A high precision measurement of the W mass at CMS

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on behalf of the CMS Collaboration

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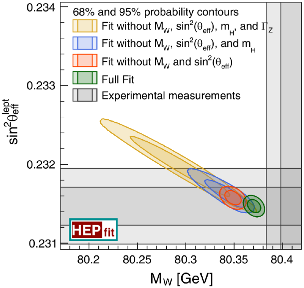
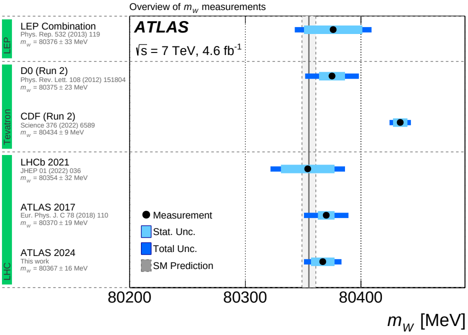
EWWG WG1 Meeting

Introduction

Phys.Rev.Lett. 129 (2022) 27, 271801

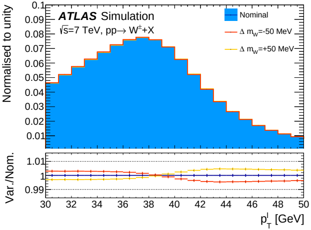


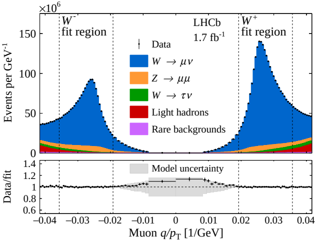


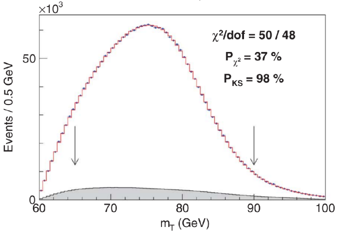
- The discovery of the Higgs and the precise measurement of its mass provides the complete set of inputs needed to overconstrain the Standard Model
- Recent CDF measurement in significant tension with SM prediction and other measurements

m_W Measurements at hadron colliders

- Hadronic channel not feasible due to huge QCD backgrounds/jet energy scale
- W cannot be fully reconstructed in leptonic channel due to neutrino
- Mass must be inferred from lepton p_T or transverse mass distributions
- m_W is sensitive to 0.1% level variations in templates
- Extreme control needed over all experimental and theoretical aspects



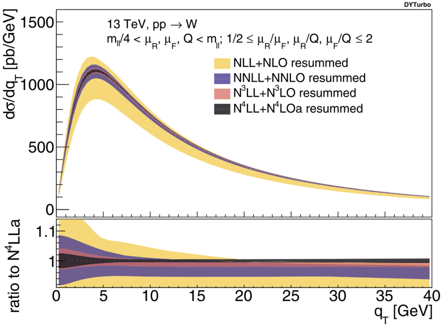




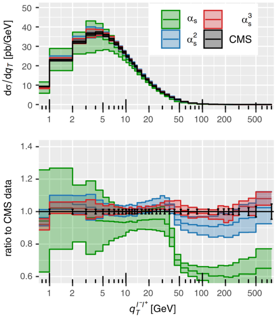
CDF

Theoretical Considerations

- W (and Z) production at hadron colliders described by PDFs + perturbative QCD and Electroweak calculations
    - Small additional non-perturbative effects from "intrinsic k_T"
- Relatively large theoretical uncertainties due to large logarithms at low W or Z p_T
- Usual strategy is to use precise Z$\rightarrow \ell\ell$ p_T spectrum from data to tune the theoretical prediction



Phys.Lett.B 845 (2023) 138125

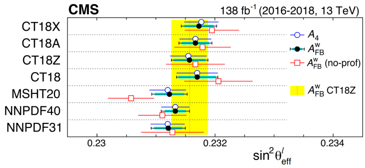


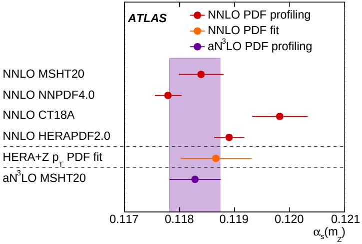
Phys. Rev. D 107, L011506, 2023

Theoretical Considerations

arXiv:2408.07622, arXiv:2309.12986

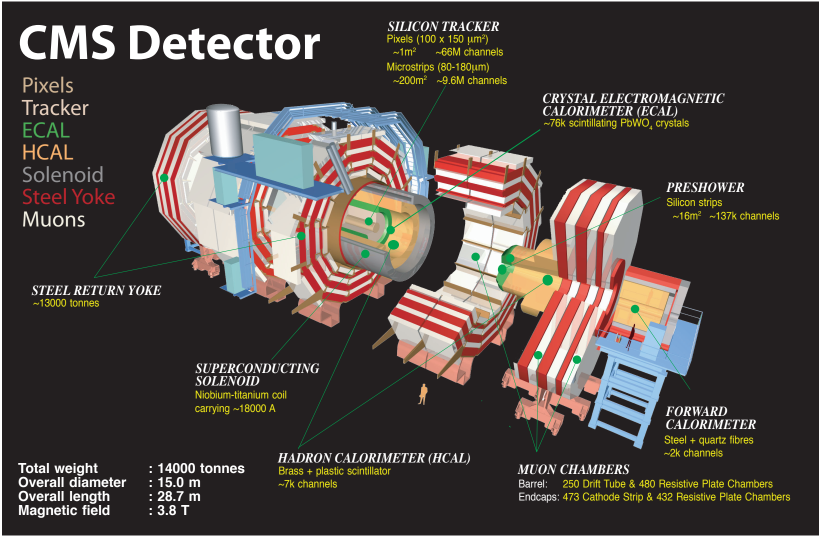
- PDFs are a challenge: In recent precision measurements at hadron colliders often a significant spread in measured values depending on the choice of PDF set
- Angular dependence of W and Z production can be decomposed in terms of angular coefficients/helicity cross sections:
- This can be a useful way to factorize theoretical corrections and uncertainties





