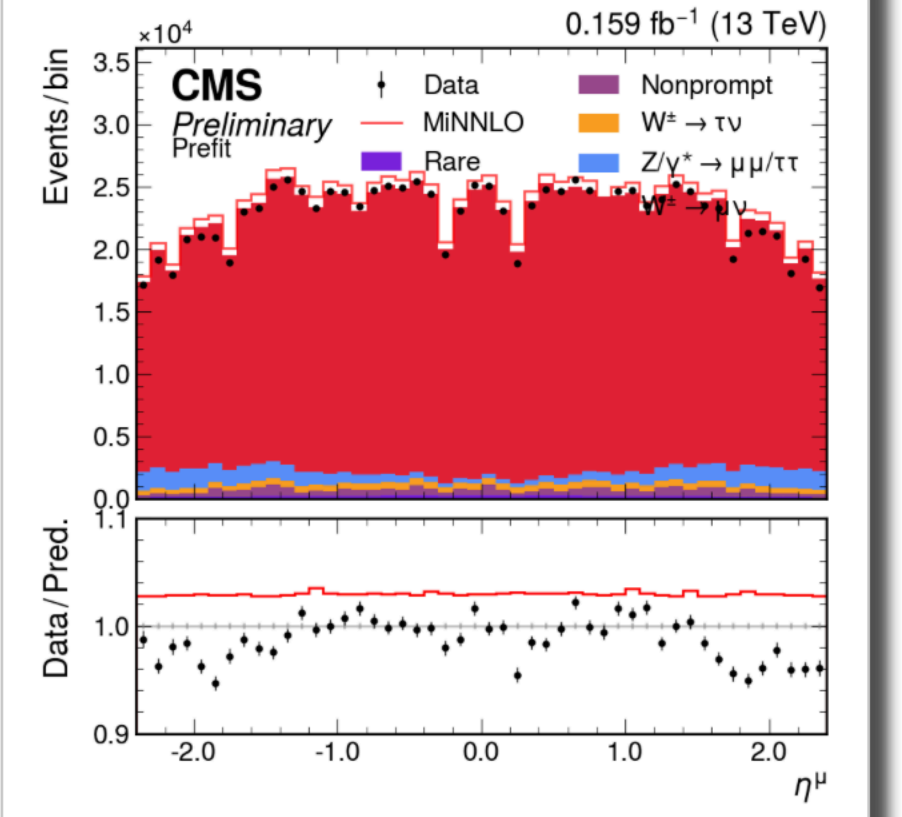
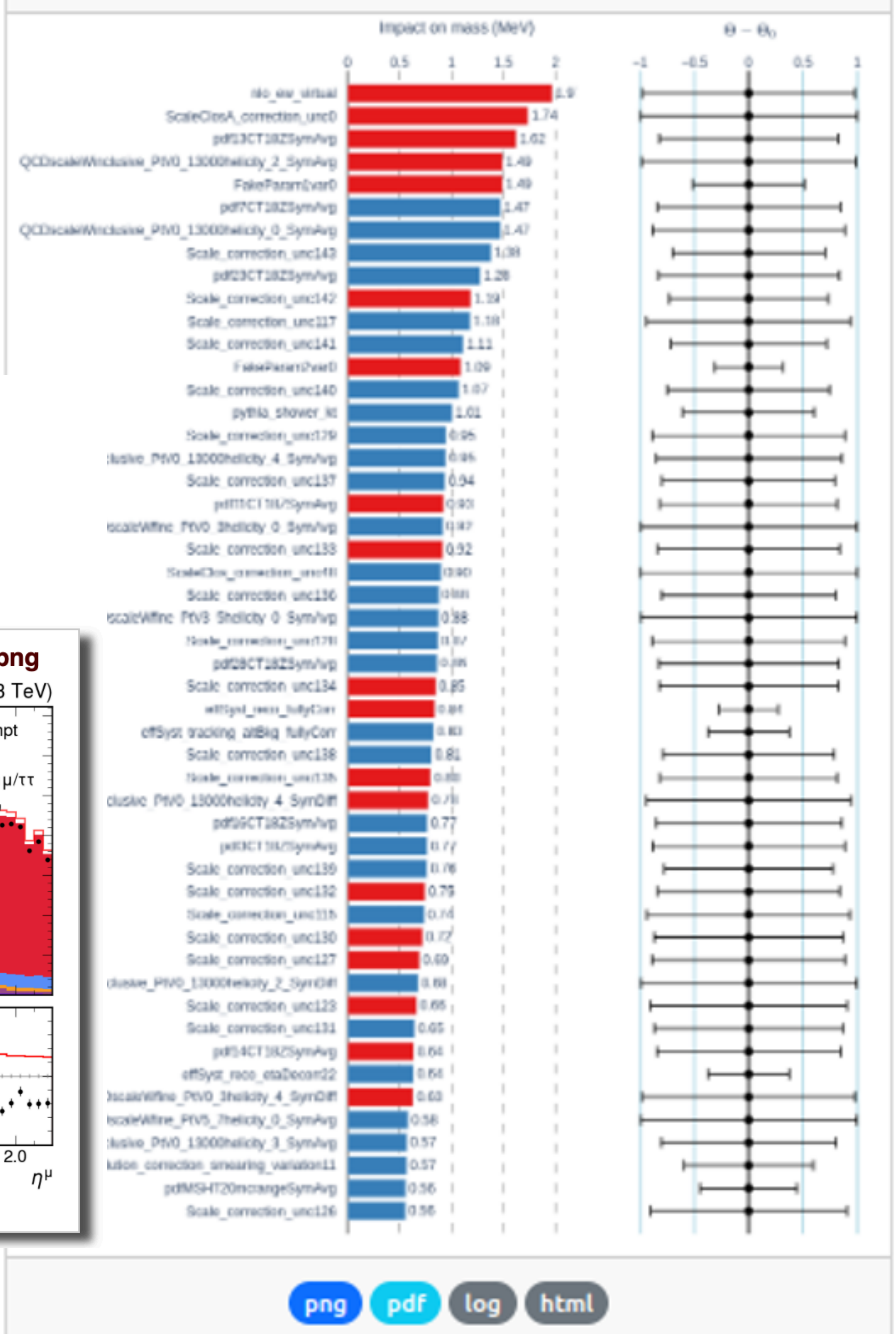
eta_nominal_uncorr_W_preliminary.png



Also as [.pdf], [.log]

