Measurement of the W boson mass at CMS

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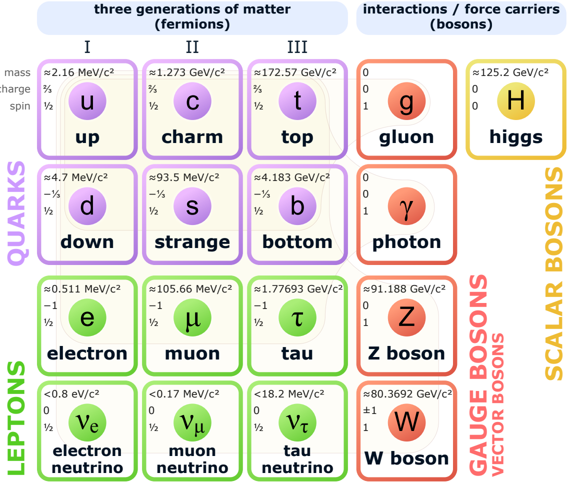
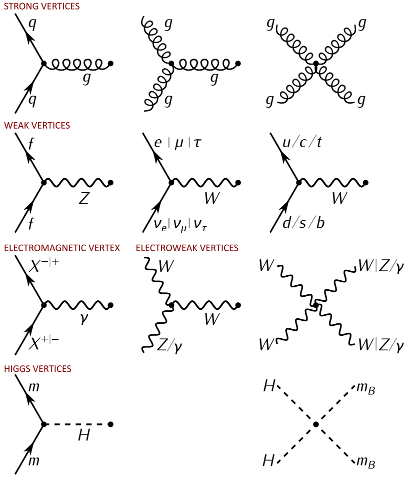
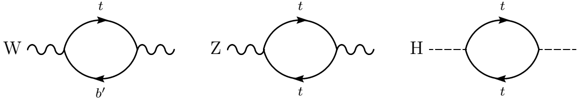
The Standard Model of particle physics



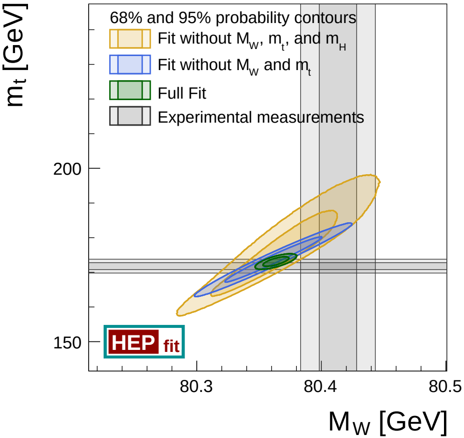


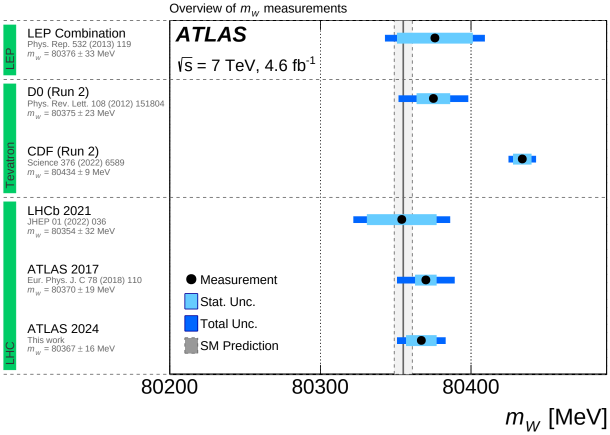
- Masses of top quark, and W, Z and H bosons related via loop corrections



The W boson mass in the electro-weak fit

- In particular, $m_W^2\left(1 - m_W^2/m_Z^2\right) = \pi\alpha/\left(\sqrt{2}G_\mu\left(1+\Delta r\right)\right)$, with Δr containing higher-order SM and possible beyond-SM corrections





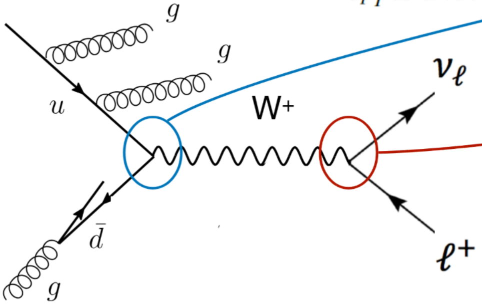
- CDF result 2022: in tension with SM and other measurements Science
- EW fit would require m_t^{pole} 10 GeV higher arXiv 2204.04204

Vector boson production and decay at the LHC

- Neutral-current Drell-Yan process: $pp \rightarrow q\bar{q} \rightarrow Z^0/\gamma^* \rightarrow \ell^+\ell^-$
- Charged-current Drell-Yan process: $pp \rightarrow q\bar{q}' \rightarrow W^\pm \rightarrow \ell^\pm\nu$

Unpolarized cross section σ_{UL}

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

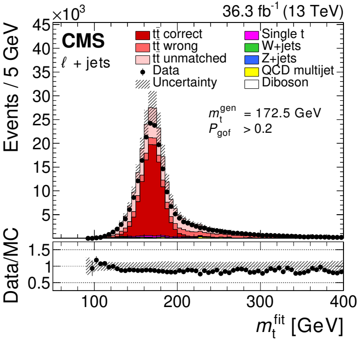


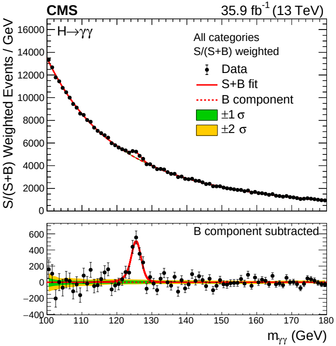
Angular decomposition valid at any order in QCD

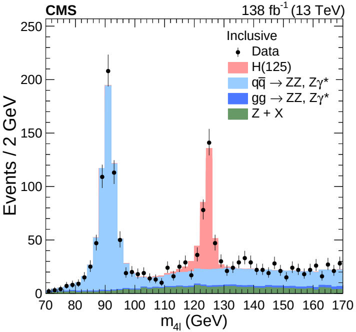
M. Cipriani

Mass measurements at CMS

- Usual strategy: select events, reconstruct invariant mass, compare with prediction





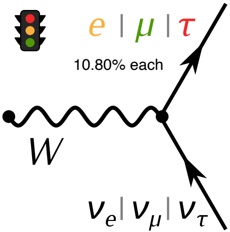


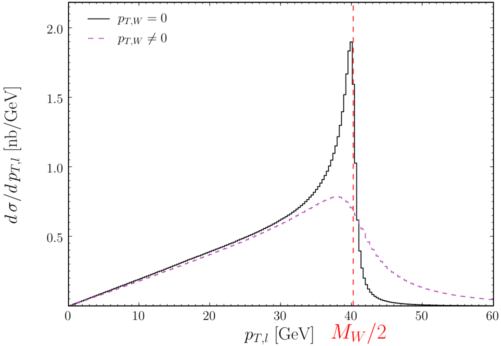
- Top quark mass from jets with 0.22%* precision CMS TOP-20-008
  *Using knowledge of W mass. W mass from jets $\sim 0.5 - 1\%$ due to jet energy scale and modeling
- Higgs boson mass from photons with 0.21% precision CMS HIG-19-004
- Higgs boson mass from leptons with 0.10%* precision CMS HIG-21-019
  *Limited by 4μ channel statistics, systematics are down to 0.05% already
- Goal for W mass: 0.02% precision (what ATLAS achieved)