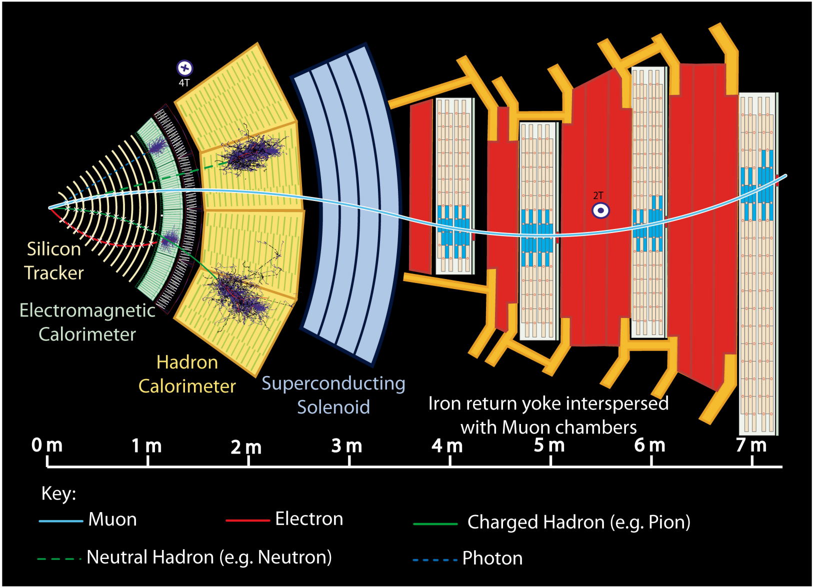
$$\frac{d^5\sigma}{dq_T^2\,dy\,dm\,d\cos\theta\,d\phi} = \frac{3}{16\pi}\frac{d^3\sigma^{U+L}}{dq_T^2\,dy\,dm}\Big[(1+\cos^2\theta)+\frac{1}{2}A_0(1-3\cos^2\theta)+A_1\sin 2\theta\cos\phi$$
$$+\frac{1}{2}A_2\sin^2\theta\cos 2\phi+A_3\sin\theta\cos\phi+A_4\cos\theta+A_5\sin^2\theta\sin 2\phi+A_6\sin 2\theta\sin\phi+A_7\sin\theta\sin\phi\Big]$$

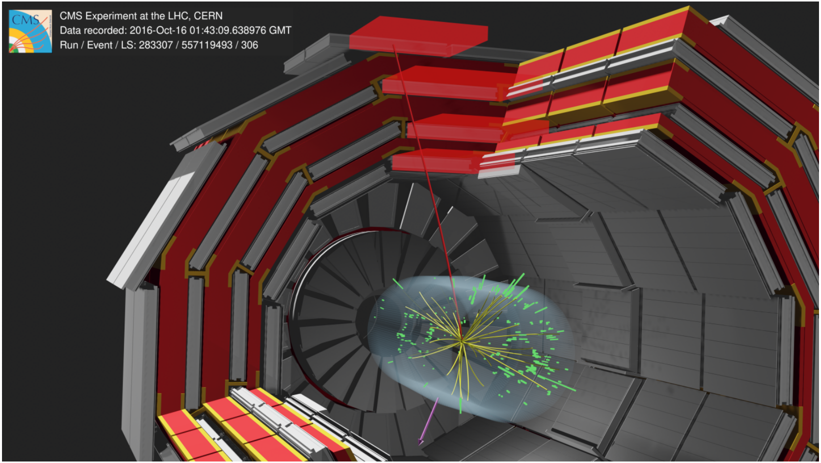
The CMS Detector



Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

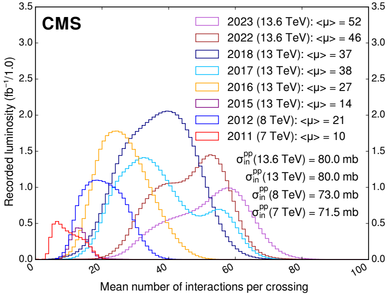
The CMS Detector




CMS Experiment at the LHC, CERN
Data recorded: 2016-Oct-16 01:43:09.638976 GMT
Run / Event / LS: 283307 / 557119493 / 306

m_W Measurement at CMS

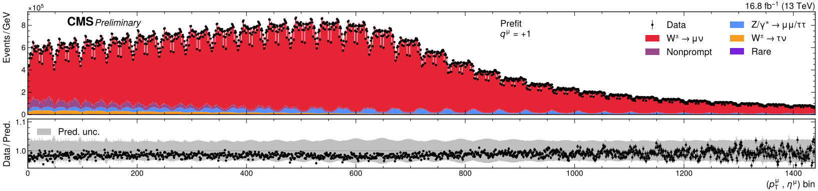
- Use well-understood subset of 13 TeV data: 16.8 fb^{-1} from later part of 2016 run ($\sim$ 30 mean interactions per crossing)
- Focus on muon channel and kinematics
    - Larger experimental systematics for electrons and hadronic recoil, especially with higher pileup
- **General strategy:** Exploit large dataset, accurate modeling of uncertainties for maximal in-situ contraints on theoretical modeling