impactsW_massShiftW100MeV_noi

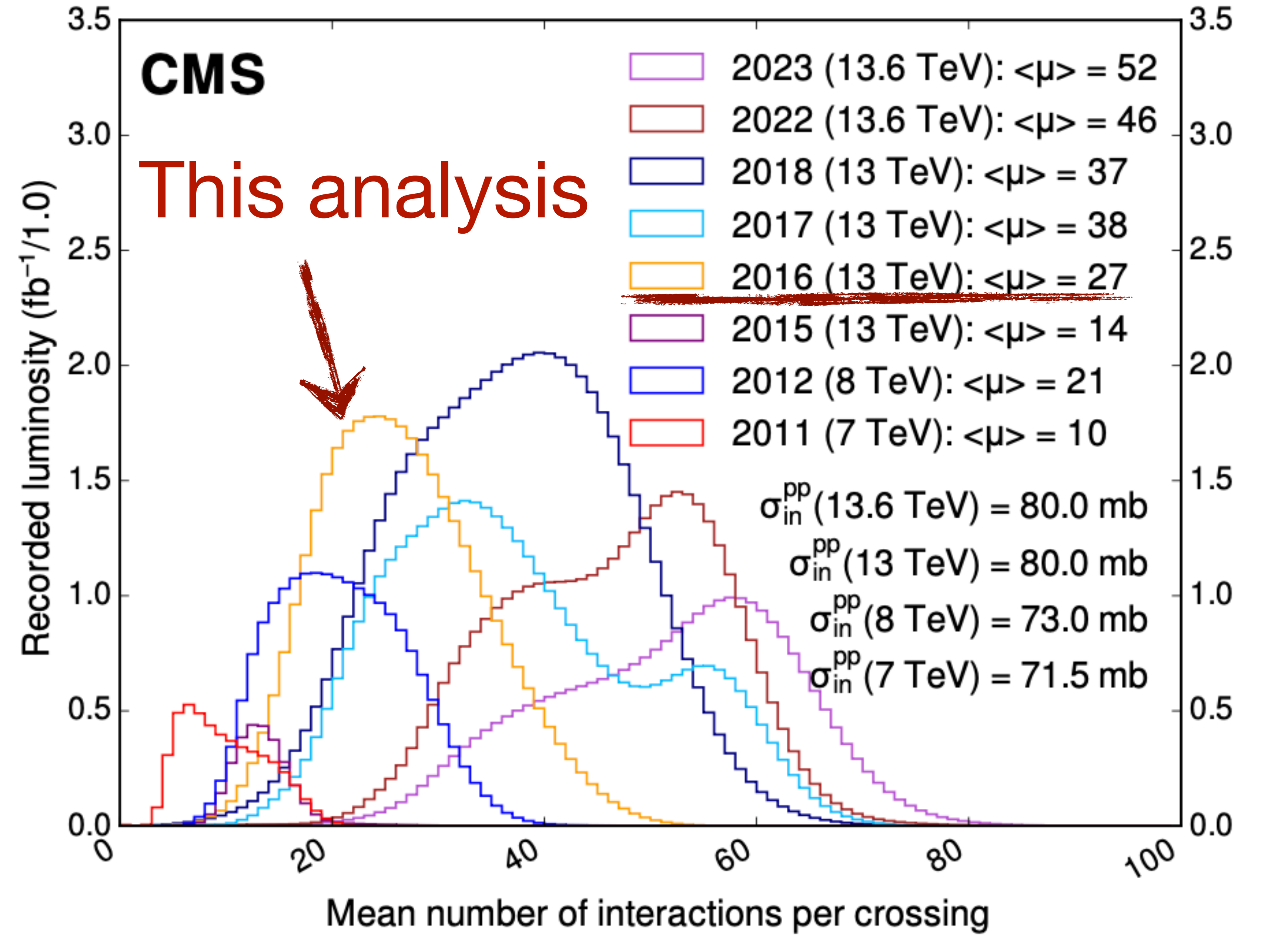


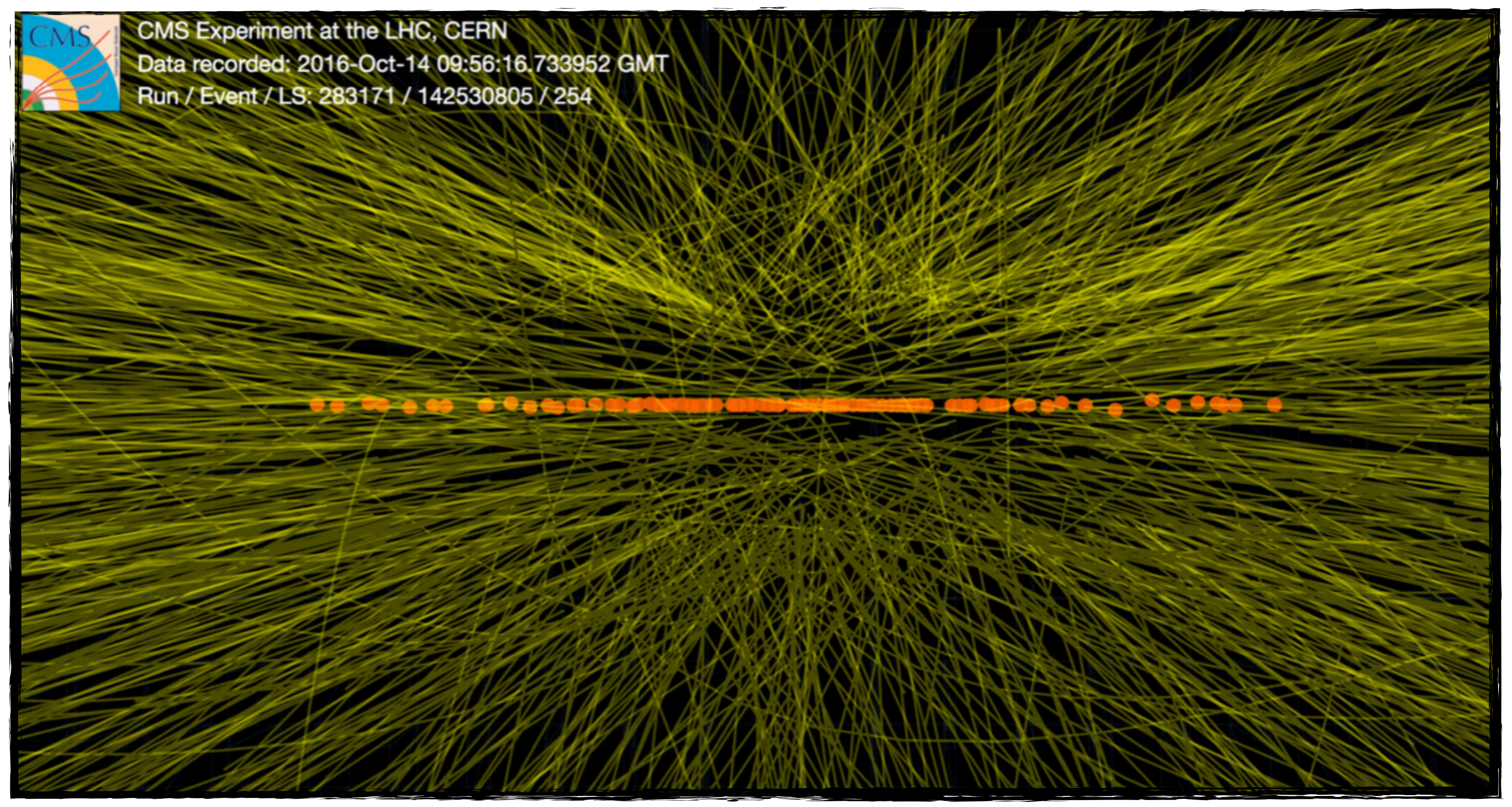
Pileup

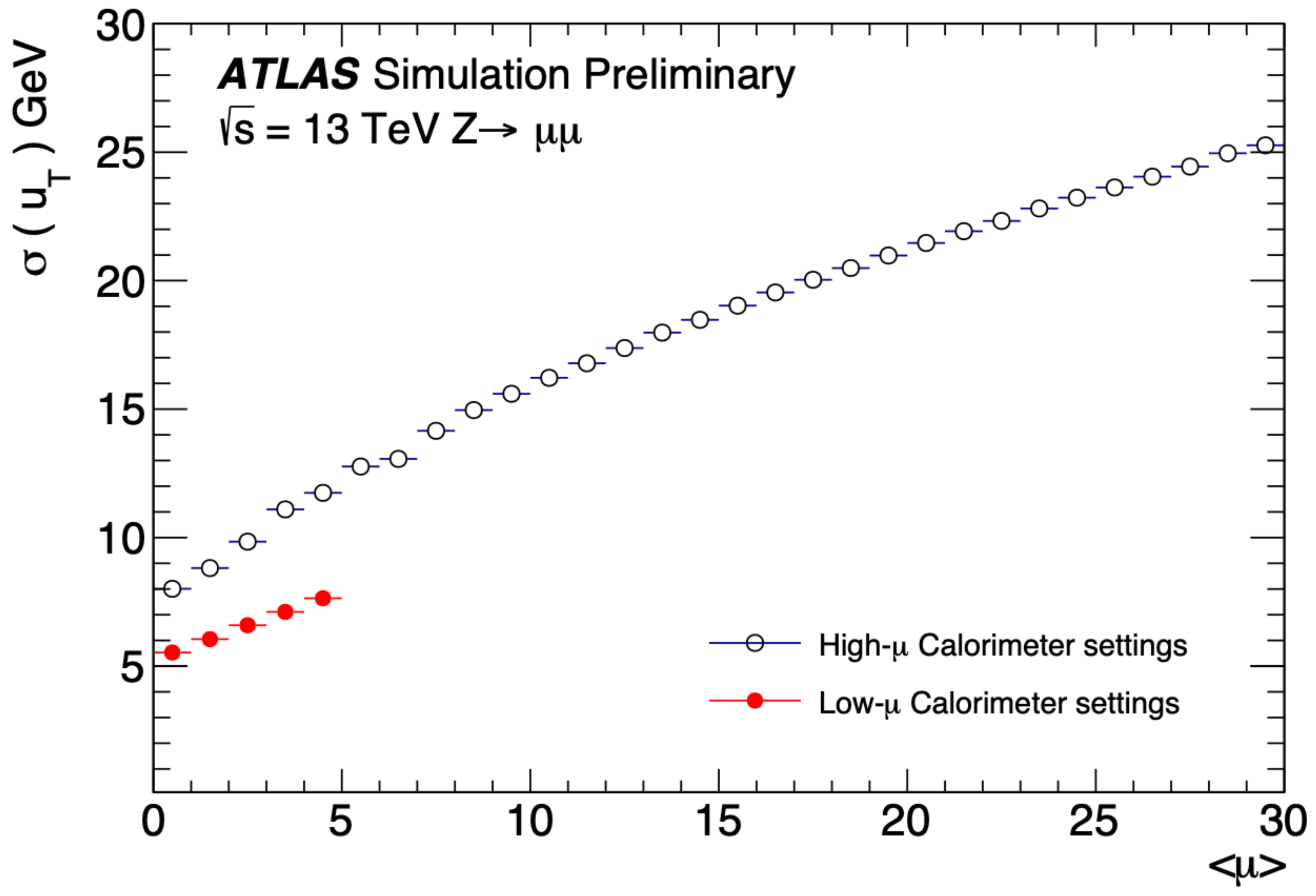
- Multiple pp interactions in one LHC bunch crossing
  - Critical to the LHC push to high luminosity, but not “for free”
- **“Is pileup really such a big deal?”** — Anonymous theory colleague
  - Most measurements: it’s worth the hit
  - Precision measurements: it’s a huge challenge!

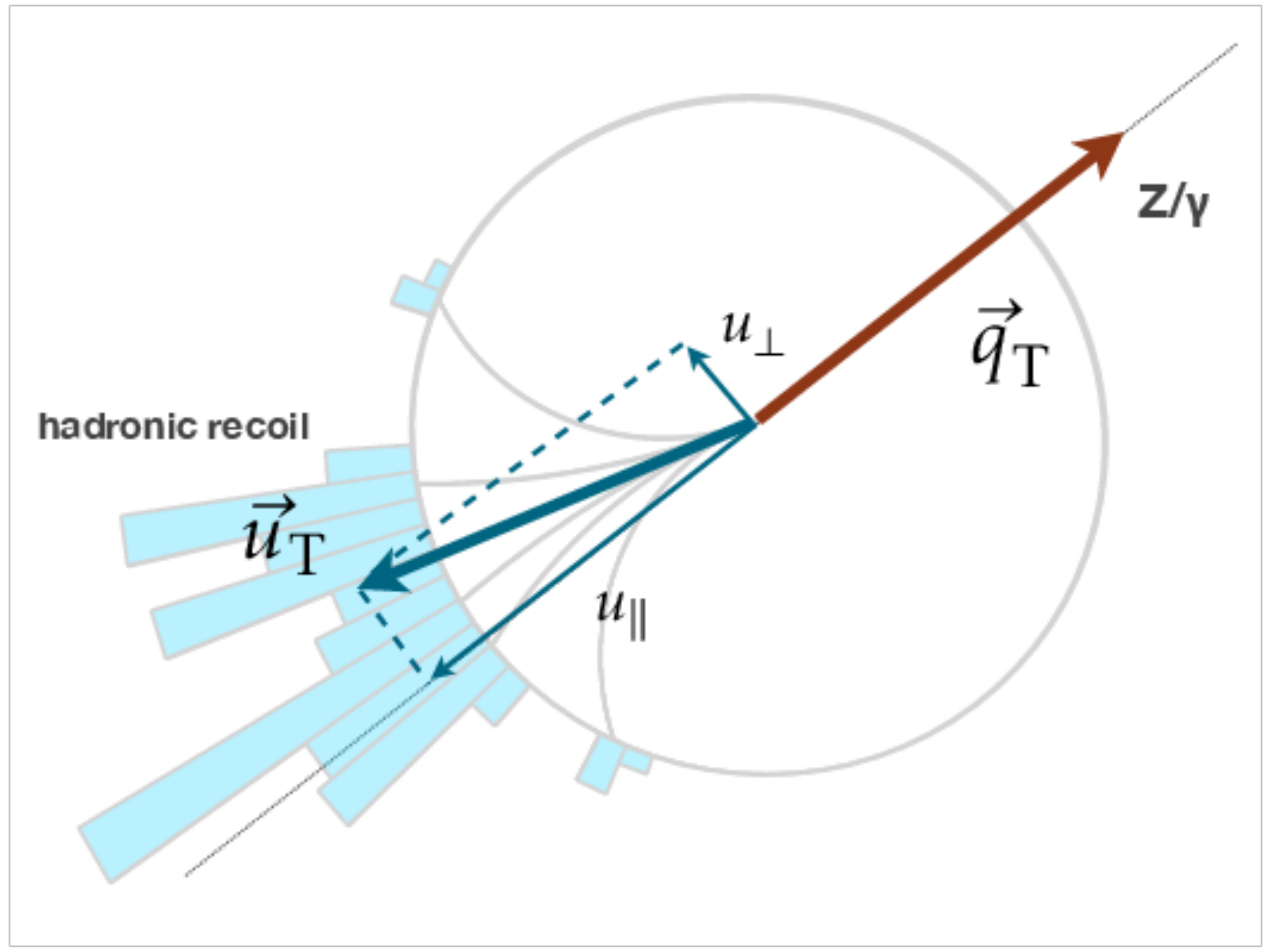
➡More stuff in the detector ⟹ more chances for confusion (e.g., tracks built from wrong hits), higher chance to mis-measure

  - Balancing act between lumi. and performance



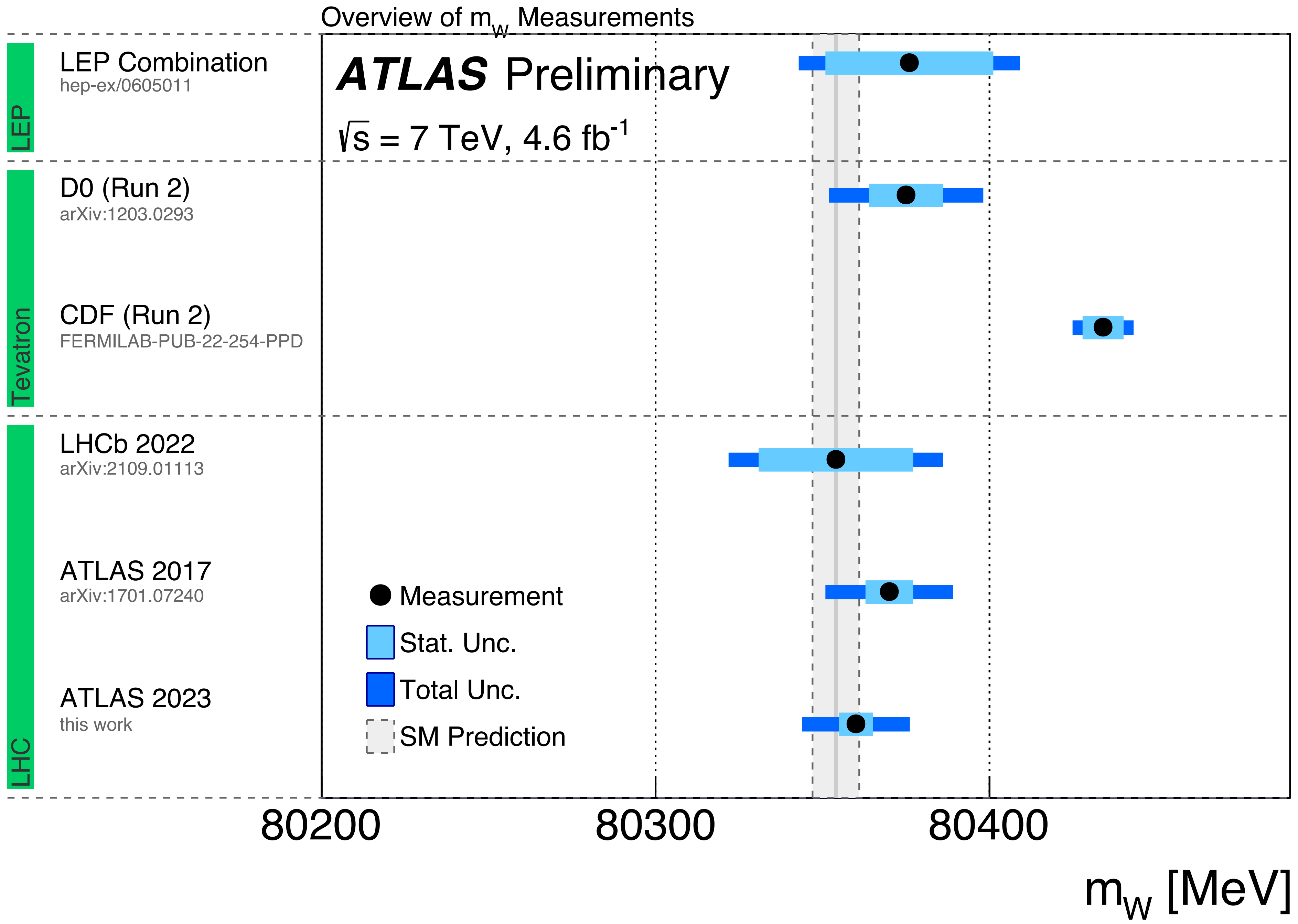






m_W measurements: current landscape

- LEP combination (2013): 33 MeV unc.
  - Semi-leptonic and fully hadronic WW decays
- Tevatron (proton-antiproton):
  - wrt LHC: Smaller W production uncertainty, better estimation of neutrino momentum
  - D0 (2013): (23 MeV unc.)
  - CDF (2022): (9.4 MeV unc.)
    - m_T+p_T^ℓ (e+μ); very precise ℓ calibration; 4.2 M events
- LHCb (2021) (32 MeV unc.)
  - 13 TeV, p_T^μ channel only; 2.4 M events
- ATLAS (15.9 MeV unc.)
  - Published 2017, updated earlier this year
  - 7 TeV data, m_T+p_T^ℓ (e+μ, 3 η categories); 14 M events
  - Driven by p_T^ℓ channel (~90%)
- CMS (9.9 MeV unc.)
  - 13 TeV data, p_T^ℓ (μ only, 48 η categories); 100 M events



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

CDF uncertainty breakdown

Comparison of measurements (previous ATLAS)

