W Mass Measurement

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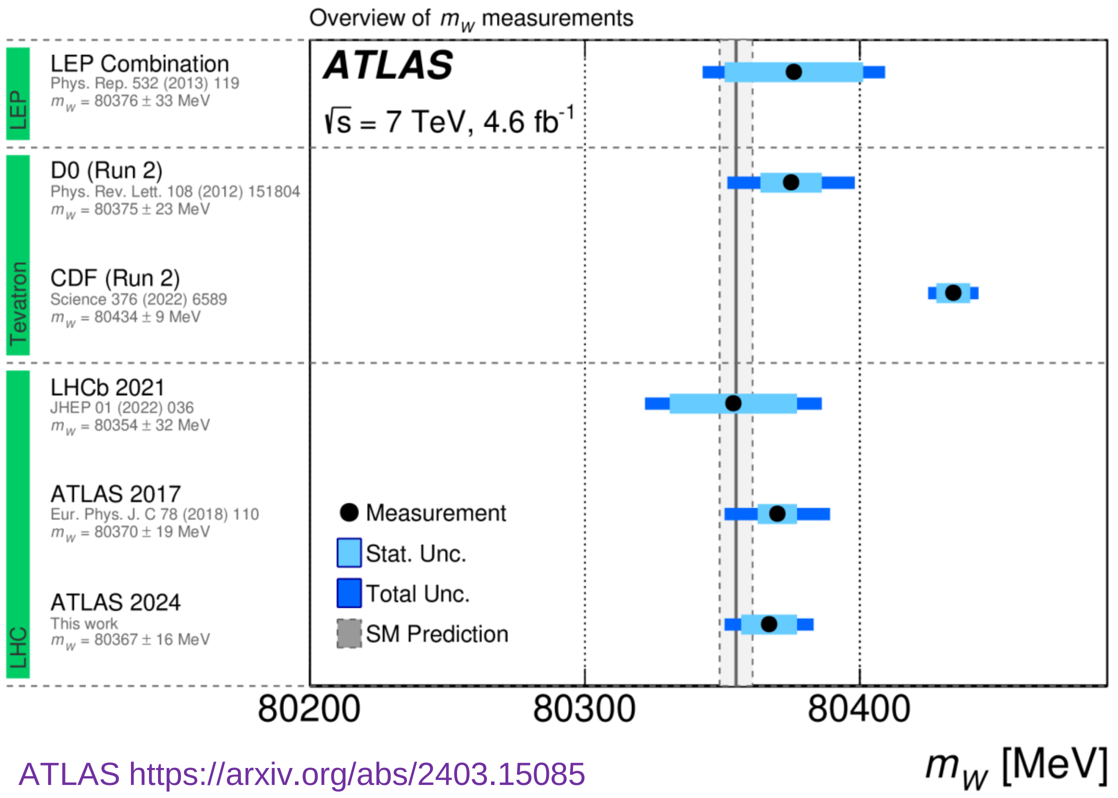
Outline

- Introduction
  - Previous measurements
  - Motivation
- New CMS measurement
  - Selection and data sample used
  - Muon momentum calibration and Z mass
  - Theory modelling
  - W-like Z mass and W mass measurement
  - Cross checks
- Summary and outlook

Current status of W mass measurements

- Several measurements at Tevatron (D0+CDF) and LHC (ATLAS, LHCb)



ATLAS https://arxiv.org/abs/2403.15085

Comparison with theory:

- W mass prediction from EW fits 80353 ± 6 MeV*
- CDF measurement (uncertainty ± 9.4 MeV) exhibits a large tension with the SM prediction from EW fits
- All other measurements in agreement within 1σ from SM

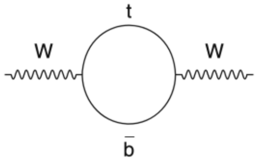
* PRD 106 (2022) 033003
EPJC 78 (2018) 675

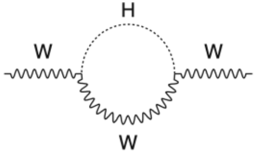
Consistency with the Standard Model

- With the Higgs boson mass known, SM is over-constrained

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha_{QED}}{\sqrt{2}G_F}\times\frac{1}{1-\Delta r}$$

- Δr is mostly affected by m_t and m_H





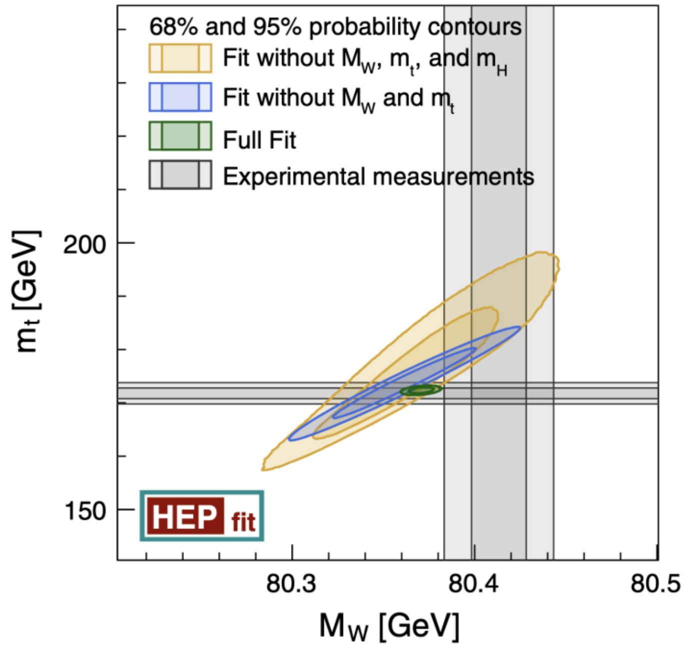
- Lack of internal consistency could be a sign of new physics

Global fit of all precision Electroweak measurements within the Standard Model

	Measurement	Posterior
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11762 ± 0.00095 [0.11576, 0.11946]
$\Delta\alpha_{had}^{(5)}(M_Z)$	0.02766 ± 0.00010	0.027535 ± 0.000096 [0.027349, 0.027726]
M_Z (GeV)	91.1875 ± 0.0021	91.1911 ± 0.0020 [91.1872, 91.1950]
m_t (GeV)	171.79 ± 0.38	172.36 ± 0.37 [171.64, 173.09]
m_H (GeV)	125.21 ± 0.12	125.20 ± 0.12 [124.97, 125.44]
M_W (GeV)	80.4133 ± 0.0080	80.3706 ± 0.0045 [80.3617, 80.3794]
Γ_W (GeV)	2.085 ± 0.042	2.08903 ± 0.00053 [2.08800, 2.09006]
$\sin^2\theta_{eff}^{lept}(Q_{FB}^{had})$	0.2324 ± 0.0012	0.231471 ± 0.000055 [0.231362, 0.231580]
$P_\tau^{pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14742 ± 0.00044 [0.14656, 0.14827]
Γ_Z (GeV)	2.4955 ± 0.0023	2.49455 ± 0.00065 [2.49329, 2.49581]
σ_h^0 (nb)	41.480 ± 0.033	41.4892 ± 0.0077 [41.4741, 41.5041]
R_ℓ^0	20.767 ± 0.025	20.7487 ± 0.0080 [20.7329, 20.7645]
$A_{FB}^{0,\ell}$	0.0171 ± 0.0010	0.016300 ± 0.000095 [0.016111, 0.016487]
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14742 ± 0.00044 [0.14656, 0.14827]
R_b^0	0.21629 ± 0.00066	0.215892 ± 0.000100 [0.215696, 0.216089]
…	…	…

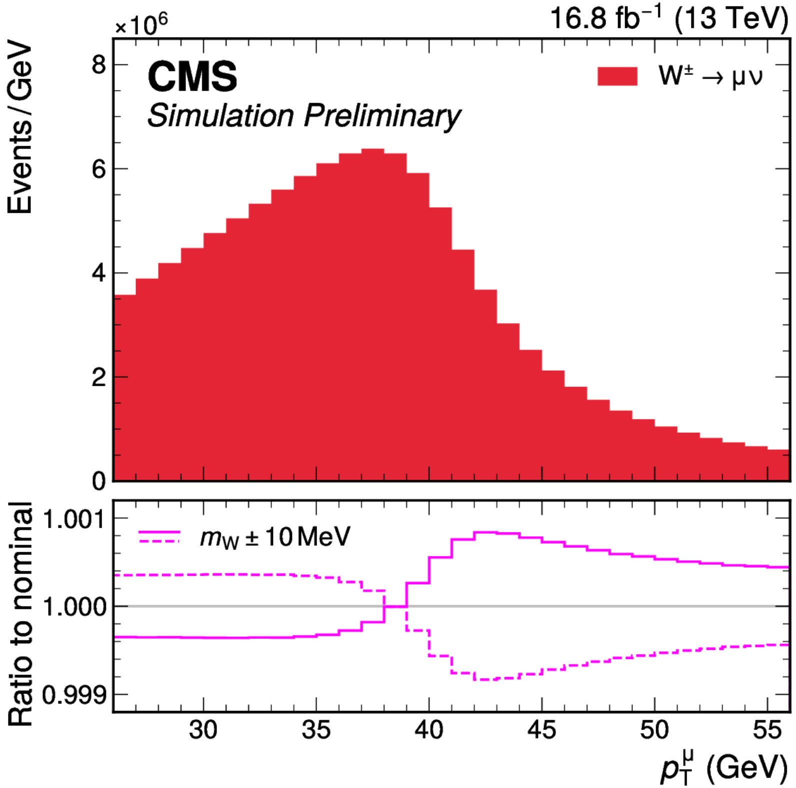
Total of 24 input EW precision measurements

PRL 129 (2022), 271801



W mass at hadron colliders

- W boson hadronic decays are affected by too much background to be useful
- Only leptonic decays are usable:
  - $W \to e\nu, W \to \mu\nu$
  - no direct mass reconstruction
- p_T^l, p_T^{miss} and m_T are sensitive to the W mass
- m_T is the transverse mass, invariant mass of p_T^l and p_T^{miss}
- They are correlated and affected by theory uncertainties, p_T^W , PDF, EW, …



