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High-precision measurement of the W boson mass with the Compact Muon Solenoid experiment

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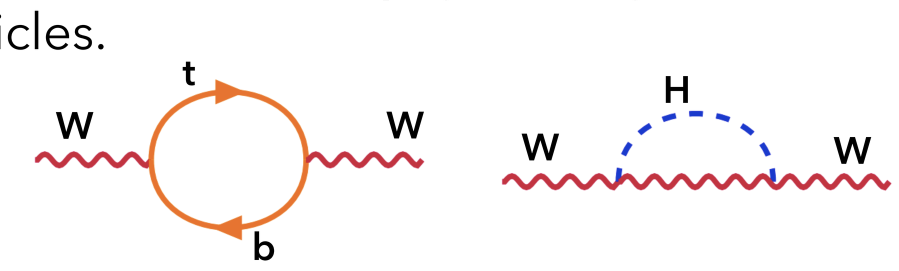
1. Precision physics

In the Standard Model (SM), W and Z boson masses are related to the electroweak (EW) coupling constants.

Any deviation from predictions would indicate **physics beyond the SM**, potentially from heavy new particles.

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

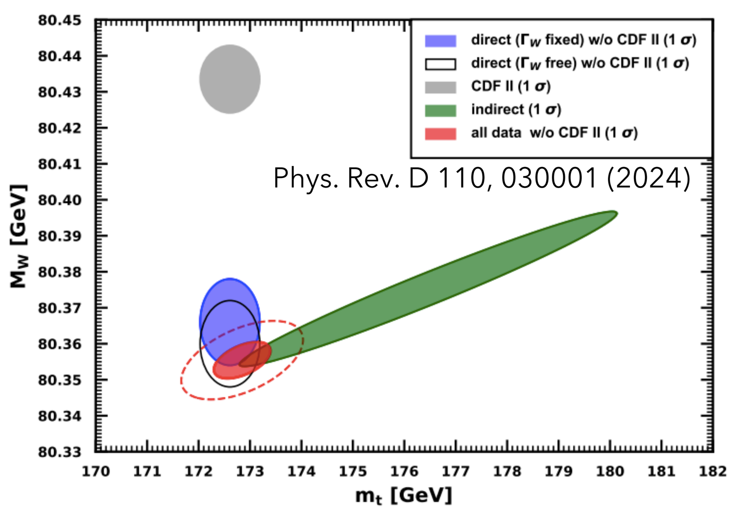


- m_Z is measured with very high precision (22 ppm)
- m_W is currently known with significantly lower precision.

Global SM EW fits, combining precision observables, predict

m_W = 80353 ± 6 MeV.

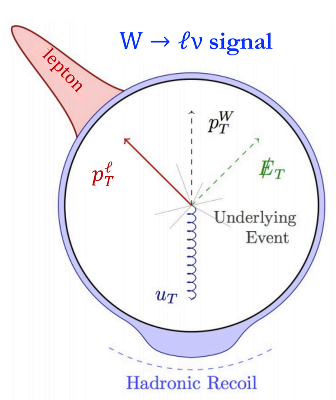
Reaching a comparable experimental precision would
- **provide a stringent test of the SM**
- **enhance sensitivity to new physics.**



One-standard-deviation regions in m_W as a function of m_t.

Measuring m_W at hadron colliders

At hadron colliders, $W \to q\bar{q}$ not viable because of limited jet energy calibration accuracy ⟶ $W \to \ell\nu$ where the neutrino escapes detection, preventing full reconstruction of W.



In the laboratory frame, lepton and neutrino transverse momenta exhibit Jacobian peaks near $\frac{m_W}{2}$.

⟶ mass can be indirectly measured through lepton transverse momentum (p_T^ℓ).

2. CMS experiment

Data in this analysis collected by the **Compact Muon Solenoid** (CMS) experiment at the Large Hadron Collider (LHC) at CERN in **2016**.

Center-of-mass energy	Integrated luminosity
13 TeV (pp)	16.8 fb^{-1}

Selected events: ~64M for W^+ ; ~51M for W^-. **Muon channel** used due to the highest experimental precision.