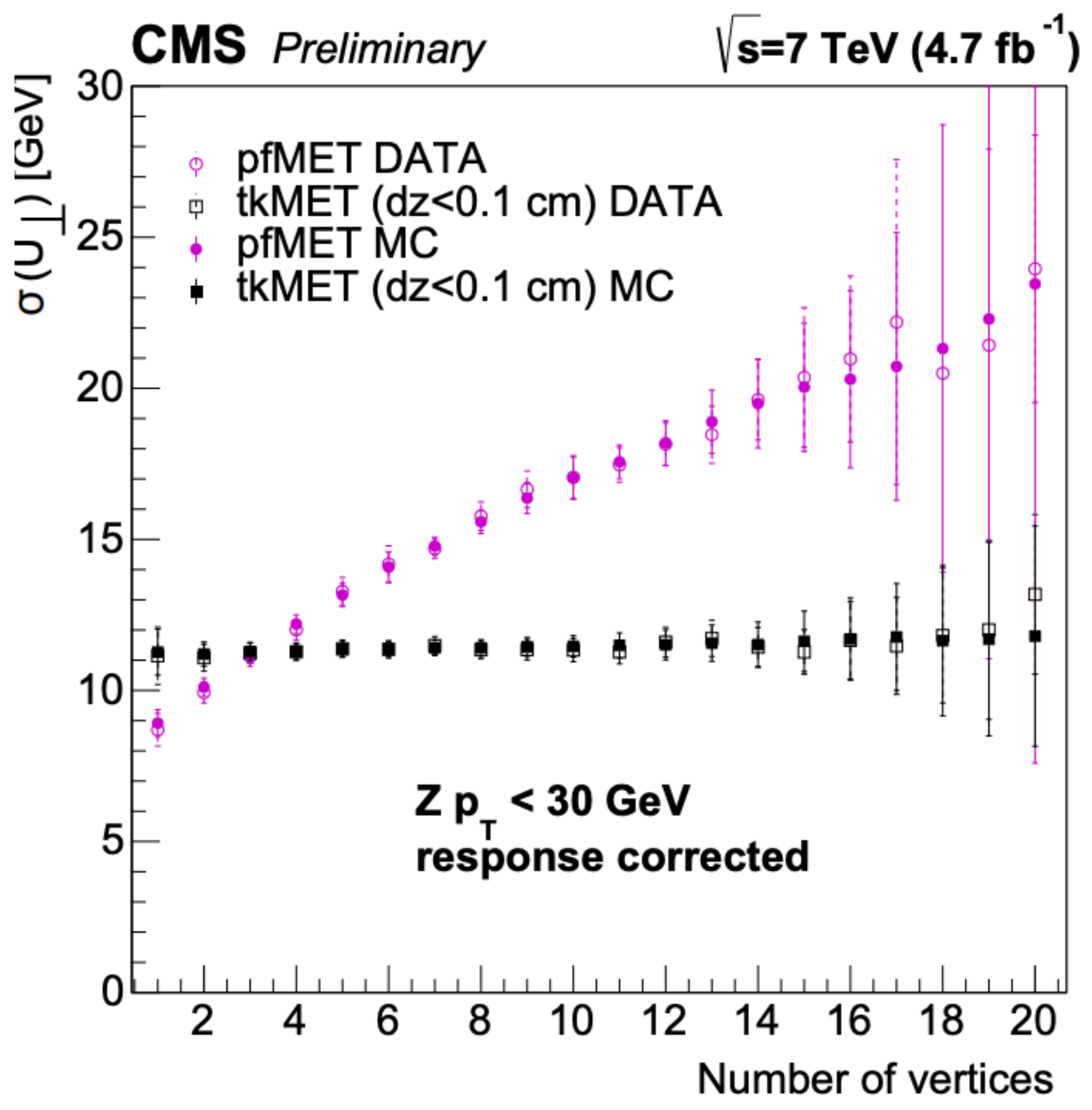
	ATLAS	LHCb	CDF
Collider	pp	pp	$p\bar{p}$
$\sqrt{s}$	7	13	1.96
$\mathcal{L}$	4.1–4.6	1.7	8.8
$N_{pileup} \sim$	9	2	3
Final states	e/μ	μ	e/μ
Fit variables	m_T, p_T^ℓ	q/p_T^ℓ, p_T^{miss}	m_T, p_T^ℓ, p_T^{miss}
$p_T^\ell >$ (GeV)	30	28	30
$p_T^\ell <$ (GeV)	50	52	55
$\eta^\ell >$	-2.5	2.2	-1.0
$\eta^\ell <$	2.5	4.4	1.0
$p_T^{miss} >$ (GeV)	30	N/A	30
$m_T >$ (GeV)	60	N/A	60
$m_T <$ (GeV)	100	N/A	100
$u_T <$ (GeV)	15	N/A	15
Selected events $\sim$	13.7M	2.4M	4.2M
MC generator	POWHEG-PYTHIA 8	POWHEG-PYTHIA 8	RESBOS
PDF set	NNPDF3.0	NNPDF3.1	NNPDF3.1

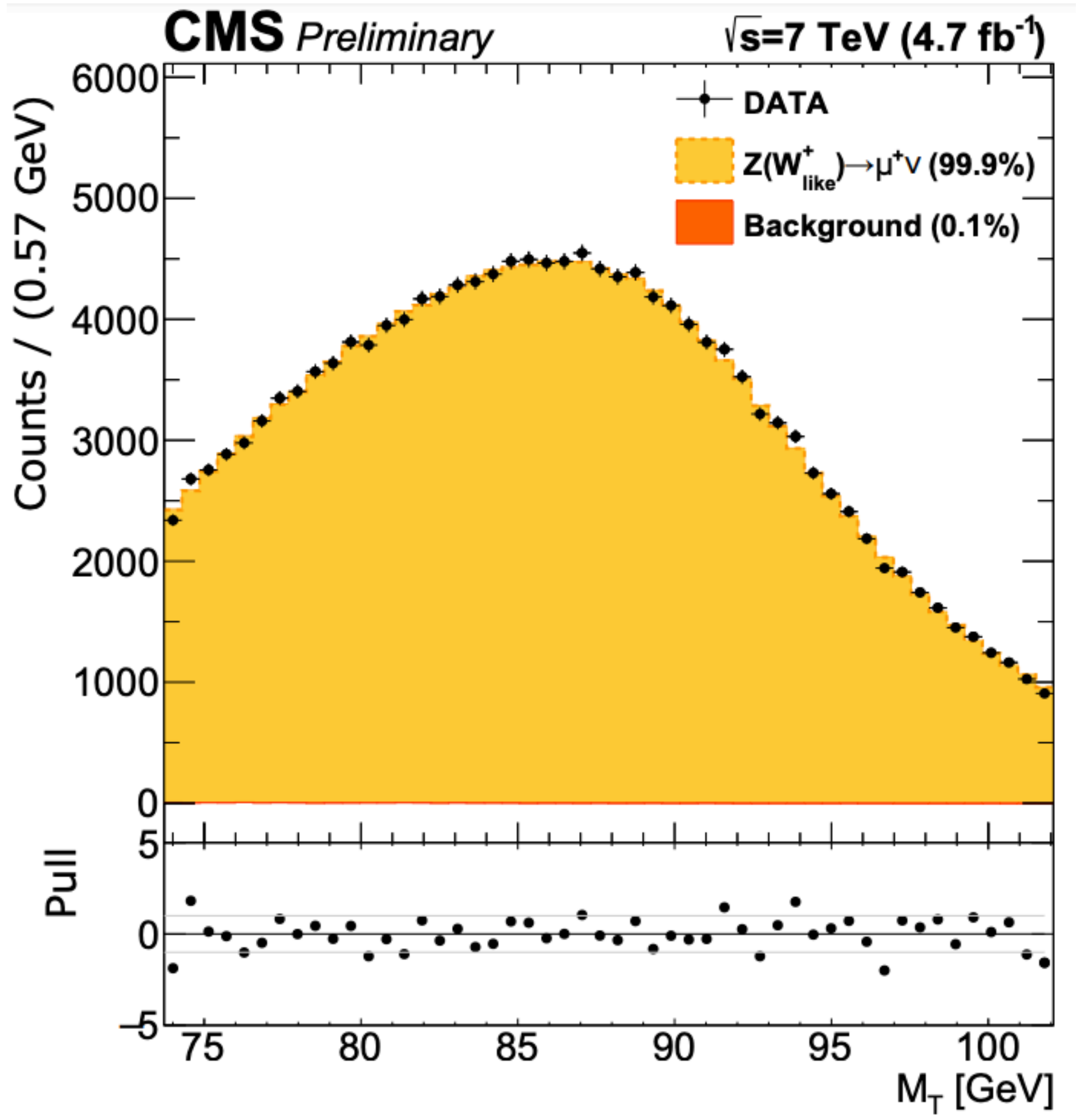
Comparison of uncertainties (previous ATLAS)

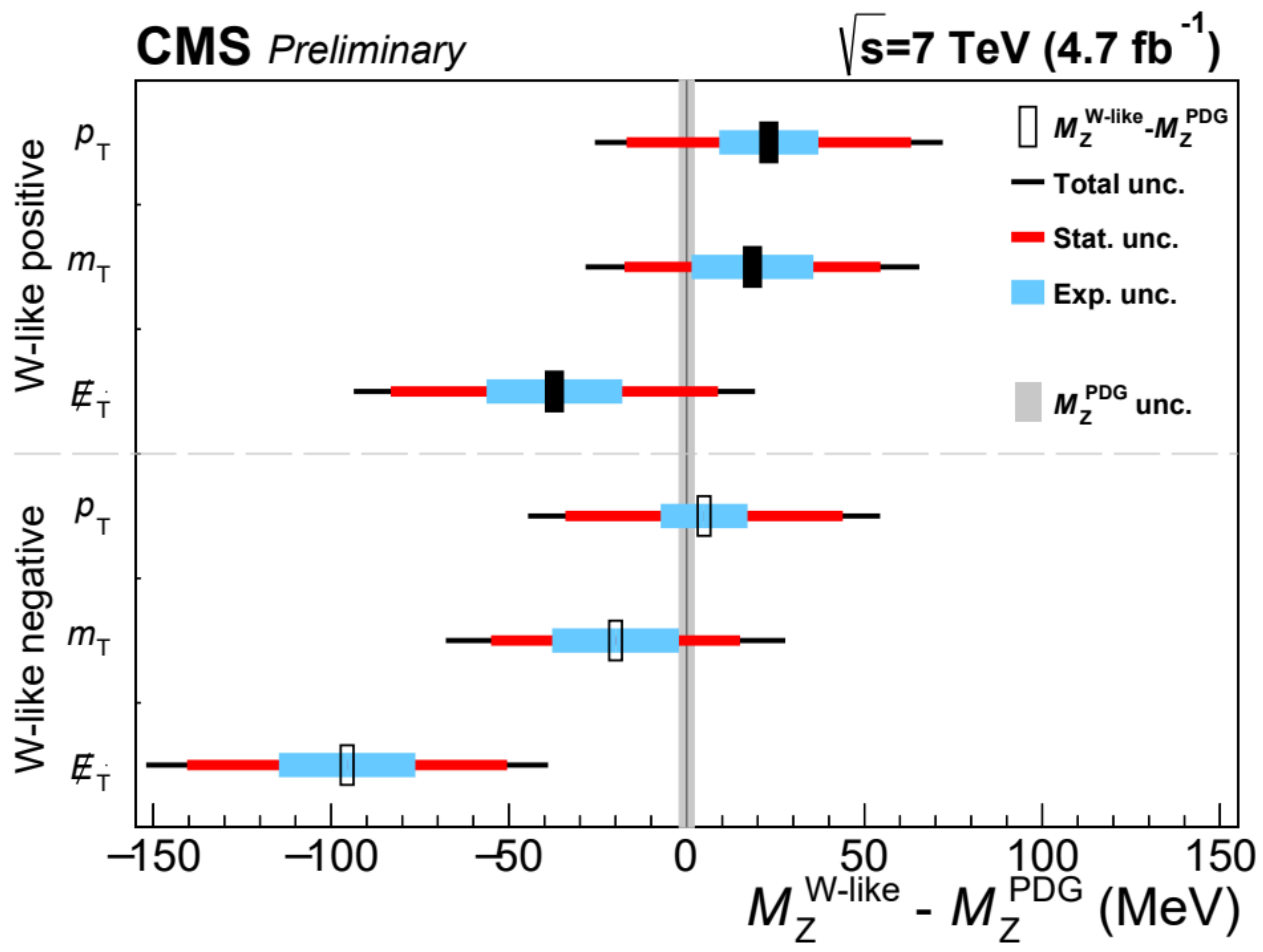
Source	ATLAS (MeV)	LHCb (MeV)	CDF (MeV)
Lepton uncertainties	9.2	10	3.5
Recoil energy scale & resolution	2.9	N/A	2.2
Backgrounds	4.5	2	3.3
Model theoretical uncertainties	9.9	17	3.5
PDFs	9.2	9	3.9
Statistical	6.8	23	6.4
Total	18.5	32	9.4

CMS W-like Z measurement

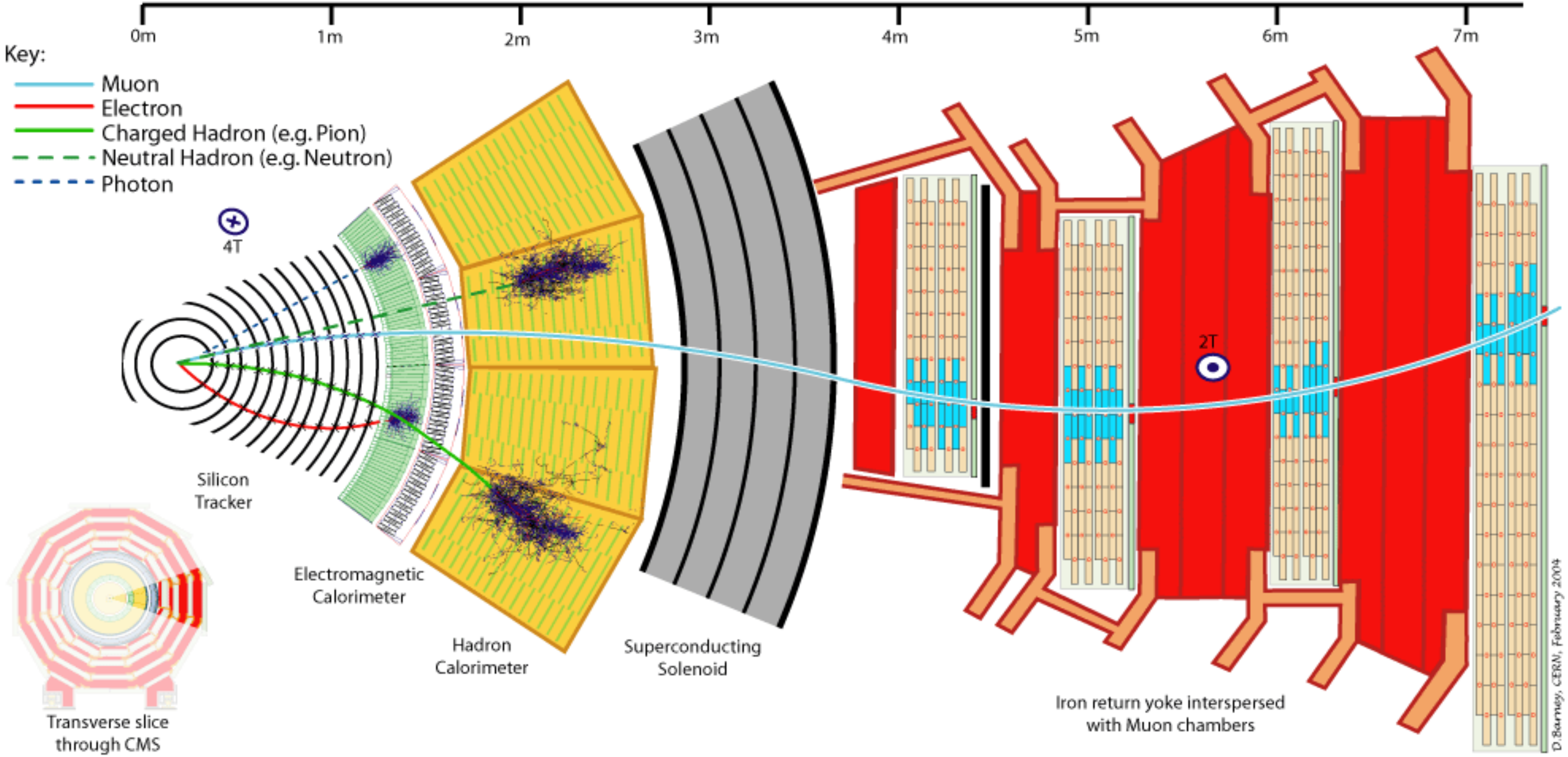
- Measurement of the Z mass in a "W-like" way: add one lepton to the p_T^{miss}
- First effort towards a W mass measurement
- Focued on calibration of muon momentum scale and recoil
  - **Limited to central muons**
- In principle, a demonstration that this is possible at CMS
- Combination of technical issues (MC production) and sociological ones (loss of person power) meant the effort stopped here







