High-precision measurement of the W boson mass at CMS

[CMS-PAS-SMP-23-002]

LHC Days
Hvar, Croatia
30 Sep – 4 Oct 2024

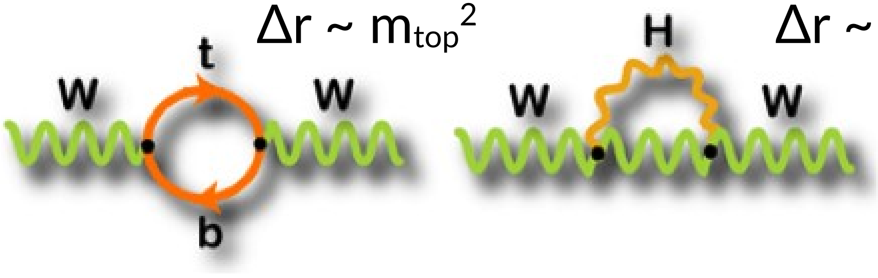
David Walter (CERN)
on behalf of the CMS Collaboration

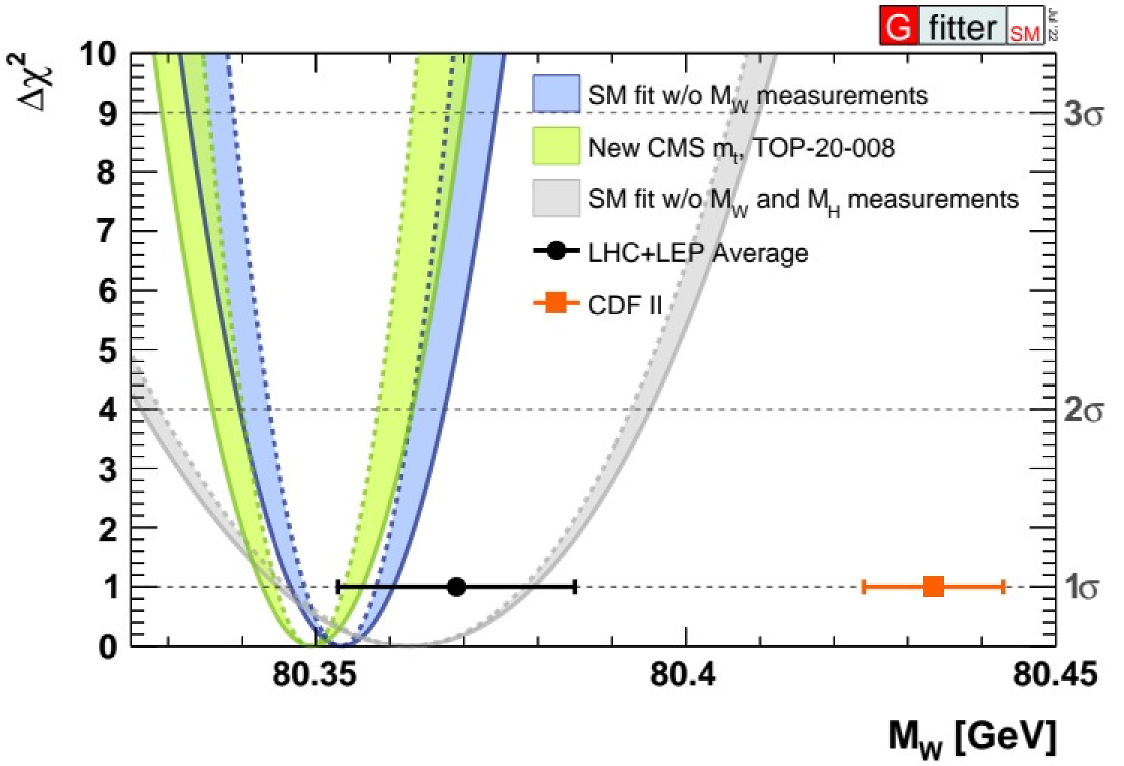
Why measure the W boson mass?

SM does not predict m_W but relationship to other parameters

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

$\Delta r \sim m_{top}^2$ $\Delta r \sim \ln(m_H)$





- Possible BSM particles can modify relation

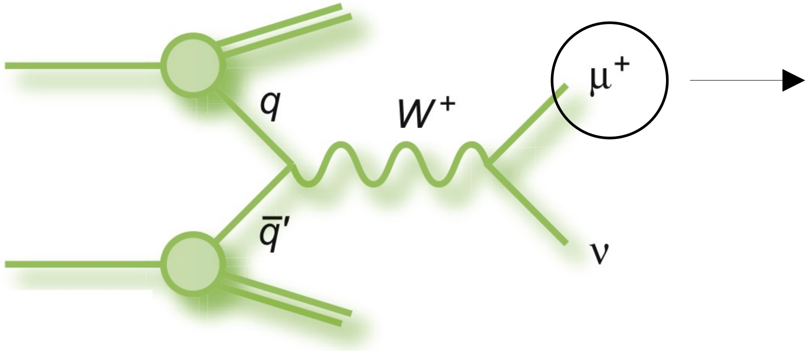
m_W can be determined indirectly in EW global fit

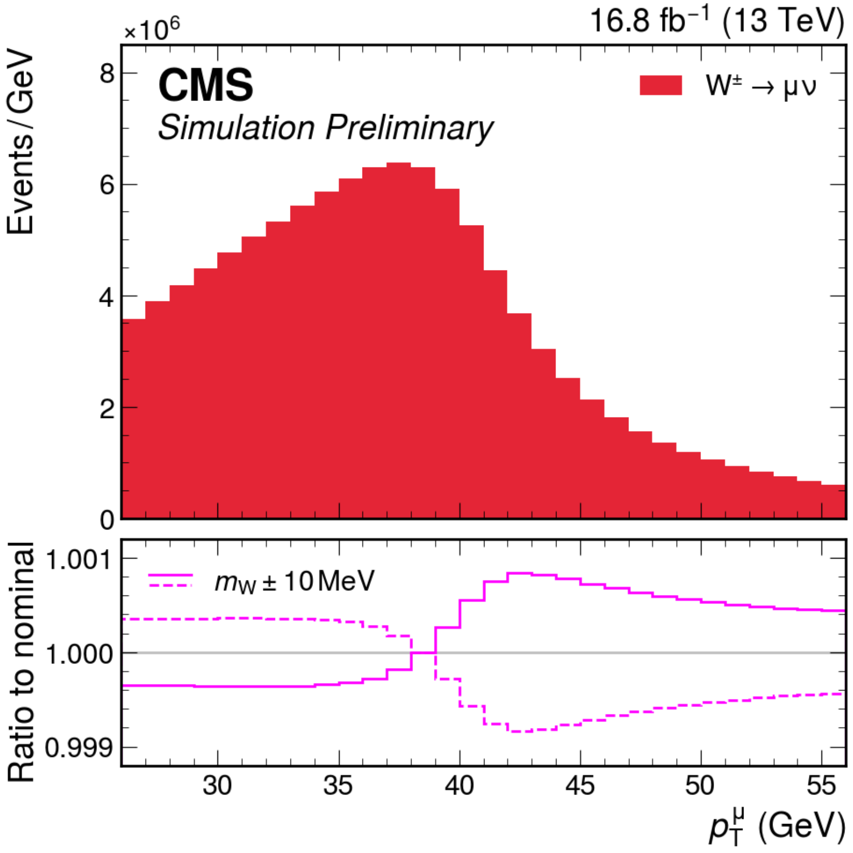
- Prediction: Δm_W^{SM} = 6MeV more precise than direct measurements
- Call for direct measurements to over constrain SM and find cracks

Measurements at hadron colliders

At pp colliders m_W is one of the most challenging measurements

- Measurement possible from partial information: m_T or p_T^ℓ
- LHC collected large amount of data
  - Use $16.8 fb^{-1}$ pp collision data set at 13TeV from 2016
- But higher pileup deteriorates p_T^{miss} resolution
  - m_T based measurement more challenging → deferred for future
  - Muons can be measured best, using muon kinematics only
    - Per mille precision required





Muon momentum scale calibration

Fundamental to measurement as muon momentum uncertainty directly translates to m_W uncertainty

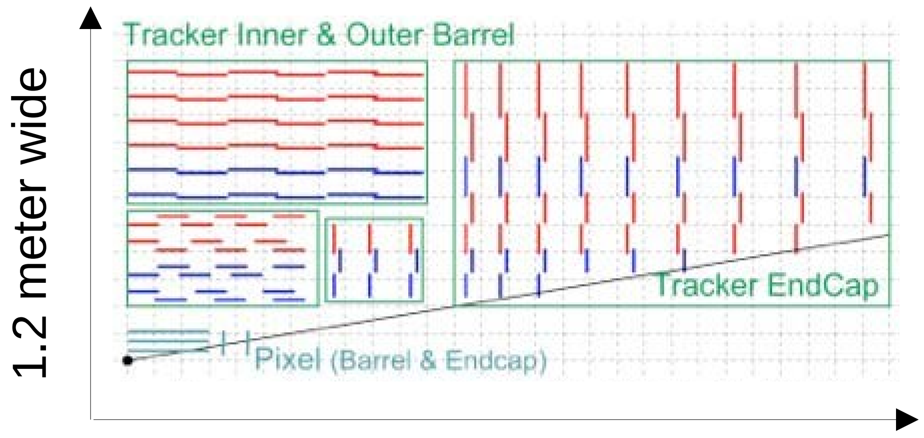
- δp_T <≈ 0.01% required for Δm_W <≈ 8 MeV calibration uncertainty
- Momentum from curvature of muon track in magnetic field – using silicon tracker only
- Designed for J/ψ → leaving Υ(1S) and Z for validation
- Extrapolation via k ≡ 1/p_T parametrization model

Magnetic field → $A_{i\eta}$, alignment → $M_{i\eta}$

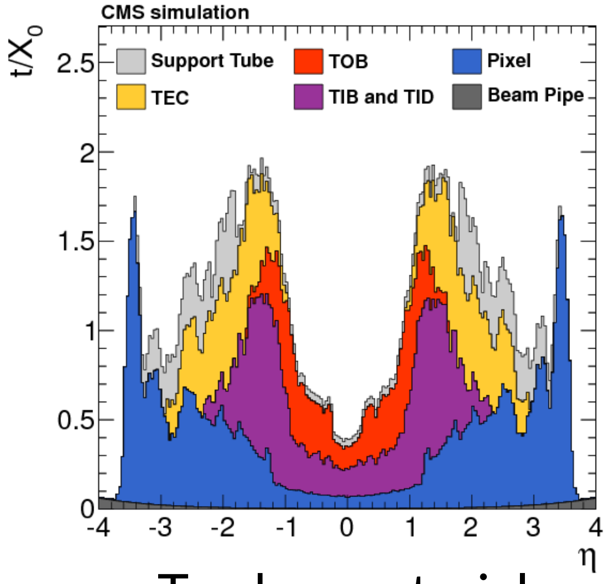
$$\delta k/k = A_{i\eta} - \epsilon_{i\eta} k + q M_{i\eta}/k$$

Energy loss (material) → $\epsilon_{i\eta}$

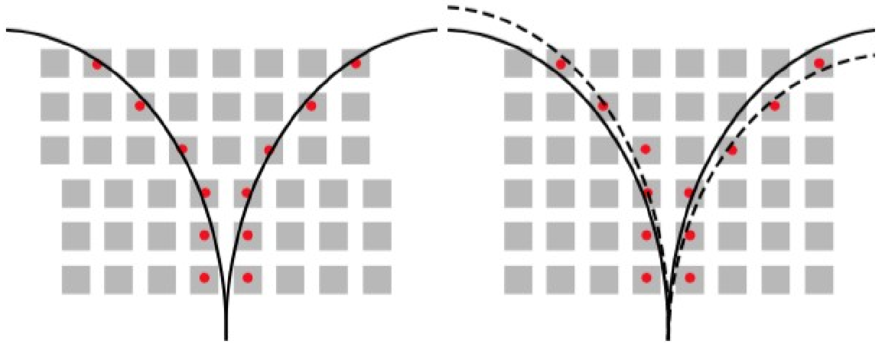
4T magnet field



2 meters long



Tracker material



Alignment effect

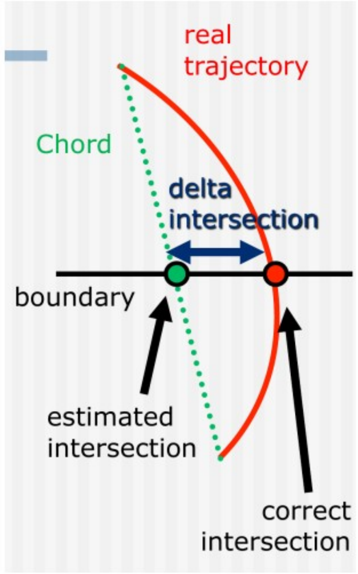
Muon momentum scale calibration

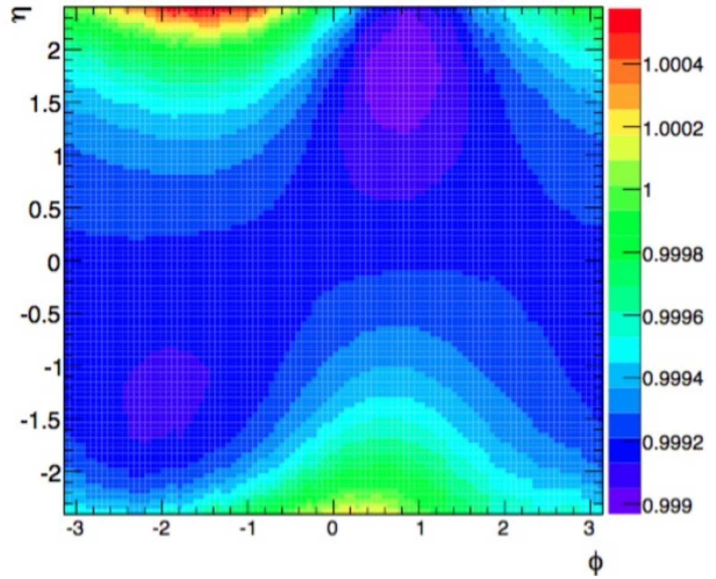
Standard CMS reconstruction breaks parametrization

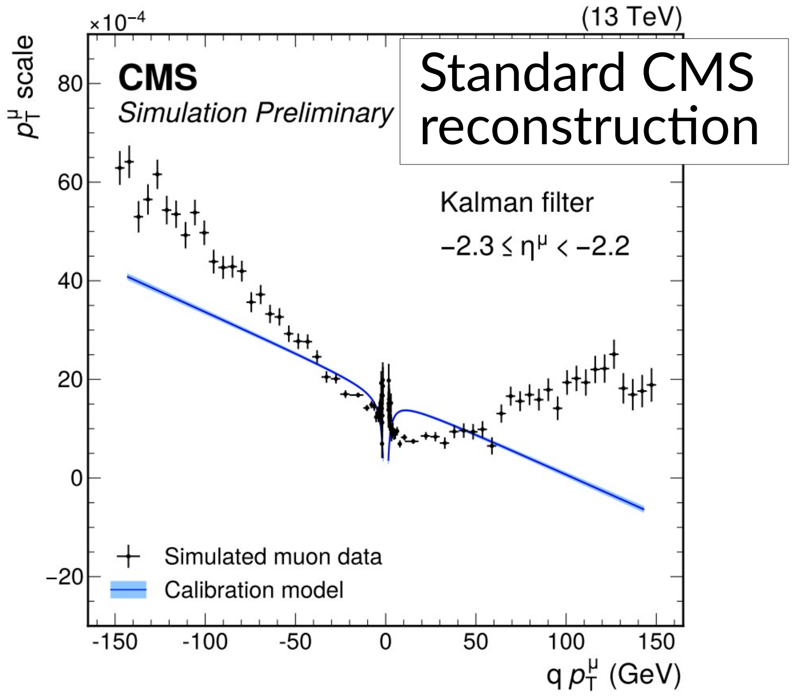
Restore parameterization

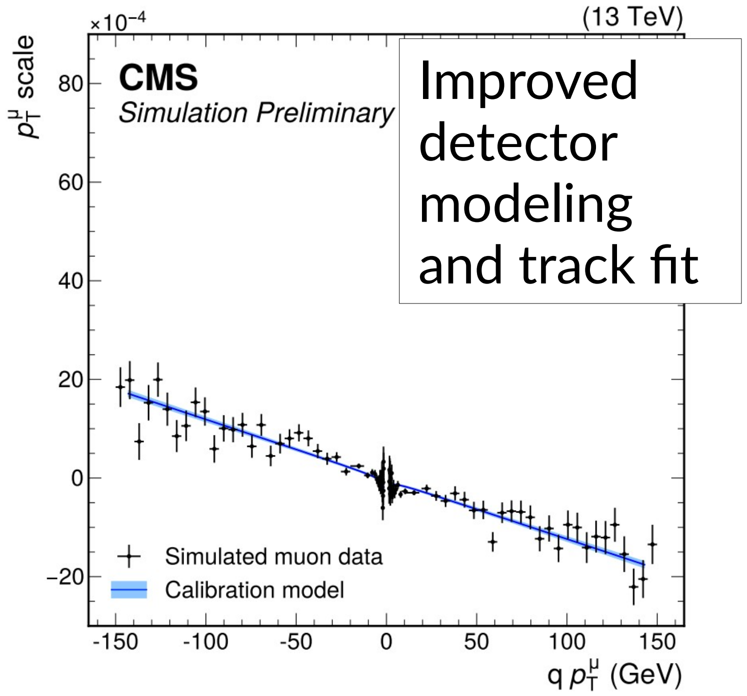
1) Improved detector modeling and track fit

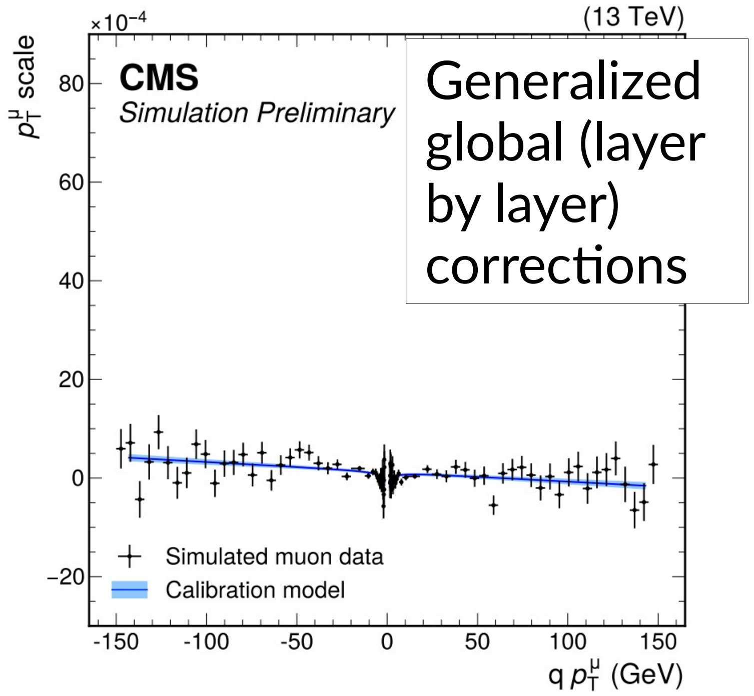
2) Generalized global (layer by layer) corrections