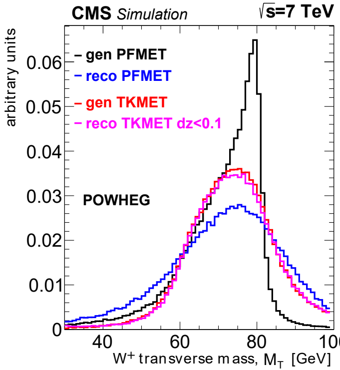
Measurement of m_W at hadron colliders

arXiv 1004.2597 CMS PAS-SMP-14-007

- Leptonic channel: neutrino prevents full reconstruction
  $\rightarrow$ use lepton p_T or transverse mass $m_T^2 = 2 p_T^\ell p_T^{\text{miss}} \left(1 - \cos\Delta\phi\left(\ell, p_T^{\text{miss}}\right)\right)$



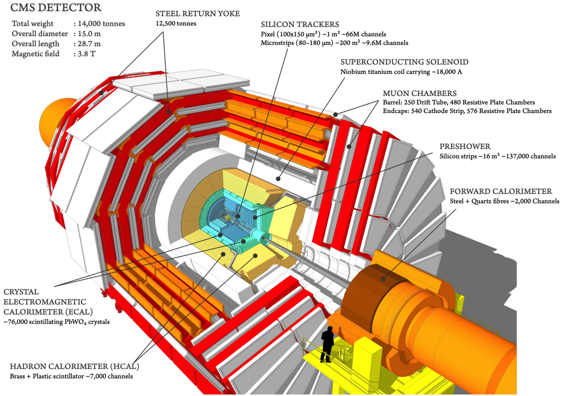


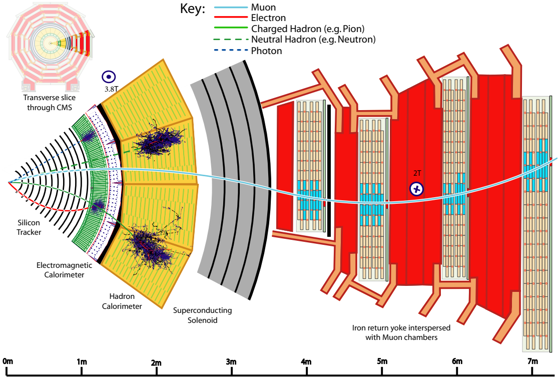


- Lepton p_T: Jacobian peak when W is at rest but smeared out at realistic W p_T
  - Extreme precision required: 1% change in lepton p_T ratio $\rightarrow$ 100 MeV in m_W
- m_T less sensitive to W p_T but poor resolution and difficult to calibrate

The CMS experiment

CMS JINST CMS PRF-14-001



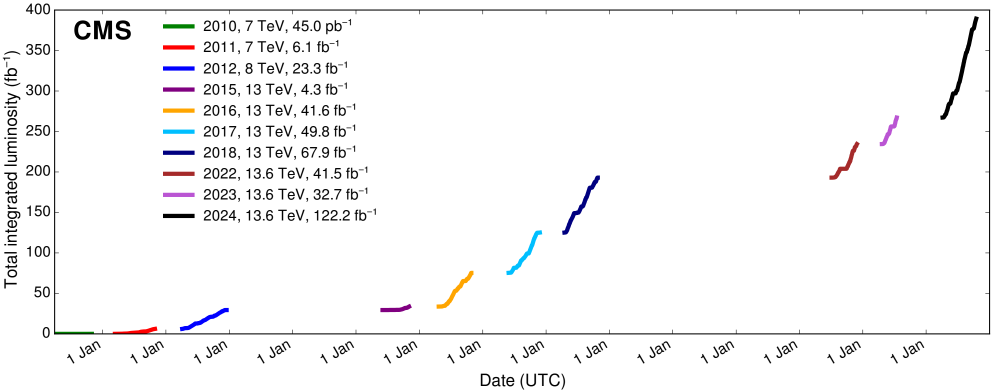


- Strong magnetic field, excellent tracker and muon systems
- Electromagnetic crystal calorimeter with excellent energy resolution
- Hermetic brass-scintillator hadronic calorimeter
- Particle flow algorithm combines tracking and calorimeter information optimally

Excellent LHC performance

CMS LumiPublicResults

- Total integrated luminosity from Runs 1, 2, and 3 close to 400 fb^{-1}



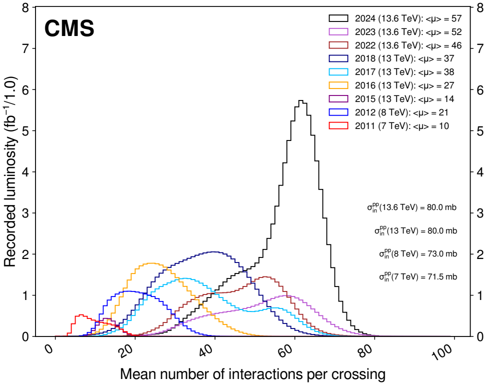
- Huge number of W bosons produced at each ATLAS and CMS:

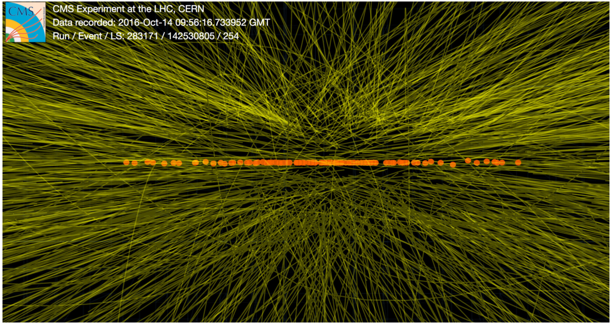
$$N_W = 400\,\text{fb}^{-1} \times \underbrace{20000\text{ pb}}_{\sigma_{W\to\mu\nu}\text{ at }13\text{ TeV}} \Rightarrow 8\text{ billion } W \to \mu\nu \text{ events}$$

Price to pay: pileup

CMS LumiPublicResults

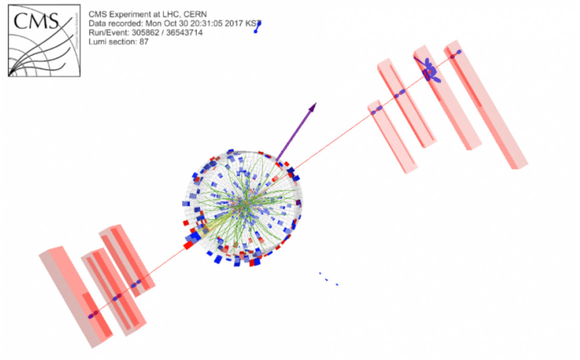
- High instantaneous luminosity → multiple pp interactions per bunch crossing

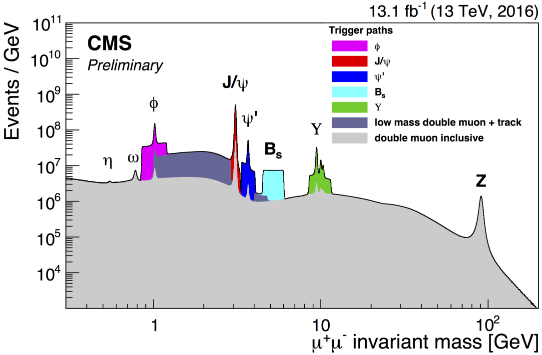




- Tracking copes well: tracks assigned to distinct interaction vertices
  - CMS Phase-2 upgrades for High-Lumi LHC will include timing capabilities → 4D vertexing
- Calorimeters: energy deposits overlap and cannot be distinguished