Particle reconstruction with the CMS detector

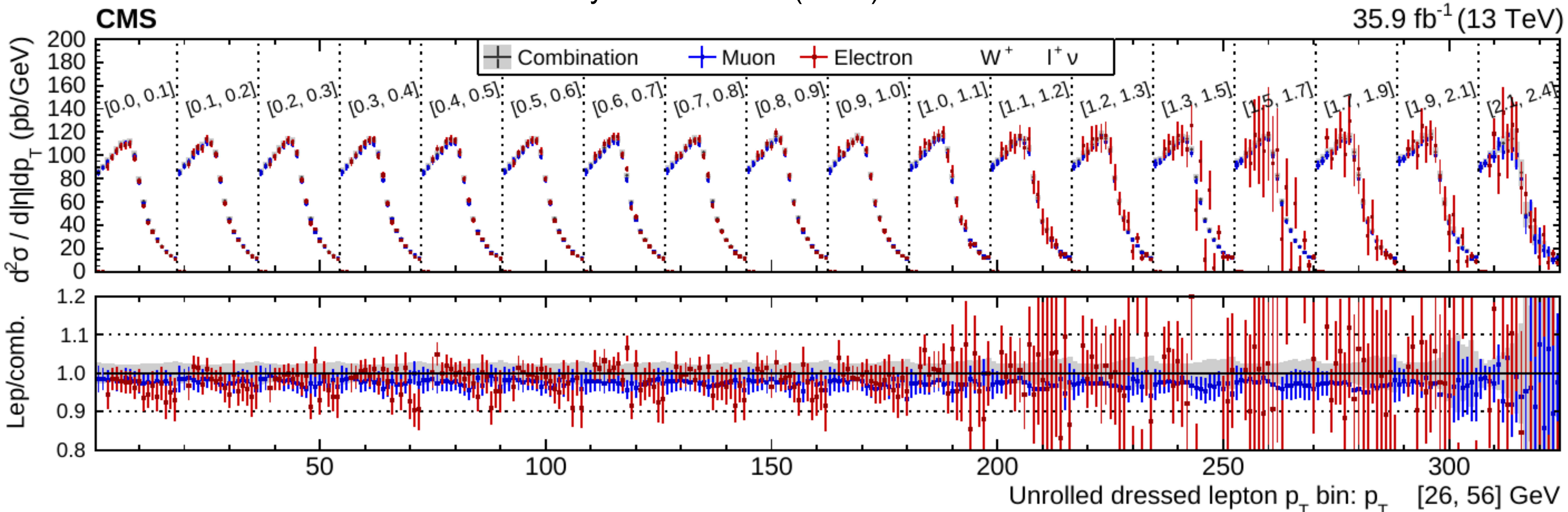


- high B-field, excellent silicon tracker + muon system ⟹ **precise μ measurement**
- Hadronic jets from clustering individual particle candidates
- Neutrino transverse momentum from conservation of momentum: **↑pileup ⟹ ↓accuracy**

Electrons vs. Muons

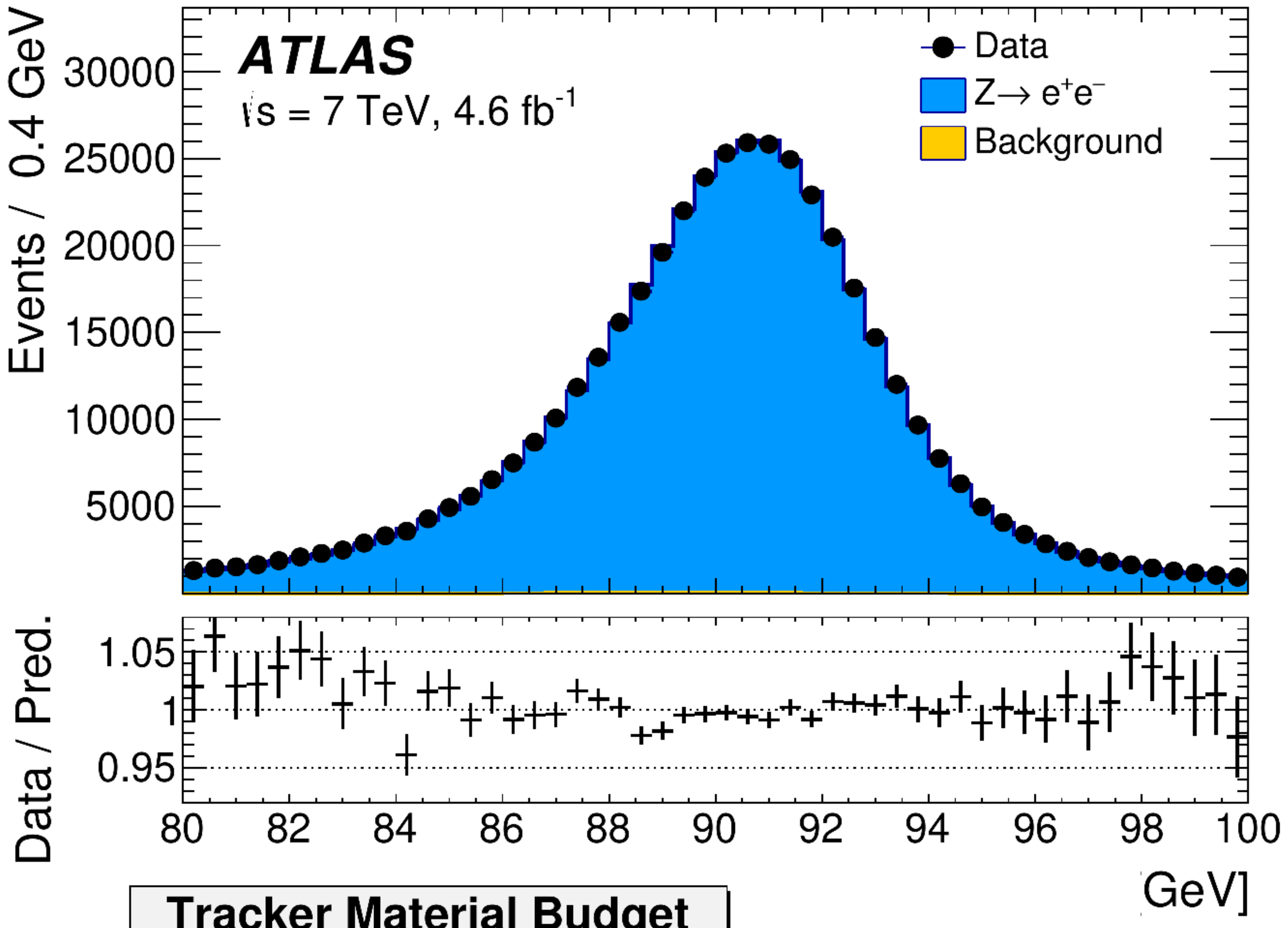
- Significantly larger statistical+experimental uncertainties for electrons already in W helicity measurement
- Energy calibration is also more challenging
- Will be difficult to be competitive with muons for m_W measurements