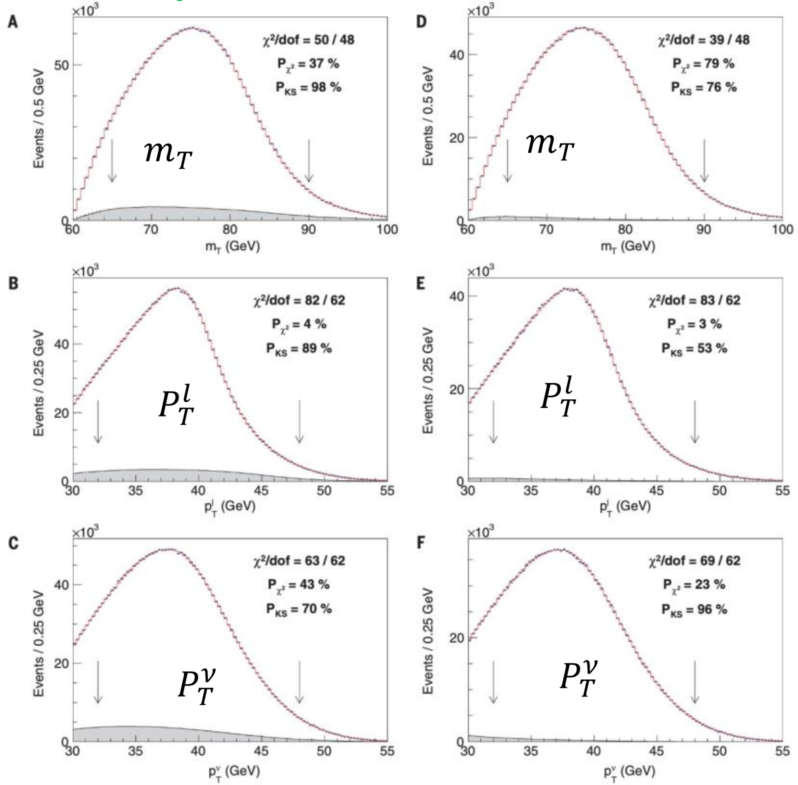
Overall momentum scale relative uncertainty of 10^{-4} gives ~10 MeV on the W mass

CDF measurement

$M_W = 80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst} = 80{,}433.5 \pm 9.4$ MeV 7σ from prediction of SM EW fit

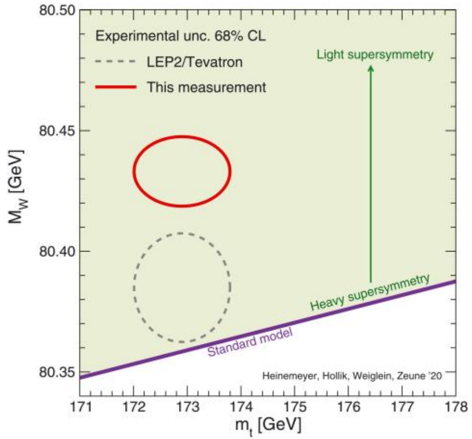
Science 376 (2022) 6589

- Tevatron Run II, $p\bar{p}$ collisions, CM Energy 1.96 TeV, $\int \mathcal{L}\, dt = 8.8$ fb^{-1}
- Use all possible information P_T^l, P_T^ν and m_T for e and μ
- Excellent lepton momentum scale calibration
  - 60 and 25 x 10^{-6} for for e and μ



Split of uncertainties

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



ATLAS measurement

https://arxiv.org/abs/2403.15085

- ATLAS recently updated their previous result
  - New PDF set, CT18
  - Move from χ^2 fit to Profile Likelihood Fit
  - Use P_T^l, and m_T for e and μ
  - Uncertainty reduced from 18 to 15.9 MeV

PDF set	p_T^ℓ fit				m_T fit			
	m_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.	m_W	σ_{tot}	σ_{PDF}	χ^2/n.d.f.
CT14	80358.3	$^{+16.1}_{-16.2}$	4.6	543.3/558	80401.3	$^{+24.3}_{-24.5}$	11.6	557.4/558
CT18	80362.0	$^{+16.2}_{-16.2}$	4.9	529.7/558	80394.9	$^{+24.3}_{-24.5}$	11.7	549.2/558
CT18A	80353.2	$^{+15.9}_{-15.8}$	4.8	525.3/558	80384.8	$^{+23.5}_{-23.8}$	10.9	548.4/558
MMHT2014	80361.6	$^{+16.0}_{-16.0}$	4.5	539.8/558	80399.1	$^{+23.2}_{-23.5}$	10.0	561.5/558
MSHT20	80359.0	$^{+13.8}_{-15.4}$	4.3	550.2/558	80391.4	$^{+23.6}_{-24.1}$	10.0	557.3/558
ATLASpdf21	80362.1	$^{+16.9}_{-16.9}$	4.2	526.9/558	80405.5	$^{+28.2}_{-27.7}$	13.2	544.9/558
NNPDF3.1	80347.5	$^{+15.2}_{-15.7}$	4.8	523.1/558	80368.9	$^{+22.7}_{-22.9}$	9.7	556.6/558
NNPDF4.0	80343.7	$^{+15.0}_{-15.0}$	4.2	539.2/558	80363.1	$^{+21.4}_{-22.1}$	7.7	558.8/558

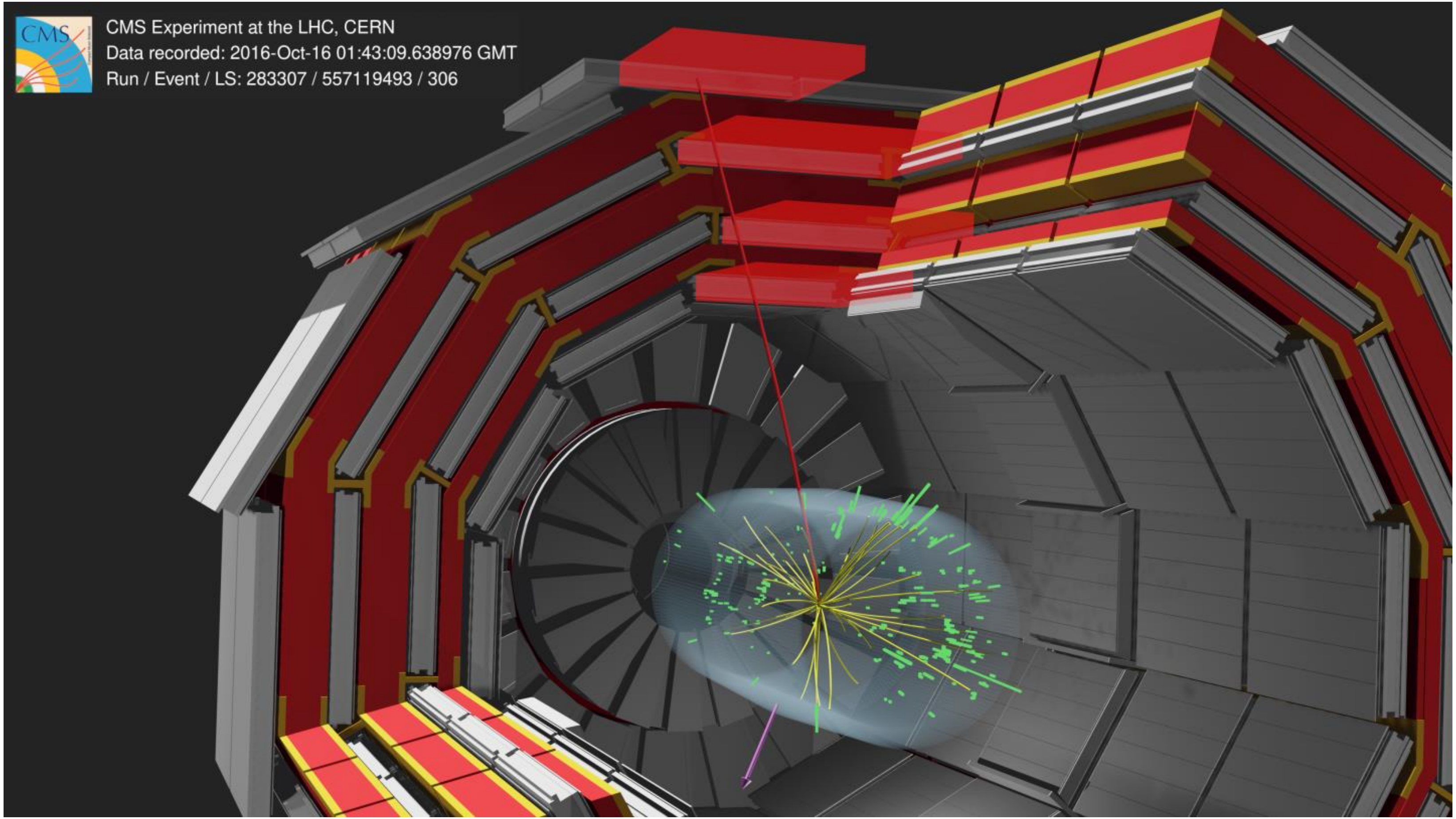
$$m_W = 80366.5 \pm 9.8\ (\text{stat.}) \pm 12.5\ (\text{syst.})\ \text{MeV} = 80366.5 \pm 15.9\ \text{MeV}$$

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

Strategy of the CMS analysis

- Well understood dataset, selection and background estimation
- Accurate P_T^{μ} calibration independent from Z and verified with Z
- Granular μ efficiency corrections with Z tag and probe
- State of the art theory description and PDF
  - Constrain the theory description in-situ thanks to the finely binned fit and relatively large dataset
- Special care with the usage of 7 state of the art PDF sets
- Z mass measurement as if it was W (removing one muon)
- Do not use the Z to tune the theory for the W mass extraction but for a cross check of the theory modelling
  - Extensive cross checks of all steps of analysis
- Extraction of the W mass in a less theory dependent manner (Helicity Fit)

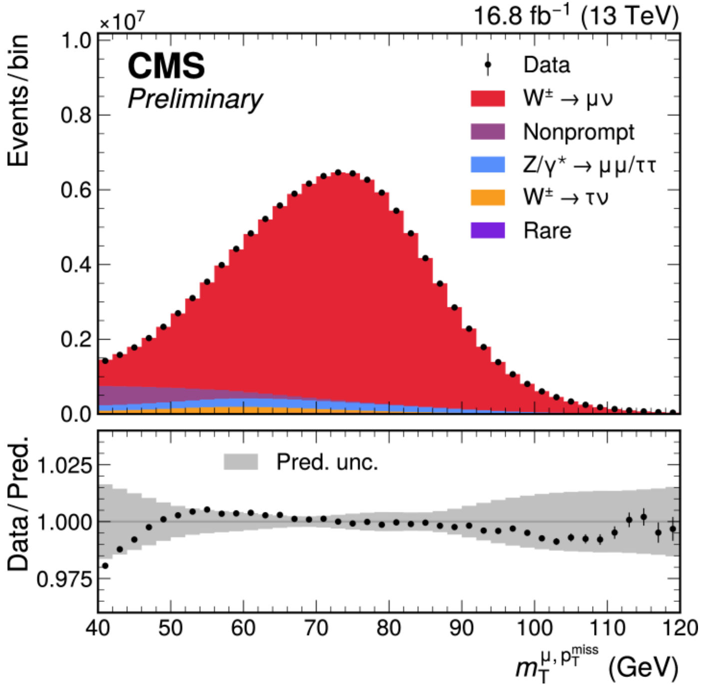
$W \rightarrow \mu\nu$ candidate reconstructed in CMS