Muon performance

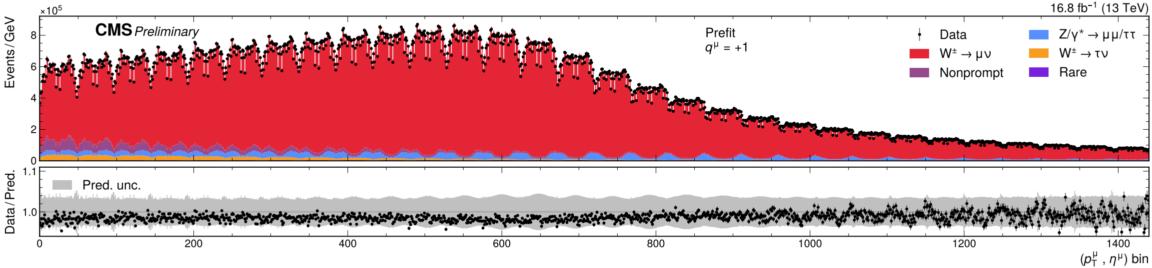




- Muons are easily identifiable even in high-PU environment
- Calibration possible via multiple known resonances
  - J/Ψ: mass uncertainty: 2×10^{-6}
  - Z boson mass uncertainty: 2×10^{-5}
- Target precision for W mass: 1×10^{-4}

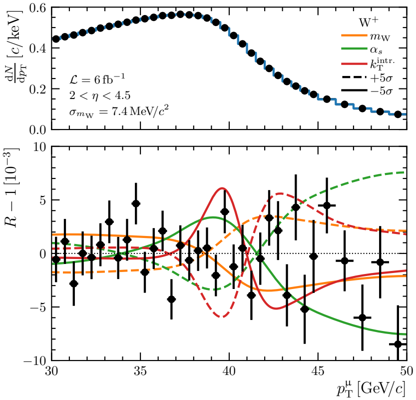
CMS measurement strategy

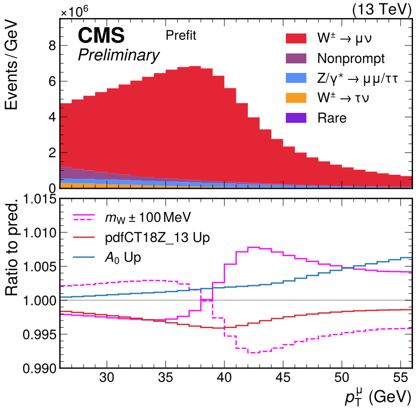
- Largest-ever dataset for m_W: 16.8 fb^{-1} from second part of 2016 run
  - 30 interactions per crossing $\rightarrow$ p_T^{miss} and m_T resolution degraded
- Focus on muon kinematics $\rightarrow$ minimize experimental uncertainties
  - Calibration from J/Ψ resonance, **reserve Z data** as independent cross check
  - Electron channel more difficult to calibrate, not needed with large statistics
- Profile likelihood fit to muon p_T, η, charge
  - Based on Tensorflow to handle thousands of bins and systematic variations
  - **In-situ constraints on theory modeling** from W data



Key idea: W mass by likelihood fit

- Simultaneous fit of W mass and leading effects on W p_T proposed in 2019 arXiv 1907.09958
- ISR α_s and intrinsic k_t shapes different wrt m_W variation
- Can float to absorb changes in the boson p_T, actually improve fit quality

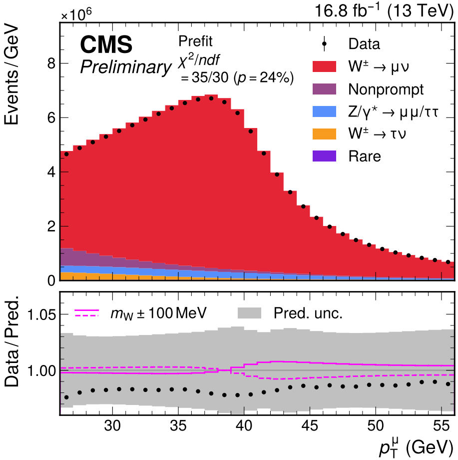




- Now: allow for adjustments of more than 4000 nuisance parameters

W event selection

- Events preselected by single-muon trigger with $p_T > 24$ GeV and loose isolation
- Muon p_T $26 - 56$ GeV, $|\eta| < 2.4$, reconstructed in tracker and muon system
- Transverse impact parameter < 500μm and additional isolation requirements
  $\rightarrow$ suppress nonprompt background
- Veto events with additional "loose" electrons/muons with $p_T > 10/15$ GeV
  $\rightarrow$ suppress $Z \rightarrow \mu\mu$, $t\bar{t}$, tW, diboson
- Require $m_T > 40$ GeV $\rightarrow$ further enhances purity
- Selected 100M events with $\sim 87\%$ $W \rightarrow \mu\nu$ signal

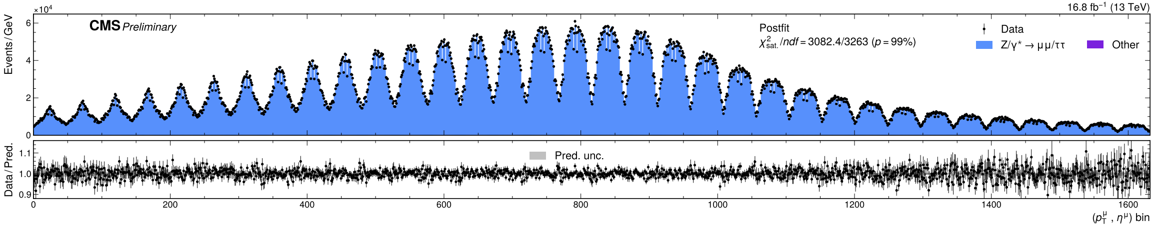


Z event selection

- Exactly 2 opposite-charge muons with $m_{\mu\mu}$ 60 – 120 GeV
- $Z \to \mu\mu$ signal purity 99.5%

W-like Z selection

- Remove 1 muon and treat it as undetected neutrino
- Split sample so that odd (even) events are used to analyze positive (negative) muons
- Muon p_T 26 – 60 GeV, $m_T > 45$ GeV, accounting for larger m_Z



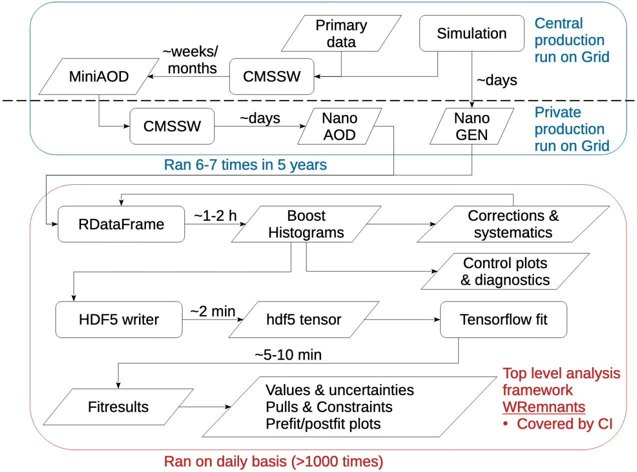
- W-like m_Z validates most aspects of m_W (except those related to backgrounds)