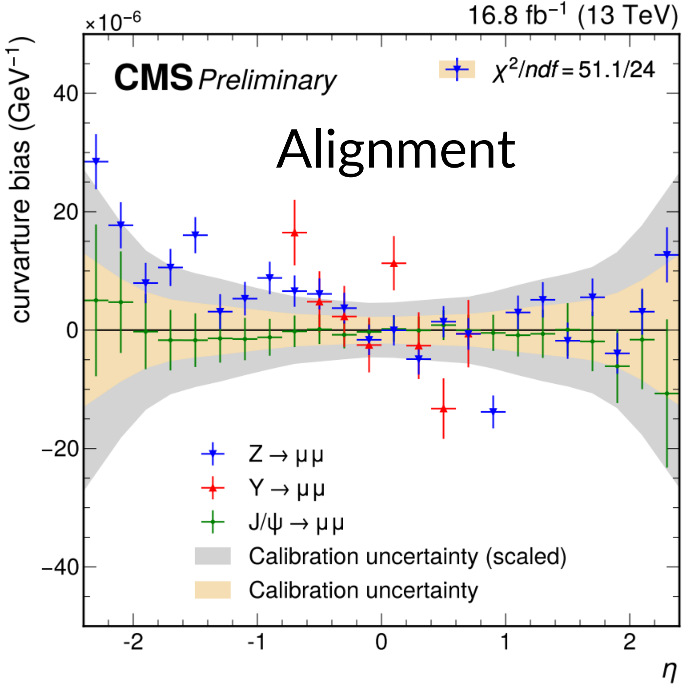




Muon momentum scale calibration

Once parameterization restored

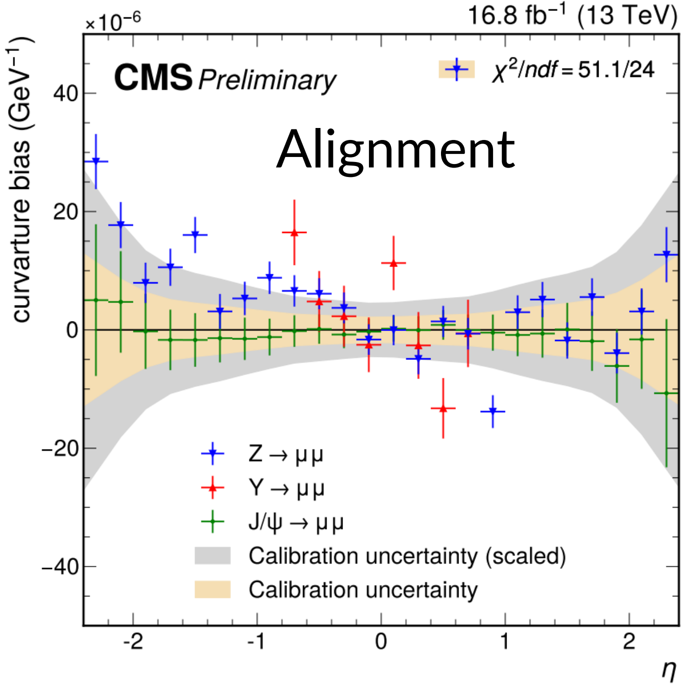
- Performed calibration on J/ψ binned in muon (η^+, p_T^+, η^-, p_T^-)
- Assess closure on Y(1S) and Z data
  - Inflate uncertainties to cover possible systematic effects



Muon momentum scale calibration

Once parameterization restored

- Performed calibration on J/ψ binned in muon (η^+, p_T^+, η^-, p_T^-)
- Assess closure on Υ(1S) and Z data
  - Inflate uncertainties to cover possible systematic effects

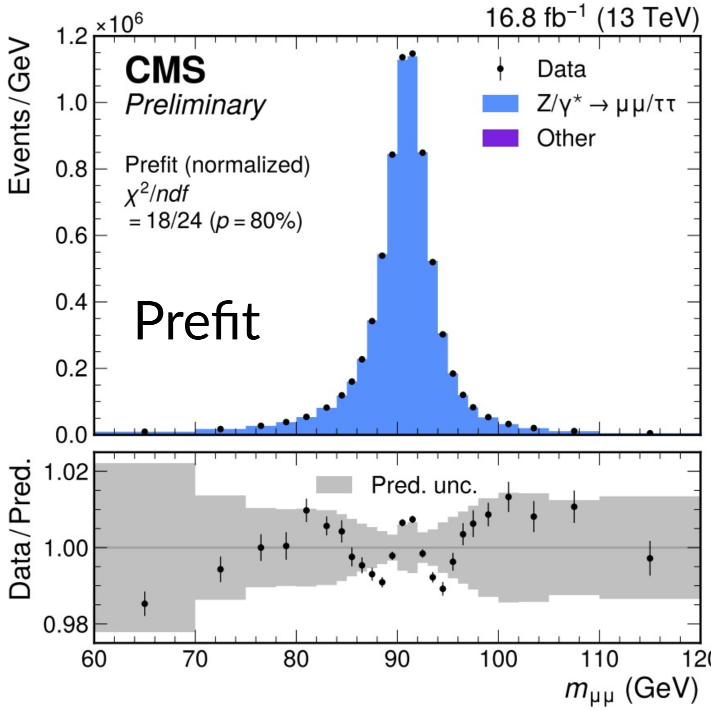


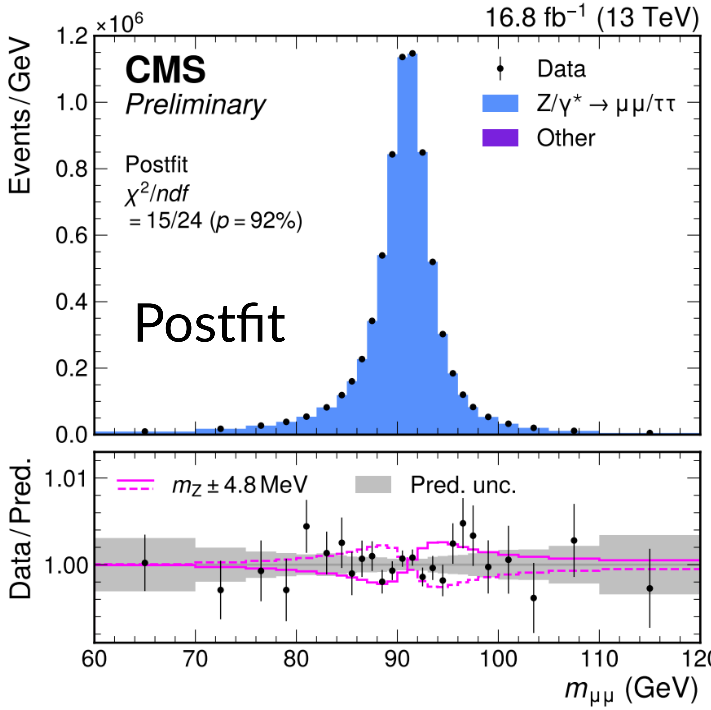
Final validation by extracting Z mass

$$m_Z - m_Z^{\mathrm{PDG}} = -2.2 \pm 4.8\,\mathrm{MeV}$$

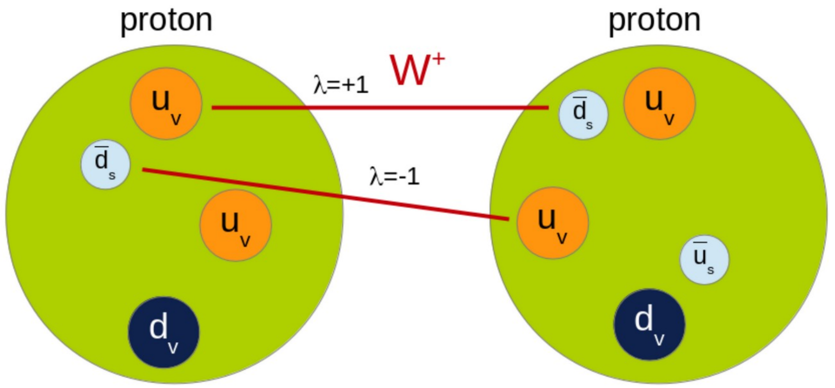
Not an independent
m_Z measurement (yet)

- Competitive m_Z measurement feasible in the near future





Theory uncertainties

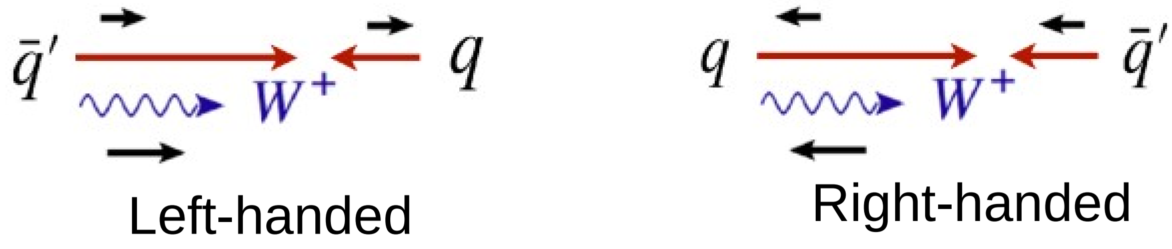


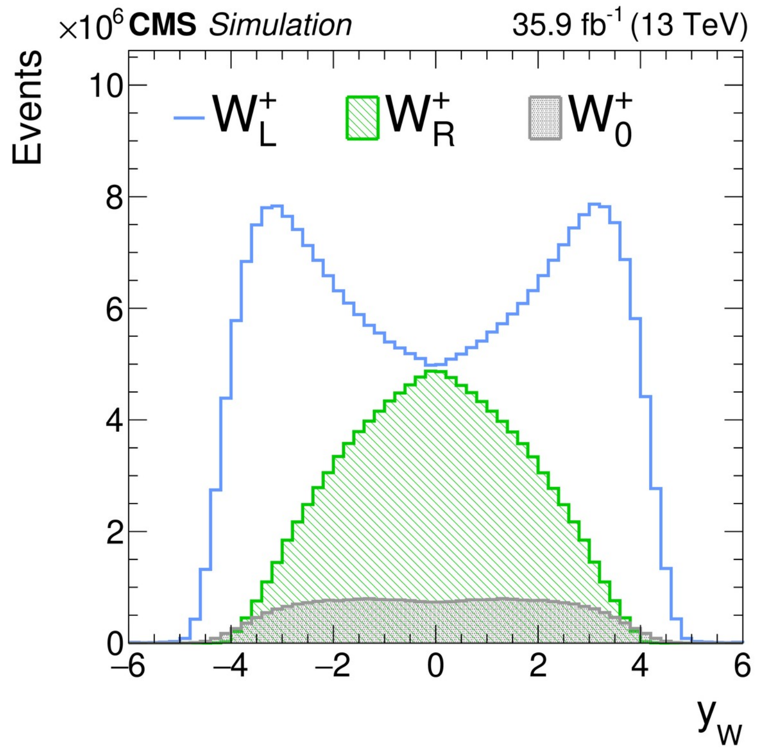
Measurement in p_T^μ strongly relies on understanding of underlying boson kinematic

- Need to distinguish a variation of m_W from uncertainty in W p_T

Use information from data – example: PDFs

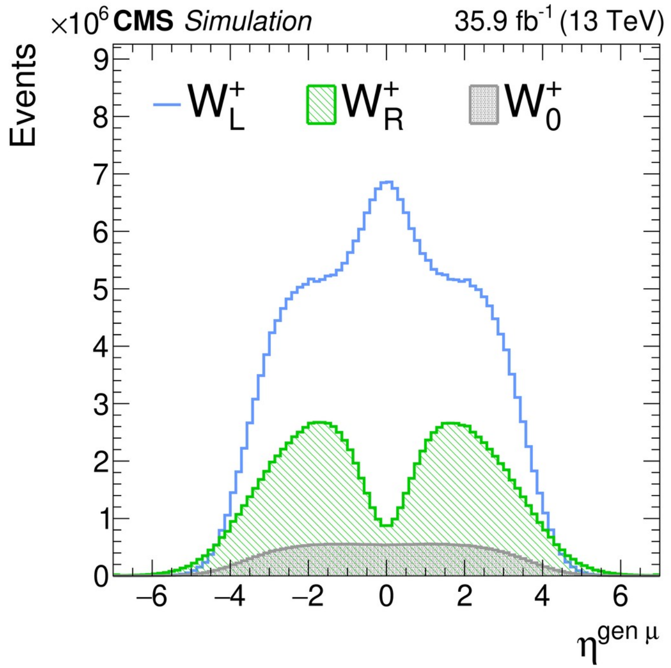
- Due to pure left handed coupling, W helicity determined by its direction relative to incoming quark
- W helicity contains information about PDFs





- Studied in W helicity analysis: arXiv:2008.04174

Measurement strategy

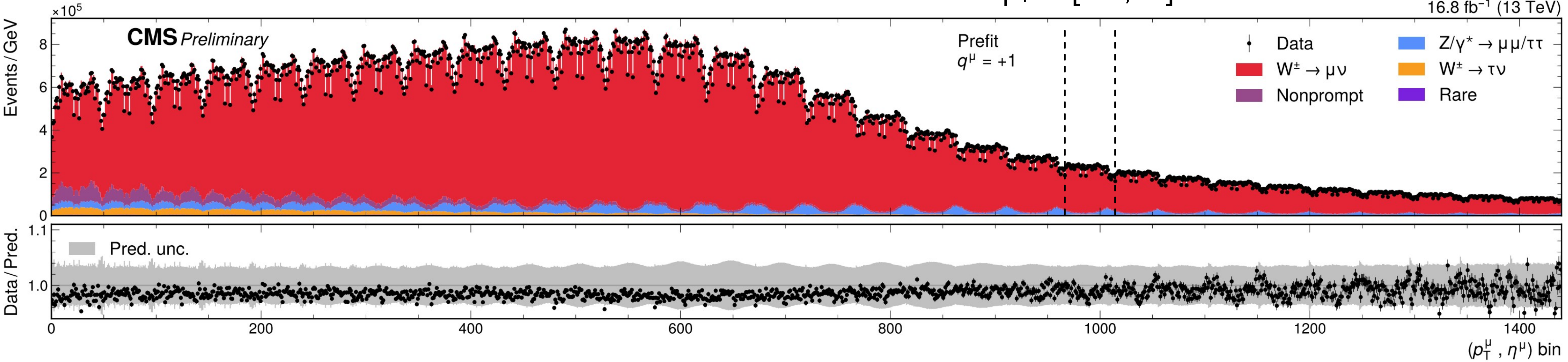


Exploit large dataset for maximal in-situ constraints on theoretical modeling

Profile likelihood fit of single muon p_T, η, charge distribution

- Sensitivity to m_W from p_T distribution
- Use η distribution to enhance constraints on theory model (PDFs, …)

p_T in [46 ,47] GeV

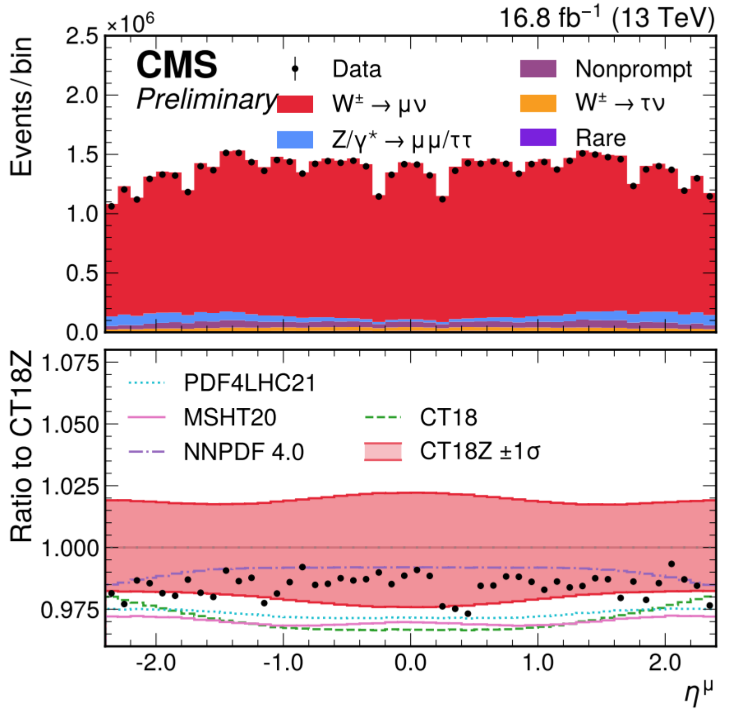


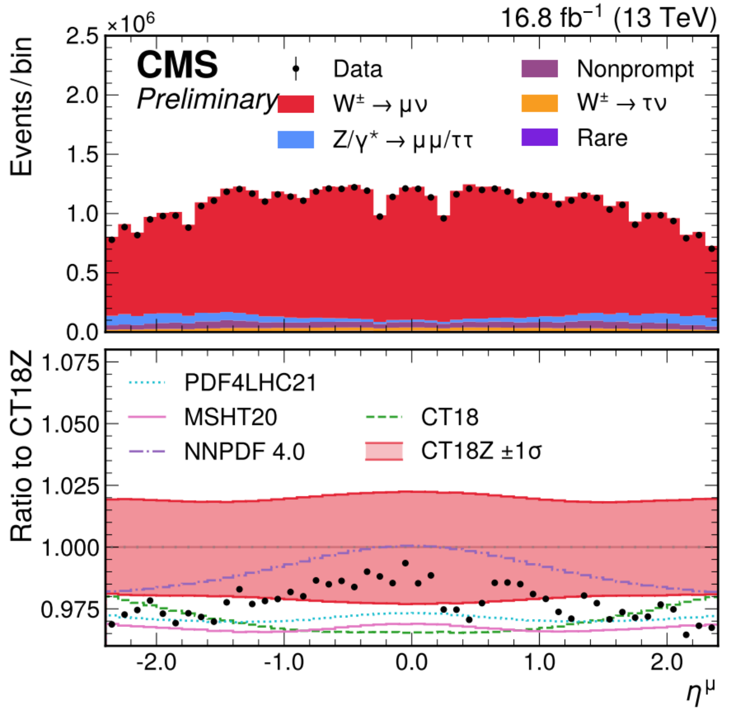
Parton distribution functions

Performed bias studies on 7 modern PDF sets

- Use one PDF set to fit the central value of the others
- Observed shift in m_W larger than PDF uncertainty
- Determine inflation factor on PDF uncertainties to cover other PDFs
- CT18Z overs all other sets without inflation → our nominal