Dataset used for the measurement

- Approximately half of the data collected by CMS In 2016 at 13 TeV CM energy is used
  - 16.8 fb^{-1}, >100 M selected $W \to \mu\nu$ candidates
  - Complemented by 4B of fully simulated MC events
- Average number of overlapping pp collision (pileup) approximately 30
- Large dataset, allows to determine in-situ PDFs and theory modeling
- Only use muons measured much more accurately than electrons
- Do not use p_T^{miss} and m_T
  - make it simple for now, leave room for improvement

Transverse mass



p_T^{miss} measurement optimized with DNN(DeepMET) corrected with $Z \to \mu\mu$ events

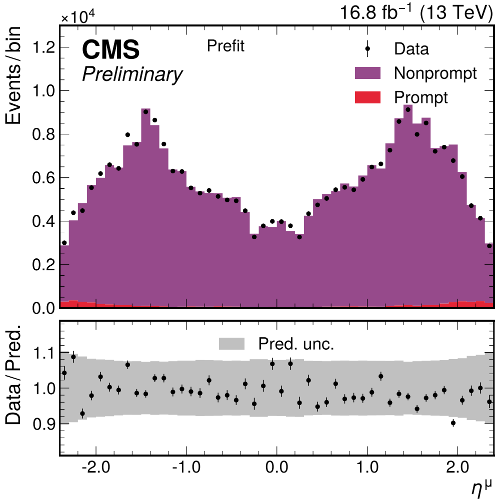
m_T only used for the W selection (m_T > 40 GeV)

Selection and background estimation

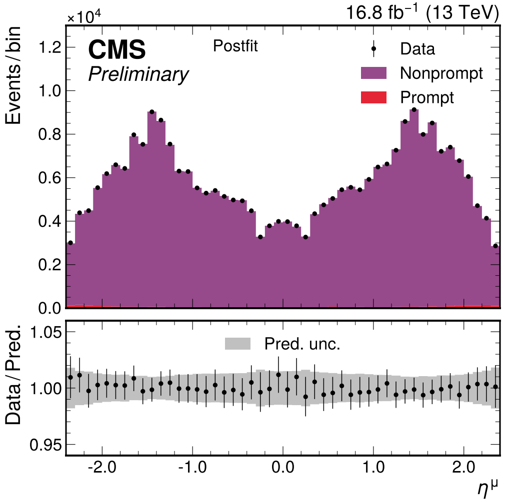
- Standard p_T, η requirements, isolation, cut on m_T, additional muon veto
- Prompt backgrounds estimated from simulation (corrected from data): $Z, W \rightarrow \tau\nu$, …
- Non prompt backgrounds estimated with data driven fake rate method using several control regions and inverting m_T and isolation cuts
- The non prompt background is negligible for the Z selection and W-like Z measurement, only relevant for the W mass measurement (effect on m_W uncertainty: 3.2 MeV)

- Comparison between the estimation and the data in a non prompt enriched phase space, selected requiring that the muon is not compatible to originate from the primary vertex

Pre-fit

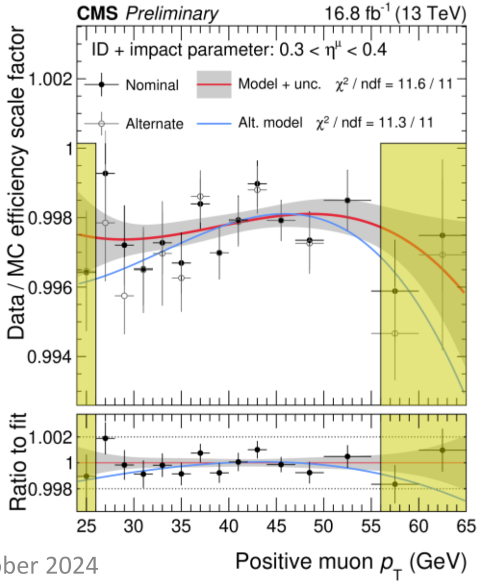


Post-fit

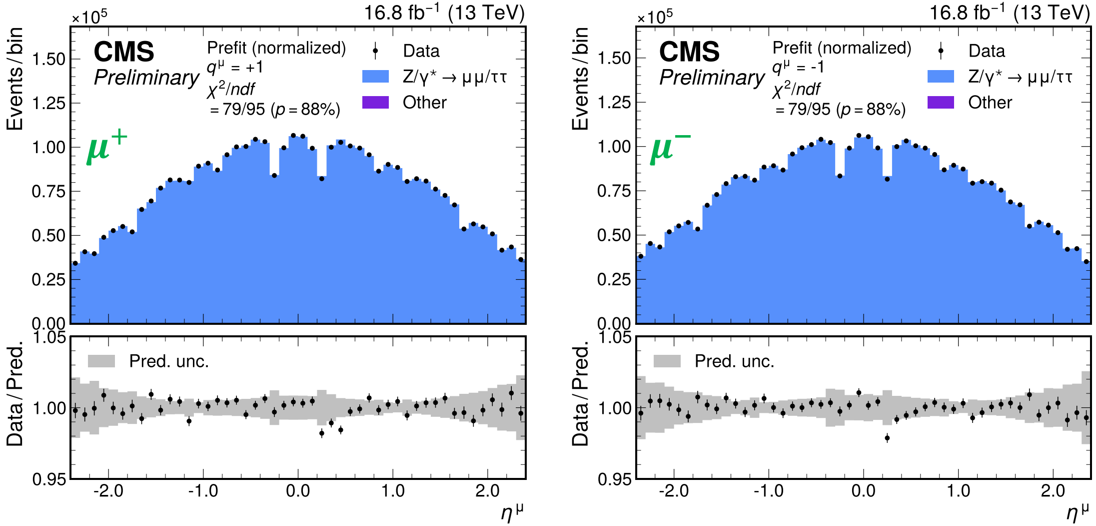


Muon efficiency measurement

- Muon efficiency is measured in data for all steps of reconstruction and identification with high granularity in p_T^μ, η^μ, and charge
- Use tag and probe method in the $Z \to \mu\mu$ sample collected in the same data period
- Efficiencies are smoothed as function of p_T^μ but not of η^μ because of detector discontinuities
  - Smoothing improves the correlation model and reduces statistical uncertainty
- Overall effect on m_W uncertainty: 3.0 MeV



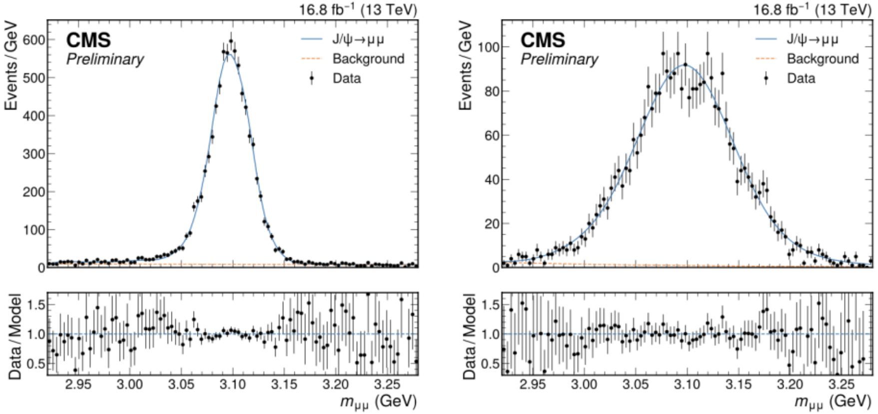
Pre-fit data-MC comparison of η^μ in $Z \to \mu\mu$ selection



Muon momentum scale

- In standard CMS muon p_T reconstruction, use inner tracker and outer muon chambers
  - Here only use the tracker
  - Improve muon reconstruction:
    - Reconstruction
    - Magnetic field description
    - Simulation of the tracker material
    - Full calibration using $J/\psi \to \mu\mu$
- Also apply additional corrections in 48 eta bins still only using $J/\psi \to \mu\mu$

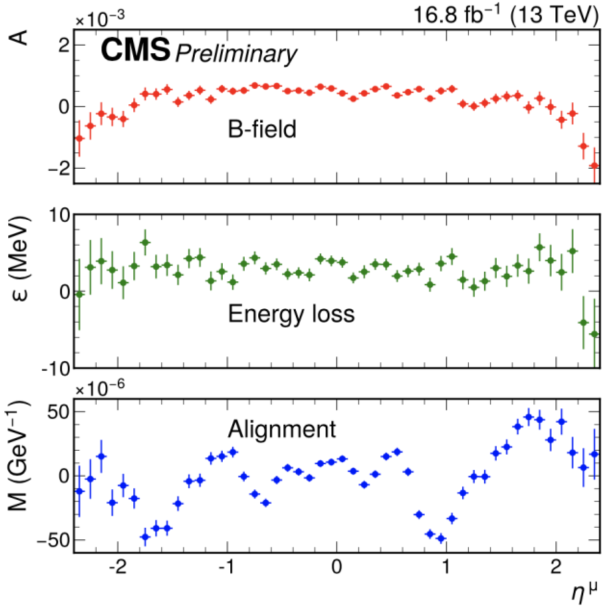
Example fits in Barrel and Endcaps



Parametrization of the bias

B field **energy loss** **alignment**

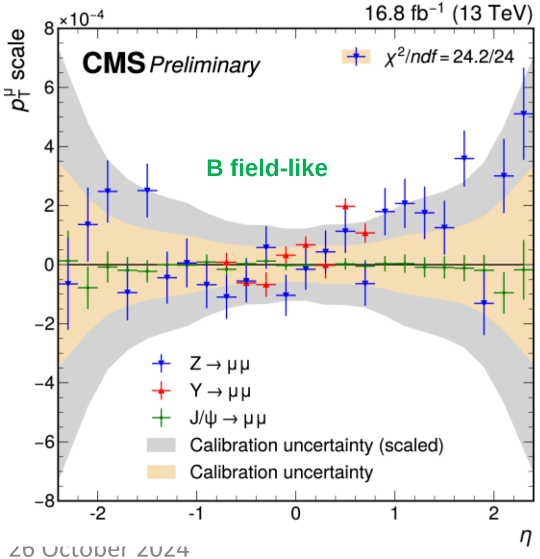
$$\frac{\delta k}{k} = A_{i\eta} - \epsilon_{i\eta}\, k + q\, M_{i\eta}/k \quad \text{where} \quad k \equiv 1/p_{\mathrm{T}}$$