Analysis workflow

- Produced 4B W/Z events with full detector simulation
- Custom NanoAod (CMS ntuple)
- Local analysis with RDataFrame on 256-thread machine
- Boost histograms for performance

Hist Type	Hist Config	Evt. Loop	Total	CPUEff	RSS
ROOT THnD	10 × 103 × 5D	59m39s	74m05s	0.74	400GB
ROOT THnD	10 × 6D	7m54s	25m09s	0.27	405GB
Boost ("sta")	10 × 6D	7m07s	7m17s	0.90	9GB
Boost ("sta")	10 × (5D + 1-tensor)	1m54s	2m04s	0.81	9GB
Boost ("sta")	1 × (5D + 2-tensor)	1m32s	1m42s	0.77	9GB

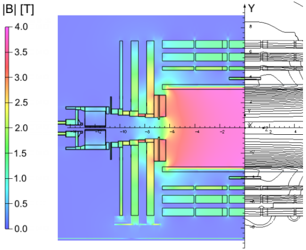
- Tensorflow 2 fit to handle large number of bins and variations
- Contributors from multiple institutes, analysis code on github
- CI tests on partial dataset



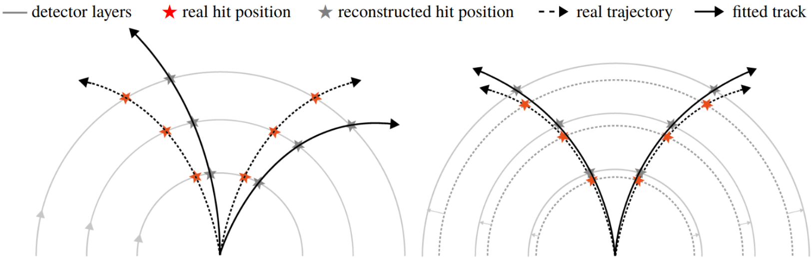
D. Walter

Muon momentum calibration

1. Improve simulation parameters (increased Geant4 precision) $\rightarrow$ new MC production
2. Improved reconstruction
   - Refit inner muon tracks with *Continuous Variable Helix* fit: incorporates continuous energy loss and multiple scattering using Geant4 propagator
   - Higher-accuracy B-field map from full 3D survey arXiv 1110.0306 arXiv 2202.02562
3. Global alignment procedure using $J/\Psi \rightarrow \mu\mu$ events
   - Determines position and orientation of silicon tracker modules
   - Additional parameters for B-field and energy loss



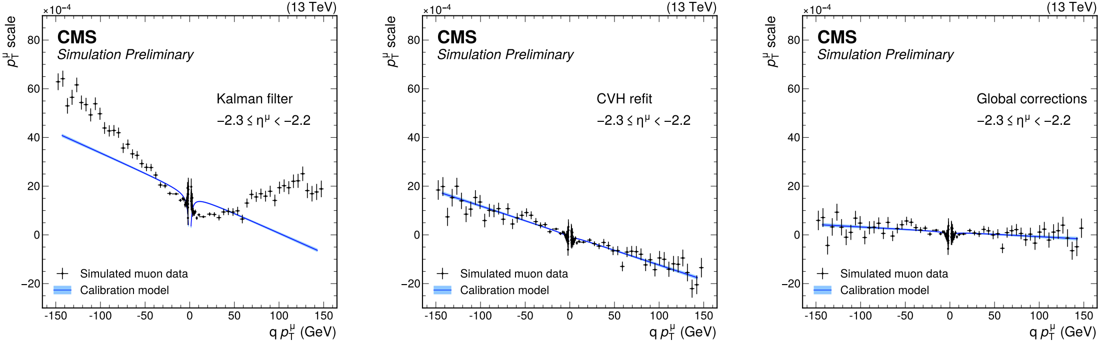
B-field CMS CFT-09-015



alignment biases: sagitta and length-scale ATLAS PHOTO-2020-018

Muon momentum calibration: after global corrections

- Bias of simulated muon scale vs p_T and charge after each steps 1 2 3

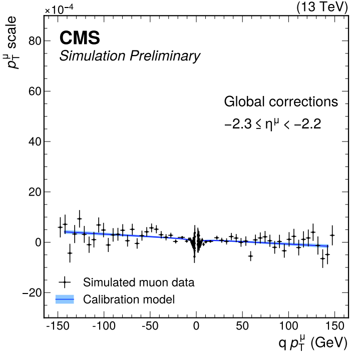


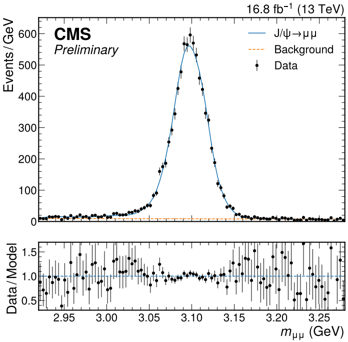
- Validate functional form of final calibration model (step 4, next slide)

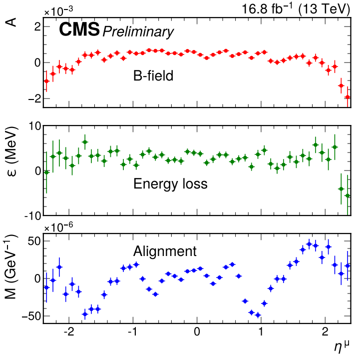
Muon momentum calibration: final corrections

4 Final correction for data/MC differences of track curvature $k = 1/p_{\mathrm{T}}$

$$\delta k/k = \underset{\text{magnetic field}}{A} - \underset{\text{energy loss}}{\epsilon k} + \underset{\text{alignment}}{qM/k}$$



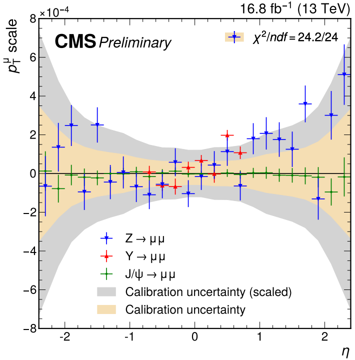


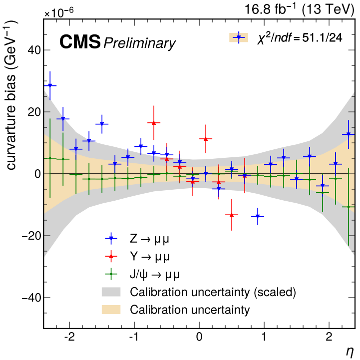


- Fit J/Ψ mass in bins of muon kinematics $\eta^+, p_{\mathrm{T}}^+, \eta^-, p_{\mathrm{T}}^-$,
- Extract η-binned calibration parameters

Muon momentum calibration: validation & uncertainties

- Charge-independent (B-field-like) and charge-dependent (alignment-like) residuals
- Closing in J/Ψ, validated in $Y(1S)$ and $Z \to \mu\mu$ events