- Reserve Z data as an independent cross-check as much as possible:
- Muon calibration from J/ψ, validated with Z
- In-situ constraints on theory modeling from W data itself, independent validation with Z

m_W Measurement at CMS

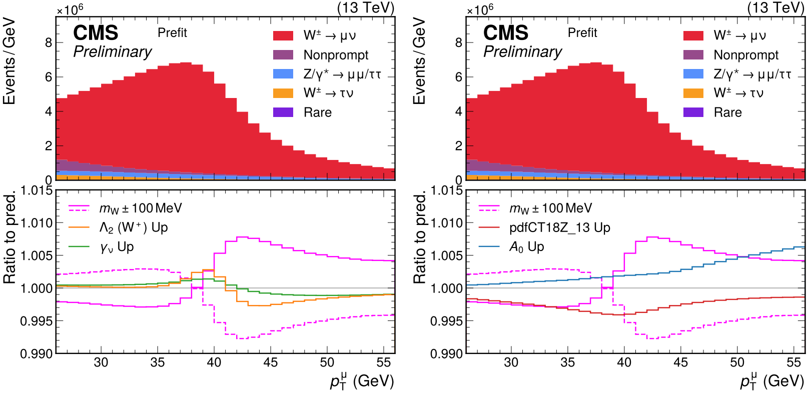
- m_W extracted from profile likelihood fit to muon (η, p_T, charge)
    - Thousands of bins and systematic variations
    - Optimized Tensorflow-based fitting framework
- Building on experimental techniques, tools, and experience from W-like m_Z measurement (2016) and W rapidity-helicity measurement (2020) which established strong in-situ constraints on PDFs from charged lepton kinematics
- 4B fully simulated MC events, >100M selected W candidates
    - Significant computing/technical challenges for a measurement of this complexity



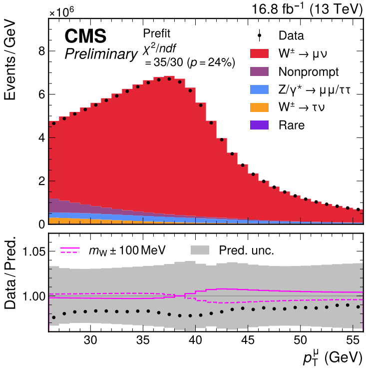
μ^+ prefit

m_W Measurement at CMS

- **Enabling feature of the measurement:** Systematic variations in W p_T, rapidity, decay angles from QCD uncertainties, PDFs, have a **different** effect on the muon kinematics as compared to a change in m_W
- PDF and boson p_T modeling uncertainties are strongly constrained in-situ by the data

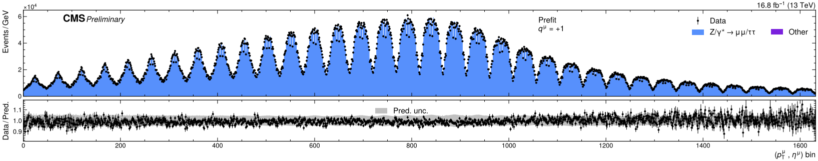


Event selection



- Straightforward single muon selection: track quality criteria, loose transverse impact parameter cut, and isolation
- Selected events are about 90% $W \to \mu\nu$
- Nonprompt background from data-driven estimate
  - Mostly from B and D decays with smaller contribution from π or K decay-in-flight
- Prompt backgrounds from simulation with all relevant corrections/uncertainties
  - $W \to \tau\nu$, $Z \to \mu\mu$ (mostly with one muon out-of-acceptance), $Z \to \tau\tau$, top, diboson

“W-like” selection of Z events



- $Z \rightarrow \mu\mu$ events are also selected with very similar selection
- One muon removed and treated as neutrino
- To avoid statistical correlations, apply trigger and use kinematics of positive (negative) muons for even (odd) numbered events
- Z mass can be extracted from single muon $(\eta, p_T,$ charge) distribution as for W case
- Validates all aspects of the actual W measurement except for non-prompt and $Z \rightarrow \mu\mu$ background
- Theory uncertainties are similar (but not identical) to final m_W measurement

Statistical treatment and technical details

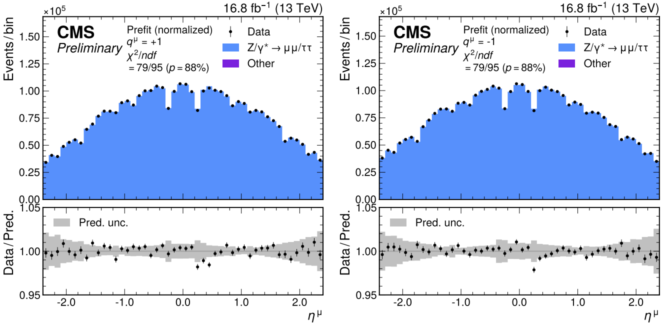
- Likelihood fit implemented in Tensorflow for fast and accurate gradient and hessian calculation for minimization and uncertainties
- NanoAOD is a standard CMS dataformat with ∼2kB/event representation of high level objects and variables sufficient for a wide range of analyses
- This measurement uses custom NanoAOD of around 4kB/event with additional information sufficient even to reapply (in a linearized way) the global alignment corrections to the muons