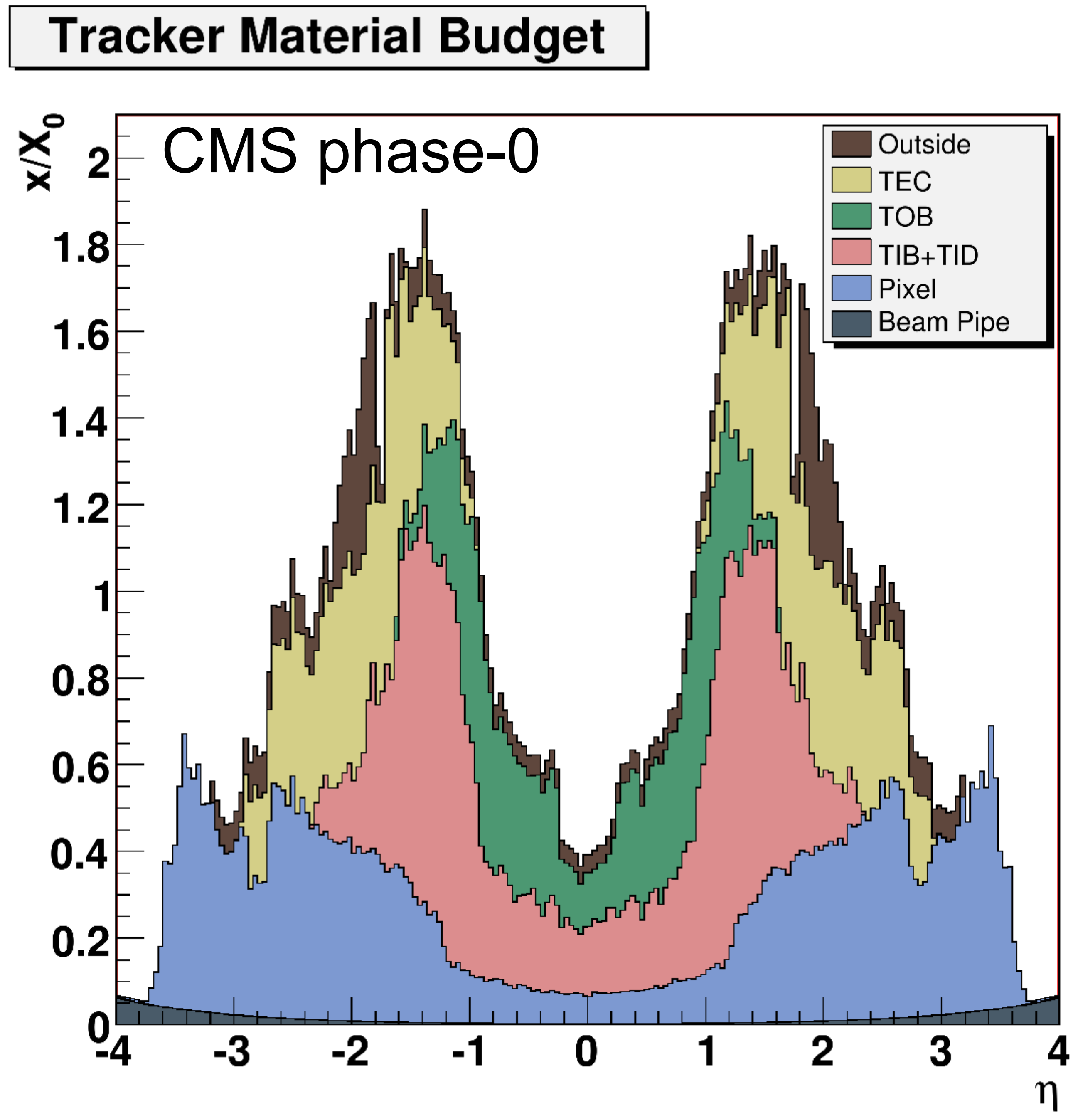
Phys. Rev. D 102 (2020) 092012

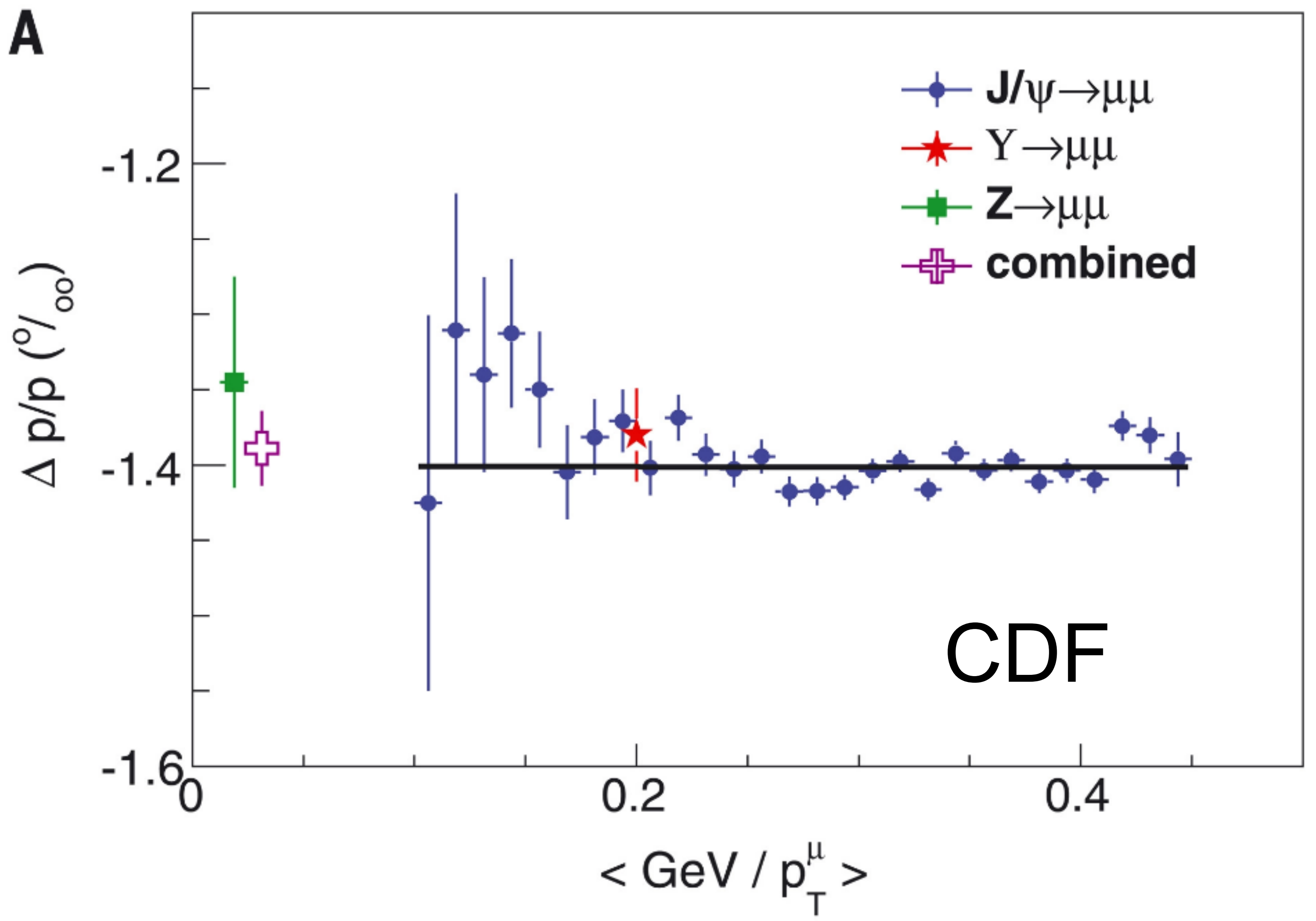


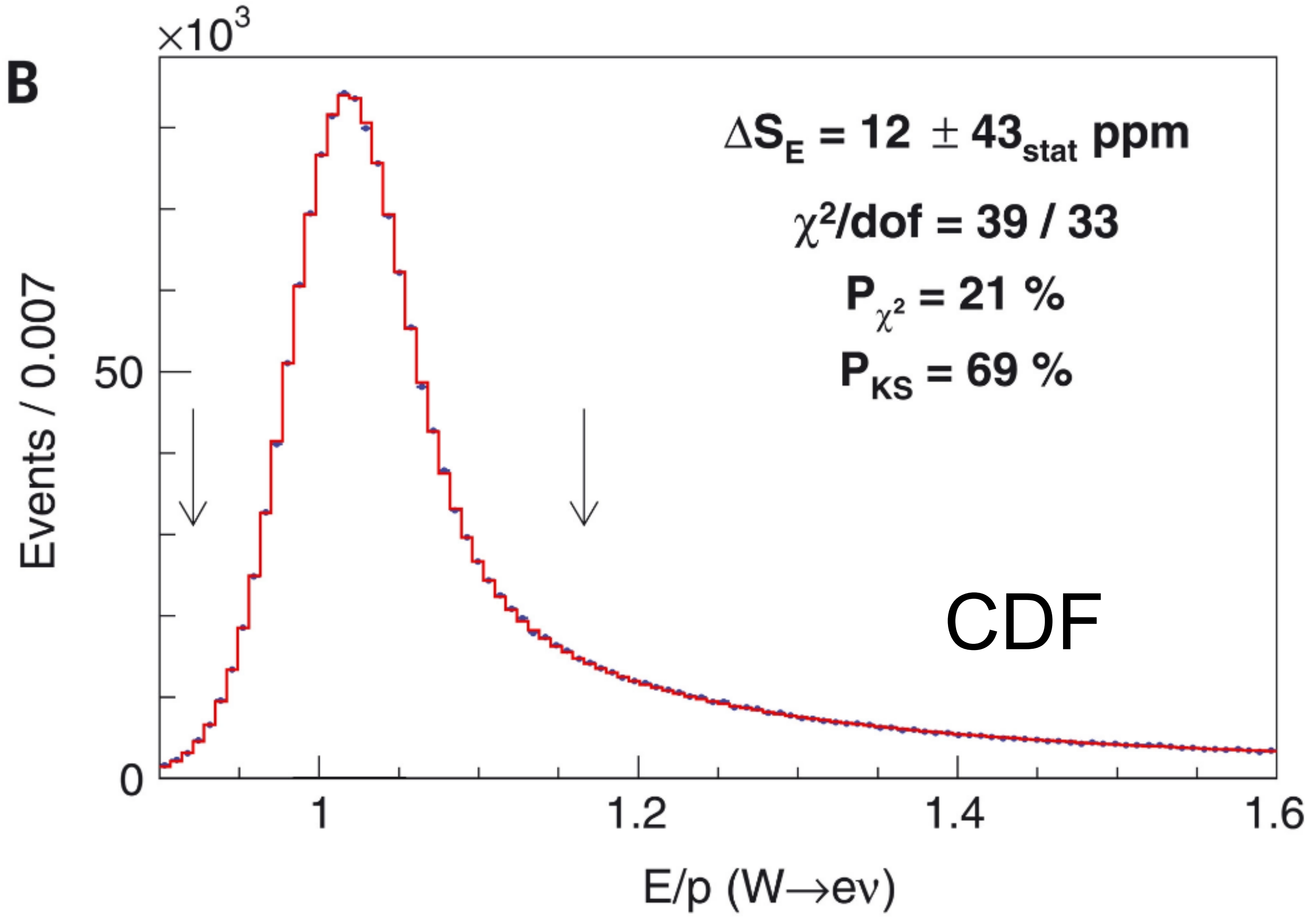
Electron energy scale calibration in CDF and ATLAS

- CDF quotes systematic uncertainties on electron energy scale < 1e-4
- Achieved by transporting ultra high precision tracking calibration from muons to electron tracks and then using E/p
- CDF has < 0.2 radiation lengths of material in the tracking volume
- Quoted ATLAS electron energy scale uncertainties are approaching 1e-4, but rely maximally on Z->ee for calibration