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





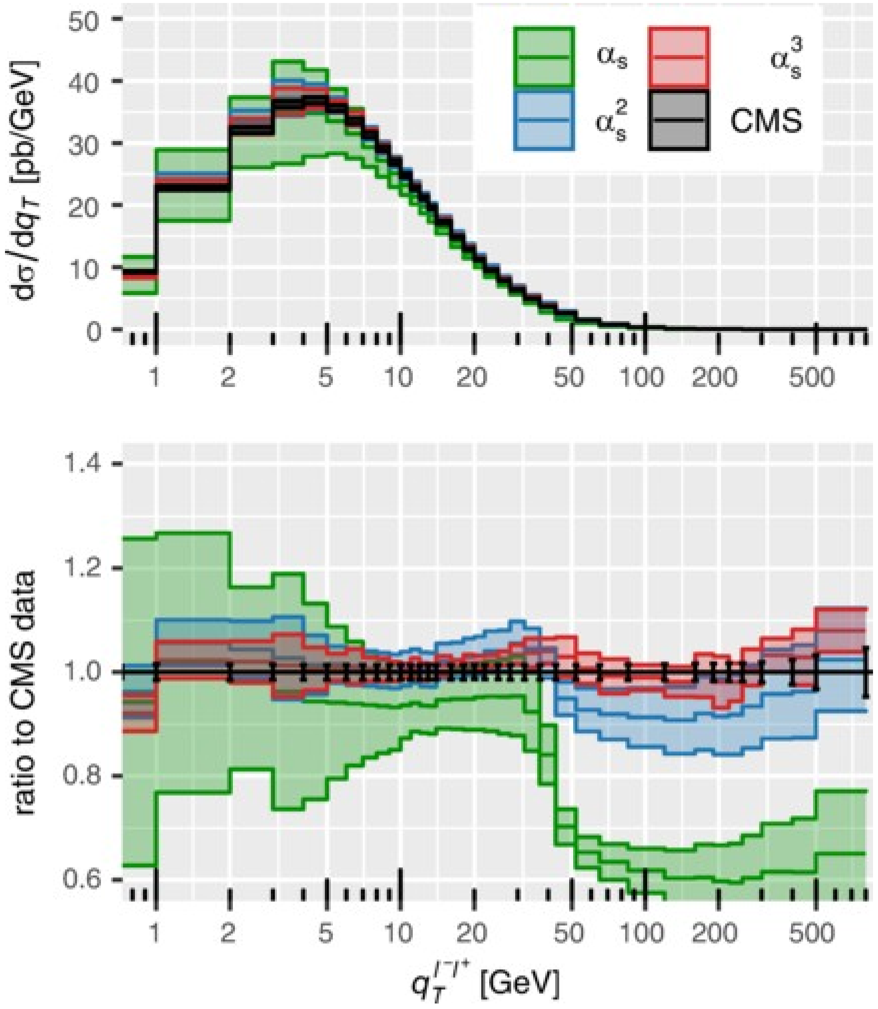
QCD uncertainties

Uncertainties in theory typically larger than measurement

- In particular at low boson p_T
- Common strategy is to correct (tune) model to Z data
- W and Z behave qualitatively the same
- But differences between W and Z may be relevant
- Once the model is corrected to Z data, no easy validation possible

An alternative approach is followed

- m_W extracted w/o use of Z in theory model
- Theory uncertainties in-situ constrained by W data
- Theory model validated using Z



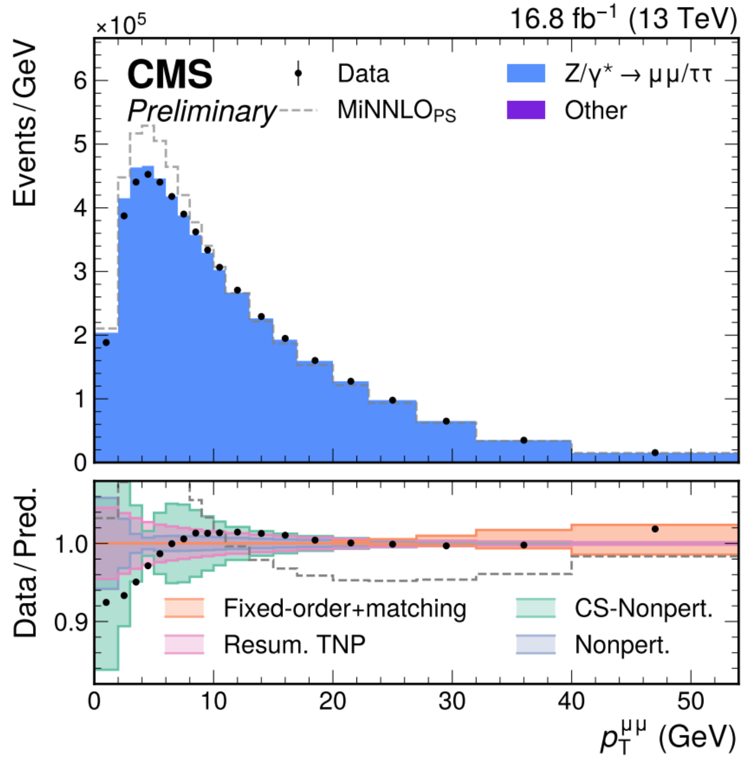
Measurement strategy validation

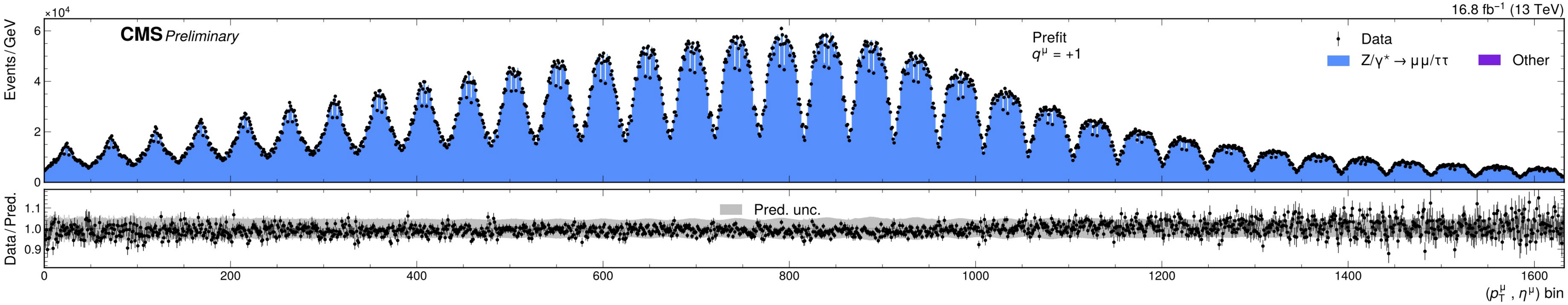
Z dilepton p_T^Z, $|y^Z|$ analysis

- Reconstruct Z kinematics with high precision

W-like Z analysis

- Fitting single muon p_T^ℓ, η^ℓ, charge
- Remove second muon and treat as missing energy





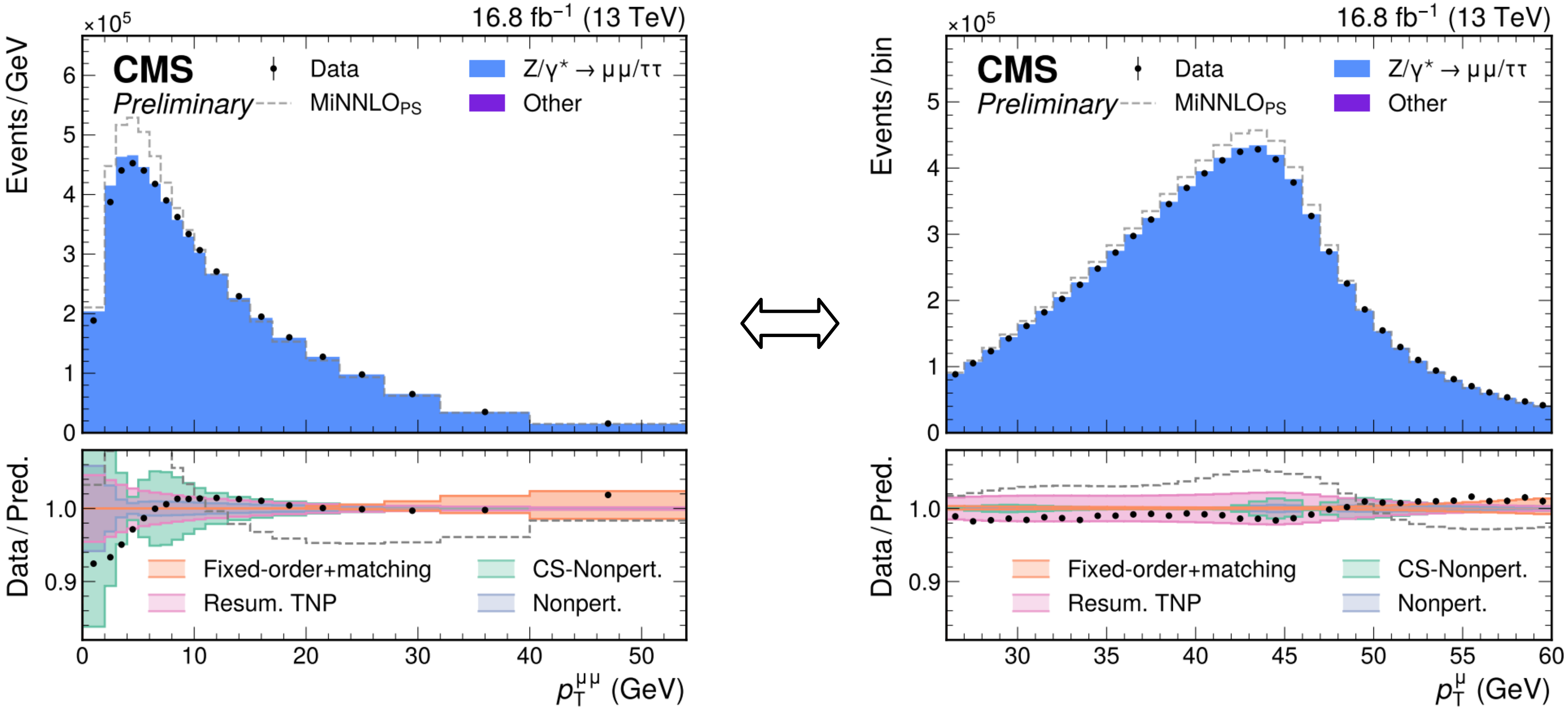
Modeling of Z transverse momentum

Different QCD effects relevant at different p_T^V regions and translate to p_T^μ spectrum

1) Perturbative α_S expansion → MiNNLO$_{PS}$ event generator with NNLO in α_S

2) Perturbative resummation → corrected to N^{3}LL from SCETlib

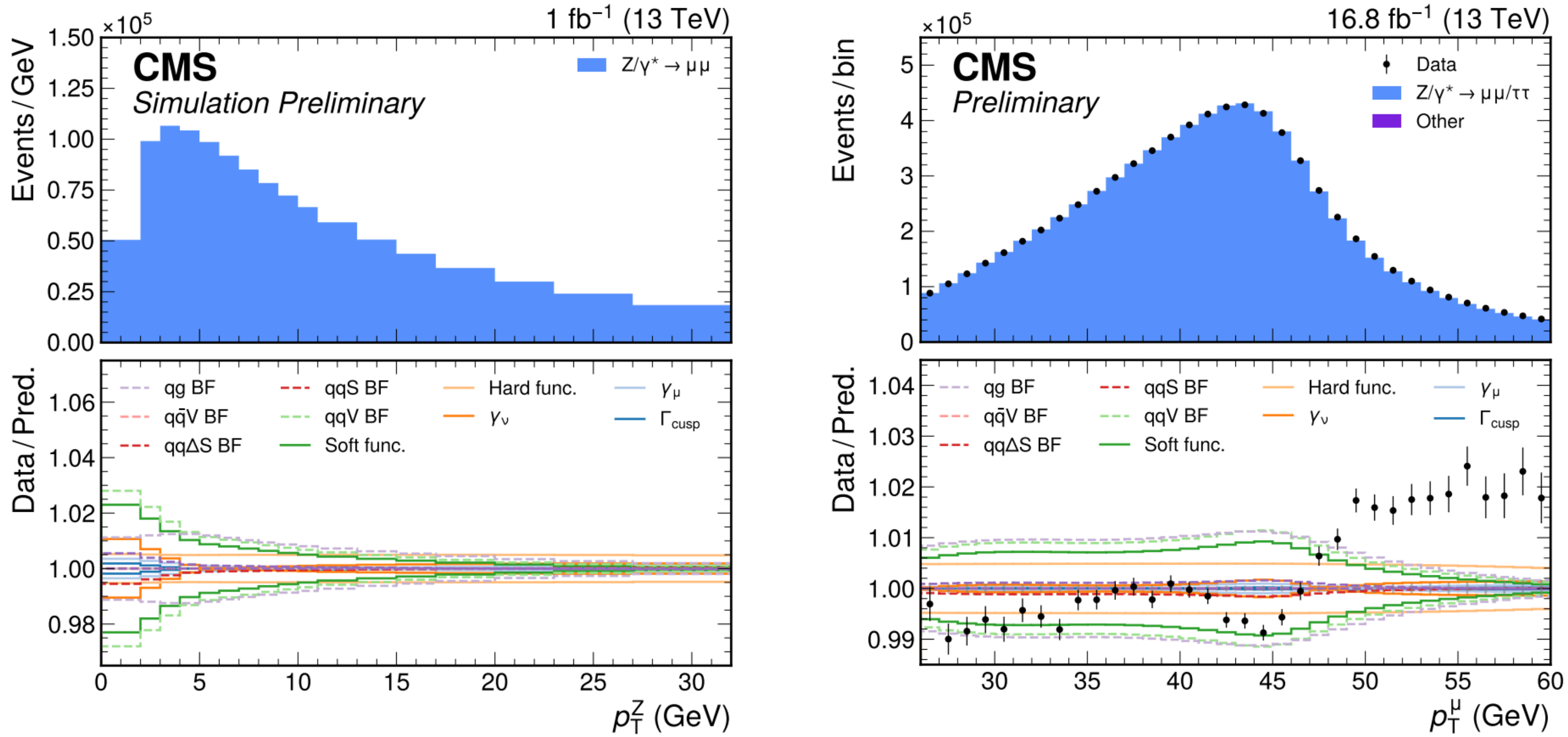
3) Non perturbative → TMD inspired phenomenological model, in situ constrained by data



Modeling of Z transverse momentum – resummation

2) Resummation expansion in $\log(p_T^V/m_V)$, relevant at medium and low p_T^V

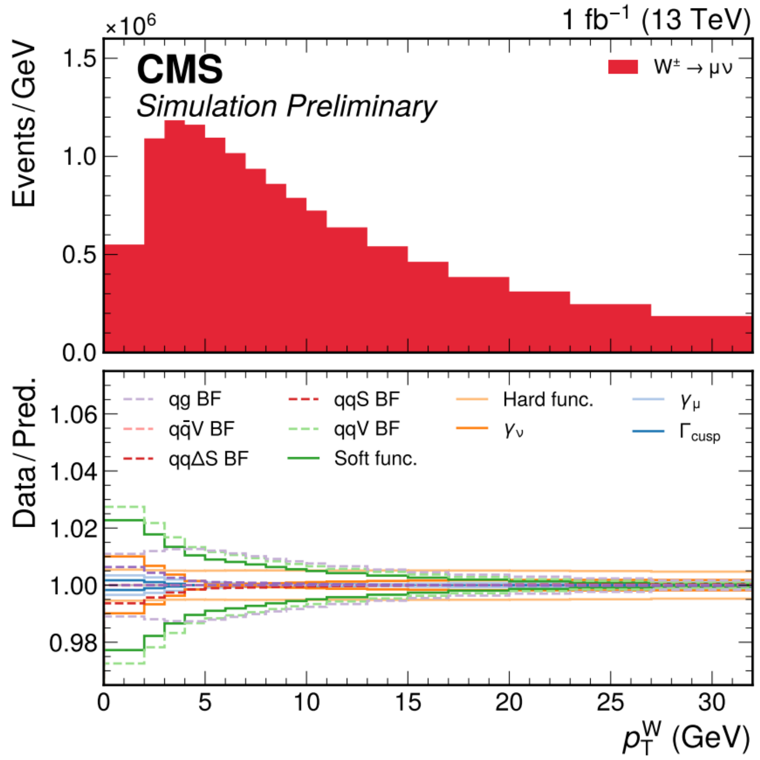
- Uncertainties from missing higher orders estimated using "theory nuisance parameters" (TNPs)
  - Exploit known structure of resummed calculation
  - Obtain basis of nuisance parameters with known functional shape → well suited for profiling

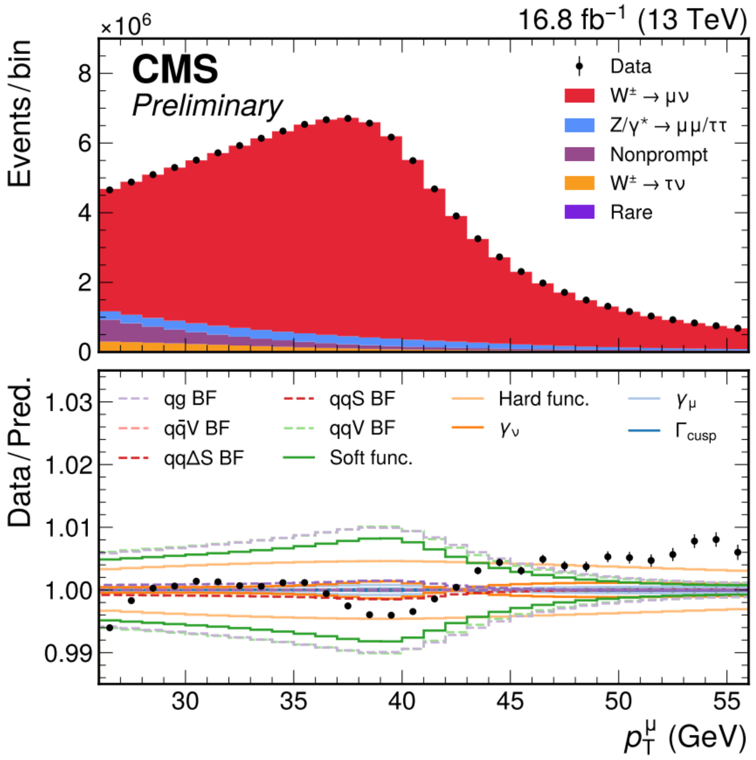


Modeling of W transverse momentum – resummation

2) Resummation expansion in $\log(p_T^V/m_V)$, relevant at medium and low p_T^V

- Uncertainties from missing higher orders estimated using “theory nuisance parameters” (TNPs)
  - Exploit known structure of resummed calculation
  - Obtain basis of nuisance parameters with known functional shape → well suited for profiling
  - Same structure for W and Z (although exact values may be different)





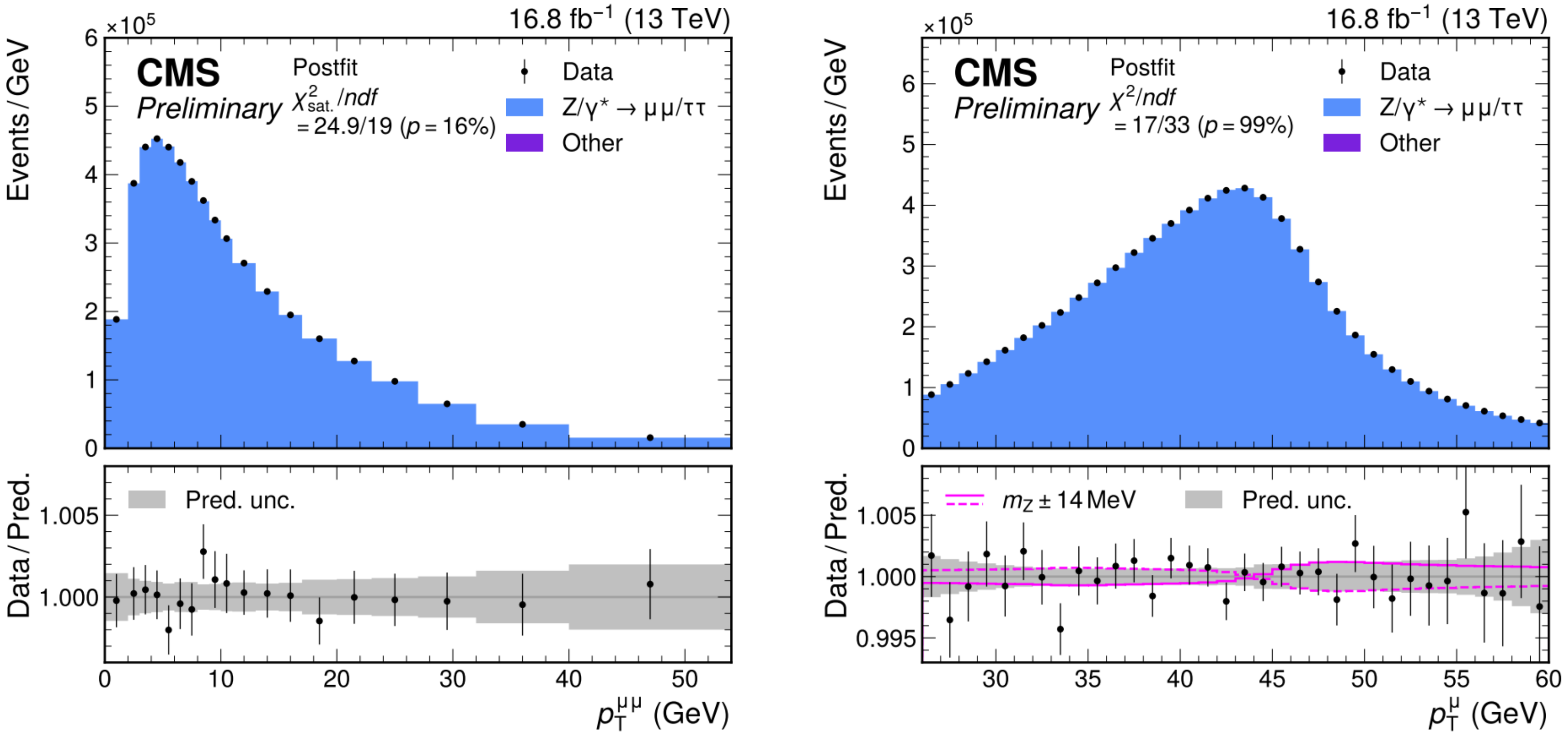
Modeling of W, Z boson transverse momentum – validation