Statistical treatment and technical details

- Analysis workflow:
  - MINIAOD → NANOAOD (including refitting of muon tracks) on the grid in 1-2 days (once every few months)
  - NANOAOD→histograms, 1.5 hours for full 4B MC samples with data, 30 mins for reduced "test" sample with $1B$ MC events and all data
    - Optimized RDataFrame based analysis with multi-dimensional boost histograms and atomic storage to avoid memory constraints
    - Typical event rate approaching 1MHz, IO at 1-10Gbytes/sec level
    - Using high core count single machine and 100gbps network+NVMe storage
  - Histograms → Fit inputs: 1-2 minutes, with heavy use of numpy semantics and functionality on multi-dimensional histograms
  - Likelihood fit: $3 - 10$ minutes
- Ultra-fast turnaround has been essential to enabling an analysis at this level of complexity

Muon Efficiencies

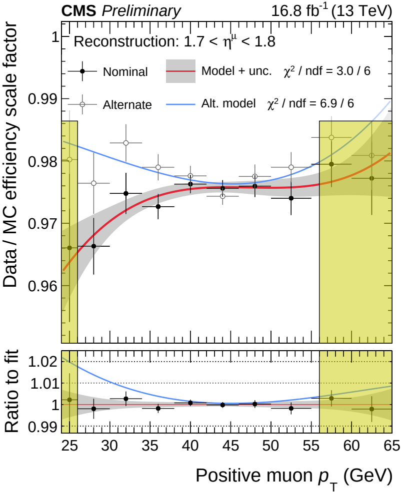
- Muon tracking, reconstruction, identification, trigger, isolation efficiencies measured with tag-and-probe from $Z \to \mu\mu$ events
- Scale factors measured differentially in muon (η, p_T) (and for most steps also split by charge)
- Isolation (and trigger) efficiencies also take into account contribution of hadronic recoil from W/Z boson to isolation sums



(a) μ^+ (prefit normalized) (b) μ^- (prefit normalized)

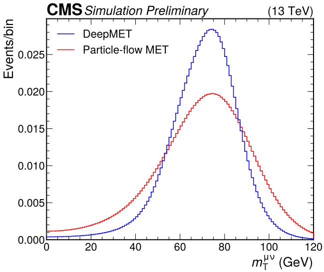
Muon Efficiencies

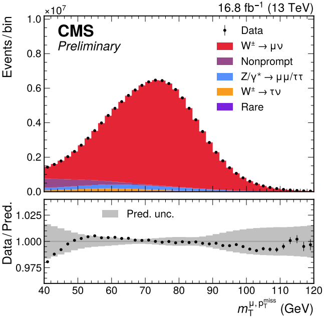
- p_T^μ and u_T dependence within each η^μ (charge) bin are smoothed with polynomials, with corresponding statistical uncertainty
- Large number of nuisance parameters to consistently account for statistical (de-)correlation of efficiency measurements across muon η and p_T
- Systematic uncertainties from alternate signal and background models for the tag and probe



Hadronic Recoil

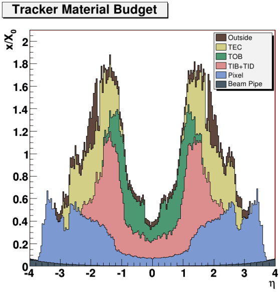
- Transverse mass is not directly used as a fit variable in the present analysis, but it's used as part of the event selection and non-prompt background estimation
- Hadronic recoil is reconstructed with "DeepMET" algorithm: DNN-based recoil reconstruction operating with inputs at the individual particle flow candidate level
- Recoil response is calibrated using Z→ $\mu\mu$ events





Muon Momentum Calibration

- **General strategy:** Calibrate with quarkonia, validate with Z
- **Muon chambers are not used for final momentum measurement**, "only" for trigger and identification
- Precise calibration requires accurate simulation track reconstruction, precise modeling of magnetic field, material, and alignment in the inner detector
- **Challenge:** Significant amount of material in the tracking volume



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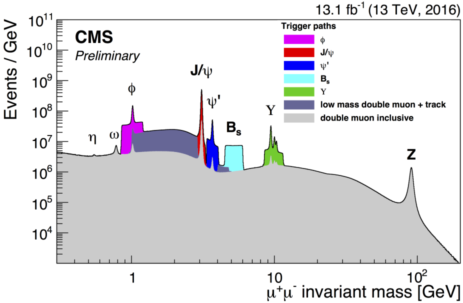


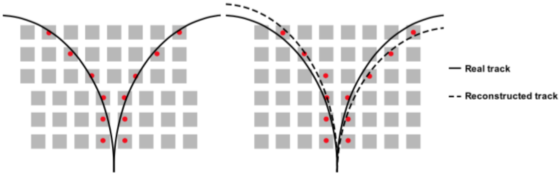
CMS-DP-2016-059

Muon Momentum Calibration

- Calibration from quarkonia and extrapolation to W/Z momentum range requires precise control over momentum dependence of the calibration
- Canonical expression for curvature bias (with $k \equiv 1/p_T$):

$$\frac{\delta k}{k} = A - \epsilon k + qM/k$$

- The three terms correspond to biases in the magnetic field, material (energy loss) and alignment
- In a silicon tracker, multiple scattering must be explicitly accounted for in the track fit
- In this case **local** biases in magnetic field, material or alignment (or small biases in simulation or reconstruction) can lead to additional non-trivial momentum dependence of the curvature bias