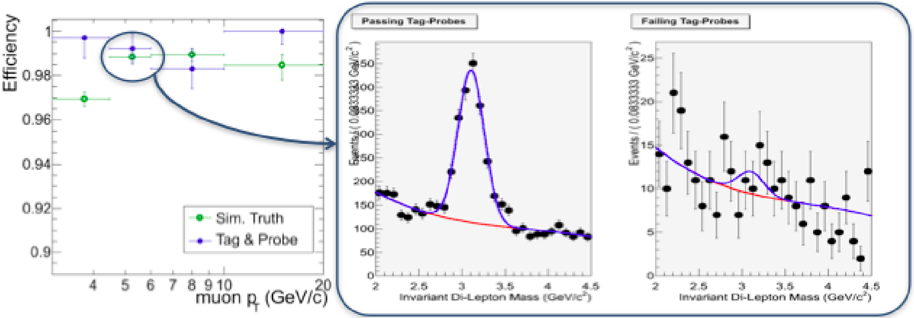


- Non-closure with Z is small, added as uncertainty, not as input or correction
- J/Ψ calibration uncertainty scaled by factor 2.1 to account for possible correlated biases
- Total muon calibration uncertainty $\to$ ± 4.8 MeV on m_W
  ATLAS: 7 MeV from Z calibration, CDF: 3 MeV from $J/\Psi, Y, Z$

Muon efficiencies: tag & probe method

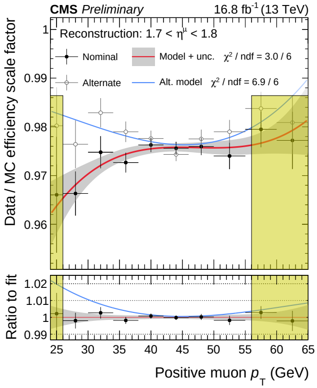
CMS MUO-16-001

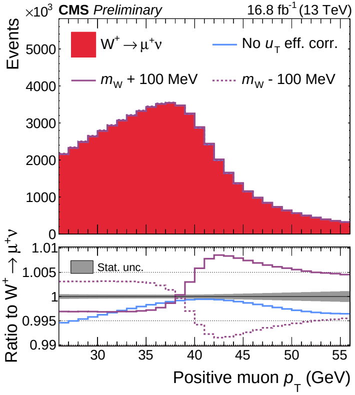
- Muon efficiencies determined using tag&probe method in J/Ψ or $Z \to \mu\mu$ events
- Select muon pairs with $m_{\mu\mu}$ close to resonance mass:
    - tag muon fulfills tight selection criteria
    - probe muon fulfills loose selection criteria
- Fit resonance in categories of passing/failing probe criteria $\to \epsilon = N_{\text{pass}}/\left(N_{\text{pass}} + N_{\text{fail}}\right)$

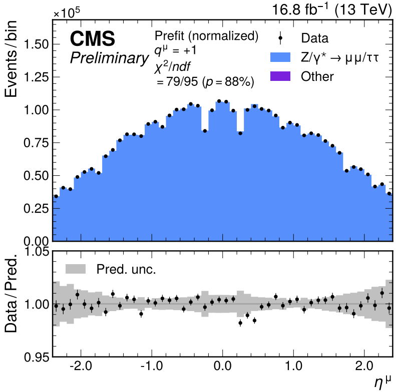


Muon efficiencies for m_W

- Measured in $Z \to \mu\mu$ events, fine-binned in muon η, split by charge
- Interpolated over muon p_T and hadronic recoil u_T (affects probe isolation)





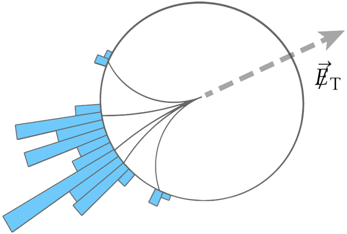


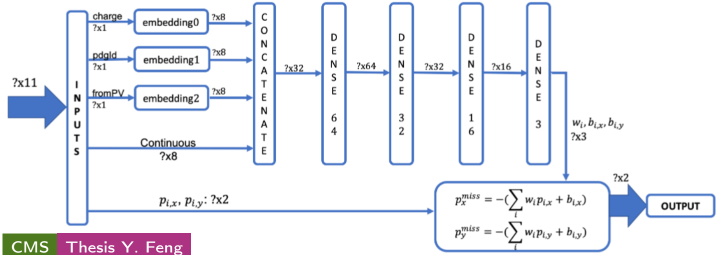
- Good closure in Z events, 3000 nuisance parameters → ± 3.0 MeV on m_W

Missing transverse momentum p_T^{miss}

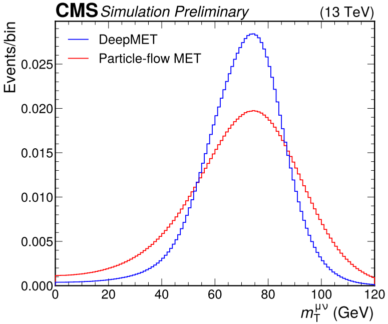
CMS JME-17-001 | CMS JME-18-001

- p_T^{miss} = negative vector $\vec{p}_T$ sum of all visible final-state particles aka **recoil**
- Resolution typically 15 – 30 GeV, depending on PU and p_T
- DeepMET algorithm: learn optimal weights of individual PF candidates for improved resolution and PU resilience





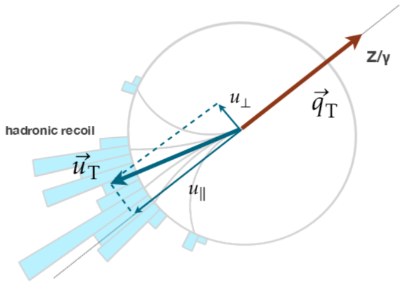
CMS Thesis Y. Feng



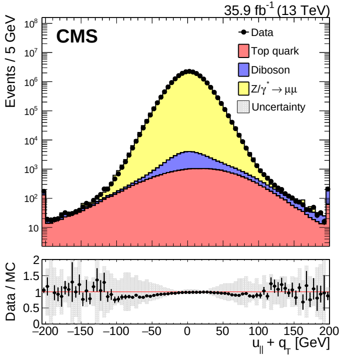
Recoil calibration

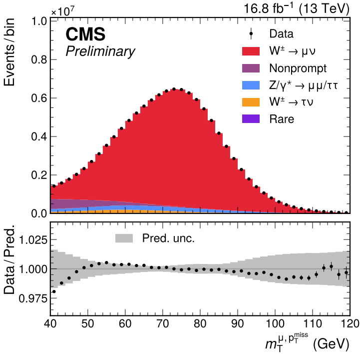
CMS PAS-SMP-14-007

- Hadronic recoil in $Z \to \mu\mu$ events should balance against $q_T = p_T^Z$
- Calibration derived in bins of q_T, applied to W with inverse CDF method



ATLAS Report G. Eppler

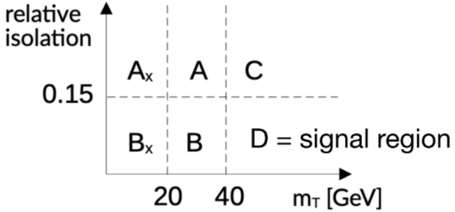


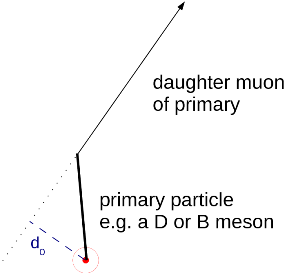


- m_T used only for event selection, impact on $m_W < 0.3$ MeV

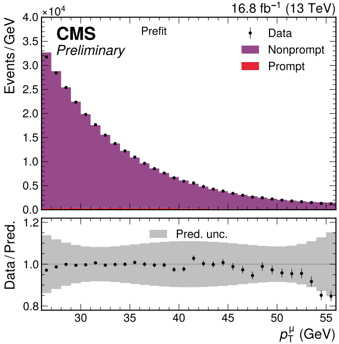
Nonprompt muon background

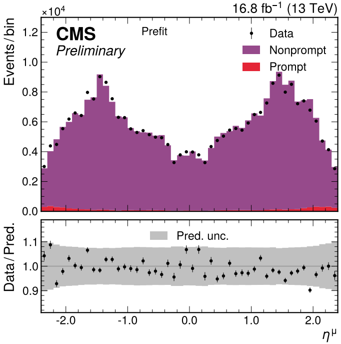
- Mostly from QCD multijet events with heavy flavors
- Data-driven estimate using extended ABCD method in m_T and isolation, $D = CA_x B^2 / \left(B_x A^2\right)$
- Validated using QCD simulation and HF-enriched control region with muons from secondary vertices
- Impact on m_W: 3.2 MeV