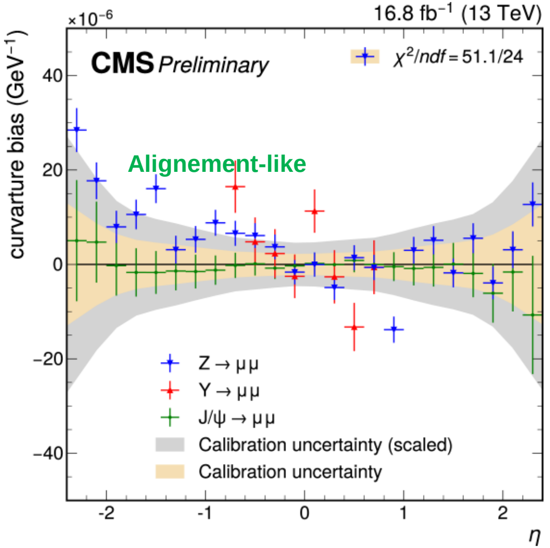
Muon momentum scale II

- Calibration performed only using only $J/\psi \to \mu\mu$
  - Validate uncertainties and closure with Υ and Z
  - Inflate uncertainties to cover the possible non closure (conservative)
- Do not use Z directly for the calibration
  - Allows a fully independent verification of the calibration using the Z, though overall uncertainty could be smaller with Z

Charge independent



Charge dependent



Calibration uncertainties

- Several possible binnings and assumptions of η symmetry, etc. as considered
- Inflating factor on muon scale calibration of 2.1 ensures that χ^2/dof > 1 for any assumption (grey band)

Cross check with Z mass "measurement"

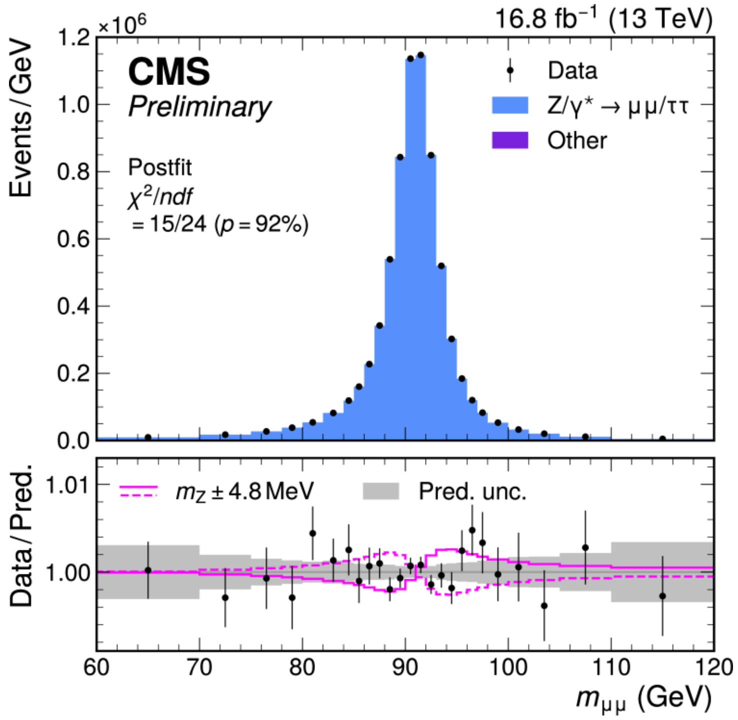
- Use a fit the Z mass for a full validation of the momentum calibration
- Extract the Z mass from the dimuon invariant mass distribution

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

- Agrees with PDG within $0.5\,\sigma$

Impact on m_W measurement

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



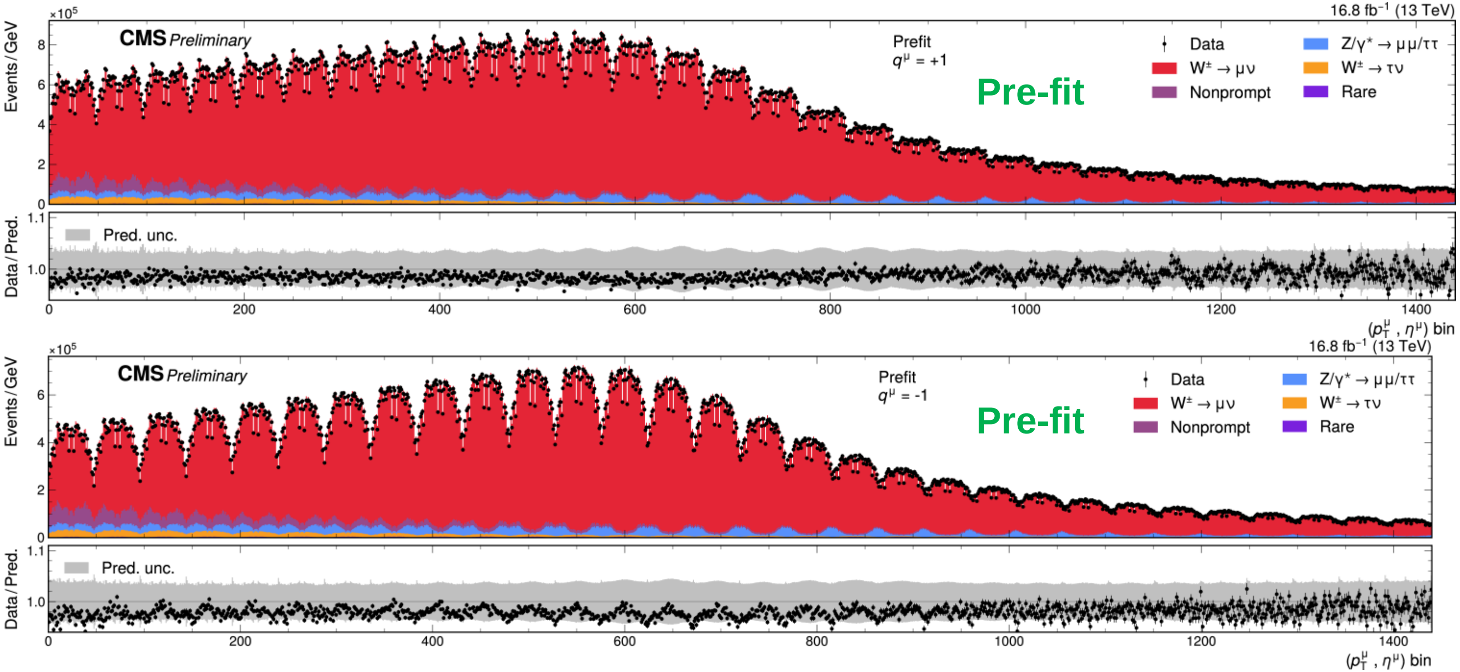
Overall effect on m_W uncertainty: 4.8 MeV

Not yet m_Z measurement because the Z mass is used to inflate the uncertainties

W mass measurement strategy in CMS

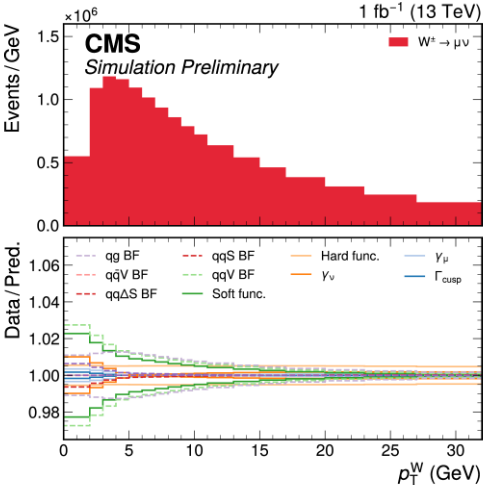
- Use 3D distribution p_T^μ, η^μ, q^μ (p_T^μ, η^μ for μ^+ and μ^- separately)
- Finely binned with 48 bins in η^μ and 30 bins (1 GeV wide) in p_T^μ
- Display unrolled p_T^μ, η^μ histograms with (p_T^μ, η^μ) bin $= 48 \times (p_T^\mu)$ bin $+(\eta^\mu)$ bin (total 2880) bins

The full p_T^μ, η^μ information for each charge allows to constrain in-situ PDF and theory uncertainties



W and Z p_T modelling

- Use state of the art theory for Z and W simulation:
  - MiNNLO$_{PS}$ + Pythia8 + Photos++ corrected to resummed SCETLIB + DYTurbo (NNLO+N3LL), correction gives large improvement



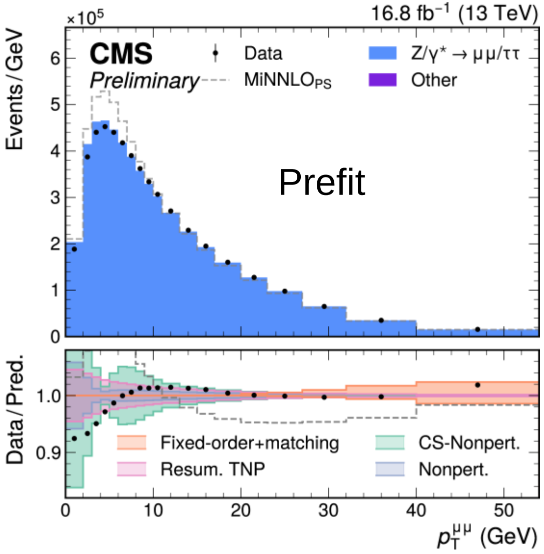
Theory Nuisance Parameters (TNPs) providing a defined correlation model between different bins and W and Z

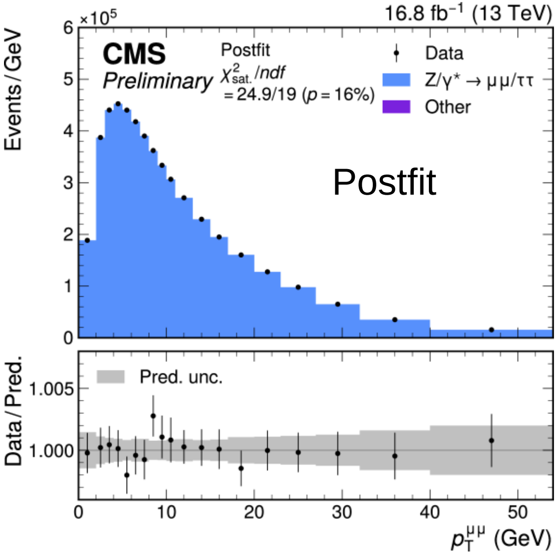
F. Tackmann
to be published

Non perturbative Uncertainties (CS + k_T of the partons inside the proton + b and c quark mass thresholds in MSHT20)

Fixed order (variation μ_R and μ_F) + matching

Z p_T compared to the data





Overall effect on m_W uncertainty: 2.0 MeV

Angular distributions and EW corrections

Angular distributions

- Differential cross section as function of muon kinematics described in terms of angular coefficients