Muon Momentum Calibration

- In a silicon tracker, multiple scattering must be explicitly accounted for in the track fit (e.g. with Kalman Filter, Generalized Broken Line Fit, etc), in this case

$$\frac{\delta k}{k} = A - \epsilon k + qM/k + \sum_{l}^{m} \frac{A_l - \epsilon_l k + qM_l/k}{1 + d_l^2 k^2}$$

- The "extra" terms are generated by **local** biases in magnetic field, material or alignment, which effectively receive a momentum-dependent weight $\frac{1}{1+d^2k^2}$ due to the competition between hit resolution and multiple scattering in the track fit
- Small biases in the simulation or reconstruction can also contribute to momentum-dependent biases

Muon Momentum Calibration

- Staged approach designed to first eliminate biases in the simulation and reconstruction and then calibrate the muons
    1. Tune simulation parameters to remove small biases
    2. Refit muon tracks to remove small biases and improve B-field and material modeling
    3. Correct for local biases in B-field, material and alignment between data and reconstruction model
    4. Final corrections for residual scale differences between data and simulation

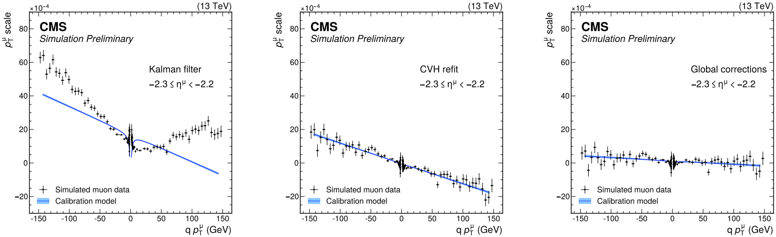
Muon Momentum Calibration

1. **Tune simulation parameters to remove small biases**
   - Increase surface intersection precision in Geant
2. **Refit muon tracks to remove small biases and improve B-field and material modeling**
   - Continuous Variable Helix (CVH) track fit developed for this measurement with improved reconstruction accuracy, better modeling of B-field and material (Geant4e propagator)
3. **Correct for local biases in B-field, material and alignment between data and reconstruction model**
   - Generalization of global alignment procedure with additional parameters for B-field and energy loss corrections and using $J/\psi \to \mu\mu$
4. **Final corrections for residual scale differences between data and simulation**
   - High accuracy determination of parameterized residual B-field, material (energy loss) and alignment biases using mass fits in $J/\psi \to \mu\mu$ events
   - Residual resolution corrections from J/ψ and $Z \to \mu\mu$ using related parameterization for multiple scattering and hit resolution

Track Refit and Generalized Global Corrections

- **Muon tracks refit using "Continuous Variable Helix" (CVH) fit:**
  - Extension of Generalized Broken Line Fit with ∼ continuous energy loss and multiple scattering via Geant4e propagator using full material model from simulation
  - Avoids small local biases related to material approximations (infinitesimal planes) and Kalman Filter smoothing
  - Higher accuracy B-field model based on three-dimensional field-map taken of CMS solenoid on the surface
  - Several other refinements with respect to nominal CMS track reconstruction
  - When B-field, material and alignment are consistent between simulation and reconstruction, gives consistent momentum scale to $\sim 5 \times 10^{-5}$ out of the box in MC
- **Generalized Global Corrections:**
  - Generalization of global alignment procedure with additional parameters for local magnetic field and material corrections
  - Parameters determined from $J/\psi \to \mu\mu$ events using muon tracks with common vertex and mass constraint
  - Sufficient to correct local biases, but limitations in Gaussian mass constraint leave significant weak modes remaining

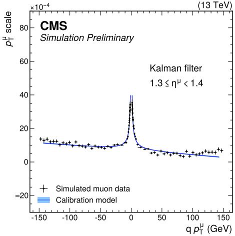
Validation of Functional Form in Simulation



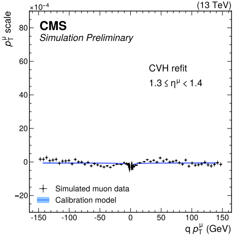
(a) Kalman Filter (b) CVH Refit (c) +global corrections

- Showing curvature bias vs charge and momentum in simulation at different stages of the reconstruction/corrections
- Curvature bias is fit using the functional form for the final calbration step which comes afterwards
- Both CVH refit and generalized global corrections are needed to remove all local biases such that the parameterization is valid in all detector regions

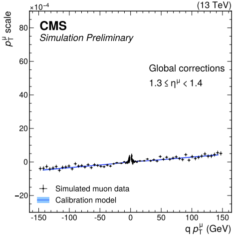
Validation of Functional Form in Simulation