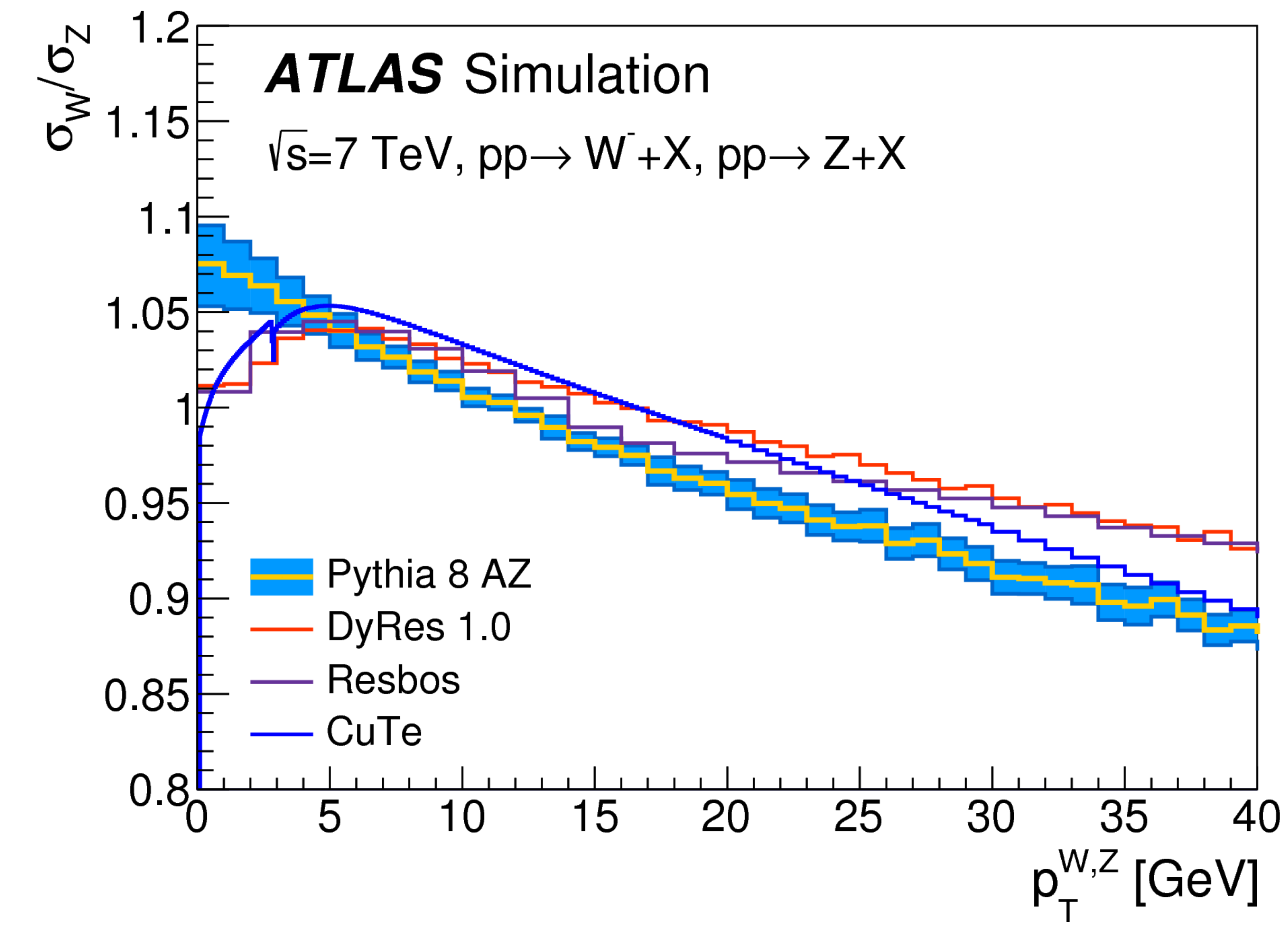


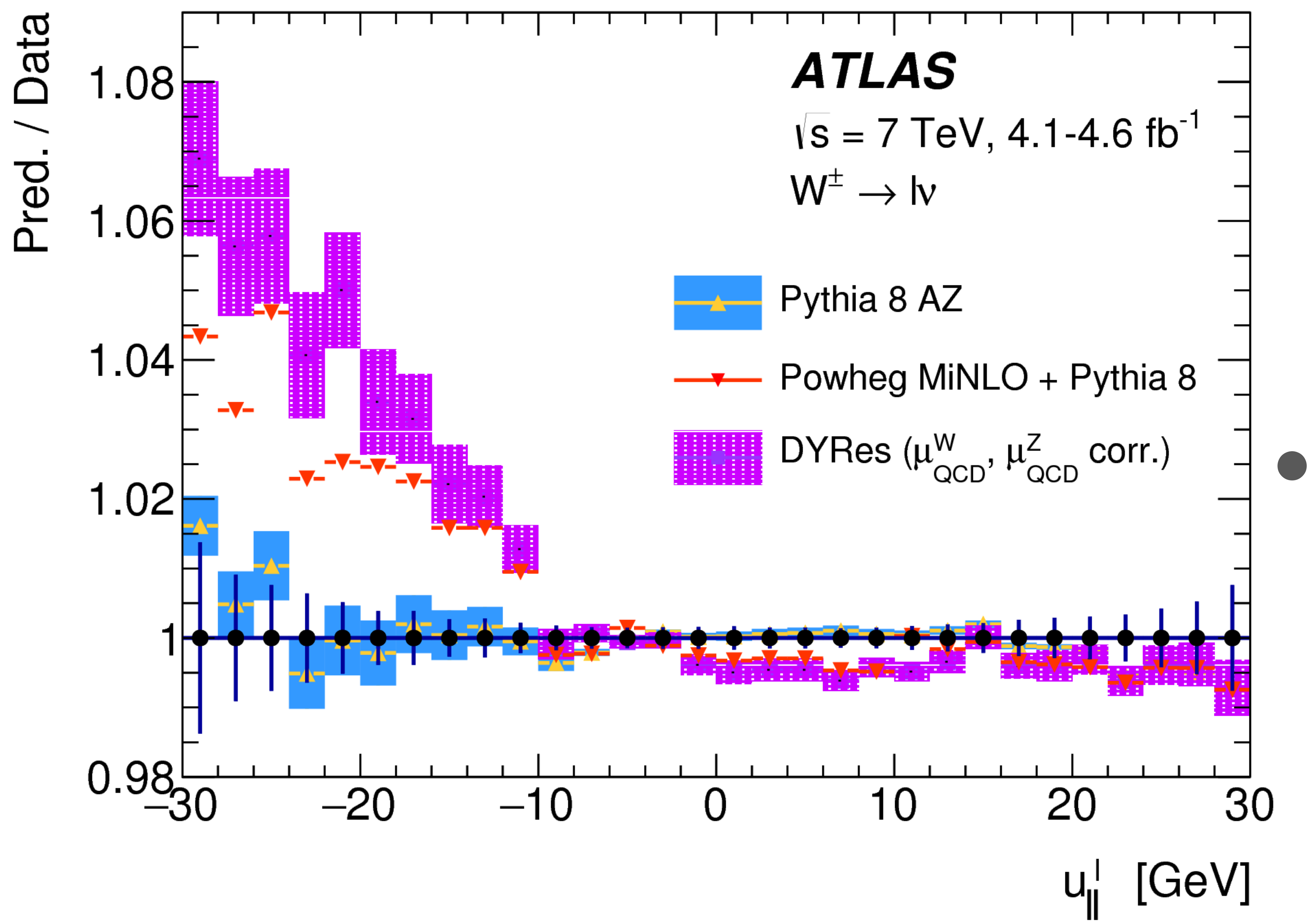


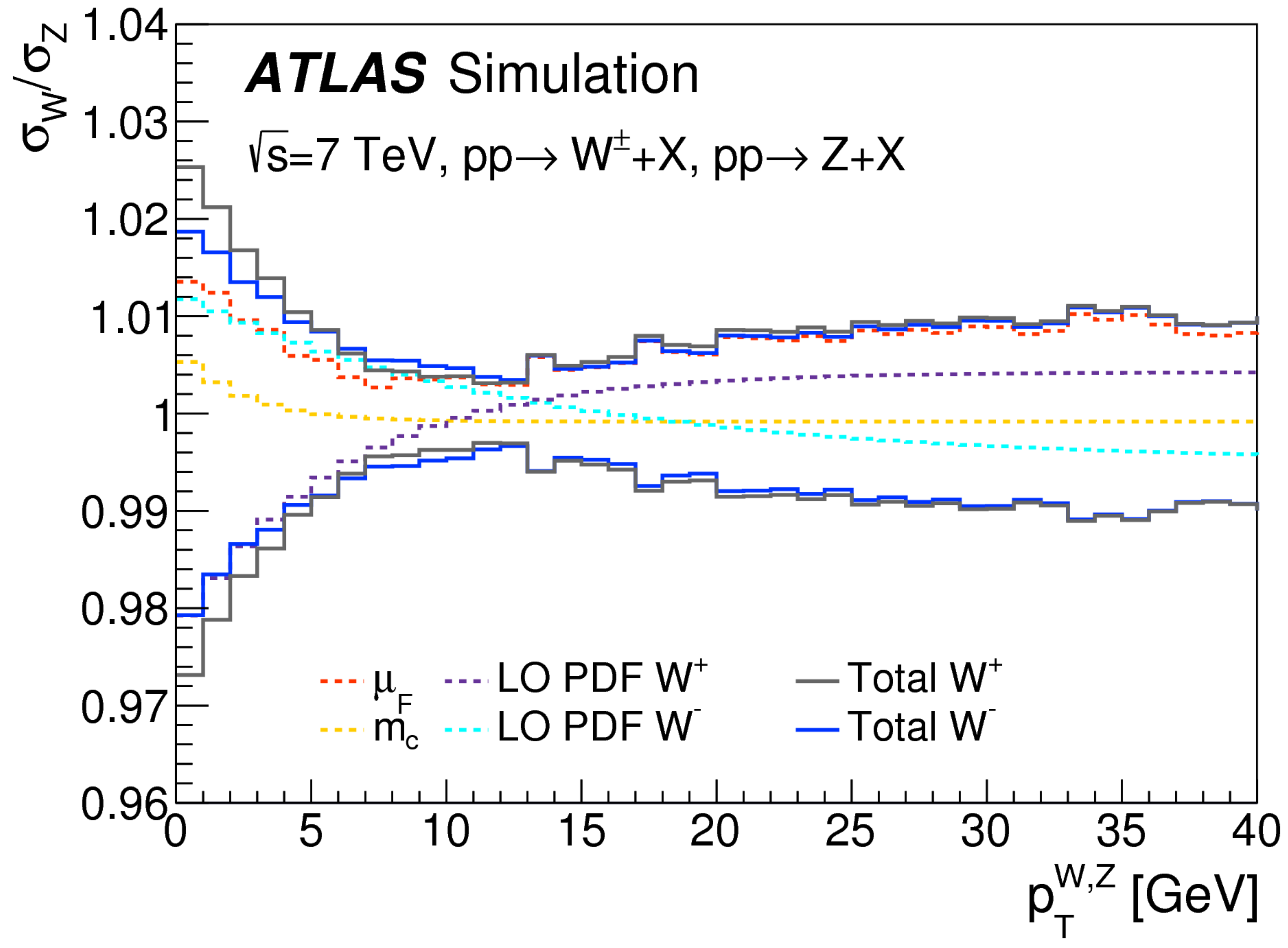


ATLAS: Production Modeling

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







- Measured hadronic recoil distribution has some sensitivity to W pT distribution, appears to disfavour more advanced calculations of W/Z pT ratio
- Measurement relies on Pythia model tuned to Z pT, with residual uncertainties for W->Z extrapolation

W-boson charge	W^+		W^-		Combined	
Kinematic distribution	p_T^ℓ	m_T	p_T^ℓ	m_T	p_T^ℓ	m_T
δm_W [MeV]						
Fixed-order PDF uncertainty	13.1	14.9	12.0	14.2	8.0	8.7
AZ tune	3.0	3.4	3.0	3.4	3.0	3.4
Charm-quark mass	1.2	1.5	1.2	1.5	1.2	1.5
Parton shower μ_F with heavy-flavour decorrelation	5.0	6.9	5.0	6.9	5.0	6.9
Parton shower PDF uncertainty	3.6	4.0	2.6	2.4	1.0	1.6
Angular coefficients	5.8	5.3	5.8	5.3	5.8	5.3
Total	15.9	18.1	14.8	17.2	11.6	12.9

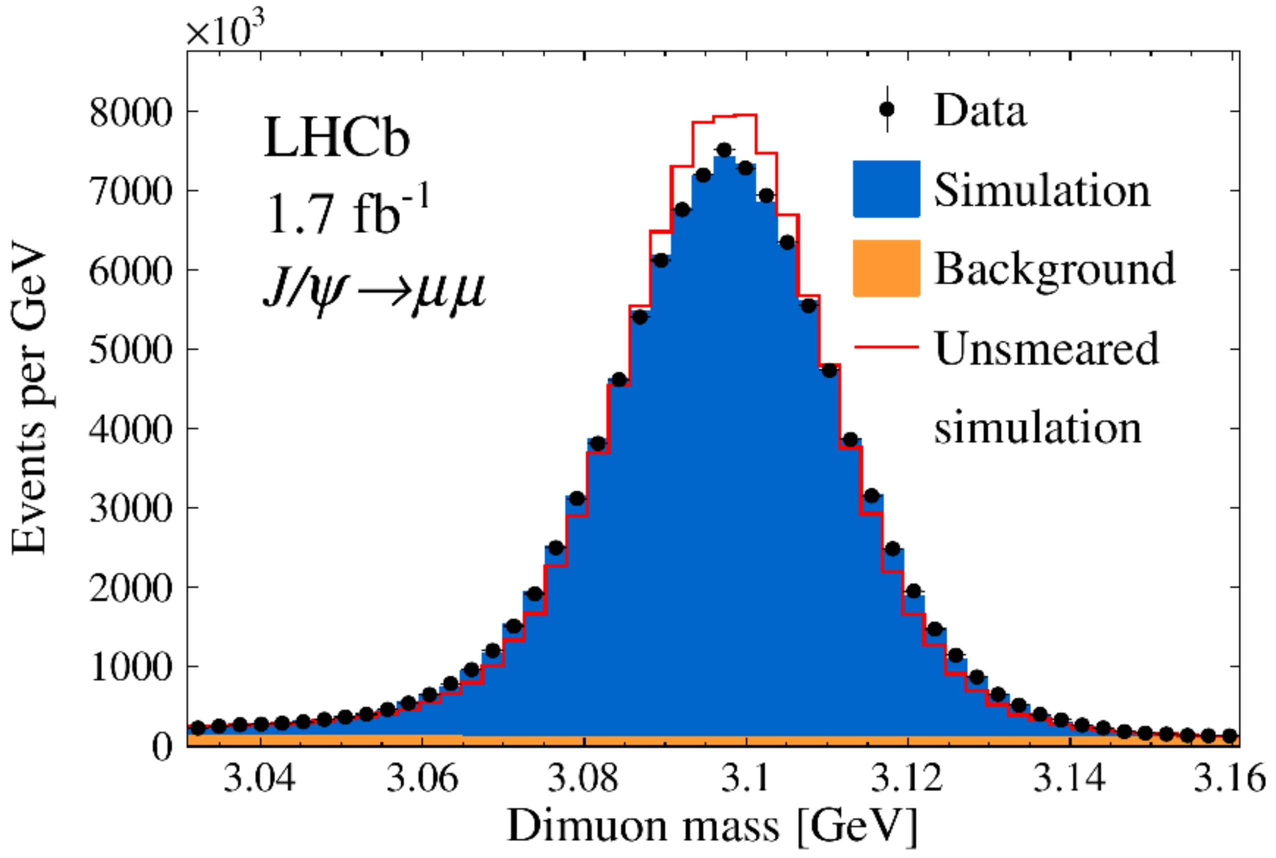
LHCb

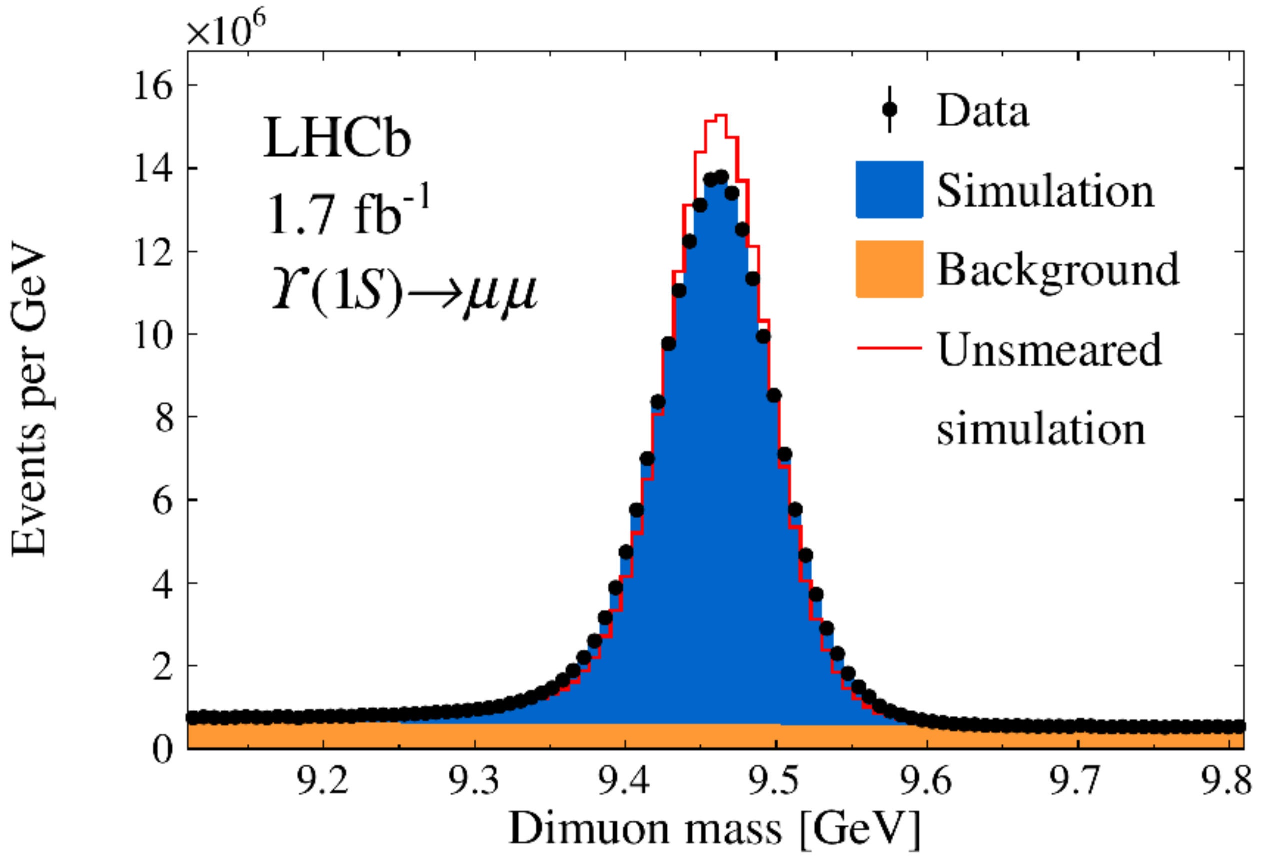
JHEP 01 (2022) 036

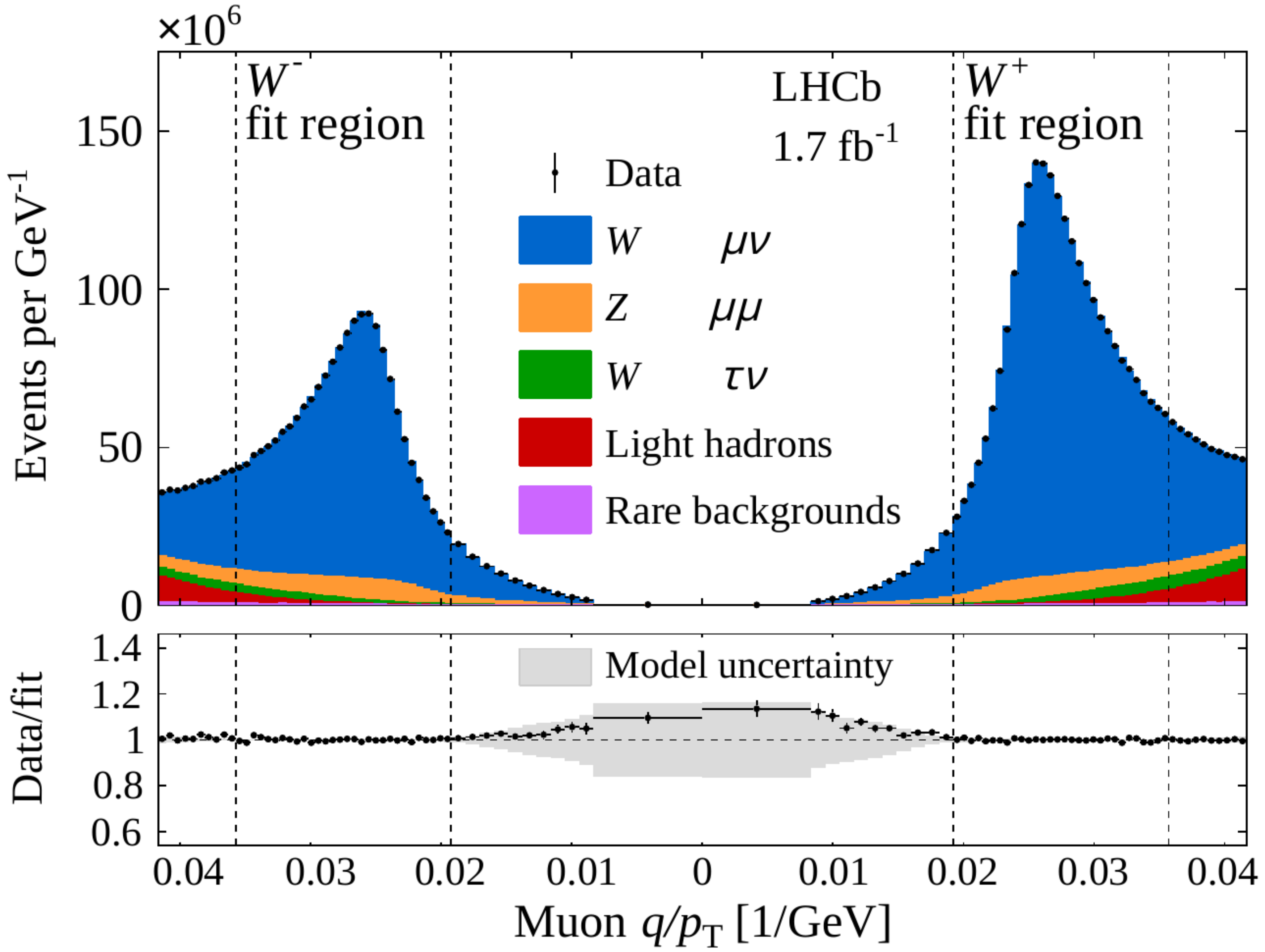
- Detector design limits measurement to muon transverse momentum, but excellent calibration possible with quarkonia
- Unique forward phase space