Theory model validated by fitting dilepton $p_T^{\mu\mu}$ distribution

- Saturated likelihood test p-value of 16% → Model able to describe the data

W-like measurement yields m_Z compatible with PDG and our dilepton m_Z

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

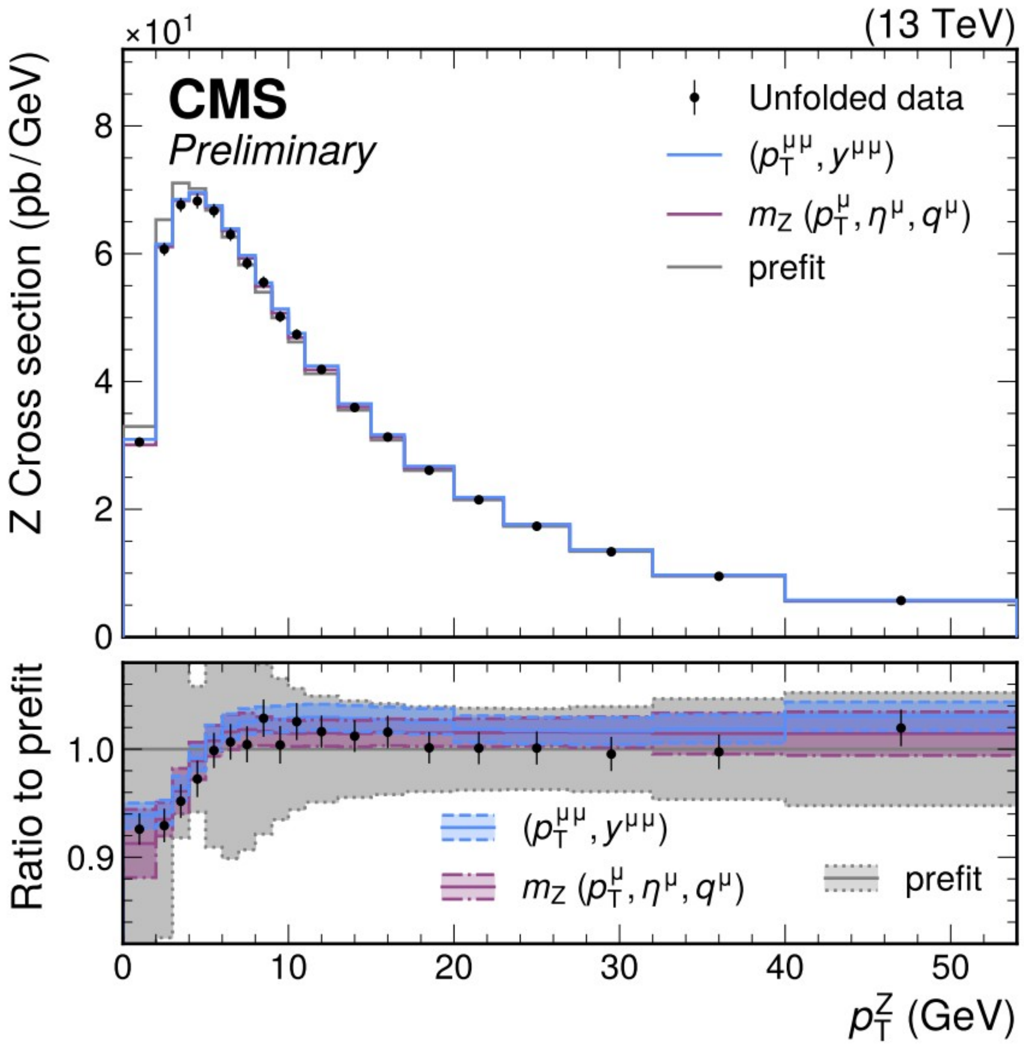


Theory model validation

Compare postfit p_T^Z distributions from W-like Z fit or direct dilepton p_T^Z y^Z fit with unfolded data

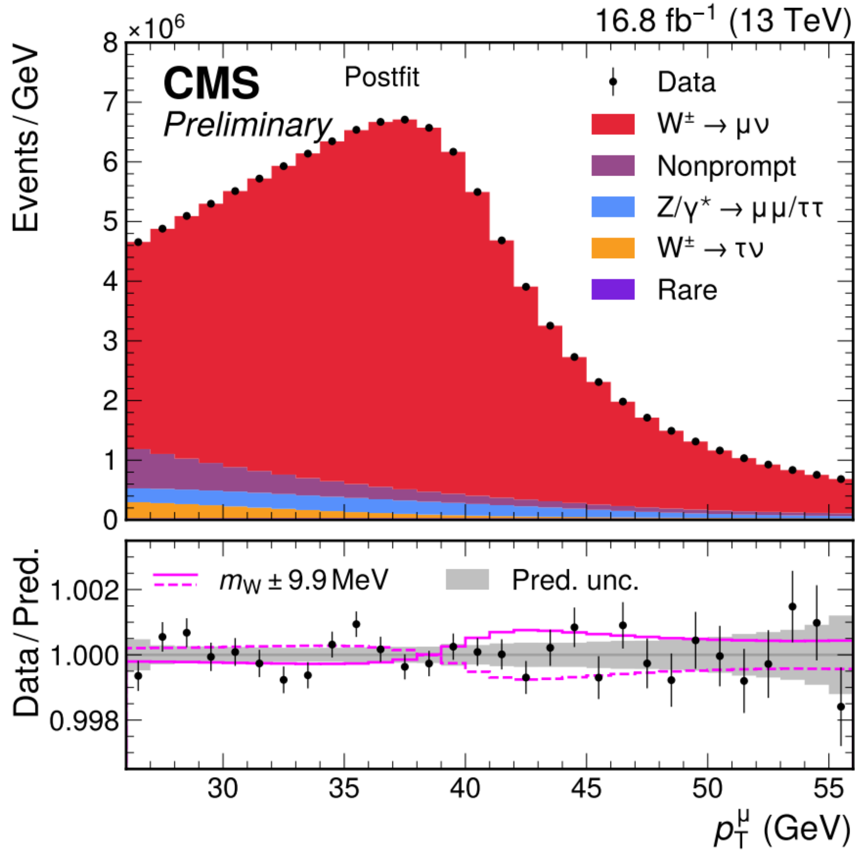
- Good qualitative agreement
- W-like Z fit to single letpon kinematics able to constrain theory uncertainties

→ W fit to single lepton kinematics able to constrain theory uncertainties



Result

$$m_{\mathrm{W}} = 80360.2 \pm 9.9\,\mathrm{MeV}$$



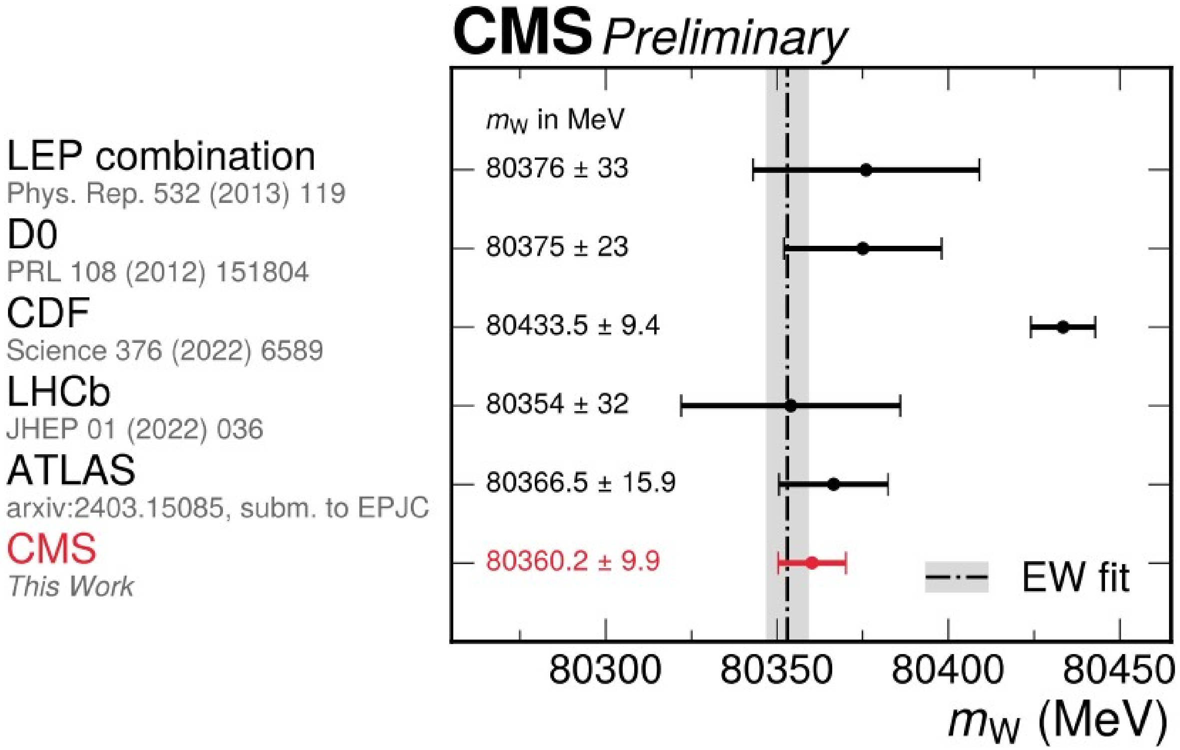
Source of uncertainty	Impact (MeV) Nominal	Impact (MeV) Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
$p_{\mathrm{T}}^{\mathrm{V}}$ modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample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

Many additional studies and cross checks performed

Summary & conclusions

First measurement of m_W from CMS

- Most precise at LHC
- In agreement with the SM
  and measurements except CDF
- Document: [CMS-PAS-SMP-23-002]
- More complete seminar (recorded)



Major advances in theory modeling and muon calibration

- Setting the base for further precision measurements

Backup

Comparison with ATLAS

Compared to ATLAS, in addition to our larger data set

- Better constraints on theory (PDFs, non perturbative, ...)
- Reduced EW unc. due to newer photos version
- Total calibration + muon eff. "only" 10% better,
  but Z-independent scale calibration, physics driven model

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
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

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

Comparison with CDF

CDF has advantages from $p\bar{p}$ collider for theory, and from low tracking material for calibration

- But they didn't do a W-like Z measurement

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
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

Event selection

Select isolated muons from single muon trigger

- $26 < p_T < 56$; $|\eta| < 2.4$; multiple quality criteria

Transverse mass cut of $m_T(\mu, \text{MET}) > 40$GeV to reject QCD multijet events with nonprompt muons (and to predict them)

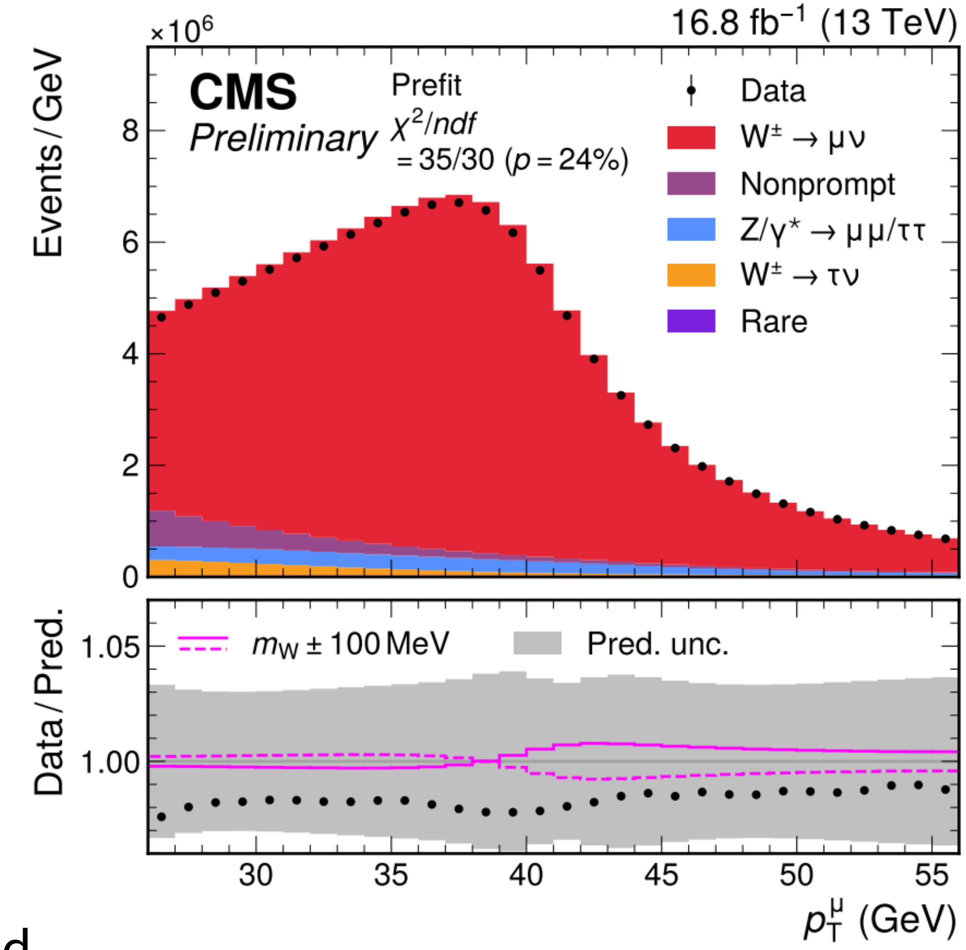
- Using DNN based DeepMET algorithm

Selected events are

- 89% $W \to \mu\nu$
- 4% $Z \to \mu\mu/\tau\tau$
- 2% $W \to \tau\nu$
- <1% Rare

} From simulation

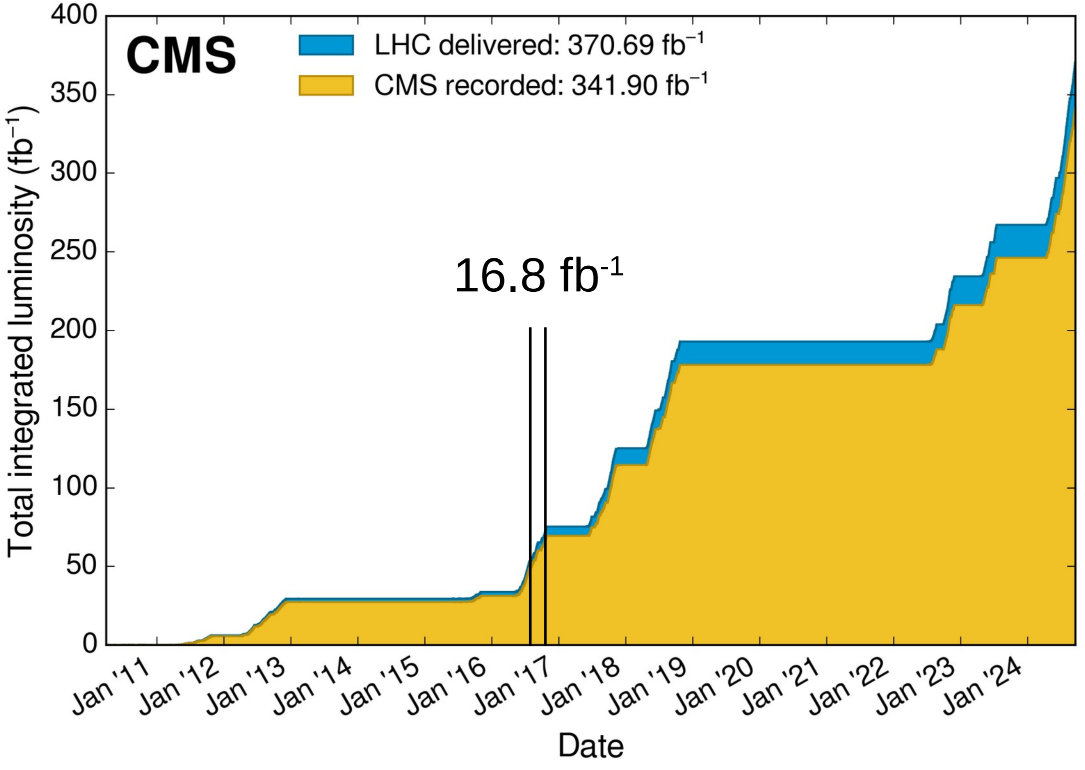
- 4% Nonprompt } From data via "extended" ABCD method
  - Verified in secondary vertex control region



The Data

Using Run 2 pp collision data with $\sqrt{s}$ = 13TeV taken in second half of 2016

- Well-understood part of Run 2 data
- On average 30 pileup interactions
- "Only" 10% of 13TeV data but largest data sample ever used for a W boson mass measurement