4. Results

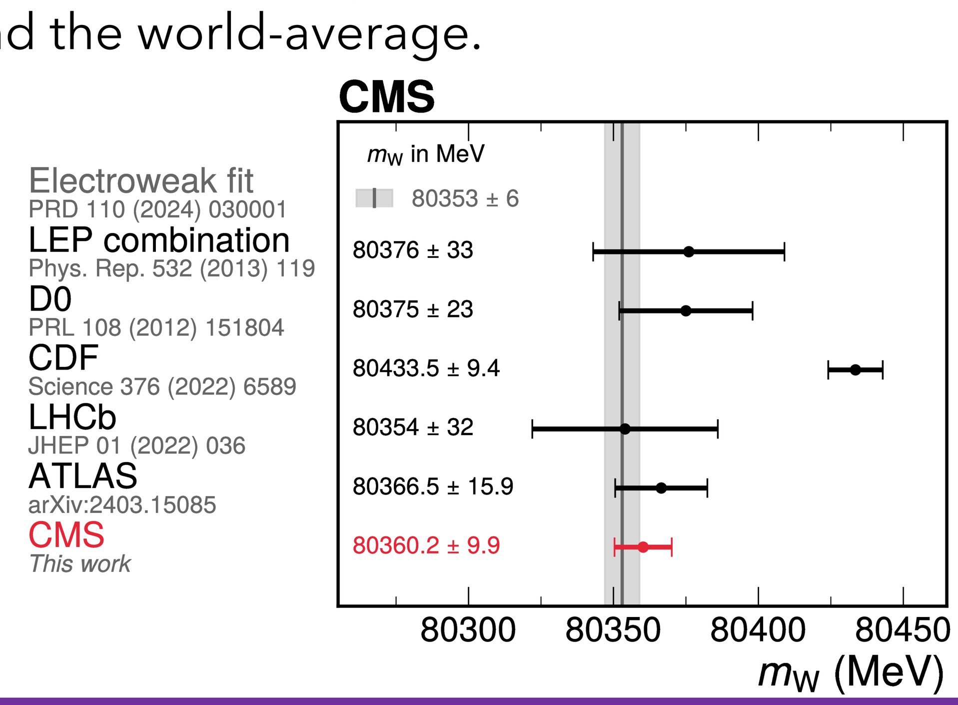
The sources of uncertainty and their impact in m_W are

Source	Impact (MeV)
Muon momentum scale	4.8
Muon reco. efficiency	3.0
W and Z angular coeffs.	3.3
Higher-order EW	2.0
p_T^W modeling	2.0

Source	Impact (MeV)
PDF	4.4
Nonprompt-muon bkg	3.2
Integrated luminosity	0.1
MonteCarlo sample size	1.5
Data sample size	2.4
Total uncertainty	9.9

The mass is **80360.2±9.9 MeV**. This is the **most precise** measurement at the LHC. It agrees with the SM and the world-average.

The m_W measurement from this analysis (in red) is compared with the combined measurement of experiments at LEP, and with the measurements performed by the D0, CDF, LHCb, and ATLAS experiments.
The global EW fit prediction is represented by the gray vertical band, with the shaded band showing its uncertainty.



References

The work presented is based on the paper by CMS collaboration (accepted by Nature)

arXiv:2412.13872 [hep-ex]