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

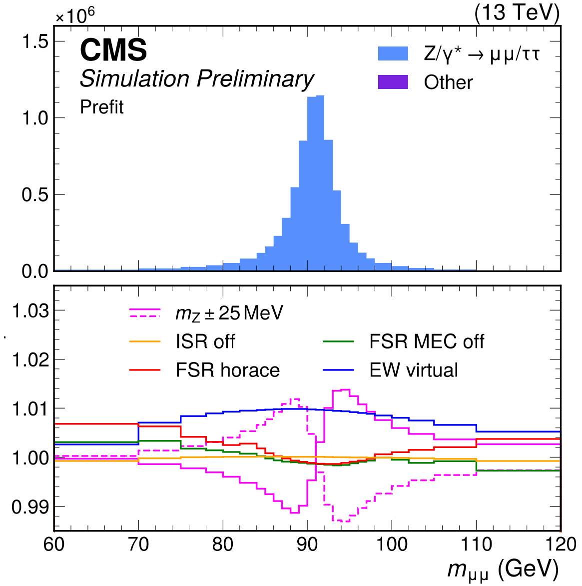
- Uncertainties from variation of μ_R and μ_F in $\text{MINNLO}_{\text{PS}}$ + PYTHIA8 shower and intrinsic k_T

Overall effect on m_W uncertainty: 3.3 MeV

Missing higher order EW corrections

- Evaluated effect of initial and final state corrections (description is at LL accuracy)
- Virtual corrections are evaluated from the difference between NLO and LO

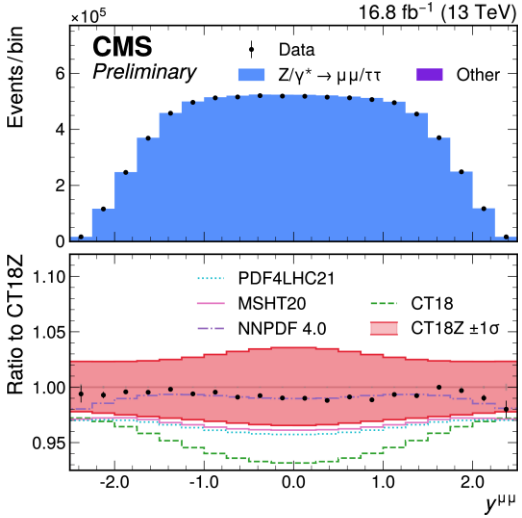
Overall effect on m_W uncertainty: 2.0 MeV



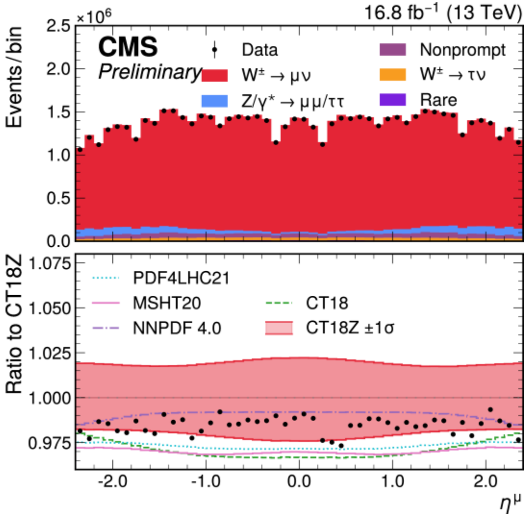
Choice of PDF and uncertainty inflation

- Seven modern PDF sets are used (CT18, CT18Z, PDF4LHC21, MSHT20, MSHT20aN3LO, NNPDF3.1, NNPDF4.1)
- In many cases predictions of one PDF set are inconsistent with others using the quoted uncertainties
- m_W is measured with all PDF sets, using generated from all others
- Requesting that all results agree within their PDF uncertainties requires to increase some of the PDF uncertainities
  - This procedure is conservative and assumes that all predictions are correct and should be consistent with others within uncertainties (uncertainties are inflated for 4 PDF sets of factors 1.5 to 5)
  - increases the robustness of the measurement, allowing to rely more on the constraints from the fit (in case PDF uncertainties could be underestimated)

Z



W



Nominal PDF set is taken as CT18Z that anyway already covers al others and does not need inflation

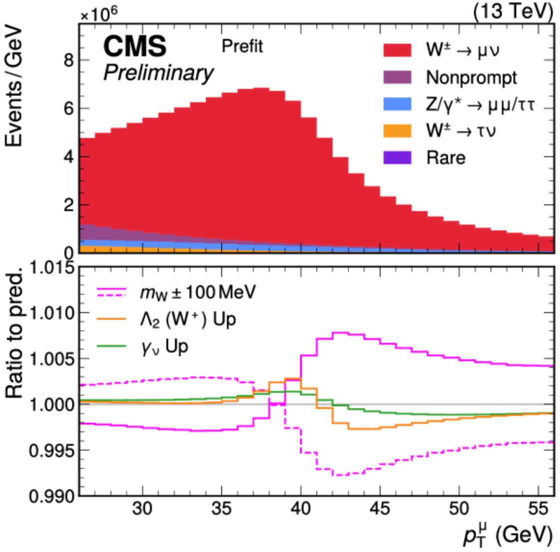
PDF set	Scale factor	Impact in m_W (MeV) Original σ_{PDF}	Impact in m_W (MeV) Scaled σ_{PDF}
CT18Z	–	4.4	
CT18	–	4.6	
PDF4LHC21	–	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0

Effect on m_W uncertainty: 4.4 MeV

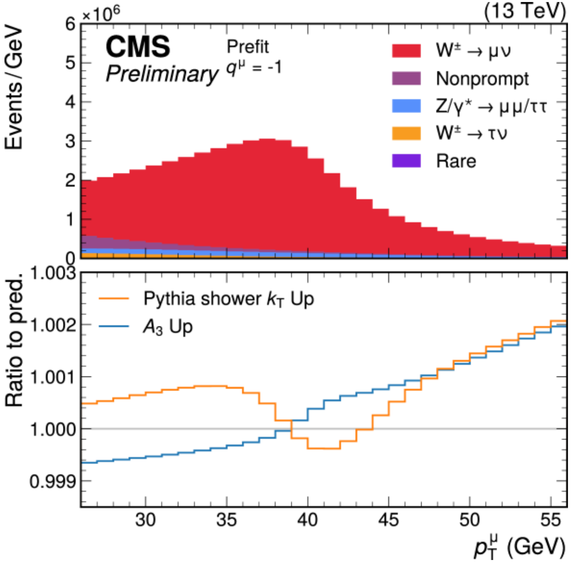
Effect of variations on p_T^{μ} spectra for W

- There are important differences in shape between a W mass variation and theory and PDF variations
- Nuisance parameters from the theory can be constrained in the fit

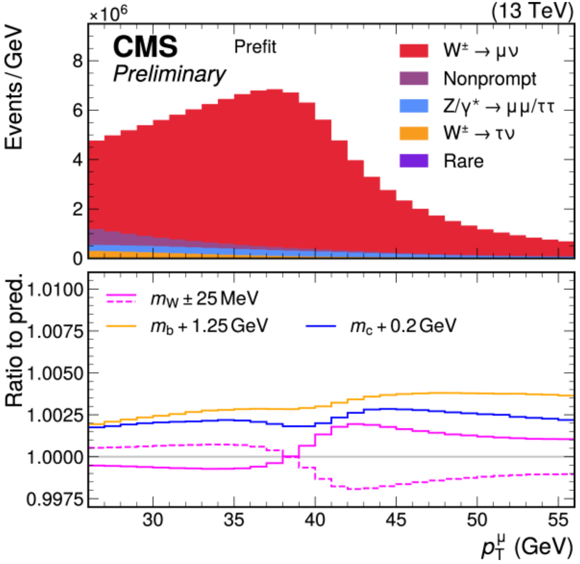
W p_T modelling



Angular Coefficients

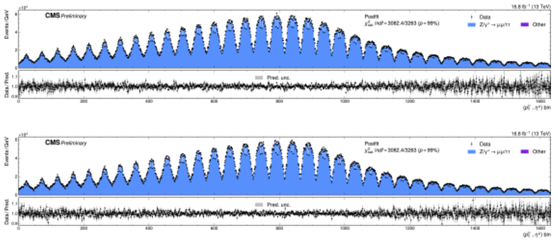


PDF



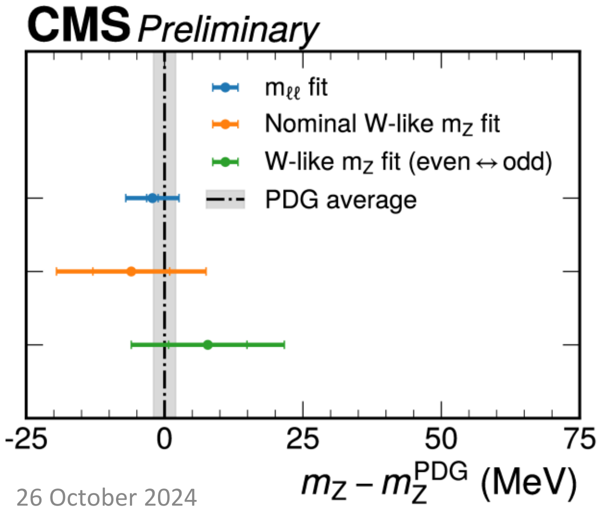
W-like m_Z measurement

- We validate almost all aspects of analysis using $Z \to \mu\mu$ events and removing one muon to have events with the same topology as W events
  - The selection uses both muons
- Only one muon is used per event and p_T^{miss} is calculated as adding the p_T of the removed muon
- The full fit is performed and results are fully consistent with the Z mass within 1 σ

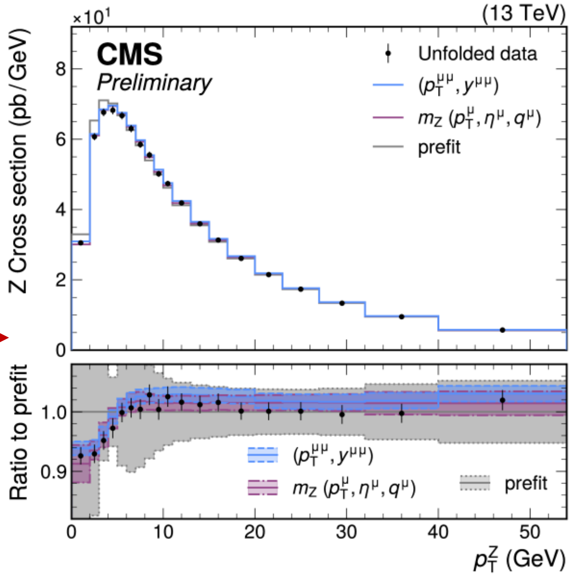


$$m_Z^{W\mathrm{-like}} = 91\,182 \pm 7\,(\mathrm{stat}) \pm 12\,(\mathrm{syst}) = 91\,182 \pm 14\,\mathrm{MeV}$$