>100 million selected events – for us, HL LHC is now

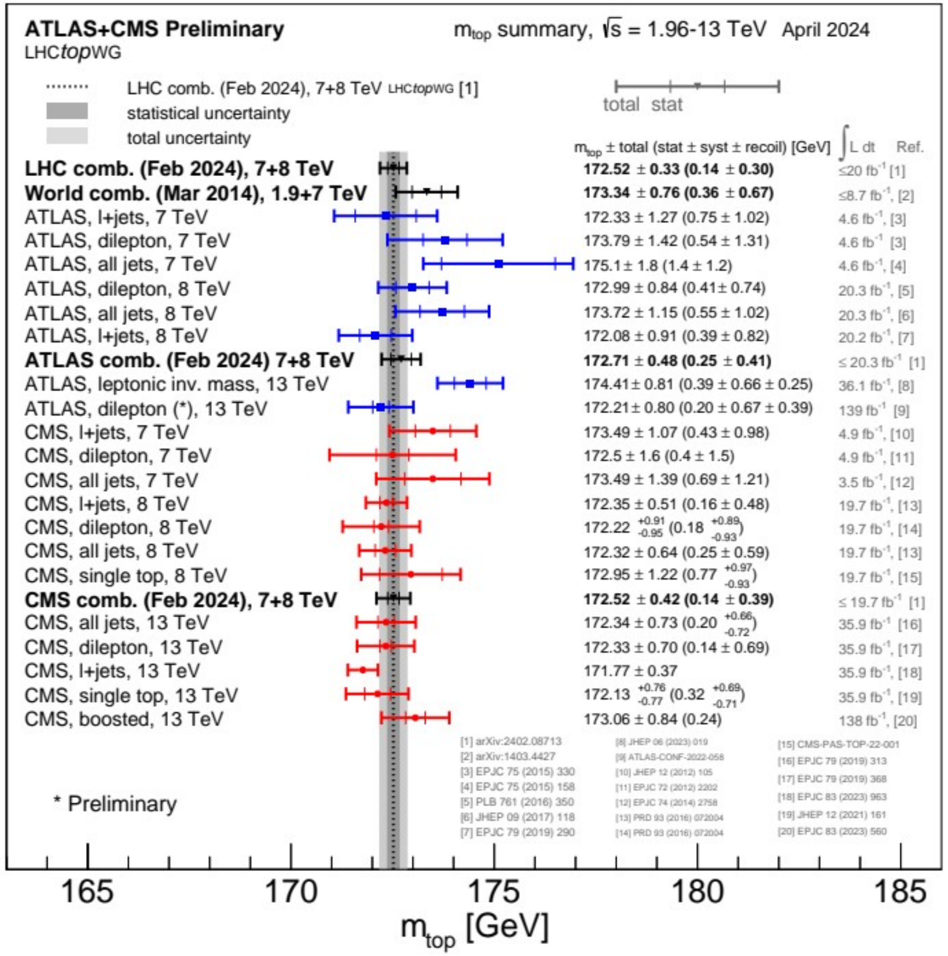
- Challenging, but also offers new opportunities

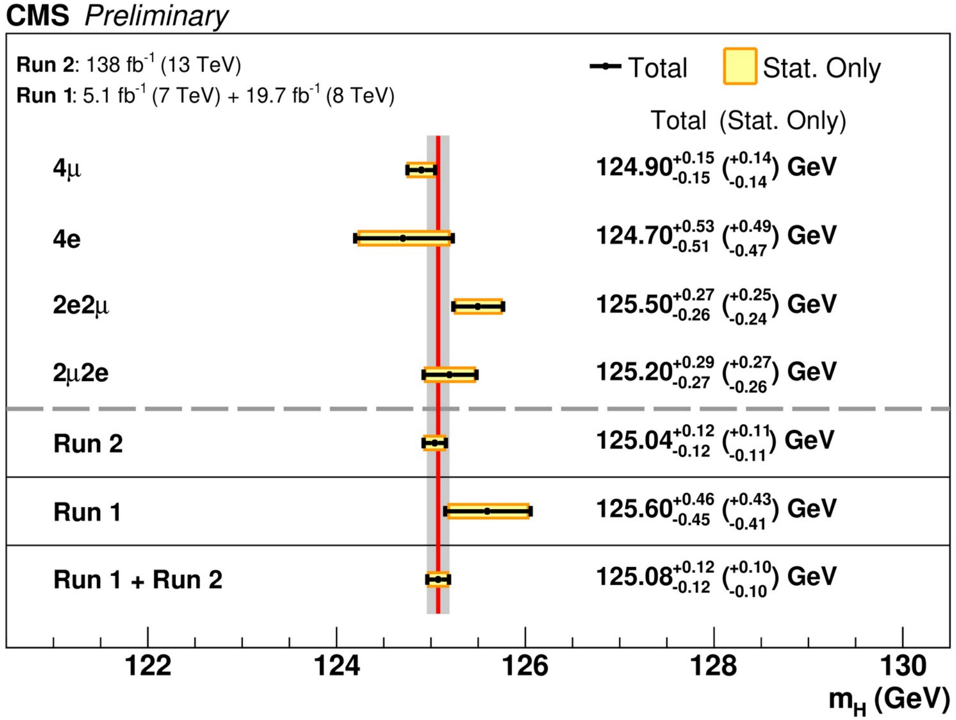
General strategy:

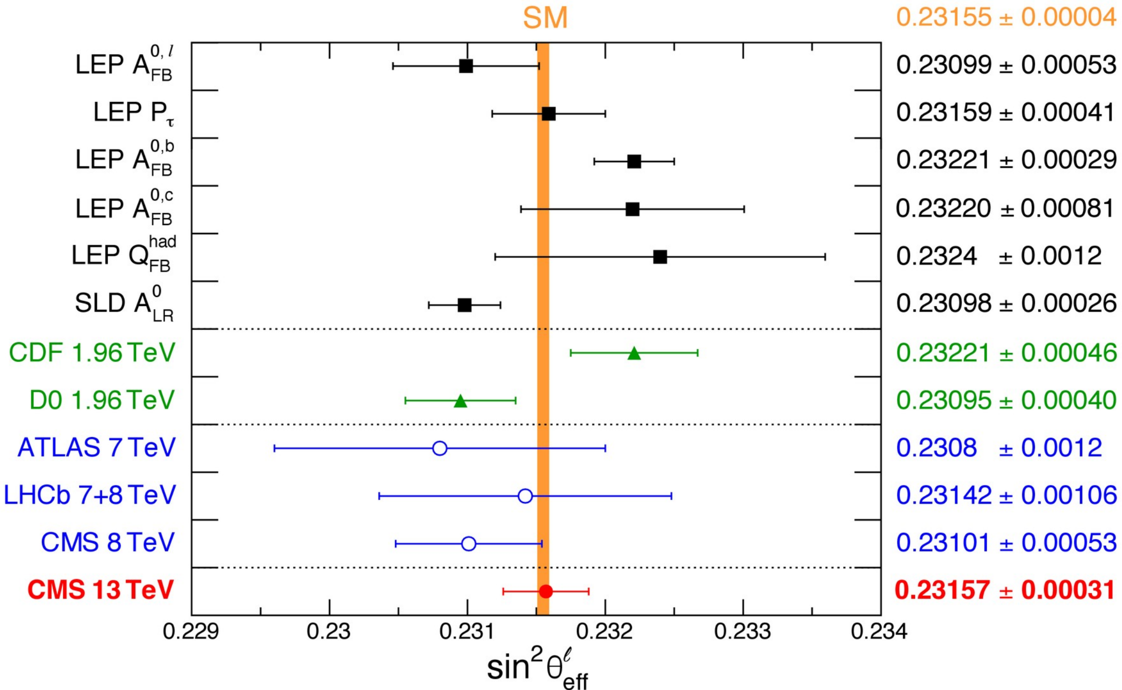
- Exploit large dataset for maximal in-situ constraints on theoretical modeling

Precision SM measurements

Recent progress in precision measurements of SM parameters







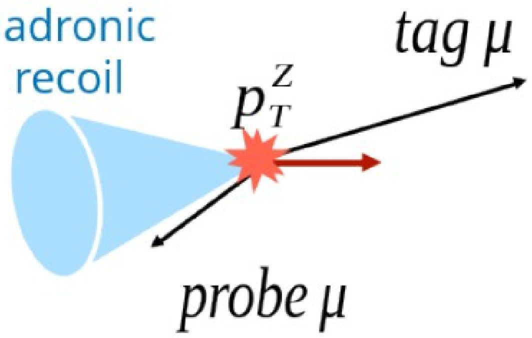
Muon selection efficiencies

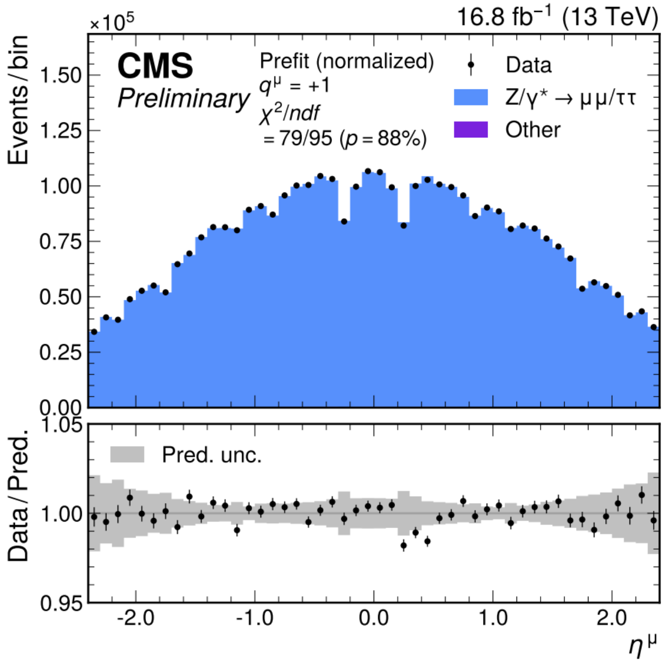
Correct simulated samples with muon selection efficiency scale factors

- Inner/outer tracking, selection, isolation and trigger efficiencies
- Measured in $Z\rightarrow\mu\mu$ data using tag and probe procedure
- Differentially in muon p_T η, charge
- Smoothing procedure in p_T to mitigate statistical uncertainties

Isolation sensitive to hadronic recoil of Z (and W)

- Probe muon at low p_T more likely to fall in hadronic recoil
- Different recoil in W and Z events
- Isolation and trigger efficiencies also measured in boson recoil u_T





Further corrections for muon prefiring

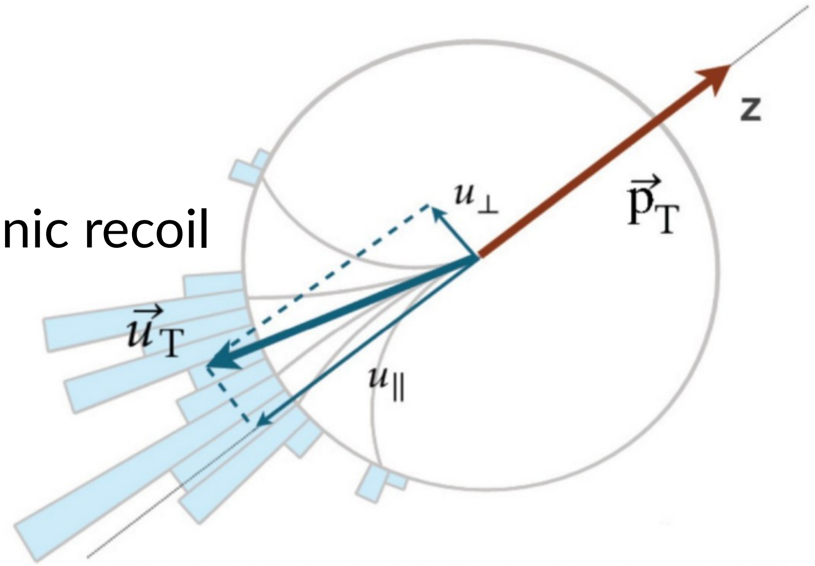
$$u_T = \frac{\vec{p}_T^{\,\mu} \cdot \vec{p}_T^{\,Z}}{|\vec{p}_T^{\,\mu}|}$$

Recoil calibration

DNN based algorithm (DeepMET) to estimate hadronic recoil for missing transverse energy

- Improved resolution and efficiency for QCD multiject background rejection
- Calibrated in $Z \to \mu\mu$ events

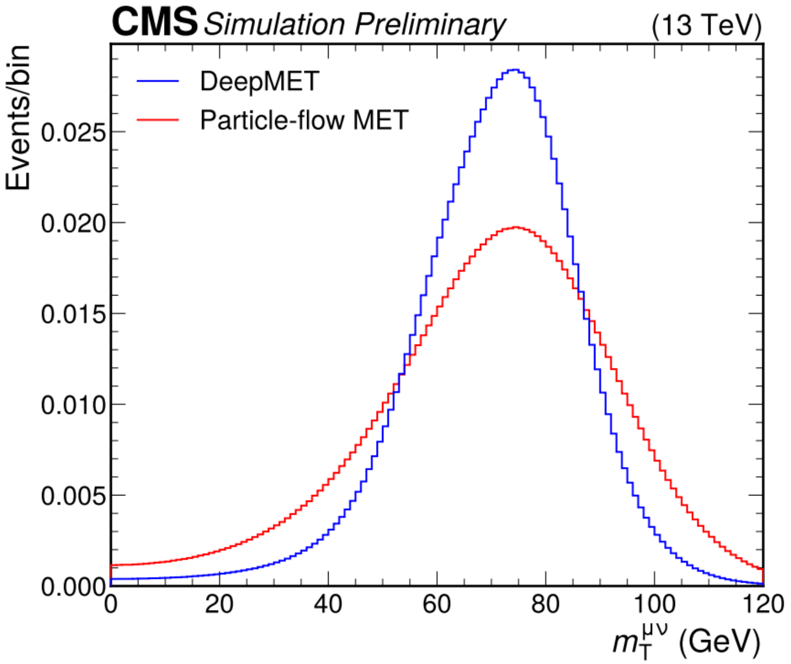
Hadronic recoil

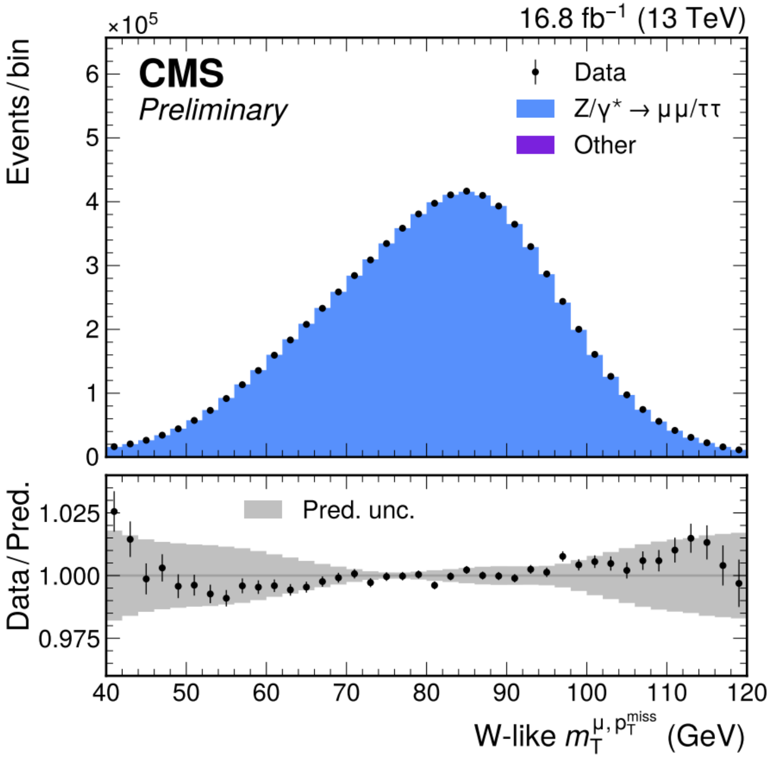


Mitigate difference between Z and W events

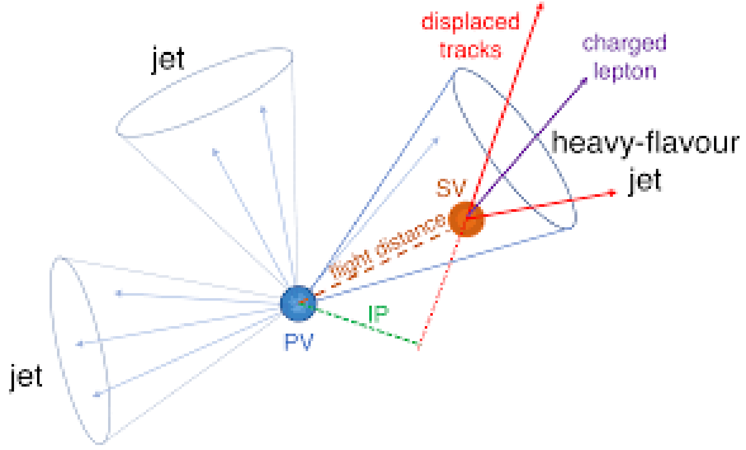
- Different vertex efficiency
  → Vertex agnostic algorithm

Resulting uncertainties negligible on final measurement (<0.3MeV)





Nonprompt background

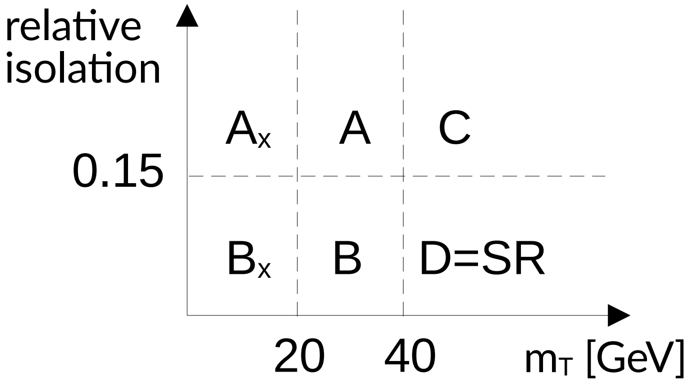


QCD multijet events with muons that are not prompt

- B hadron decays, Light meson in flight decays, …
- Large cross section and insufficient modeling

Estimated from sideband regions in data

- Extended ABCD method with 3 bins m_T and 2 bins in isolation
- Evaluated in fine bins in p_T, η, charge
- Prompt background in sideband region subtracted from simulation, repeated for each systematic variation



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

Nonprompt background

Smoothing each sideband region with exponential of a polynomial to maintain good statistical properties

Agreement between prediction and observation checked in QCD simulation

- Total correction factor of 0.85 derived
- Additional uncertainties assigned to cover residual shape and normalization differences

$$f_i(p_\mathrm{T}) = \mathrm{e}^{P_i(p_\mathrm{T})}$$

$$f_\mathrm{D}(p_\mathrm{T}) = \mathrm{e}^{\sum_i w_i P_i(p_\mathrm{T})}$$

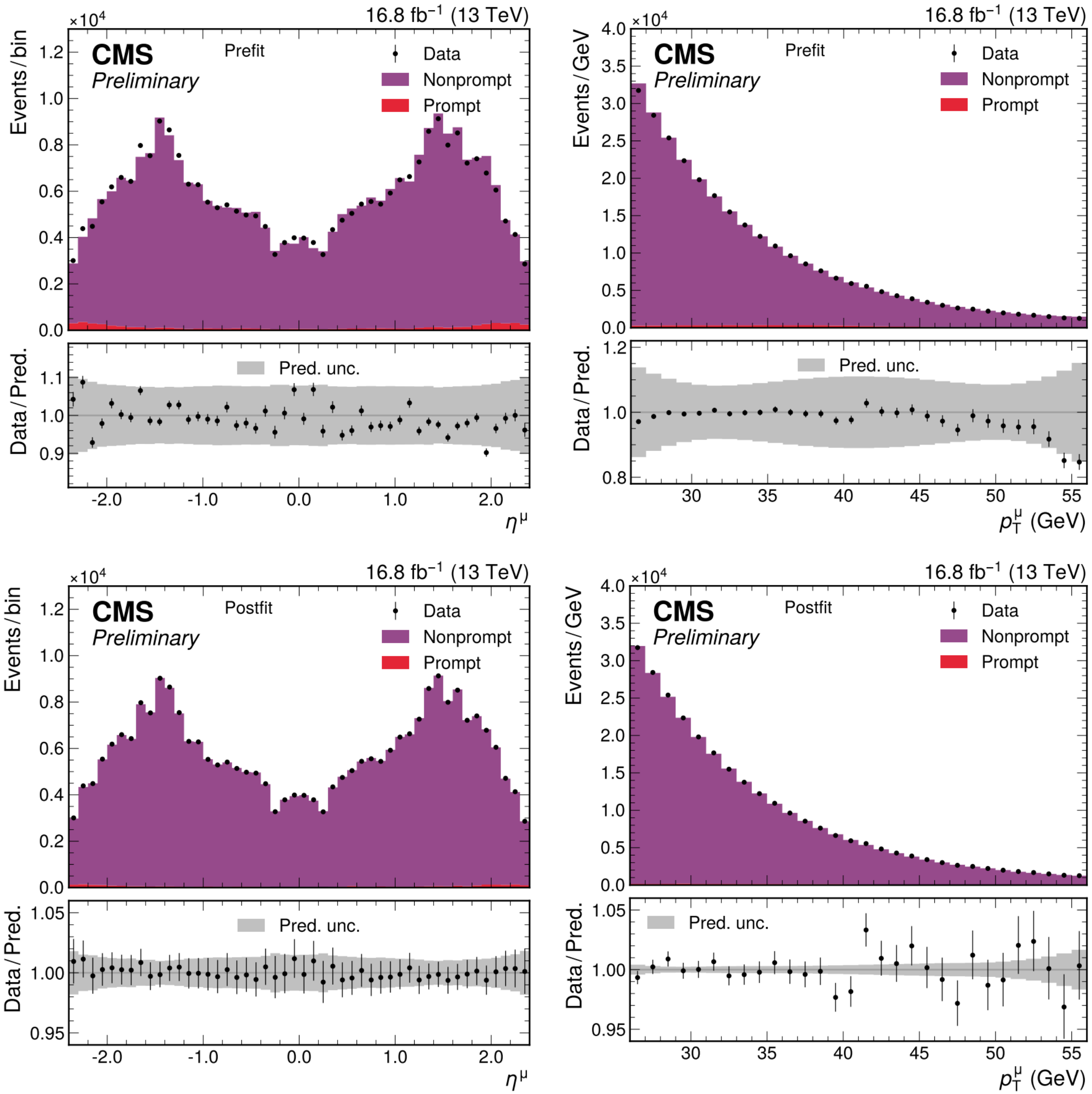
Nonprompt background

Estimation validated in secondary vertex region in data

- Events with a muon coming from from a secondary vertex
- Very pure in QCD multijet events