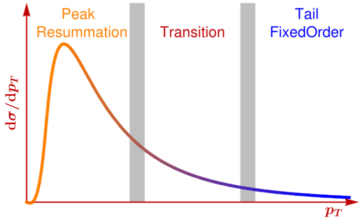
ATLAS Thesis M. Scherzer

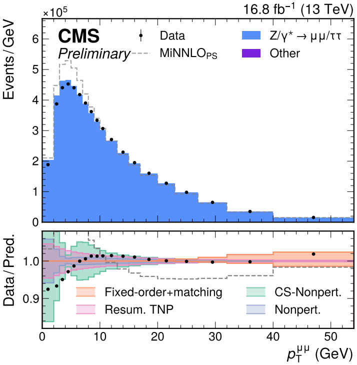


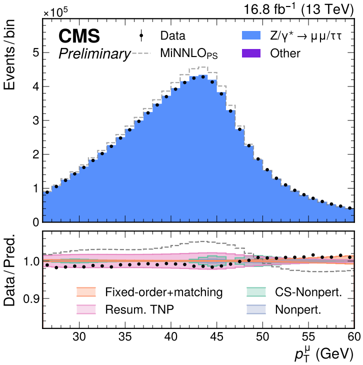


W/Z boson p_T modeling

- Most W/Z bosons produced at low-p_T, theory description requires resummation of multiple gluon emissions and non-perturbative model (intrinsic k_t)
- MC prediction: Powheg MiNNLO + Pythia 8 parton shower → NNLO+LL accuracy
- Reweighted to resummed calculation SCETlib+DYTurbo → N^{3}LL+NNLO

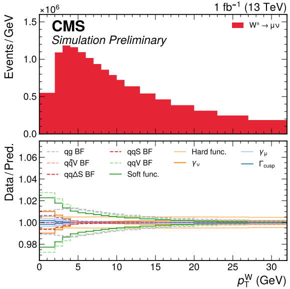


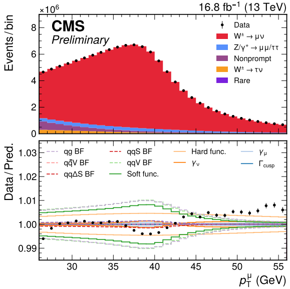


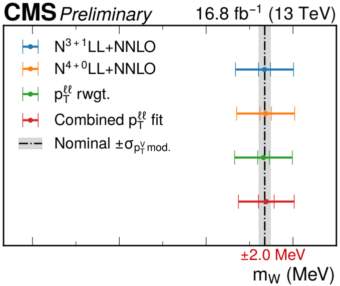


p_T uncertainty model

- Theory nuisance parameters instead of scale variations for resummation Tackmann
  - Coefficients in the resummation, meaningful shape variations, constrainable from data
  - $N^{3+0}LL$ scheme: perturbative structure at N^3LL, with TNP variations around known values
  - Also tested N^4LL schemes but would need to be matched to N^3LO





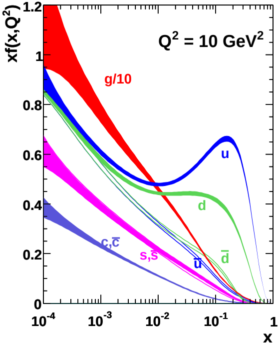


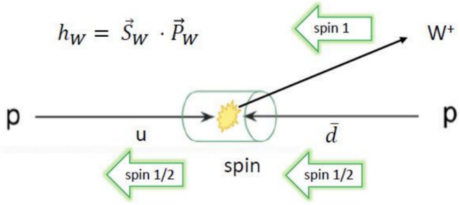
- Scale and matching uncertainties for NNLO part, variation of heavy quark masses
- Non-perturbative model with 10 parameters inspired by lattice QCD arXiv 2201.07237
- In total 32 nuisance parameters → ± 2.0 MeV uncertainty

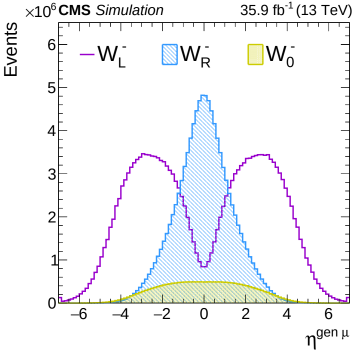
Parton distribution functions

arXiv 1004.2597 CMS SMP-18-012

- PDFs parametrize probability to find initial parton with momentum fraction x
- Determines the energy available for the W production $\rightarrow$ impact on p_T spectrum





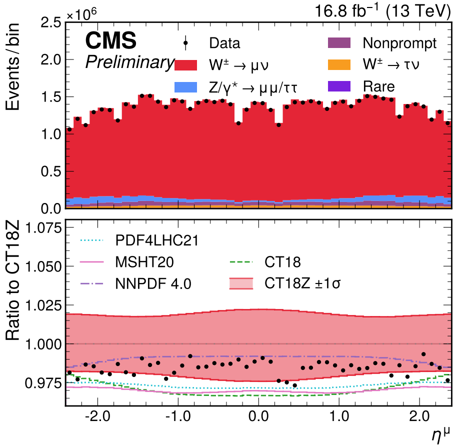


- Left-handed valence quarks have higher x than right-handed "sea" anti-quarks

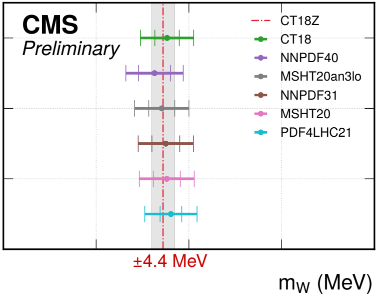
$\rightarrow$ forward (central) W bosons most likely left-handed (right-handed), imprint on lepton η

Parton distribution functions

- Consider 7 different PDF sets, profiling their uncertainty eigenvectors
- Derive scale factors to cover m_W extracted with other PDFs



PDF set	Scale factor	Impact in m_W (MeV) Original σ_{PDF}	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



- Very good consistency between PDF sets, CT18Z as default PDF → ±4.4 MeV

Angular coefficients

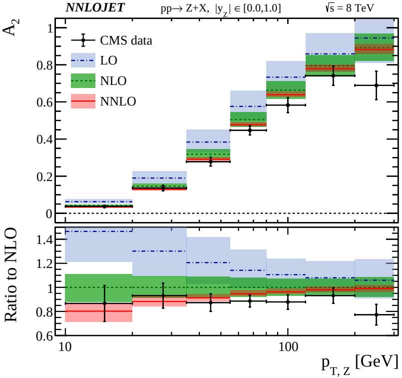
CMS SMP-13-010 arXiv 1708.00008

- W/Z production and decay cross section can be decomposed as

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

- A_i's change relationship between boson and lepton p_T
- Measured by ATLAS and CMS for Z bosons
- Prediction by MiNNLO MC consistent with fixed-order calculations
- Smearing effect from Pythia → additional uncertainty
- Evaluate NNLO scale uncertainties in 10 bins of p_T^V