For the alternate muon choice: $91\,196 \pm 14\,\mathrm{MeV}$



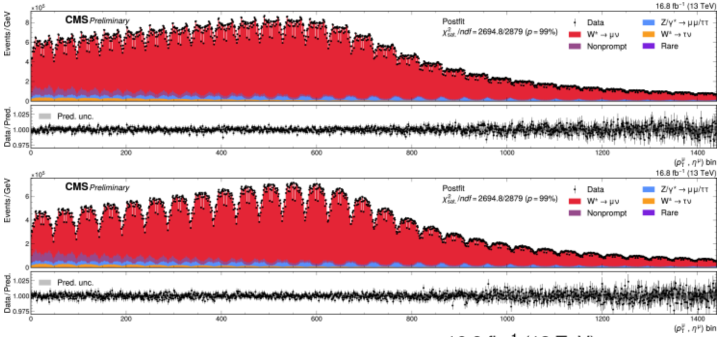
- p_T^Z obtained from the W-like fit is compared with the one obtained by a $p_T^{Z\to\mu\mu}$ fit, the pre-fit simulated, and the unfolded data
- The agreement is excellent and confirms the power of the fit to constrain the p_T^Z here and p_T^W (with even larger statistics) in the m_W fit

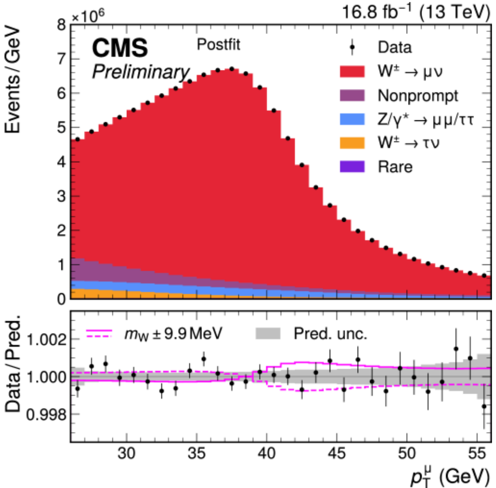


m_W measurement

- From the fit using the W selection:

$$m_W = 80\,360.2 \pm 2.4\,(\text{stat}) \pm 9.6\,(\text{syst}) = 80\,360.2 \pm 9.9\,\text{MeV}$$



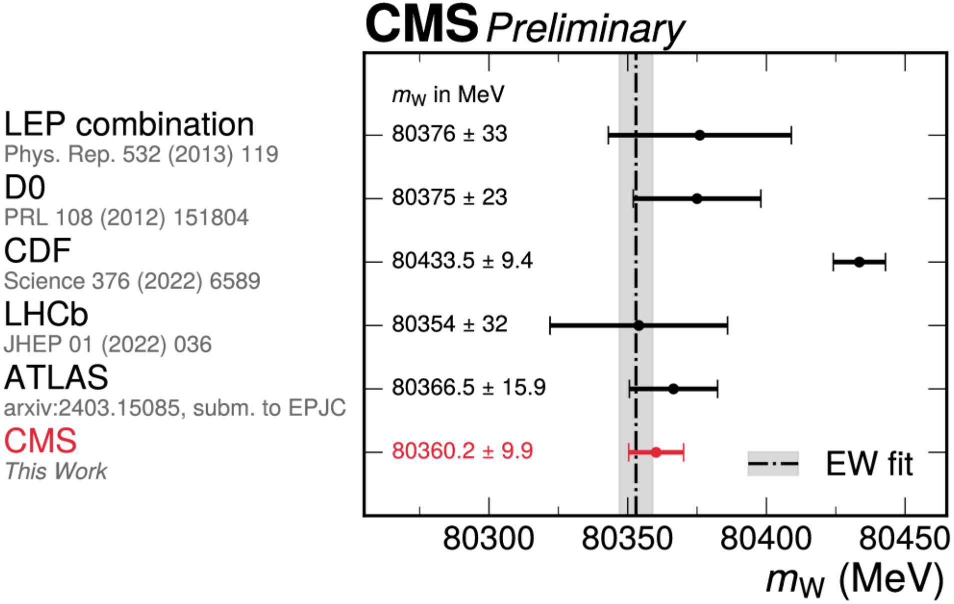


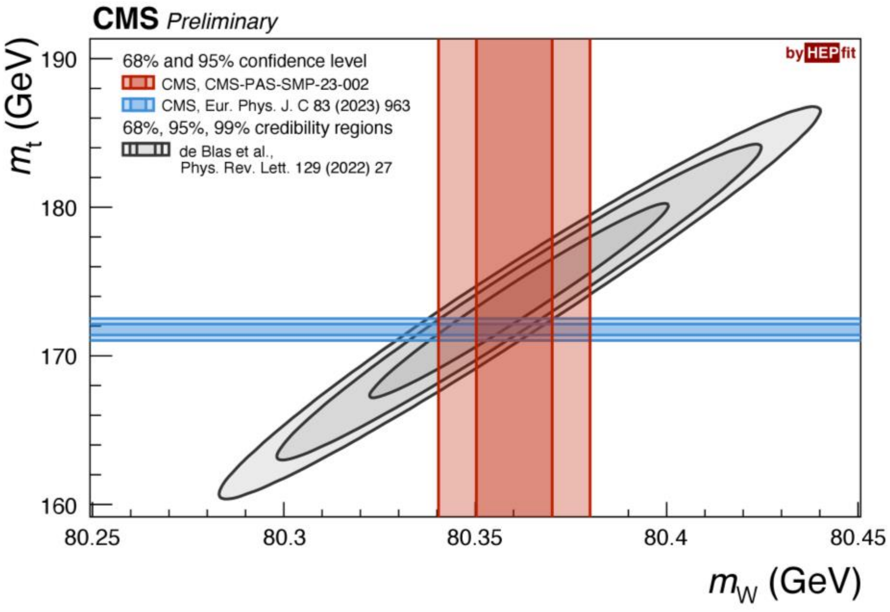
Contribution of different sources to the uncertainty for the m_Z **W-like** and m_W measurements

Source of uncertainty	Nominal	
	in m_Z	in m_W
Muon momentum scale	5.6	4.8
Muon reco. efficiency	3.8	3.0
W and Z angular coeffs.	4.9	3.3
Higher-order EW	2.2	2.0
p_T^V modeling	1.7	2.0
PDF	2.4	4.4
Nonprompt background	–	3.2
Integrated luminosity	0.3	0.1
MC sample size	2.5	1.5
Data sample size	6.9	2.4
Total uncertainty	13.5	9.9

Comparison with previous results and SM

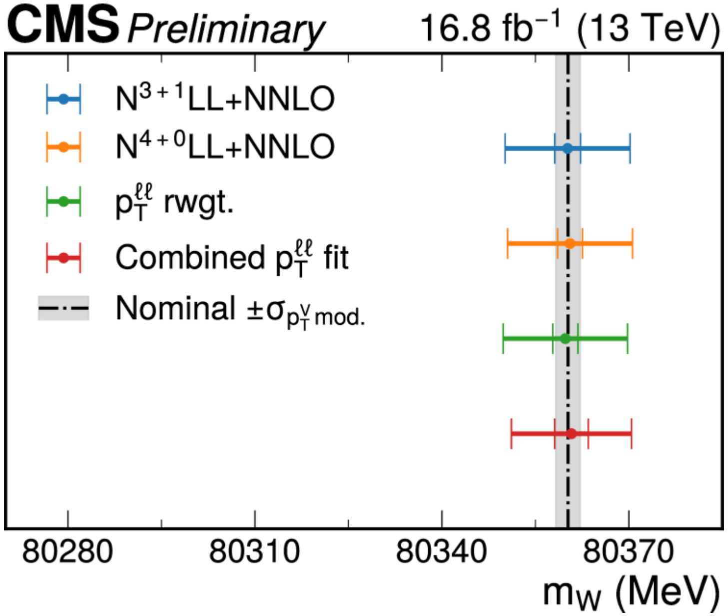
- The CMS W mass measurement shows
  - Very large tension with the CDF measurement
  - Excellent agreement with all other measurements
  - Excellent agreement with SM prediction, based on the fit EW precision parameters

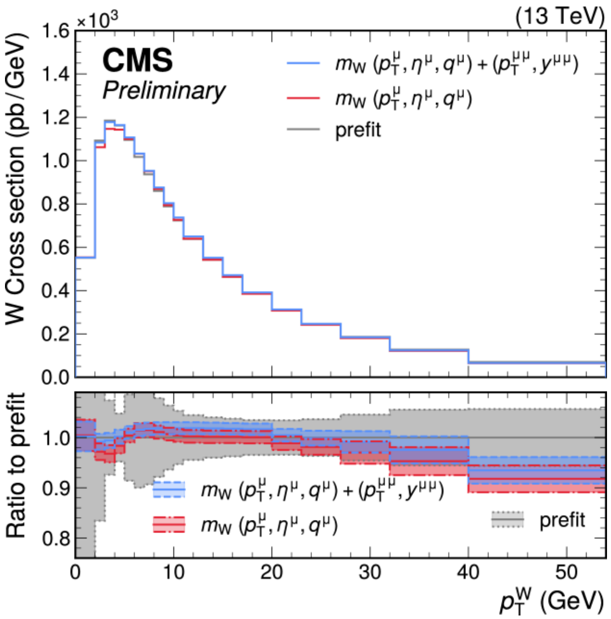




Different p_T^W modelling

- As across check, we used different p_T^W modelling (implemented in SCETLIB) and also a combined fit to p_T^{μ} (standard) and $y^{\mu\mu}$ (added)
- Very similar results (shift in m_W of 0.6 MeV) with somewhat reduced uncertainties (± 9.6 MeV) from the combined fit





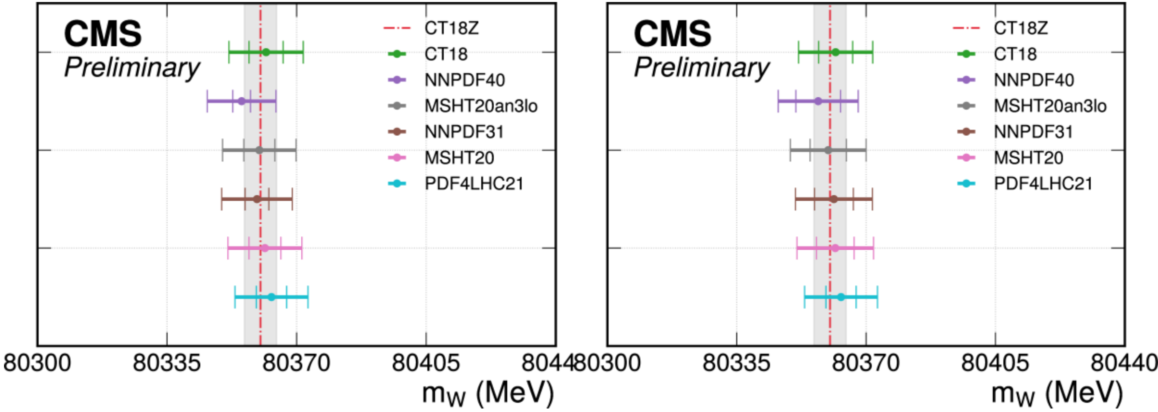
Measurements with other PDF sets

- The W mass measurement is repeated with the other six PDF sets, without and with uncertainty inflation
- All results ar in very good agreemnt
- After uncertainty inflation, measurements with different PDF set agree within their PDF uncertainties of 4-6 MeV