Performed fit in bins of (p_T, η, charge)

- Good visible agreement
- p-value of 98%



Muon veto efficiencies

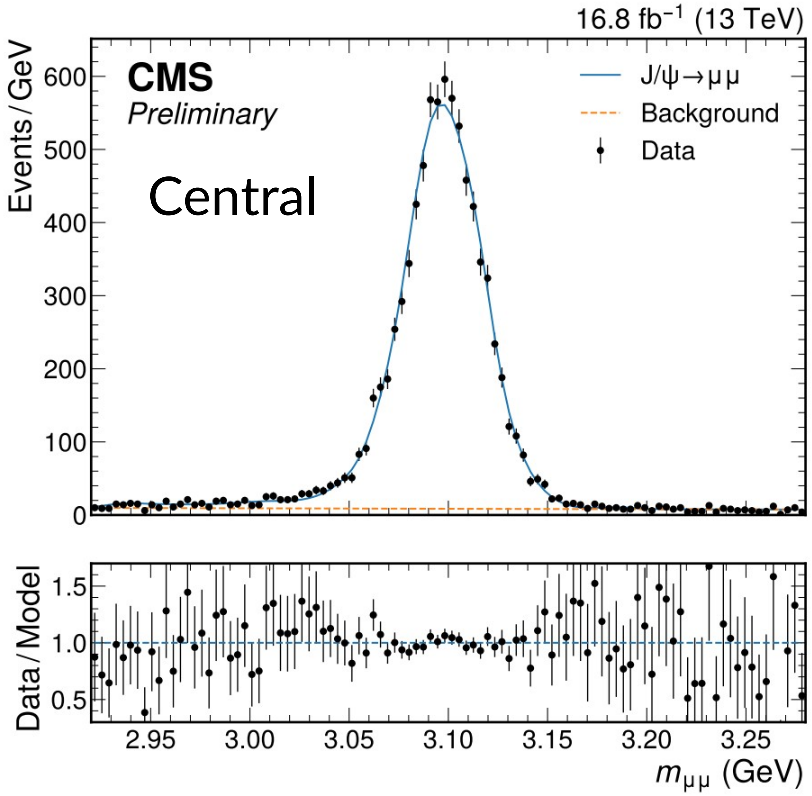
Mainly $Z \rightarrow \mu\mu$ events with both muons in acceptance but one is not reconstructed or identified

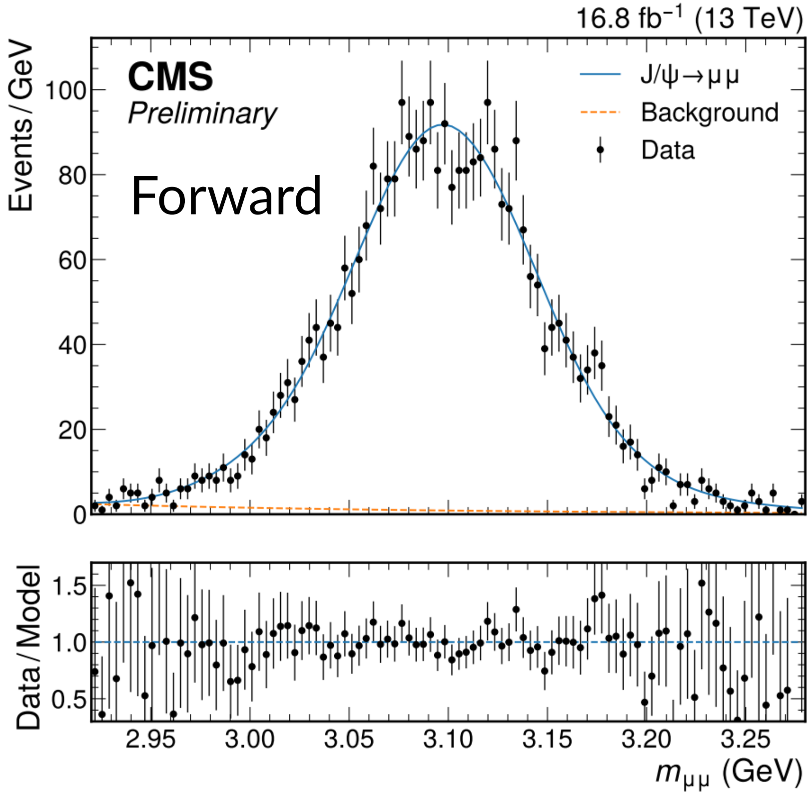
- Shape of background similar to W but shifted to lower p_T
  - can introduce large bias on m_W if not corrected
- Delicate topic, can not be tested in W-like Z measurement
- Measured based on generator level quantities
- Alternative veto selection and scale factors as cross check

Muon momentum scale calibration

After restoring parameterization, fitting model to J/ψ data

- Fits are finely binned in di-muon kinematics (η^+, p_T^+, η^-, p_T^-)
- Extract J/ψ mass from peak of distribution





Muon momentum scale calibration

Extracted J/ψ mass values translated into model parameters via χ^2 fit

Magnetic field → $A_{i\eta}$; alignment → $M_{i\eta}$

$$\delta k/k = A_{i\eta}k - \epsilon_{i\eta} + qM_{i\eta}/k$$

Energy loss (material) → $\epsilon_{i\eta}$

Muon momentum calibration

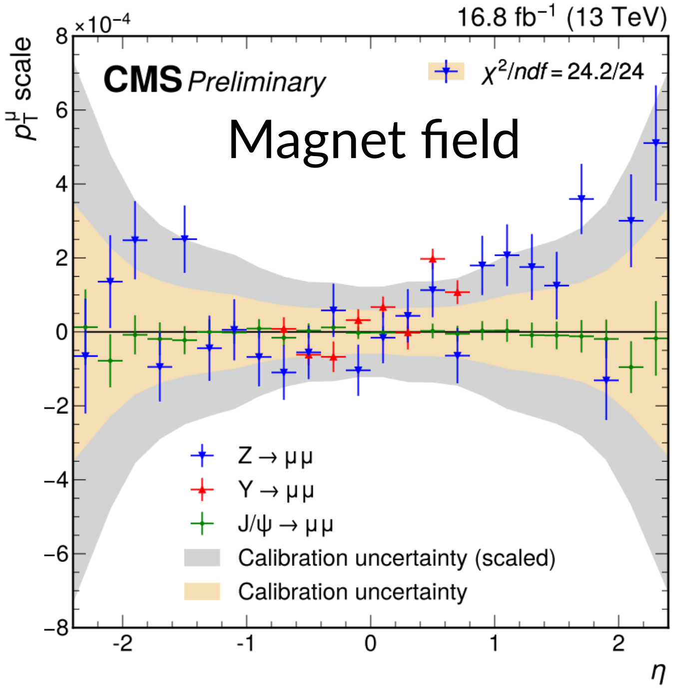
Assess calibration closure by re-evaluating model on Υ(1S) and Z data

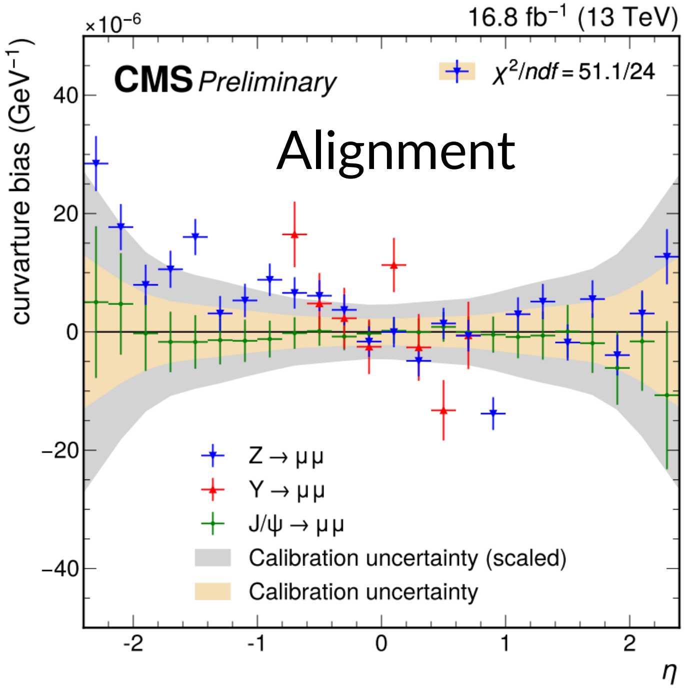
- Υ only in central due to worse resolution at high |η| and overlapping peaks
- No significant bias in magnet field term
- Slight tension in alignment term

Uncertainty on calibration parameters from J/ψ inflated by factor of 2.1

- Cover all possible biases
- Proxy for missing systematic 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





Muon momentum resolution calibration

Resolution corrected with similar parameterized model

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

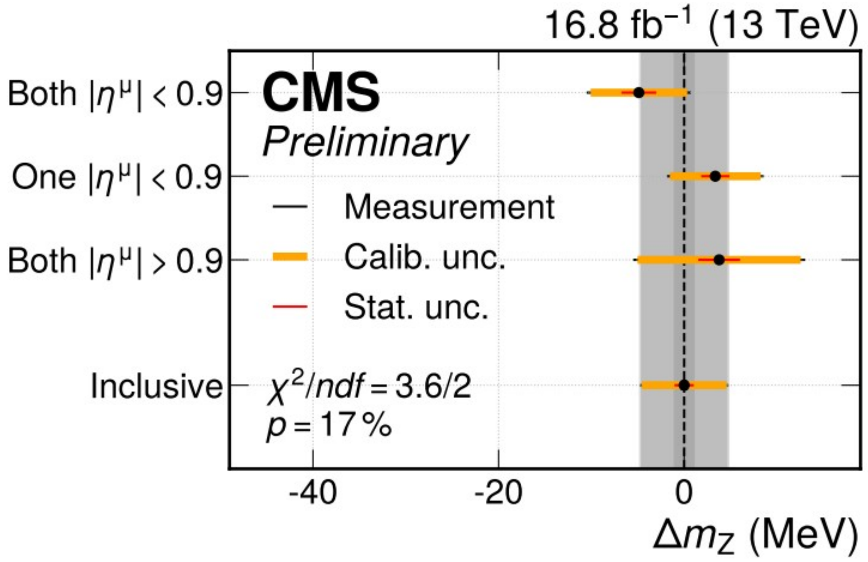
Correlations

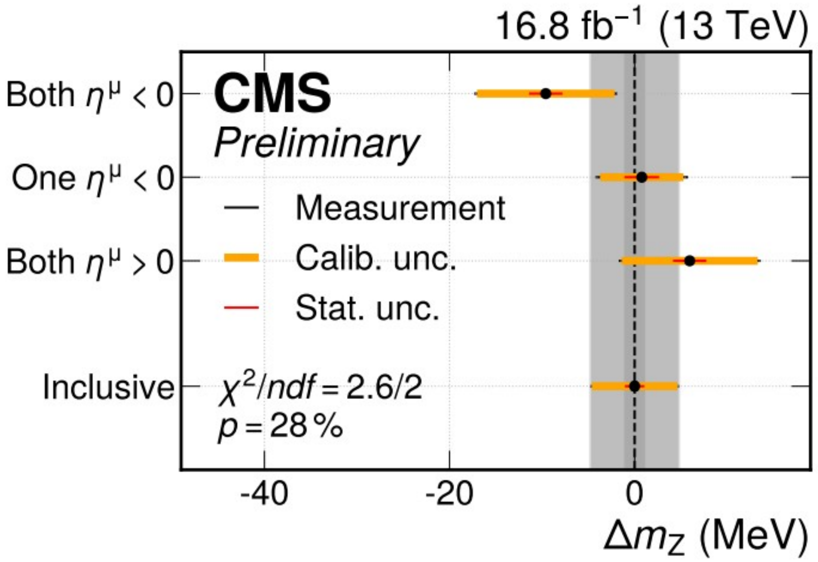
Multiple scattering   Hit resolution

- Extracted from J/ψ and Z data
- Negligible impact on m_Z or m_W

Muon momentum calibration

Assigning separate mass parameter in different phase space regions





Electroweak effects

Main EW effect from QED FSR included in simulation

- Using Photos++ with QED LL including γ→ee/μμ pair production and matrix element corrections (MEC) ~NLO QED

Factorize higher order EW uncertainties:

ISR < 0.1 MeV

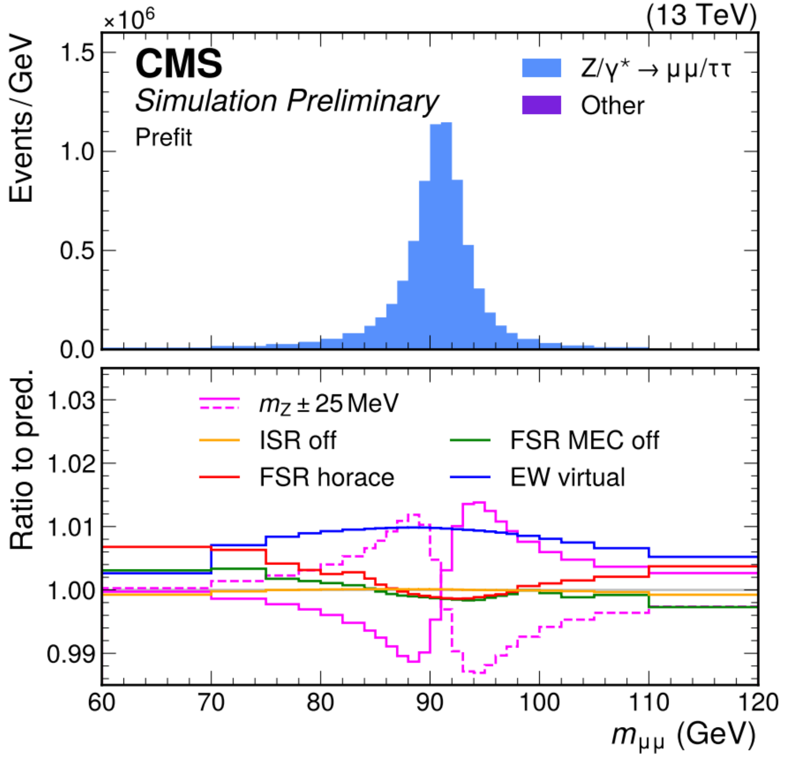
- Switching on/off QED ISR in pythia

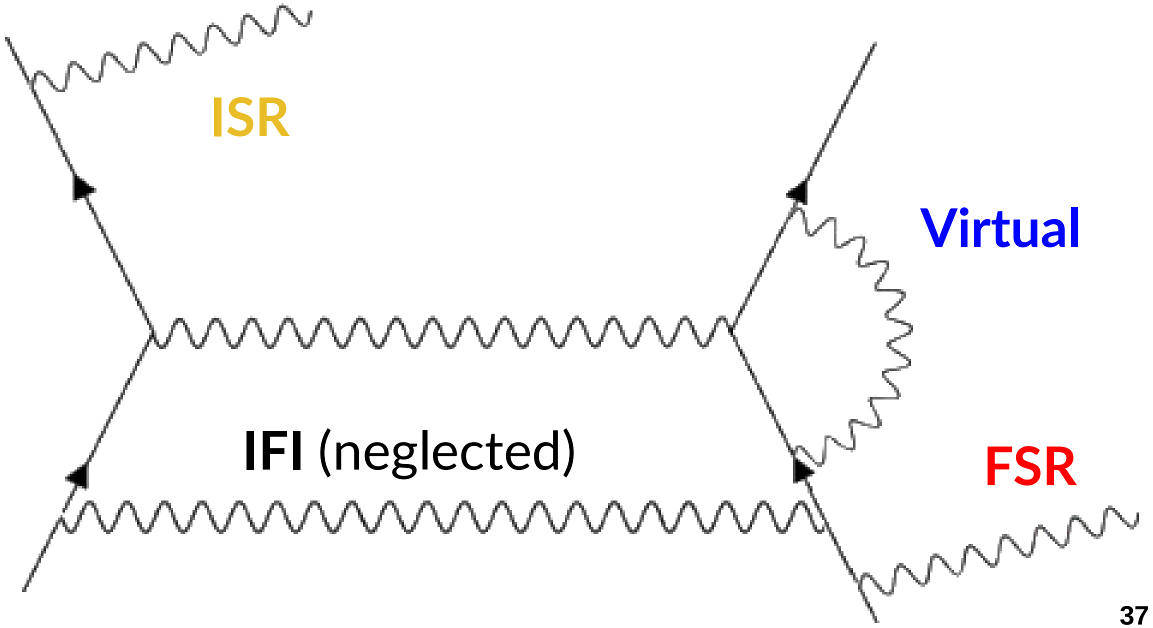
FSR ~ 0.3 MeV

- Horace QED FSR
- Photos++ MEC off

Virtual ~1.9 MeV

- Z: Powheg NLO+HO EW
- W: ReneSANCe NLO+HO EW

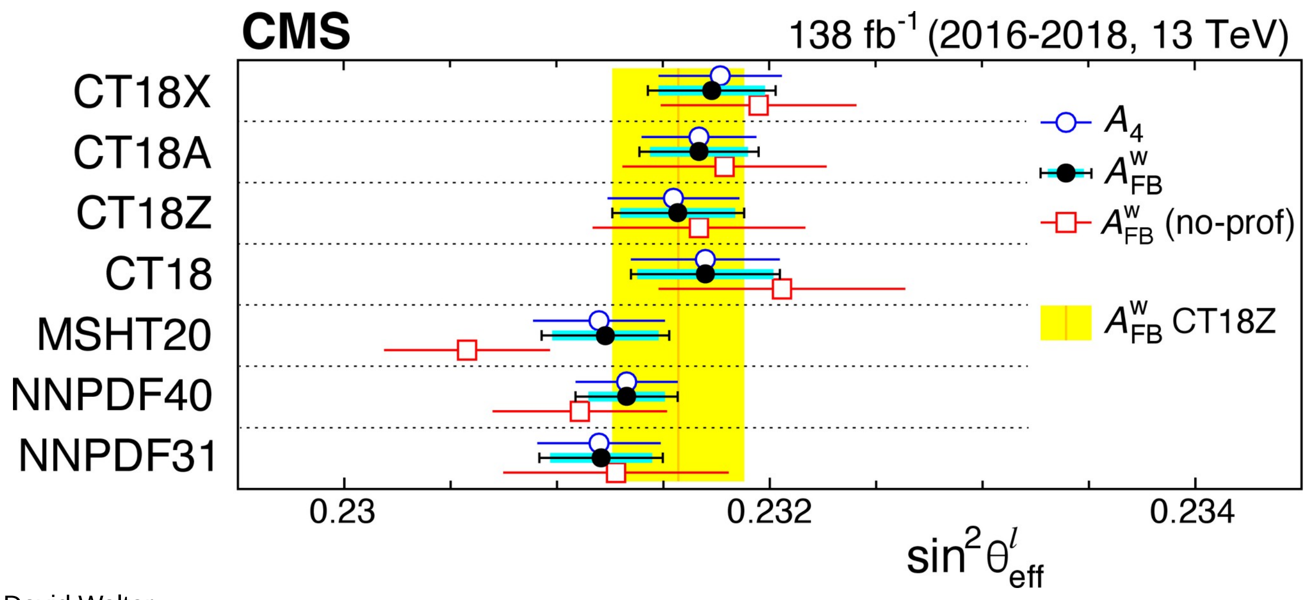


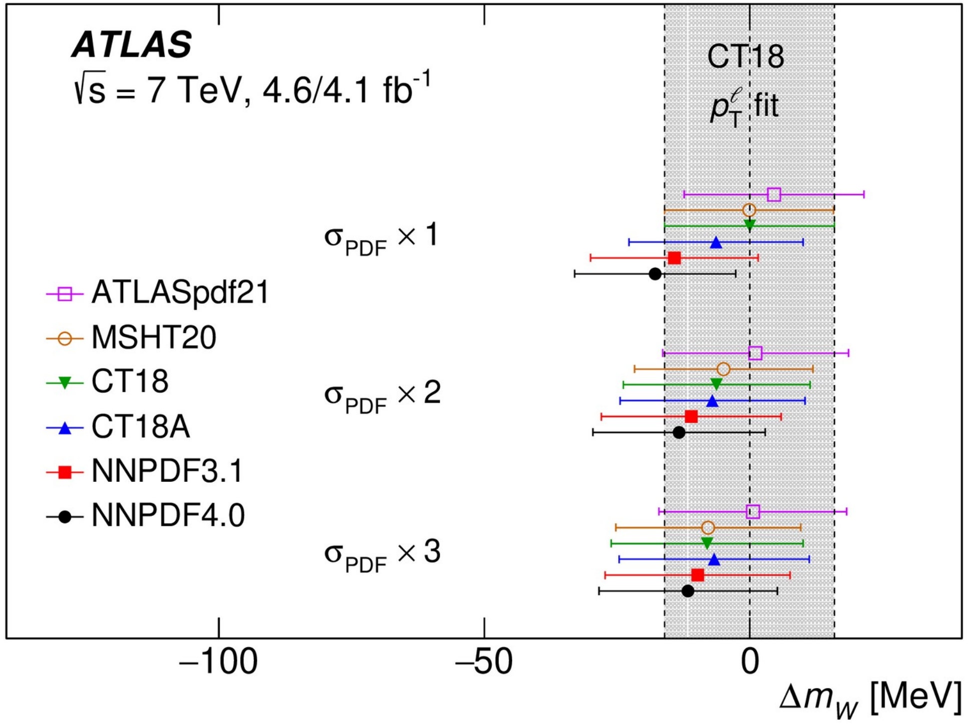


Lepton transverse momentum based m_W measurement

At the LHC, boson production described in parton distribution functions (PDFs)

- Previous measurements have shown large spread for different PDF sets
  - E.g. missing theory uncertainties in PDFs
  - But can be directly constrained from data

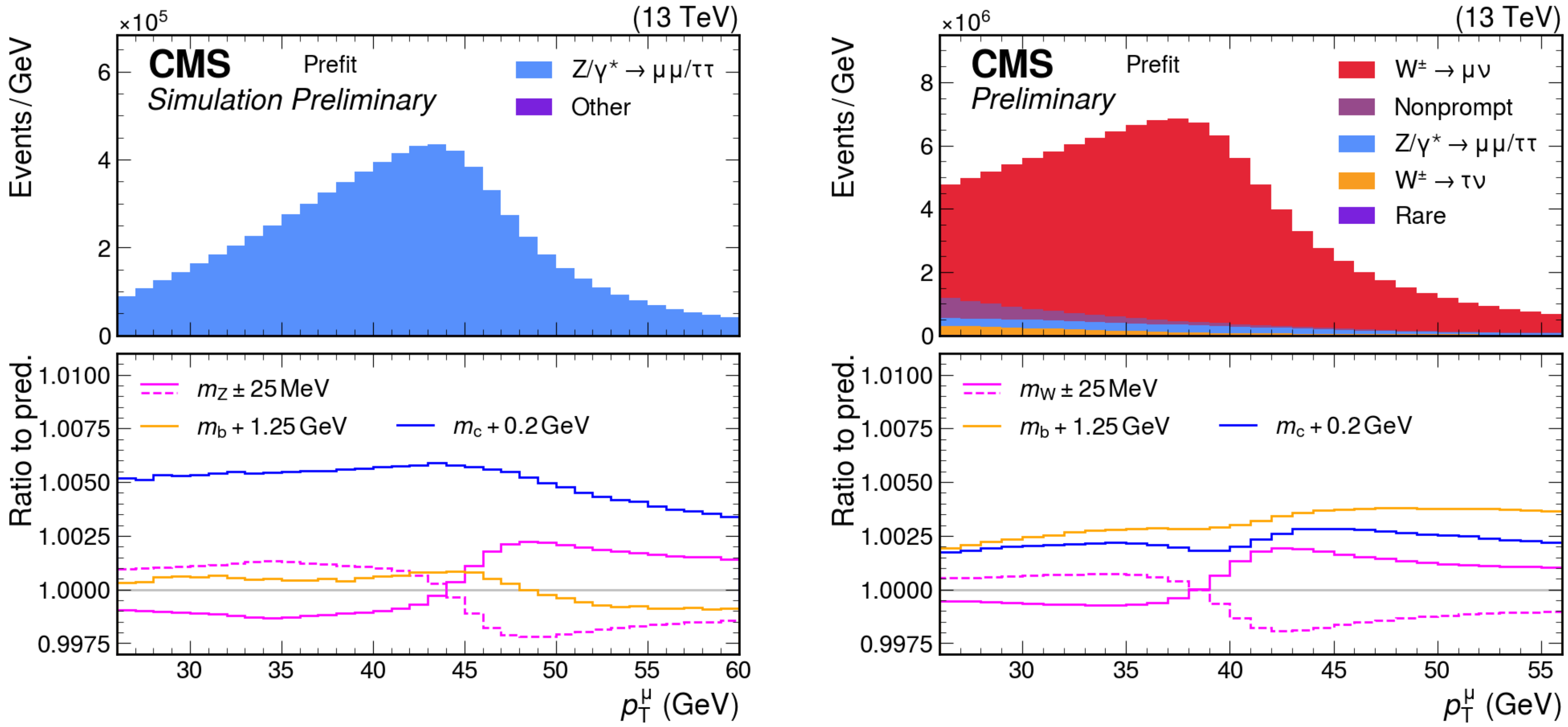




Heavy quark mass effects

Different contributions from heavy flavor quarks in production of W and Z

- Effect of quarks masses in variable flavor scheme PDFs accounted for

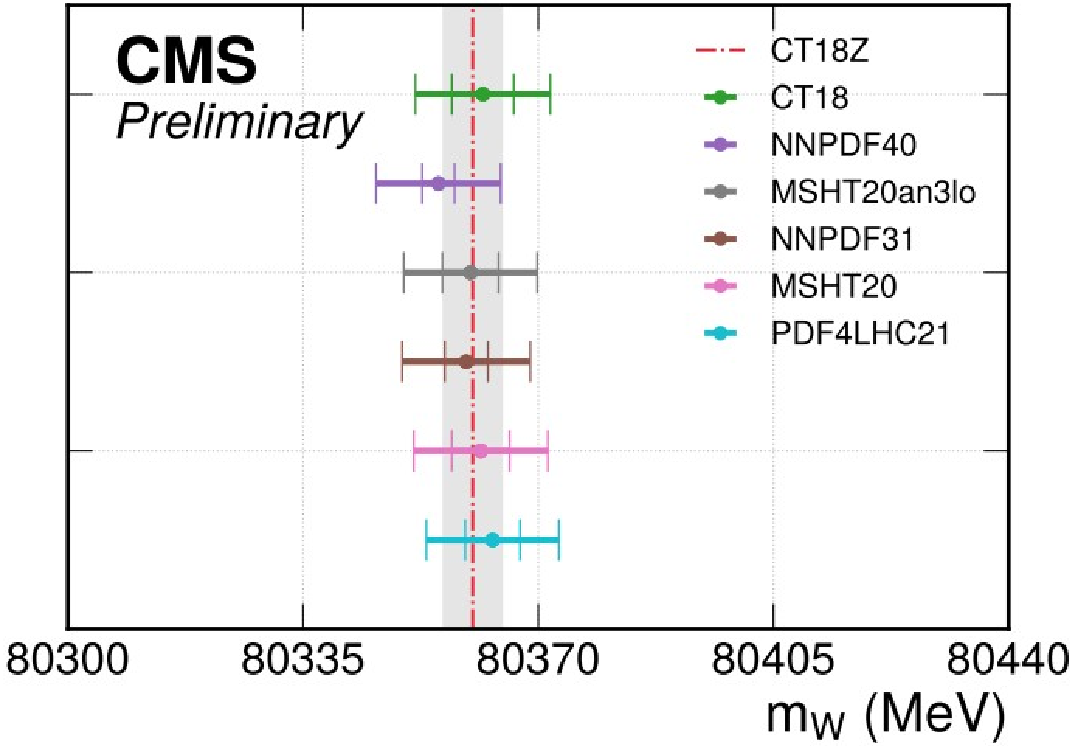


Results from different PDF sets

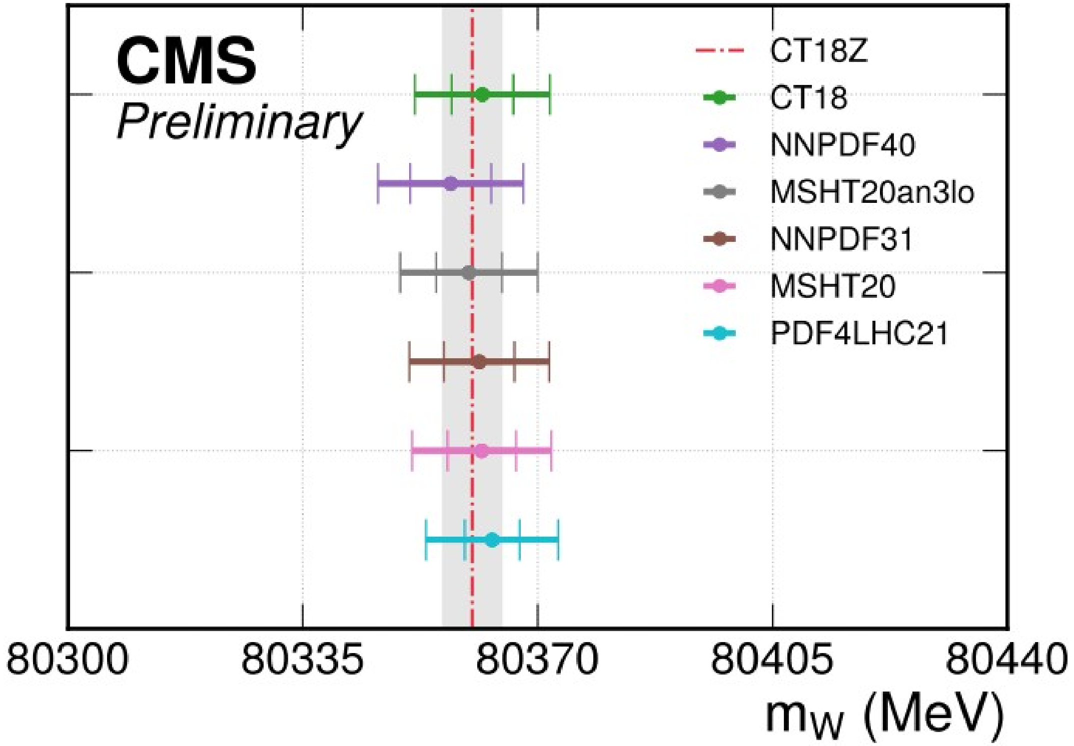
Measurement repeated for different PDF sets

- If not inflated, spread larger than assigned uncertainty
- If inflated, consistent values

Without inflation



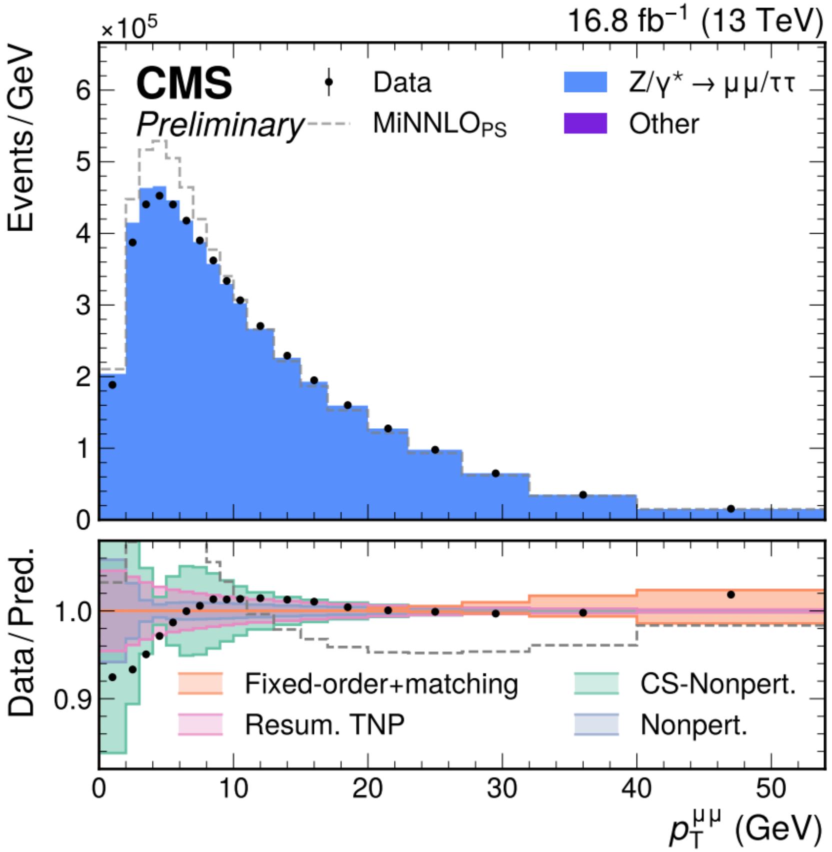
With inflation

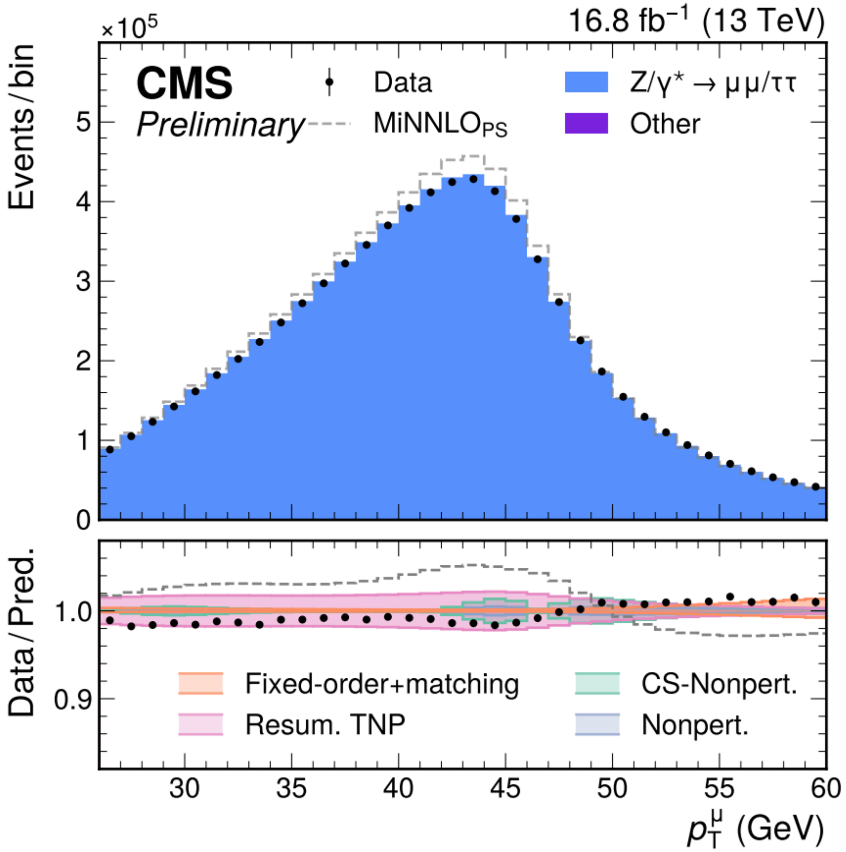


Modeling of W, Z boson transverse momentum – fixed order α_S

1) Fixed order expansion in α_S, relevant at $p_T^V > 30$GeV

- Nominal prediction from MiNNLO$_{PS}$ event generator has NNLO in α_S
- Missing higher orders subdominant source of uncertainty
- Assessed by varying μ_R and μ_F → also used for angular coefficients