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}.$$

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

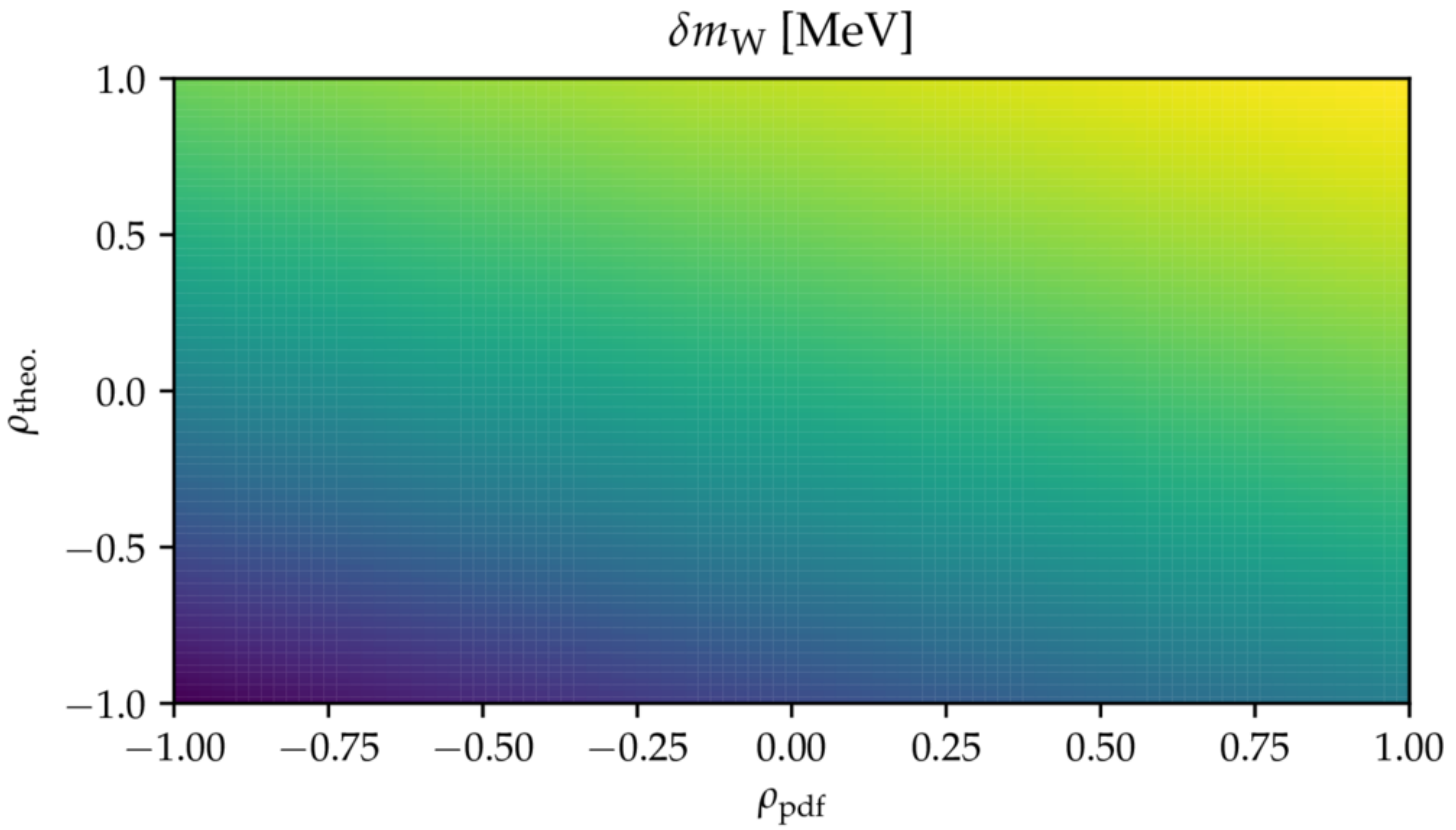


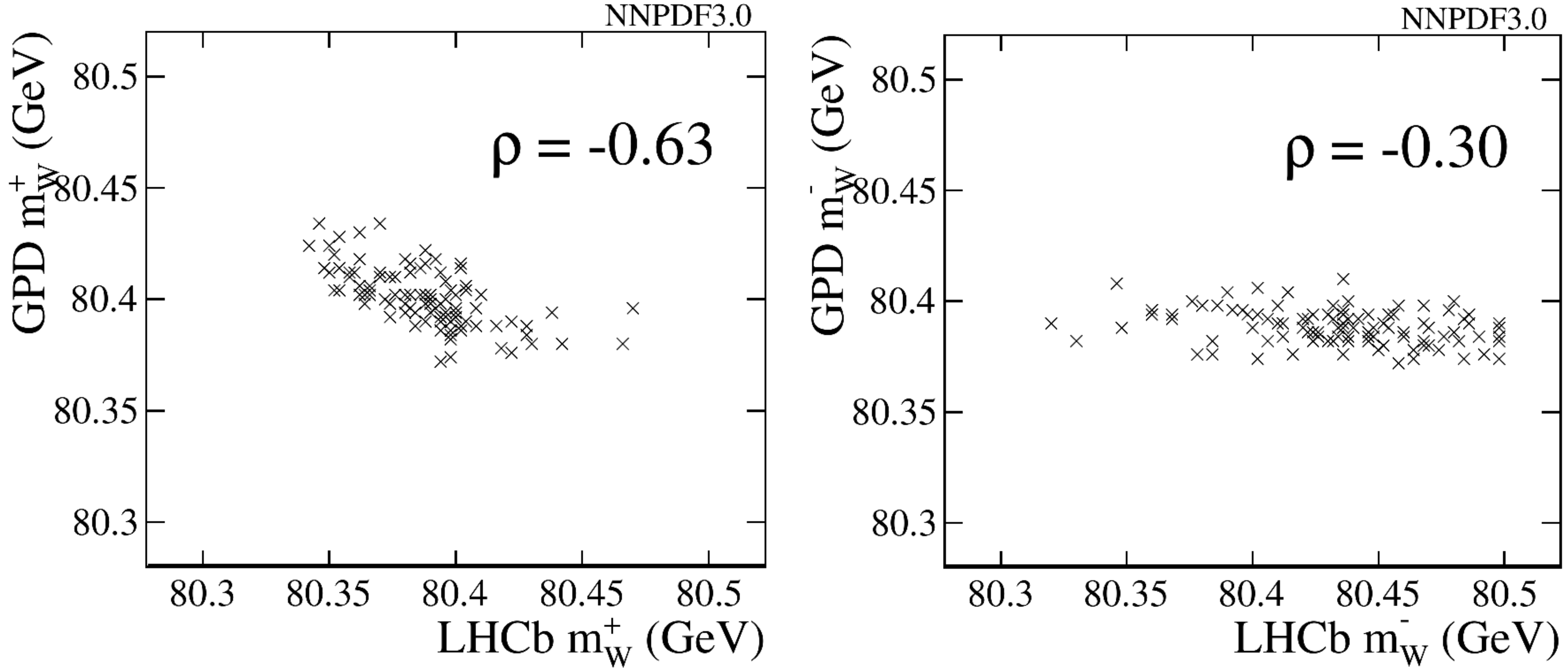




LHCb Combination prospects

- Forward phase space with respect to ATLAS and CMS leads to an anti-correlation of PDF uncertainties
- PDF uncertainties can be further reduced in combination





Eur. Phys. J. C **75**, 601 (2015)