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

Original uncertainties

Inflated uncertainties

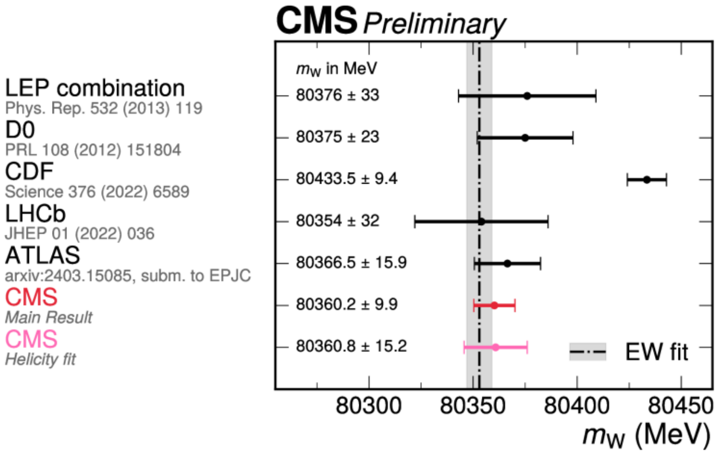


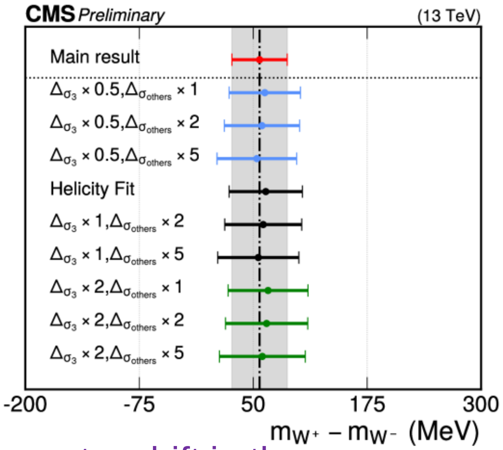
Helicity fit

- Important cross check, allows much more freedom in the theory
- Fit the individual helicity cross section components ($\sigma_i = \sigma^{U+L} A_i$) with uncertainties covering PDF and scale variations and even larger for the total cross sections (min 50%) and σ_4 (min 100%)
- The result is fully consistent, with a larger uncertanty of 15.2 MeV

$$m_W = 80\,360.8 \pm 15.2\,\mathrm{MeV}$$

Inflate or shrink the uncertainties to verify the stability of the W mass result

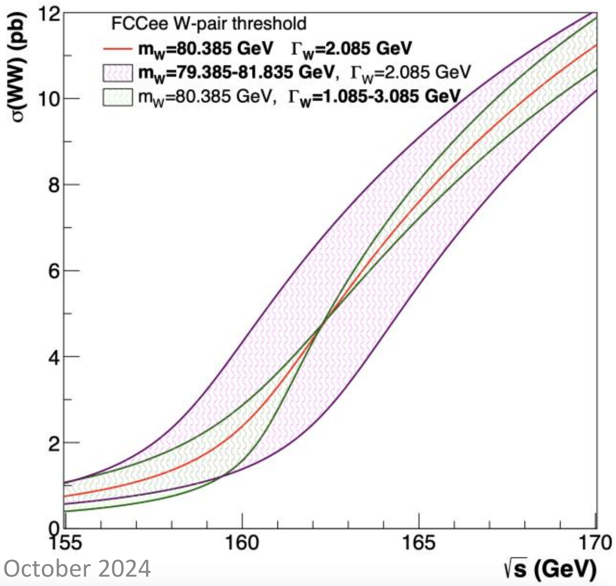




If for any reasons the theory description was not adequate, expect a shift in the measurement

Possible future improvements

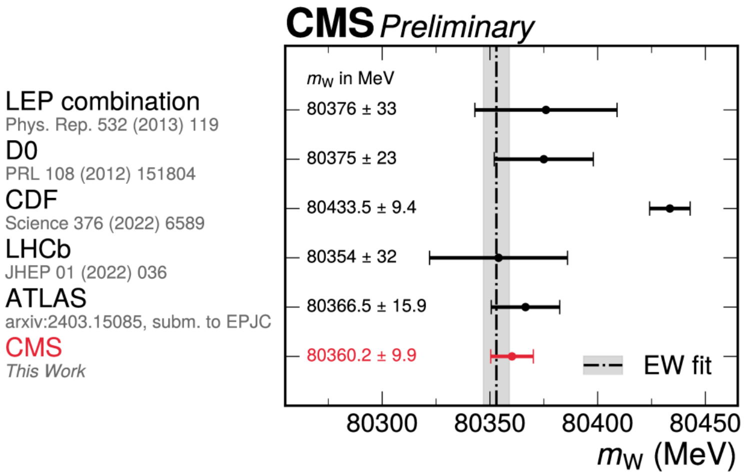
- The precision of the measurements can further improve in CMS and other experiments
  - CMS only used 16.9 fb^{-1} of the >300 fb^{-1} collected, more data may allow to better constrain theory nuisances
  - Muon momentum scale calibration can be further improved and m_T can be used
  - Future low pileup runs are considered for an improved m_T measurement
- Combination of all experiments will also lead to reduced uncertainty

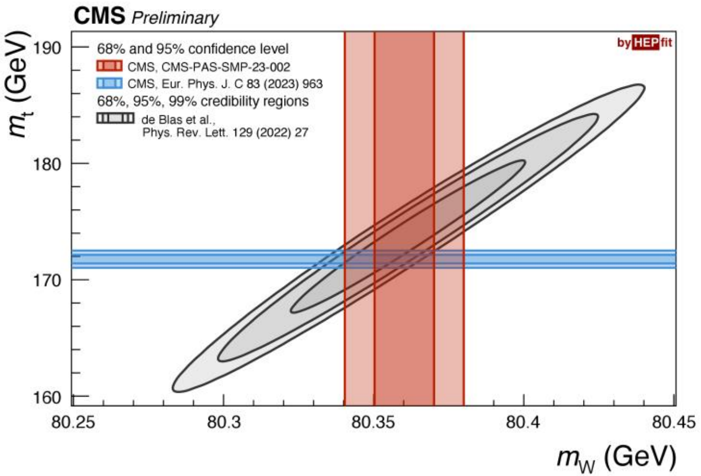


- Large improvement expected at the next e^+e^- colliders (CEPC or FCC-ee)
  - Most promising method is the measurement of the W pair production cross section at threshold, expected statistical uncertainties 0.3 MeV
  - An uncertainty on the W mass of 0.5 MeV seems achiavable with an integrated luminosity of O(10 ab^{-1})
  - Direct reconstruction of the W decays (most precise method at LEP) can help to further reduce the uncertainty but systematic uncertainties seem harder to tackle

Summary

- W mass measurements at the LHC continue
- CMS carried out its first measurement of the W boson mass:
  - $m_W = 80360.2 \pm 9.9$ MeV
- Do not use Z for calibration and tuning but for checking the analysis validity
- Extensive cross checks give very consistent results
- The new CMS measurement is fully compatible with the SM theory and all other measurements (except CDF)
- Measurements and their combination will further improve at the LHC but a breakthrough of an order of magnitude in precision can only come from the next e^+e^- collider





Backup

Uncertainties in CDF, ATLAS, and CMS

CDF

$M_W = 80{,}433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80{,}433.5 \pm 9.4$ MeV

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

ATLAS

$m_W = 80366.5 \pm 9.8\ (\text{stat.}) \pm 12.5\ (\text{syst.})\ \text{MeV} = 80366.5 \pm 15.9\ \text{MeV}$

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

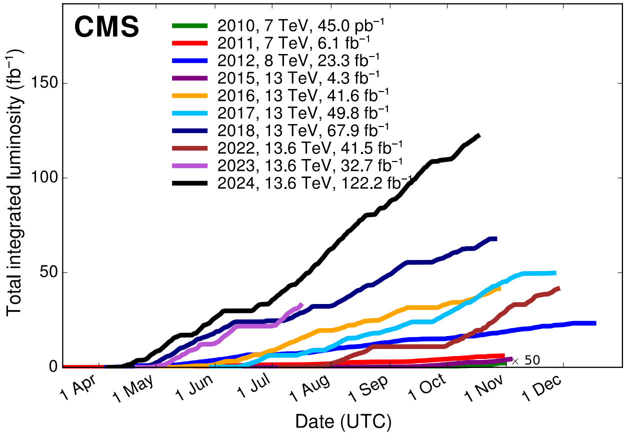
CMS

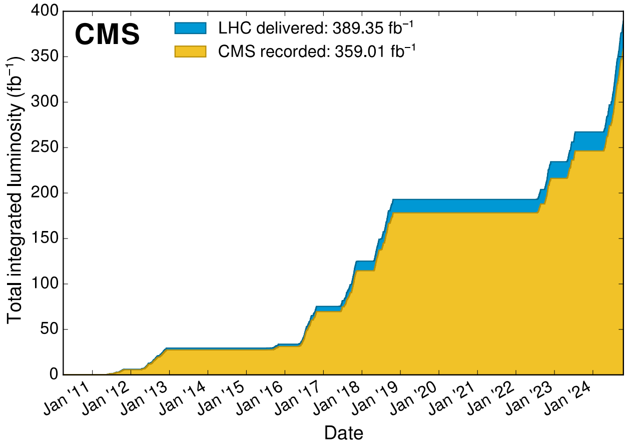
$m_W = 80\,360.2 \pm 2.4\,(\text{stat}) \pm 9.6\,(\text{syst}) = 80\,360.2 \pm 9.9\ \text{MeV}$

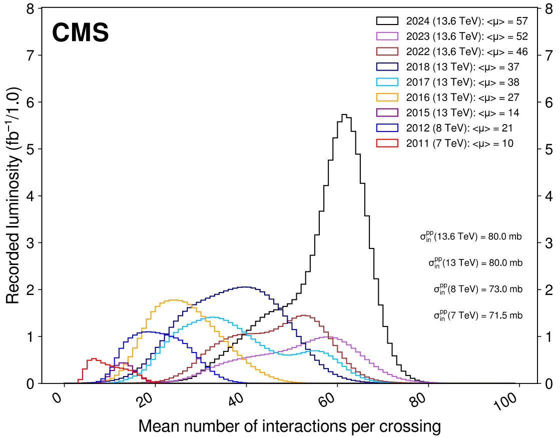
Source of uncertainty	Impact (MeV) Nominal in m_Z	Nominal in m_W	Global in m_Z	Global in m_W
Muon momentum scale	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt background	–	3.2	–	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