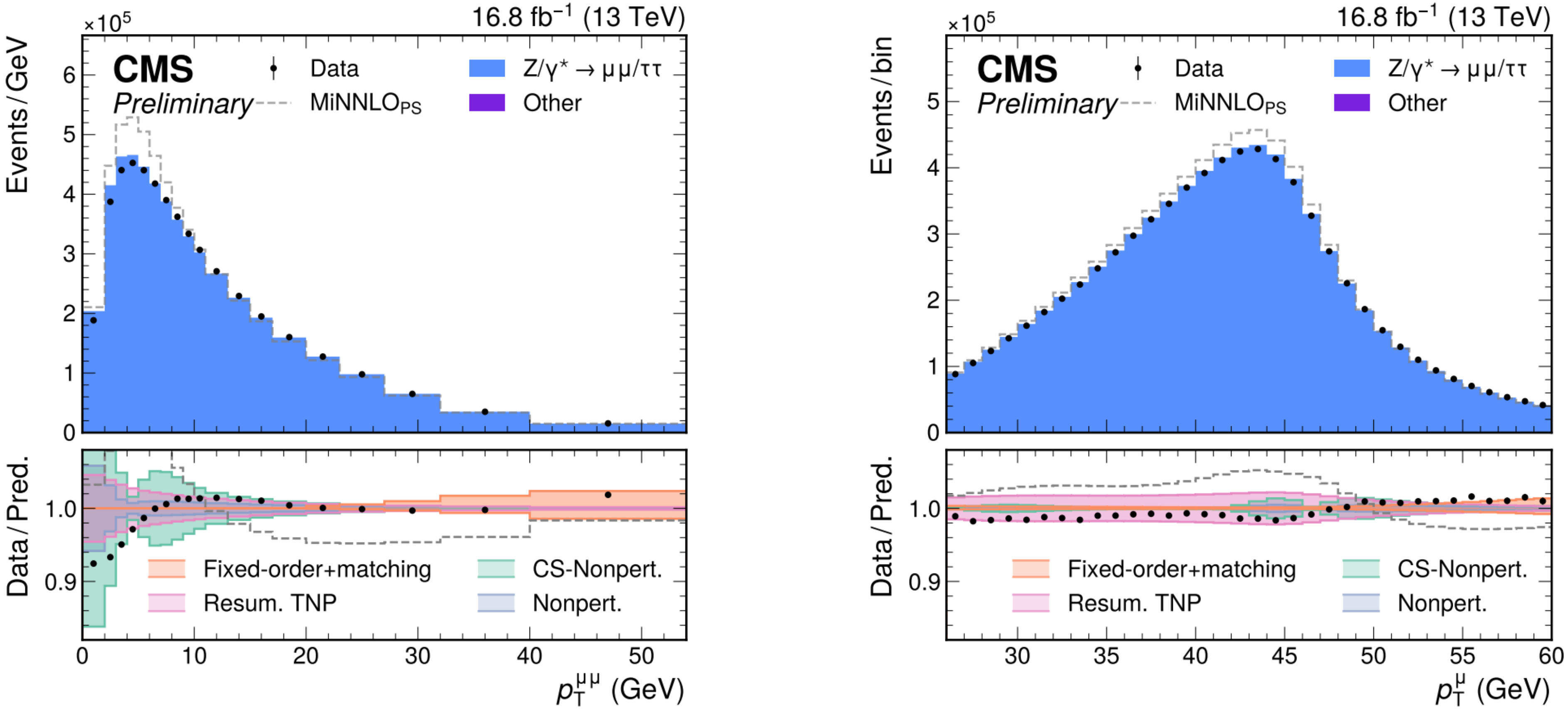




Modeling of W, Z boson transverse momentum – fixed order α_S

2) Resummation expansion in $\log(p_T^V/m_V)$, relevant at medium and low p_T^V

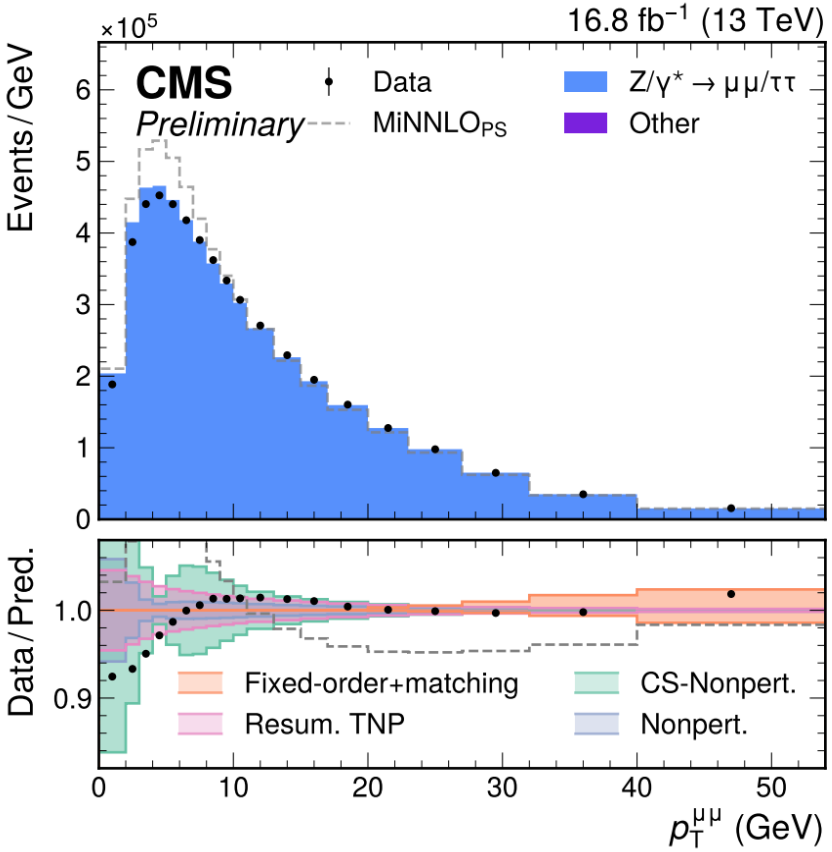
- Nominal prediction corrected with N^3LL from SCETlib



Modeling of W, Z boson transverse momentum – non perturbative

3) Non perturbative, relevant at p_T^Z < 10GeV

- E.g. Residual transverse motion of partons inside proton (intrinsic k_T)
- Active field of research (TMD PDFs, lattice QCD)
- Using phenomenological models to be tuned to the data
- Collins–Soper (CS) kernel, universal for W and Z
- Others (Intrinsic k_T) not universal for W and Z
- Using SCETlib program with loosely constrained to minimal nonperturbative effects



Simultaneous fit of W and Z dilepton

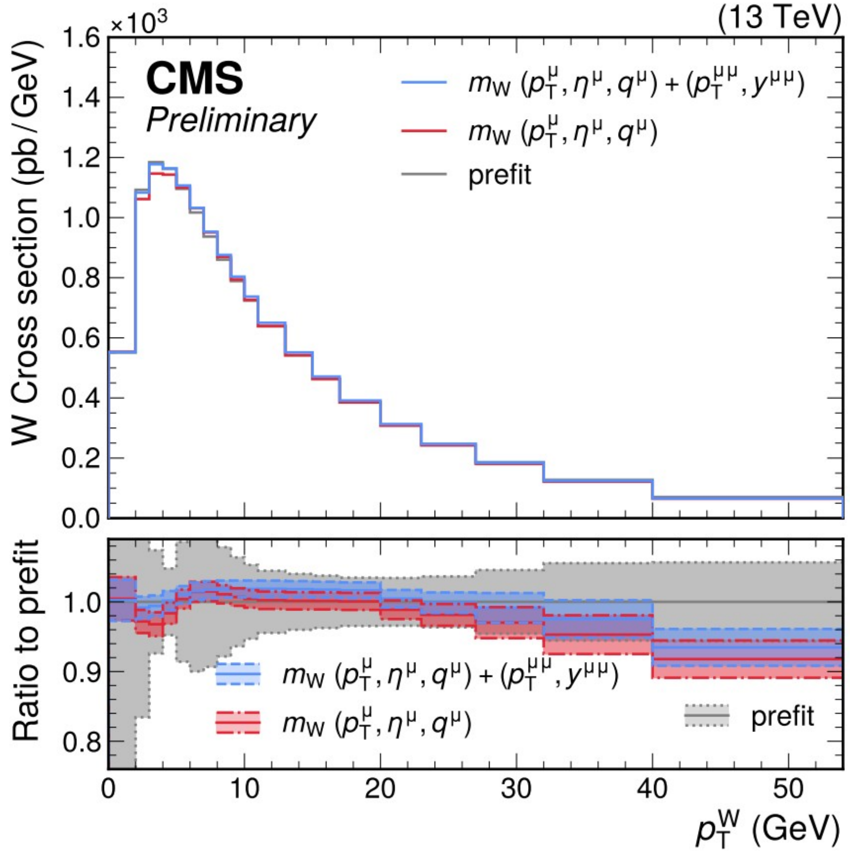
Extract m_W by simultaneously fitting single lepton p_T, η, charge and dilepton p_T, y distributions

Obtained result w.r.t. nominal fit Δm_W = +0.6 MeV

- Decreased uncertainty to 9.6MeV
- Postfit p_T^W distribution largely consistent with nominal fit

Only used as cross check since correlations of theory uncertainties between W and Z are less well understood

- E.g. no complete flavor dependent model



Helicity cross section fit

W production at LHC described by a decomposition into angular coefficients using spherical harmonics of second order

$$\underbrace{\frac{d\sigma}{dp_T^2\,dm\,dy}}_{\text{W differential cross section}}\underbrace{\,d\cos\theta^*\,d\phi^*}_{\text{Decay angles from muons in W rest frame}} = \frac{3}{16\pi}\underbrace{\frac{d\sigma_{UL}}{dp_T^2\,dm\,dy}}_{\text{Unpolarized cross section}}\left[(1+\cos^2\theta^*) + \sum_{i=0}^{7}\underbrace{A_i(p_T, m, y)}_{\text{Angular coefficients encode W polarization}} \cdot \underbrace{P_i(\cos\theta^*, \phi^*)}_{\text{Spherical harmonics encode W decay}}\right]$$

W differential cross section | Decay angles from muons in W rest frame | Unpolarized cross section | Angular coefficients encode W polarization | Spherical harmonics encode W decay

If angular coefficients and unpolarized cross section are known for all values of p_T^W, y^W and W charge, muon kinematics are known

Idea: simultaneous extraction of m_W and helicity cross sections in bins of p_T^W, y^W, charge

- Reduced theory/model dependence for larger statistical uncertainty

Angular coefficients

W production at LHC described by a decomposition into angular coefficients using spherical harmonics of second order

$$\underbrace{\frac{\mathrm{d}\sigma}{\mathrm{d}p_{\mathrm{T}}^{2}\,\mathrm{d}m\,\mathrm{d}y}}_{\text{W differential cross section}}\underbrace{\,\mathrm{dcos}\,\theta^{*}\,\mathrm{d}\phi^{*}}_{\text{Decay angles from muons in W rest frame}} = \frac{3}{16\pi}\underbrace{\frac{\mathrm{d}\sigma_{\mathrm{UL}}}{\mathrm{d}p_{\mathrm{T}}^{2}\,\mathrm{d}m\,\mathrm{d}y}}_{\text{Unpolarized cross section}}\left[(1+\cos^{2}\theta^{*}) + \sum_{i=0}^{7}\underbrace{A_i(p_{\mathrm{T}},m,y)}_{\text{Angular coefficients encode W polarization}}\cdot\underbrace{P_i(\cos\theta^{*},\phi^{*})}_{\text{Spherical harmonics encode W decay}}\right]$$

W differential cross section

Decay angles from muons in W rest frame

Unpolarized cross section

Angular coefficients encode W polarization

Spherical harmonics encode W decay

Angular coefficients describe translation from p_T^V to p_T^μ spectrum

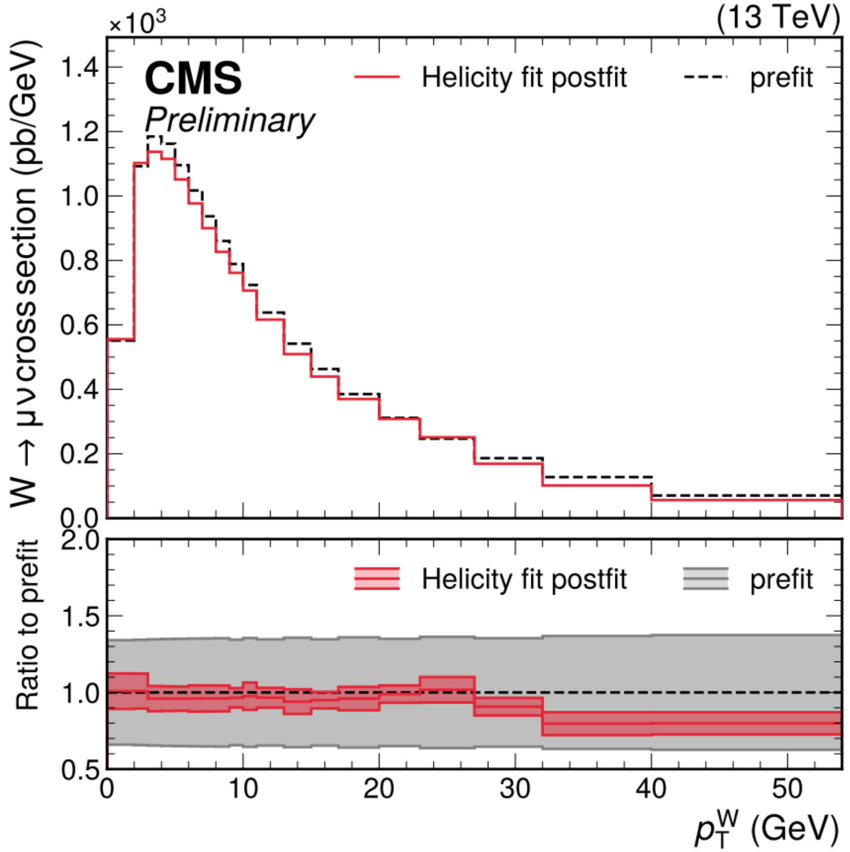
Modeled with NNLO accuracy in α_S from MiNNLO$_{PS}$ event generator

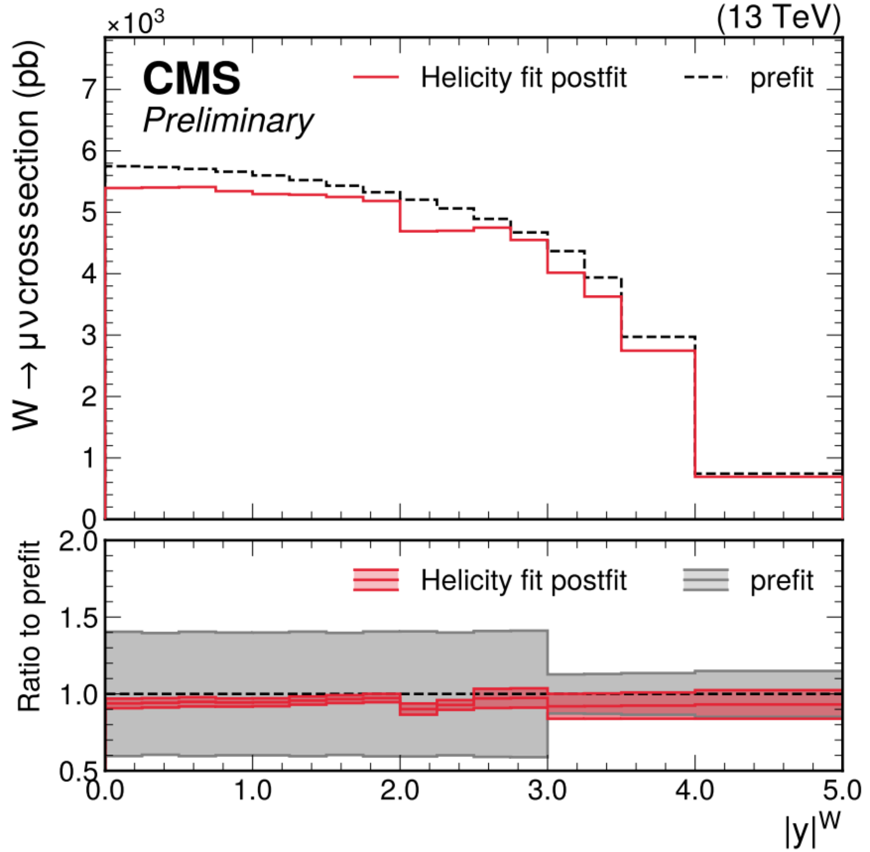
- Scale variations μ_R and μ_F decorrelated for A_i to account for missing higher orders

Helicity cross section fit

Limited sensitivity to constrain all components in current fit

- Only consider σ_0 - σ_4
- Regularize with constraints to nominal predictions
- Relevant theory uncertainties retained





Helicity cross section fit

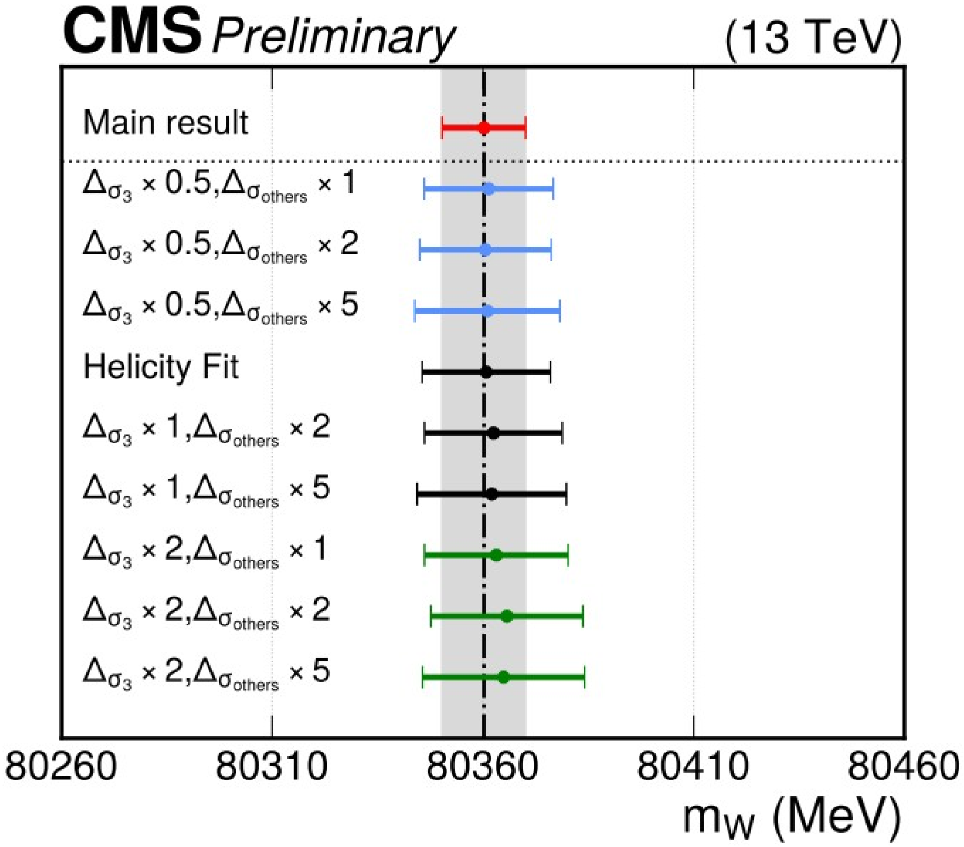
Consistent result obtained

$$m_{\mathrm{W}} = 80360.9 \pm 15.2\,\mathrm{MeV}$$

Measured W mass stable vs. magnitude of prefit uncertainties

σ_3 more sensitive to W mass and less well constrained

- scaled independently from everything else



Uncertainties

Nominal

- Change in m_W when varying systematic group by 1σ
- Correlations across different sources
- Statistical uncertainty in case of no systematics

Global

- Systematic uncertainties constrained by data are counted as statistical
- Different sources are uncorrelated
- Statistical uncertainty is expected spread of result

Difference between nominal and global impacts indicate level of constraints

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

Some technical remarks

In total, >4000 nuisance parameters

Fitted distribution with >2000 bins

Fast turnaround has been essential to enabling an analysis at this level of complexity

- Multi-threaded RDataFrame to process events to high-dimensional boost histograms
- Tensorflow based profile likelihood fit
- Full analysis runs in ~2 hours

<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>

Further cross checks

Separate m_W parameters defined in different phase space regions gives good compatibility

Measurements of mass difference between

- $\eta<0$ and $\eta>0$: 5.8 ± 12.4 MeV
- Central and forward η: 15.3 ± 14.7 MeV
- W^+ and W^-: 57 ± 30 MeV

Comment on charge difference

- Correlation between m_{W^+} and m_{W^-} is -40%
- But correlation between m_W and $m_{W^+} - m_{W^-}$ is 2%