(a) Kalman Filter



(b) CVH Refit

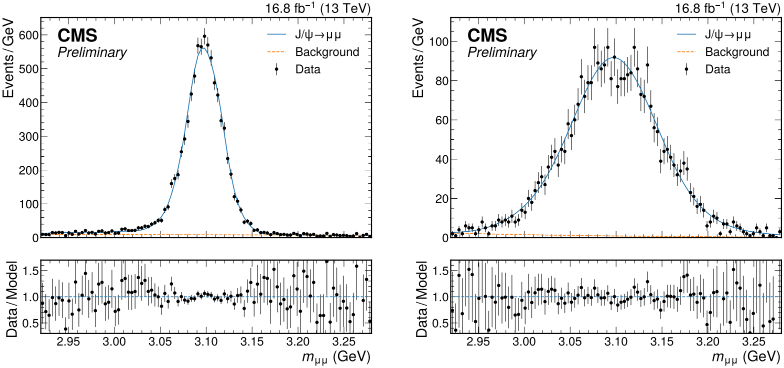


(c) +global corrections

- Curvature bias vs charge and momentum is fit using the functional form for the final calbration step which comes afterwards
- Both CVH refit and generalized global corrections are needed to remove all local biases such that the parameterization is valid in all detector regions
- Track refit also dramatically improves the description of the energy loss in some detector regions

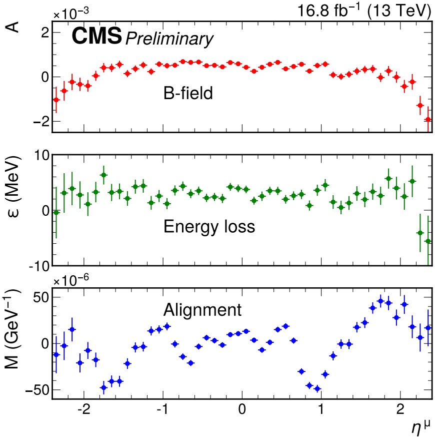
Final Parameterised Corrections

- Residual difference in mass scale between data and simulation is determined by fitting the $m_{\mu\mu}$ distribution in $J/\psi \rightarrow \mu\mu$ events
- Fits are finely binned in two-muon kinematics $(\eta^+, p_T^+, \eta^-, p_T^-)$



Final Parameterised Corrections

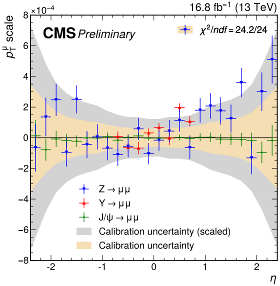
- Global χ^2 is constructed and minimized over all mass bins to extract calibration parameters at the single muon level, binned in η and parametrizing the p_T-dependence of the residual correction
- For muons in the relevant momentum range, residual corrections from $\sim 5 \times 10^{-4}$ in the central region up to a few 10^{-3} in the forward region



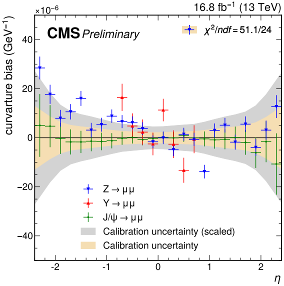
$$\frac{\delta k}{k} = A - \epsilon k + qM/k$$

Validation and uncertainties

charge-independent



charge-dependent



- Calibration is validated with $\Upsilon_{1S} \to \mu\mu$ and $Z \to \mu\mu$ in terms of B-field and alignment-like residual parameters
- B-field-like term for Z is consistent with zero within statistical uncertainties, alignment-like almost so
- Statistical uncertainty on calibration parameters from J/ψ scaled by 2.1 to cover all possible correlated patterns of bias across the detector from any not-explicitly-accounted-for systematic effects

Calibration Uncertainties

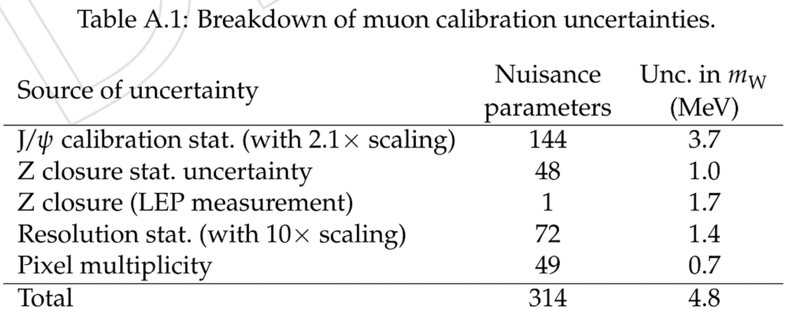


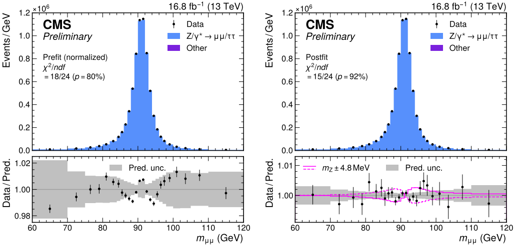
Table A.1: Breakdown of muon calibration uncertainties.