→ uncertainty from A_i's $\pm 3.3\,\text{MeV}$



Higher-order electroweak effects

QED final-state radiation

- Most important effect but already simulated in nominal MC sample: MiNNLO + Pythia + **Photos++**
  - Including ME corrections and lepton pair production
- Compare to MEC off and alternative generator (Horace)
- Impact ± 0.3 MeV

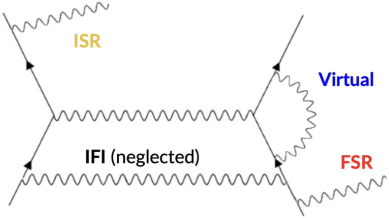
QED initial-state radiation

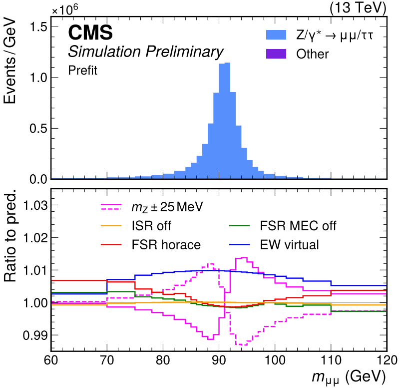
- Full QED ISR shower vs turning it off in Pythia
- Impact < 0.1 MeV

Virtual corrections

- Estimated at NLO with Powheg for Z, Renesance for W
- Largest impact: ± 1.9 MeV

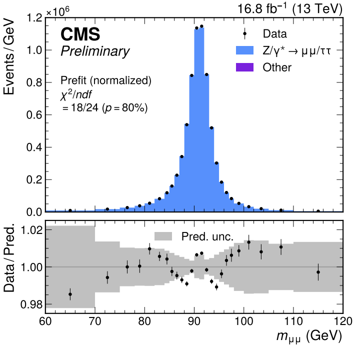
→ total impact on m_W: ± 2.0 MeV

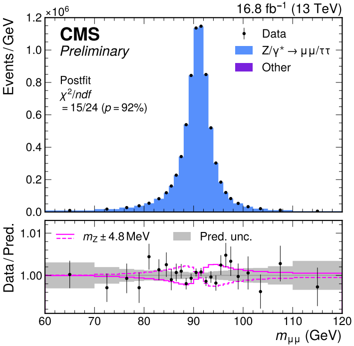


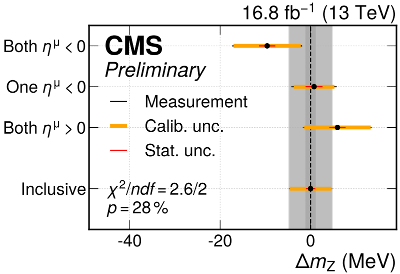


Z boson mass from $Z \to \mu\mu$

- Extracting m_Z by fit to dilepton mass
- Agreement with PDG: $m_Z - m_Z^{PDG} = -2.2 \pm 4.8\,\text{MeV}$ ✓
- Due to calibration uncertainty **not** an independent measurement of m_Z (yet)



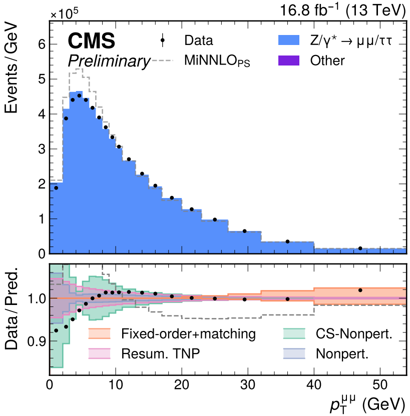


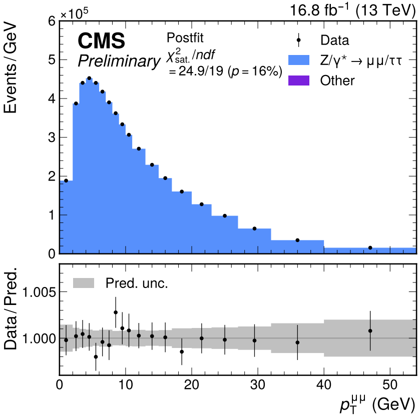


- Checked stability of result across muon η ✓

Z boson p_T from $Z \to \mu\mu$

- Fit theory model to dilepton p_T to verify it can describe the data

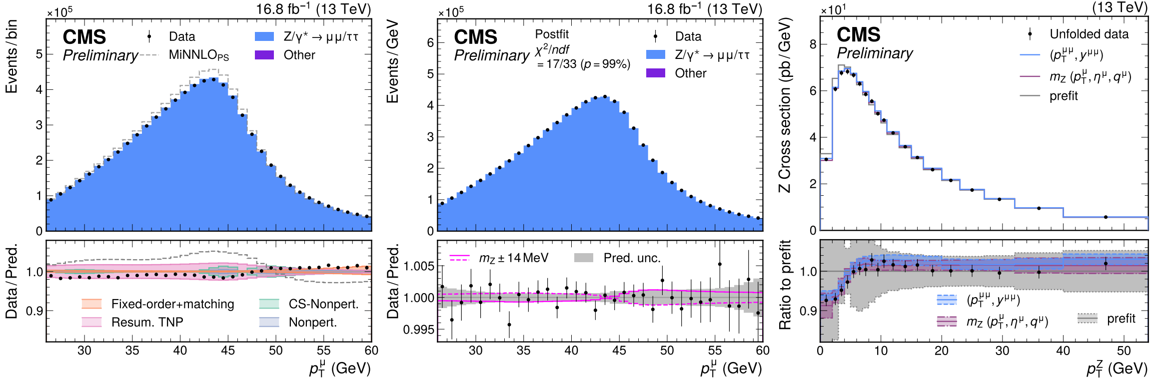




- Initial discrepancy due to untuned NP parameters, fully absorbed
- Postfit description at the 0.1% level ✓

Z boson p_T from W-like $Z \to \mu\not{\mu}$

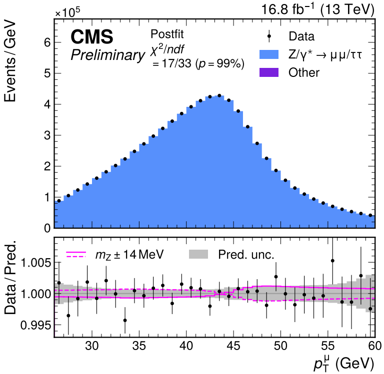
- Run full W-like fit using single muon (p_T, η, charge) in Z events, other muon ignored

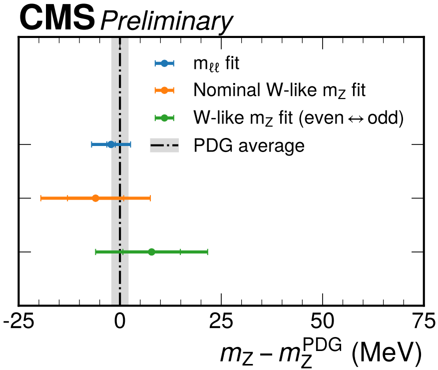


- Theory model is able to accommodate lepton p_T very precisely ✓
- Good agreement between W-like and dilepton p_T fit ✓