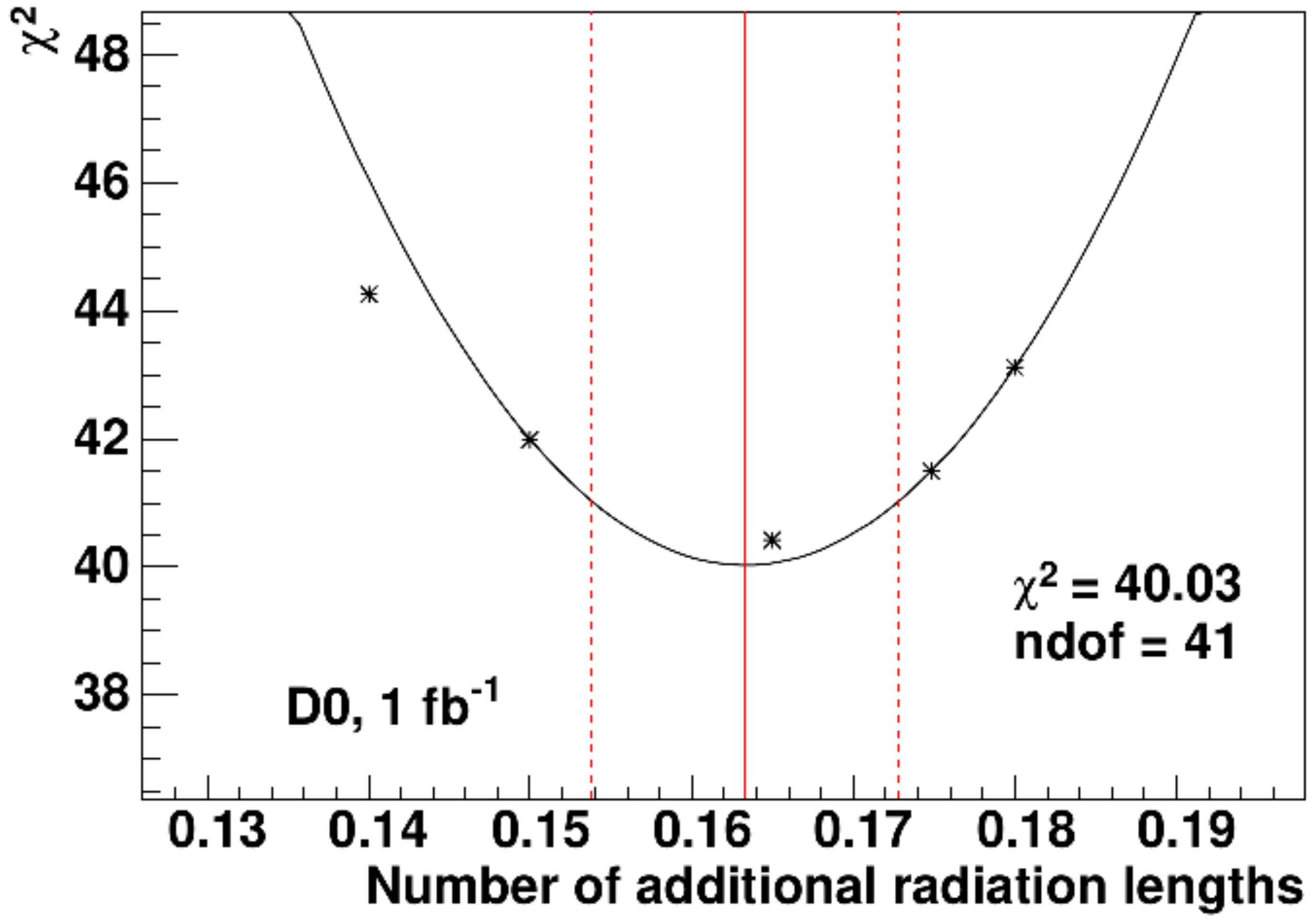
D0

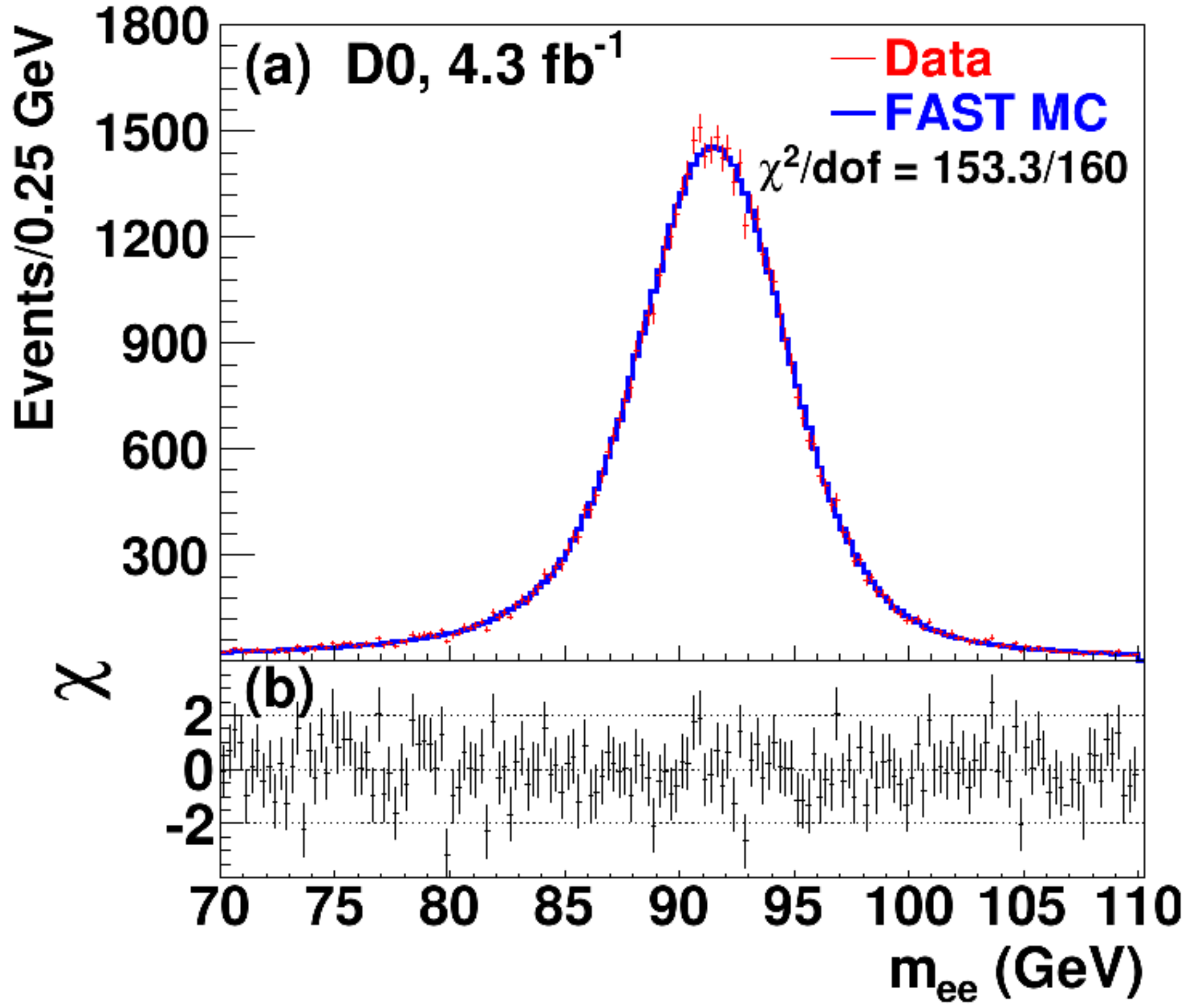
Phys. Rev. D 89, 012005 (2014)

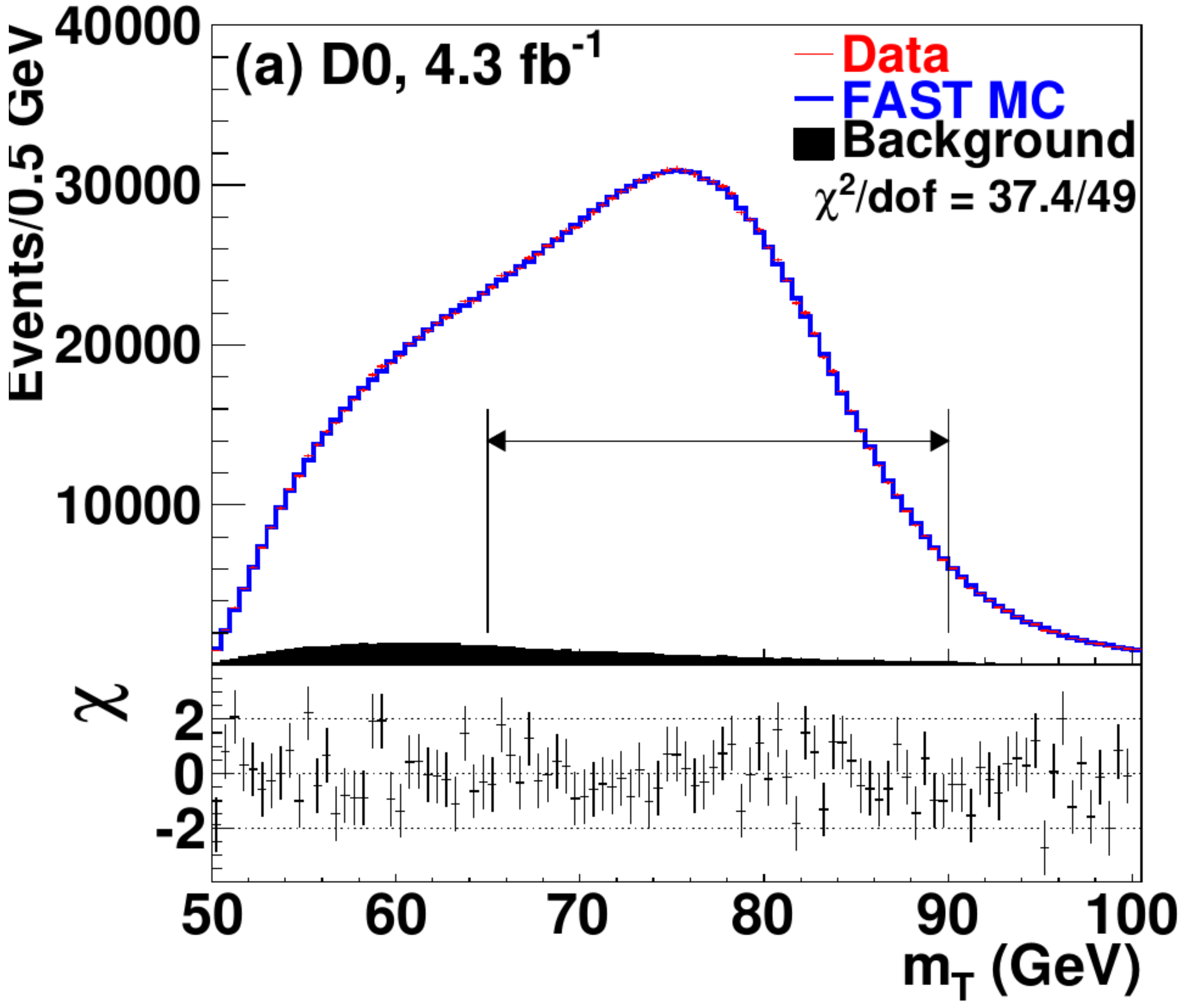
- Measurement with 4.3 +1.0/fb in electron channel
- Electron energy scale, hadronic recoil, theory model calibrated/tuned with Z->ee

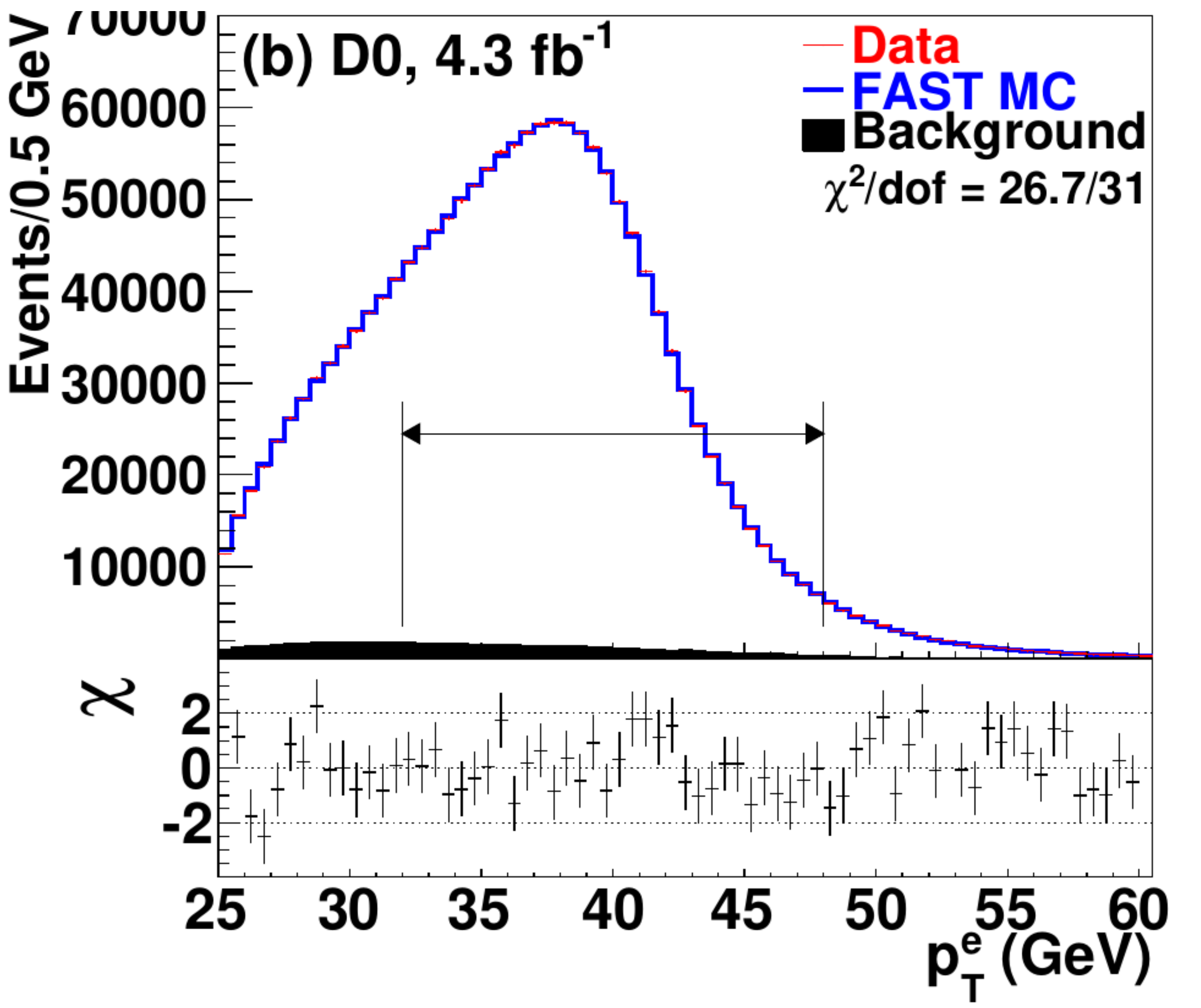
$$M_W = 80.375 \pm 0.023\ \text{GeV}.$$

Source	m_T	p_T^e	$\not{E}_T$
Experimental			
Electron Energy Scale	16	17	16
Electron Energy Resolution	2	2	3
Electron Shower Model	4	6	7
Electron Energy Loss	4	4	4
Recoil Model	5	6	14
Electron Efficiencies	1	3	5
Backgrounds	2	2	2
$\sum$(Experimental)	18	20	24
W Production and Decay Model			
PDF	11	11	14
QED	7	7	9
Boson p_T	2	5	2
$\sum$(Model)	13	14	17
Systematic Uncertainty (Experimental and Model)	22	24	29
W Boson Statistics	13	14	15
Total Uncertainty	26	28	33









Variable	Fit Range (GeV)	Result (GeV)	χ^2/d.o.f.
m_T	$65 < m_T < 90$	80.371 ± 0.013	37/49
p_T^e	$32 < p_T^e < 48$	80.343 ± 0.014	27/31
$\not{E}_T$	$32 < \not{E}_T < 48$	80.355 ± 0.015	29/31

PDF comparisons in m_W combination

Measurement	NNPDF3.1	NNPDF4.0	MMHT14	MSHT20	CT14	CT18	ABMP16
CDF y_Z	24 / 28	28 / 28	30 / 28	32 / 28	29 / 28	27 / 28	31 / 28
CDF A_W	11 / 13	14 / 13	12 / 13	28 / 13	12 / 13	11 / 13	21 / 13
D0 y_Z	22 / 28	23 / 28	23 / 28	24 / 28	22 / 28	22 / 28	22 / 28
D0 $W \to e\nu$ A_ℓ	22 / 13	23 / 13	52 / 13	42 / 13	21 / 13	19 / 13	26 / 13
D0 $W \to \mu\nu$ A_ℓ	12 / 10	12 / 10	11 / 10	11 / 10	11 / 10	12 / 10	11 / 10
ATLAS peak CC y_Z	13 / 12	13 / 12	58 / 12	17 / 12	12 / 12	11 / 12	18 / 12
ATLAS W^- y_ℓ	12 / 11	12 / 11	33 / 11	16 / 11	13 / 11	10 / 11	14 / 11
ATLAS W^+ y_ℓ	9 / 11	9 / 11	15 / 11	12 / 11	9 / 11	9 / 11	10 / 11
Correlated χ^2	75	62	210	88	81	41	83
Total χ^2 / d.o.f.	200 / 126	196 / 126	444 / 126	270 / 126	210 / 126	162 / 126	236 / 126
p(χ^2, n)	0.003%	0.007%	$< 10^{-10}$	$< 10^{-10}$	0.0004%	1.5%	10^{-8}

Table 6: χ^2 per degree of freedom for the Tevatron Z-rapidity and W- and l-asymmetry measurements at $\sqrt{s} = 1.96$ TeV, and the LHC Z-rapidity and W lepton-rapidity measurements at $\sqrt{s} = 7$ TeV. The total χ^2 is the sum of those quoted for individual measurements along with a separate contribution for correlated uncertainties, where the latter is extracted using a nuisance parameter representation of the χ^2 [47]. The CT14 and CT18 PDF uncertainties correspond to 68% coverage, obtained by rescaling the eigenvectors by a factor of 1/1.645. The probability of obtaining a total χ^2 at least as high as that observed is labelled p(χ^2, n).