Source of uncertainty	Nuisance parameters	Unc. in m_W (MeV)
J/ψ calibration stat. (with 2.1× scaling)	144	3.7
Z closure stat. uncertainty	48	1.0
Z closure (LEP measurement)	1	1.7
Resolution stat. (with 10× scaling)	72	1.4
Pixel multiplicity	49	0.7
Total	314	4.8

- Z is not used in the final scale calibration, but uncertainties associated with the J/ψ vs Z closure are included since this is the precision with which the calibration is validated
- Small additional uncertainty for pixel hit multiplicity which mainly affects matching of data vs simulation resolution in the tails (but also results in some increase for the overall resolution uncertainties)

m_Z dilepton mass fit

- Final validation of calibration/uncertainties by extracting m_Z, dominated by calibration uncertainties
- 2D profile-likelihood fit in $m_{\mu\mu}$ and pseudo-rapidity of the most forward muon
- $\mathbf{m_Z - m_Z^{PDG} = -2.2 \pm 4.8}$ **MeV** $= -2.2 \pm 1.0$ (stat) ± 4.7 (syst) MeV



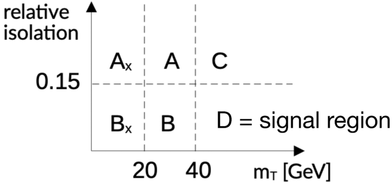
(a) prefit (normalised)

(b) postfit

- Since J/ψ vs Z closure was used to tune calibration and enters the uncertainty model, not (yet) a fully independent measurement for inclusion in world average

Non-prompt Background

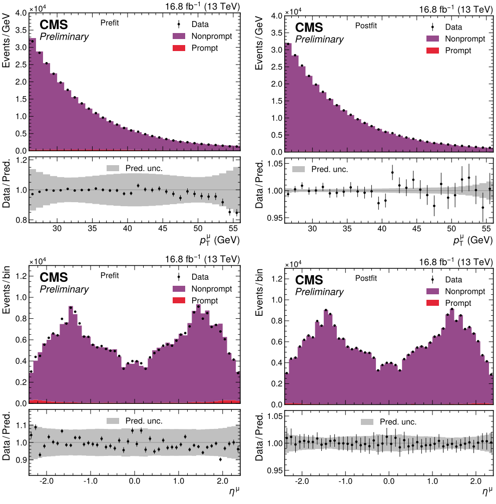
- Non-prompt background from QCD multijet event, mostly heavy flavour
- Data-driven estimate using extended ABCD method with 3 regions of transverse mass and 2 regions of isolation



$$D = C\frac{A_x B^2}{B_x A^2}$$

- Prompt contamination in sideband regions dominated by W and Z events, estimated from simulation with all corrections and uncertainties
    - including “anti-isolation” scale factors consistently anti-correlated with the isolation scale factors
- Non-prompt distributions are smoothed with polynomials
- Precedure validated using QCD Simulation and secondary-vertex control region in data

Nonprompt Background



(a) prefit (b) postfit

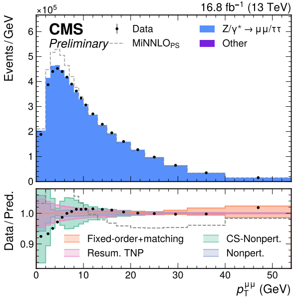
- Validation plots comparing extended ABCD nonprompt prediction to data in secondary vertex control region
- Very small prompt contamination
- 15% normalization correction applied (consistent between SV control region and QCD MC)
- additional normalization and shape uncertainties to cover residual differences

Theoretical Modeling

- **Overall strategy:** construct the best possible theoretical model for the W and constrain in-situ directly with the W data
- Z data is "only" used for validation
- **Nominal Theory uncertainties:**
  - Perturbative QCD
  - PDFs
  - Additional non-perturbative QCD (e.g. transverse momentum of partons within proton)
  - Electroweak effects
- **In addition:** Helicity cross section fit is used as a cross-check which augments or replaces the theory uncertainties by directly varying the different components of the angular decomposition
  - Reduced theory/model-dependence at the cost of increased statistical uncertainty

Theoretical Modeling: Technical Details

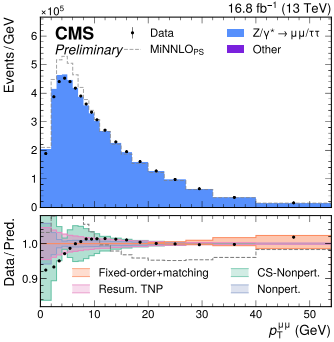
- Fully coherent theoretical treatment for W and Z (both μ and τ decays)
- Fully simulated MC samples with MiNNLOPS + Pythia 8 + Photos
  - $\mathcal{O}(\alpha_s^2)$ accuracy (also for angular coefficients), but limited logarithmic accuracy for W/Z p_T modeling from POWHEG emissions and shower

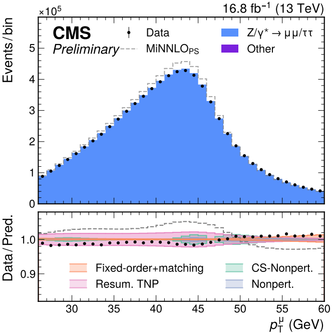


- σ^{U+L} is corrected double (triple) differentially for W (Z) production using resummed SCETLIB prediction matched to fixed order DYTurbo prediction ($N^3LL + NNLO$ for nominal predictions)
- Angular coefficients are left as-is (validated against MCFM and DYTurbo fixed order predictions)*