Z boson mass from W-like $Z \rightarrow \mu\not{\mu}$

- Nominal W-like result: $m_Z - m_Z^{PDG} = -6 \pm 14\,\text{MeV}$, $m_Z^+ - m_Z^- = 31 \pm 32\,\text{MeV}$
- Reversed event selection: $m_Z - m_Z^{PDG} = 8 \pm 14\,\text{MeV}$, $m_Z^+ - m_Z^- = 6 \pm 32\,\text{MeV}$



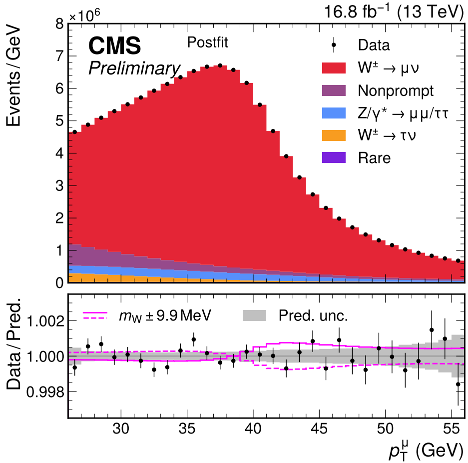


- Good agreement with $m_{\ell\ell}$ fit and LEP/PDG value ✓

→ Demonstrated ability to measure m_V without direct access to p_T^V spectrum!

W boson mass fit

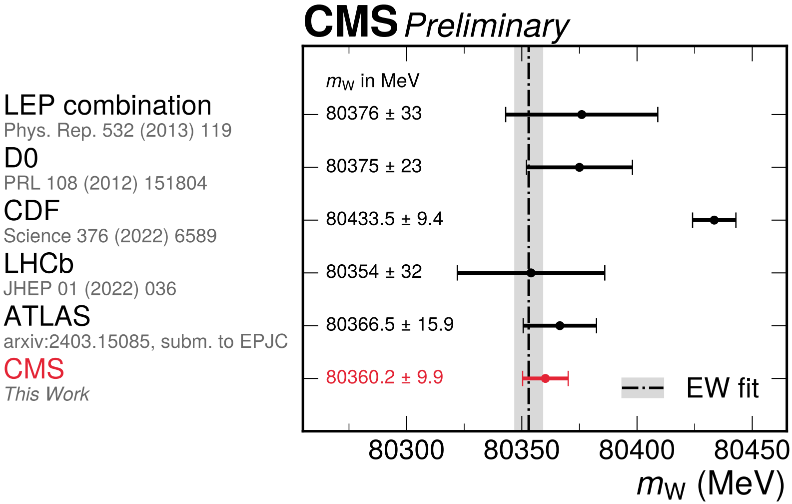
- All ingredients in place to run the final fit!



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

- Total uncertainty ±9.9 MeV → most precise measurement at the LHC

W boson mass result

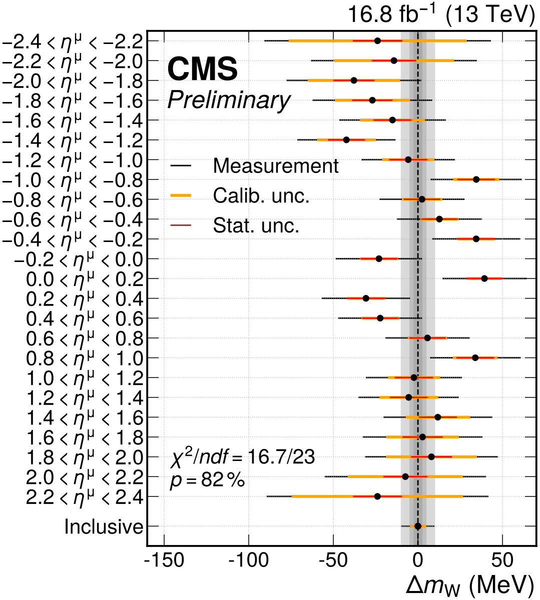


- Compatible with the Standard Model expectation ✓
- In clear tension with CDF measurement

Stability checks

Mass difference measured between

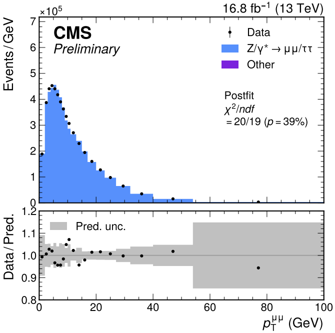
- muon $\eta < 0$ vs $\eta > 0$: 5.8 ± 12.4 MeV
- barrel vs endcap: 15.3 ± 14.7 MeV
- W^+ vs W^-: 57 ± 30 MeV
  - Strong anti-correlations in alignment and theory uncertainties (A_i's for $\mu^\pm$)
  - Several cross checks done, m_W results stable within < 1 MeV
- simultaneous fit to Z p_T, y: 0.6 MeV

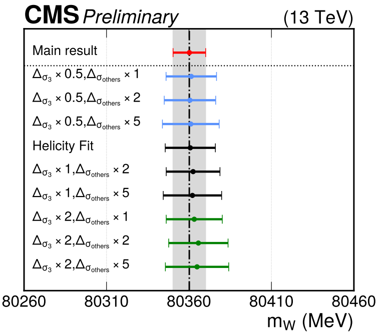


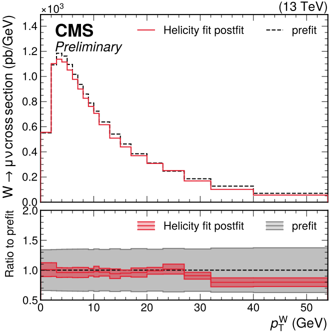
Helicity fit

arXiv 1707.09344

- Alternative fit setup with reduced model dependence
- Free-floating p_T^W and y^W (8x7 bins), loose constraints on A_{0-4}







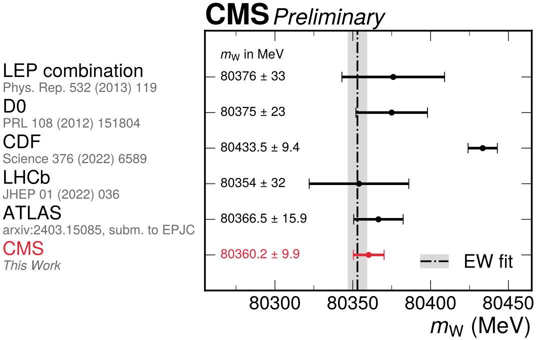
- Z p_T predicted from W-like helicity fit agrees with measured $p_T(\ell\ell)$
- Difference to main result 0.6 MeV, with slightly larger uncertainty ± 15.2 MeV
- Extracted W p_T, y spectrum agrees with prefit model

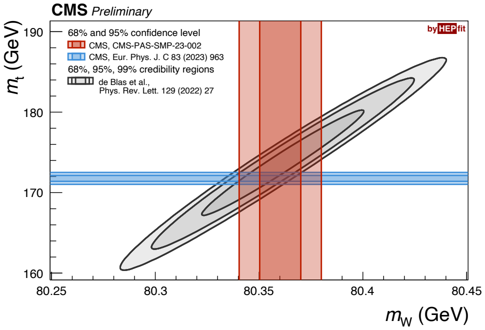
Summary

- First measurement of the W boson mass by CMS!

$$m_W = 80360.2 \pm 9.9 \text{ MeV}$$

- Most precise at the LHC, in clear tension with previous CDF result





- Good agreement with EW fit – "The standard model is not dead" Nature
- Documented in CMS PAS-SMP-23-002 – to be submitted to journal soon