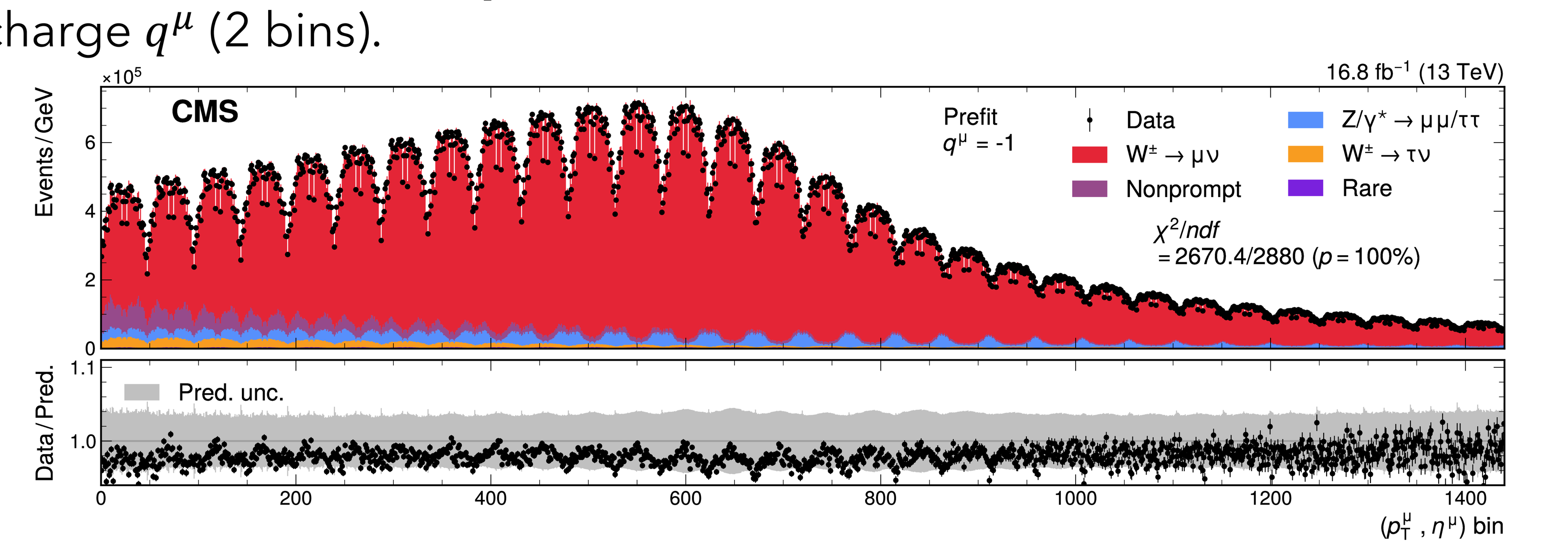
Stay tuned

Interested in the subject? Consider connecting to the **Open symposium on W mass**

2-3 March 2026, Pisa

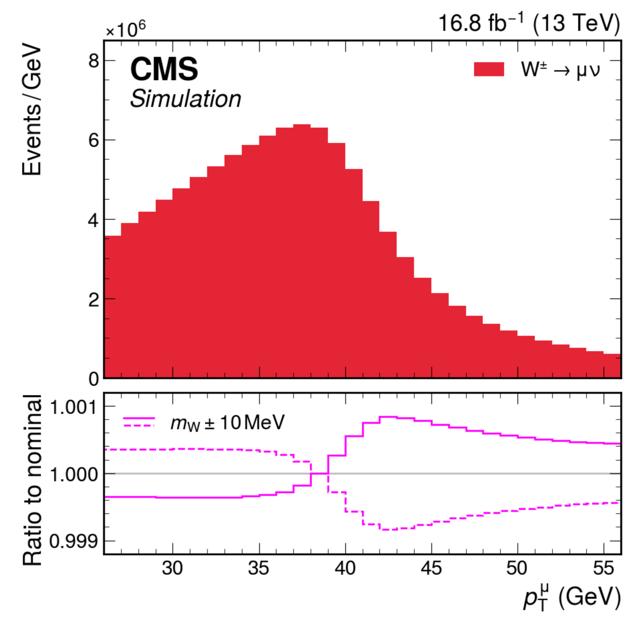
3. Challenges

m_W extracted from a binned maximum likelihood fit to a 3D distribution depending on muon p_T^μ (30 bins), pseudo-rapidity η^μ (48 bins), electric charge q^μ (2 bins).



"Unrolled" measured and predicted (p_T^μ, η^μ) distribution for negatively charged muons. The gray band represents the uncertainty in the prediction, before the fit to the data. The bottom panel shows the ratio of the number of events observed in data to the nominal prediction.

The measurement relies on a deep understanding of both the **experimental and theoretical systematic uncertainties**. For example, to reach a precision of few MeV on the mass one of the goal is a p_T^μ scale better than 0.1%.



Simulated distribution of the p_T^μ. The lower panel shows the ratio to the nominal prediction for changes of the W boson mass by ±10 MeV.

Experimental uncertainty: muon momentum scale calibration

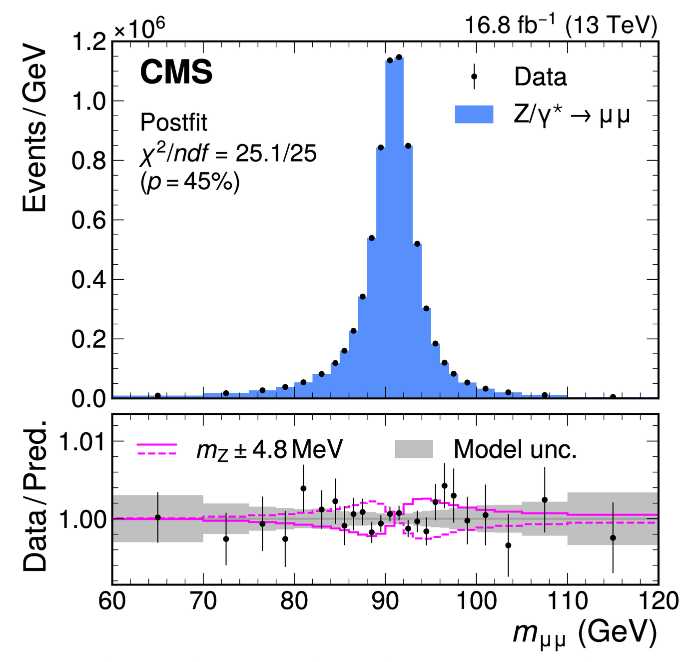
p_T^μ scale calibration requires knowing of features affecting tracks:

- alignment of tracking detector components
- magnetic field
- material distribution

$$\frac{\delta p_T}{p_T}=A-\frac{\epsilon}{p_T}+qMp_T$$

Calibration done with dimuon decays of J/ψ resonance and validated with muons from Υ(1S) meson and Z boson.

⟶ **4.8 MeV** in m_W



Measured and simulated $Z \to \mu\mu$ dimuon mass distributions. The bottom panel shows the ratio between the number of events observed in data and the total nominal prediction.

Theoretical: parton distribution functions (PDFs)

PDFs strongly affect the W boson polarization and, hence, the kinematic distributions of the decay muons. Unlike in previous measurements, **PDFs are constrained from data** with profile likelihood fits.

Different sets tested and **CT18Z** selected for the nominal prediction.

⟶ **4.4 MeV** in m_W

Theoretical: p_T^W modeling

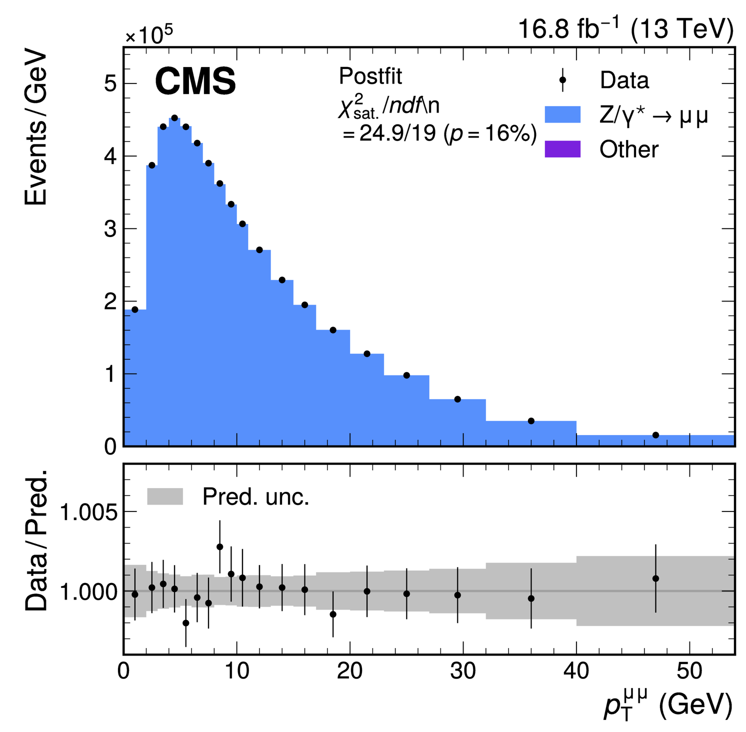
p_T^μ distribution depends on the theoretical modeling of the p_T^W spectrum limited in precision by missing p_T resolution.

Estimation with

$$\left(\frac{1}{\sigma_W}\frac{d\sigma_W}{dp_T^W}\right)_{pred}=\frac{\left(\frac{1}{\sigma_W}\frac{d\sigma_W}{dp_T^W}\right)_{model}}{\left(\frac{1}{\sigma_Z}\frac{d\sigma_Z}{dp_T^Z}\right)_{model}}\left(\frac{1}{\sigma_Z}\frac{d\sigma_Z}{dp_T^Z}\right)_{meas}$$

requires a precise knowledge of the uncertainties in the ratio.

⟶ p_T^W calculated with MINNLO$_{PS}$ and SCETLIB+DYTURBO (**N^3LL+NNLO**) and then **profiled with maximum likelihood fits to data.**



Measured and simulated $p_T^{\mu\mu}$ distributions in selected $Z \to \mu\mu$ events, with the normalization and uncertainties of the prediction set to the postfit values.

Predictions validated by fitting the p_T^Z spectrum with a permille agreement.

⟶ **2.0 MeV** in m_W