- CDF and CMS use the nominal definition of impacts (in blue)
- ATLAS uses the global defintion of impacts (in green) also provided by CMS
- They only differ in how the total uncertainty is split into individual contributions

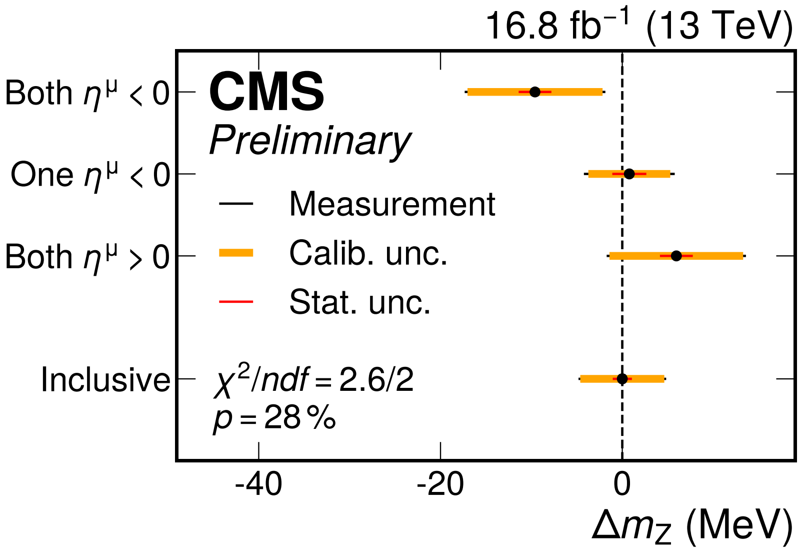
CMS collected data

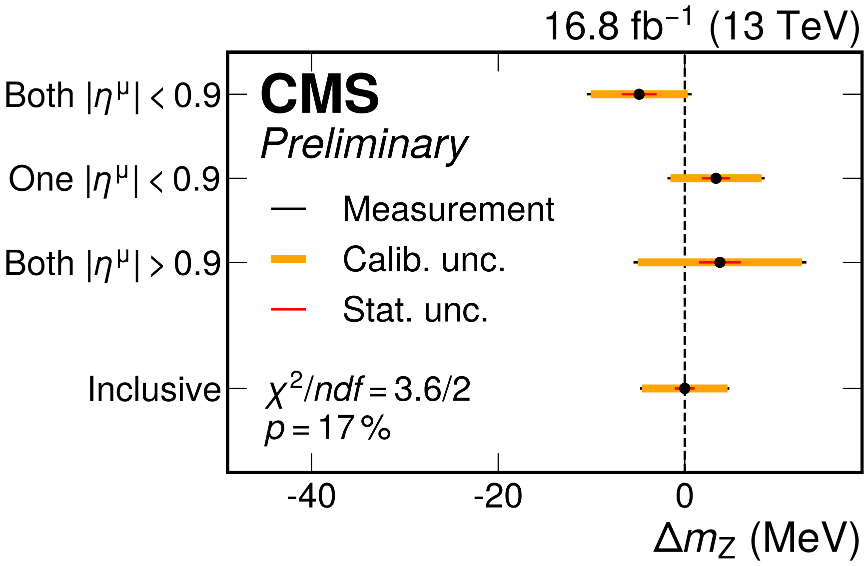




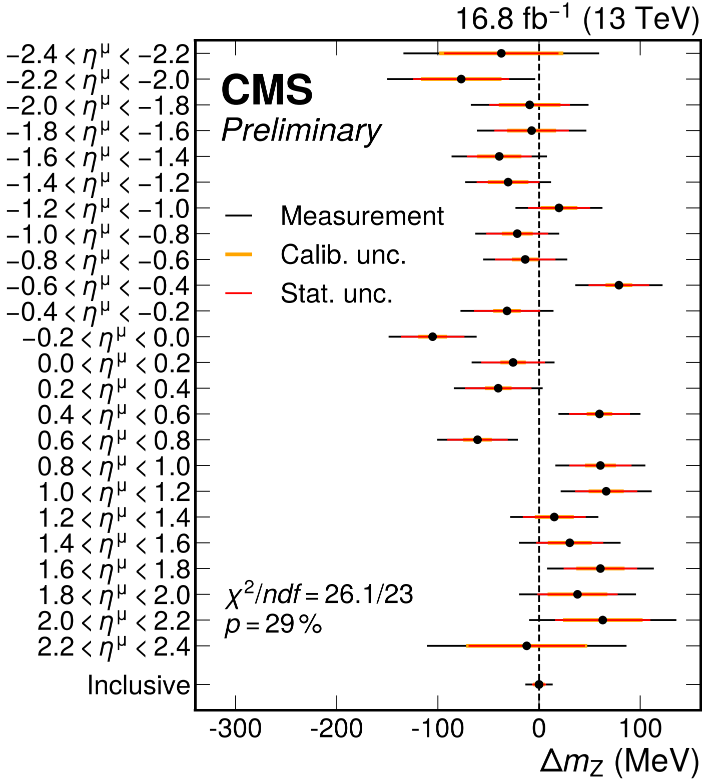


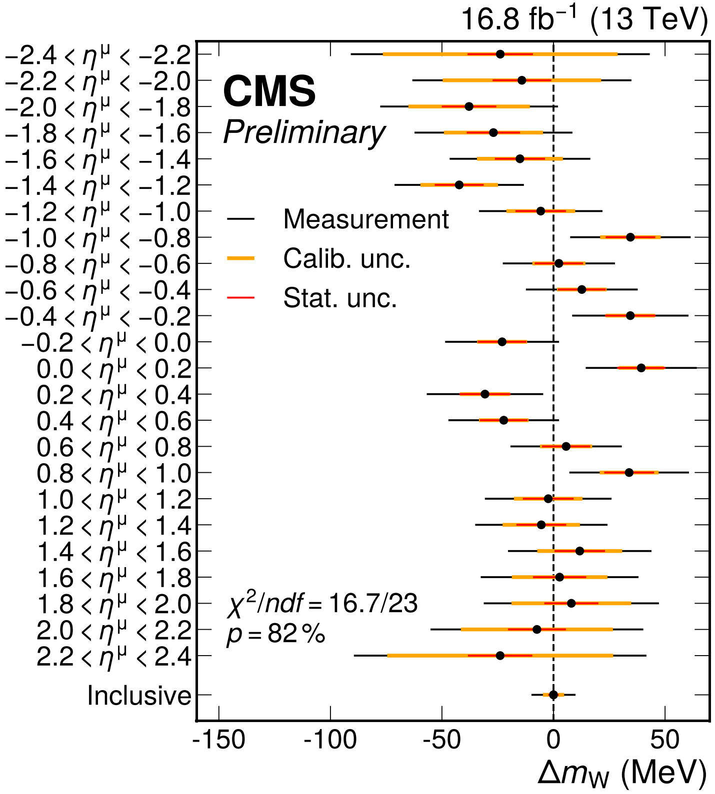
m_Z extraction with $m_{\mu\mu}$ fits in η regions





m_W and W-like m_Z mesaurements in η bins





$m_{W^+} - m_{W^-}$ difference

- The measurement assumes that $m_{W^+} = m_{W^-}$

$$m_{W+} - m_{W-} = 57.0 \pm 30.3\,\text{MeV}$$

- This is the test that presents the largest tension (1.9σ, p-value = 6%) with the expectation
- Uncertainty is much larger than for the m_W measurement due to the strong anticorrelation related to the alignment
- Verified that the correlation coefficient of $m_{W^+} - m_{W^-}$ with m_W is only 2%
- Even if we changed the alignment calibration by 3σ, the effect on m_W would be only 0.6 MeV

Source of uncertainty	Nominal impact (MeV) in $m_{Z^+} - m_{Z^-}$	in m_Z	in $m_{W^+} - m_{W^-}$	in m_W
Muon momentum scale	23.1	5.6	21.6	4.8
Muon reco. efficiency	7.1	3.8	7.2	3.0
W and Z angular coeffs.	14.5	4.9	18.7	3.3
Higher-order EW	0.2	2.2	1.5	2.0
p_T^V modeling	0.6	1.7	7.4	2.0
PDF	0.9	2.4	11.8	4.4
Nonprompt background	–	–	7.5	3.2
Integrated luminosity	< 0.1	0.3	0.1	0.1
MC sample size	4.9	2.5	3.0	1.5
Data sample size	13.9	6.9	4.7	2.4
Total uncertainty	32.5	13.5	30.3	9.9

Analysis bins and number of nuisances in the fits

- There are $30 \times 48 \times 2 = 2880$ analysis bins in the fit
- A new fitting program was developed specifically for this measurement

<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>
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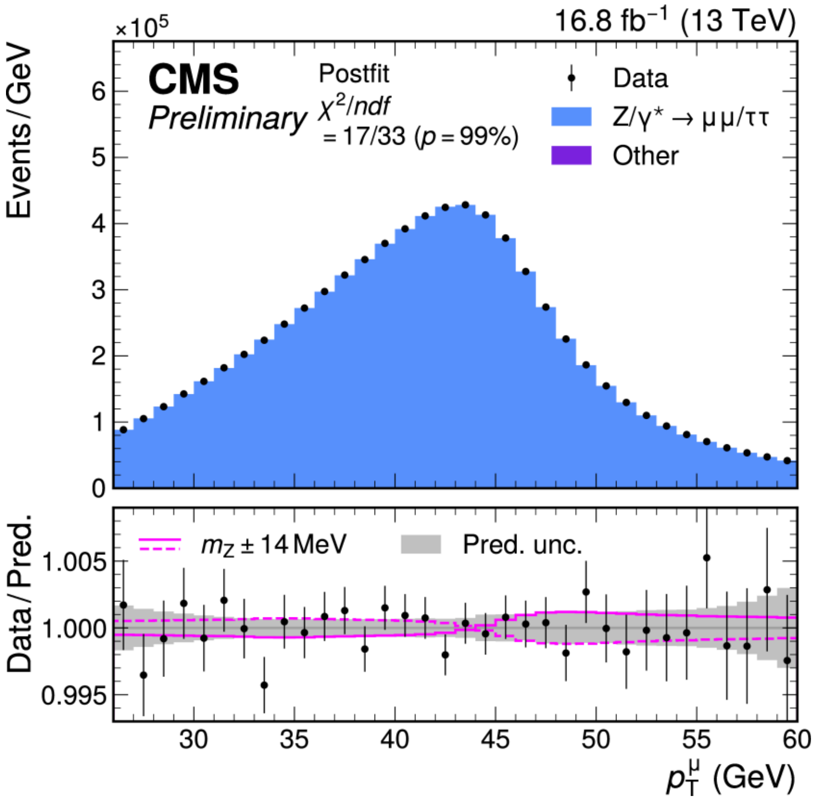
W-like m_Z measurement



Differential cross section from helicity fit