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

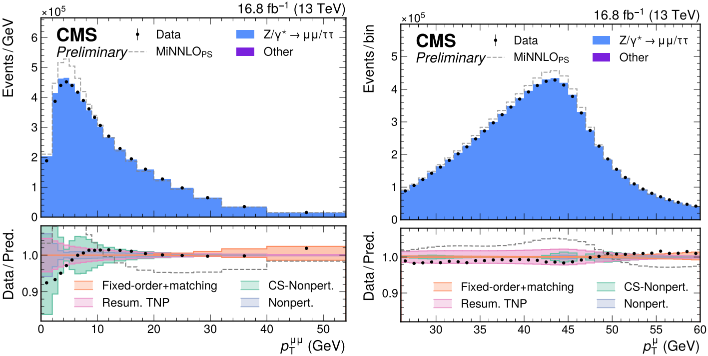
Boson p_T Modeling Uncertainties





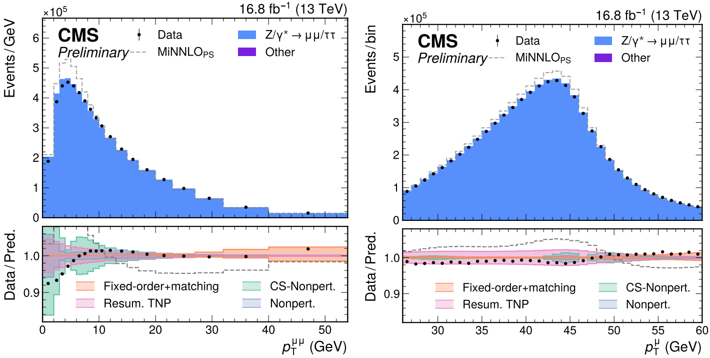
- **Non-perturbative:** Intrinsic momentum of partons (TMD PDF), non-perturbative uncertainties in resummation
- **Resummation** (perturbative): "Theory Nuisance Parameters" corresponding to coefficients in resummed calculation
- **Matching:** Variation in matching scale
- **Fixed order:** Missing higher orders in α_s assessed through μ_r, μ_f variations

Boson p_T Modeling Uncertainties: Non-perturbative effects



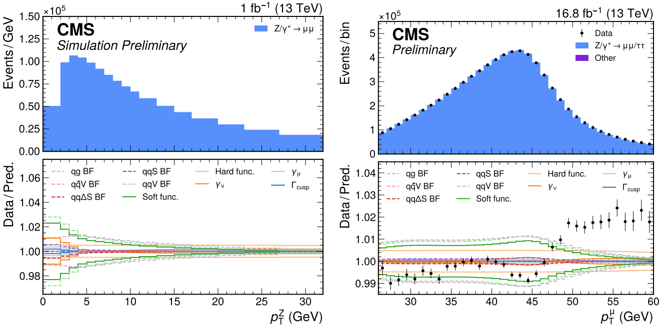
- **Empirical model inspired by TMD PDFs:** ∼Gaussian smearing of parton momentum, with additional freedom to account for possible x and flavour dependence
- The associated parameters cannot be predicted a priori, but must be determined from data (or lattice calculations)
- Initial values are somewhat arbitrary, with large uncertainties applied → **intended to be constrained from data**

Boson p_T Modeling Uncertainties: Non-perturbative effects



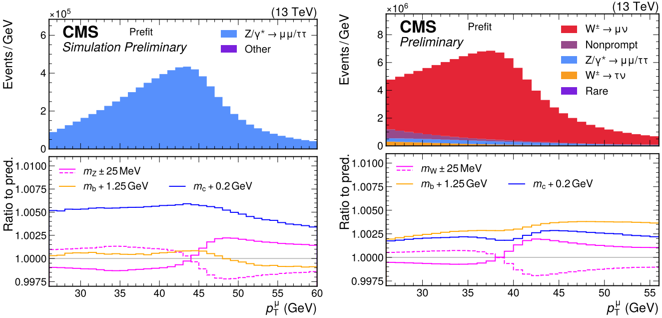
- CS kernel is related to matching of non-perturbative model to resummation and is "universal" (fully correlated between W and Z)
- The rest of the NP model is taken as decorrelated between W^+, W^- and Z, and with an additional rapidity-dependent term for the degree of smearing to account for possible x and flavour dependence

Boson p_T Modeling Uncertainties: Resummation



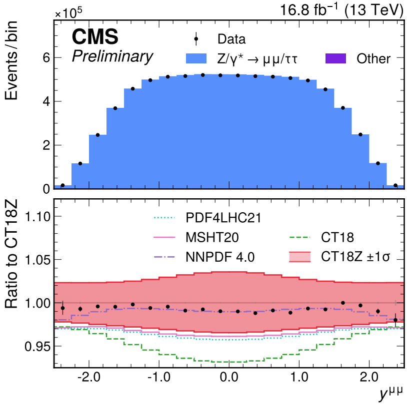
- Use "Theory Nuisances Parameters" corresponding to the terms appearing in the resummed calculation
- In contrast to scale variations, this provides a well defined correlation model across phase space (and between W and Z) and therefore better suited to profiling (see e.g. talk from F. Tackmann **here**)
- Propagating the uncertainty in this way facilitates constraining the theory from W data alone, but **also** makes the correlation model between W and Z more robust for a simultaneous fit/tuning

Boson p_T Modeling Uncertainties: Heavy Quark Mass Effects



- Impact of heavy quark mass effects at least partly evaluated by varying charm and bottom thresholds in MSHT20 PDF set
- Contribution to uncertainty on m_W: 0.6 MeV
- Somewhat different effects on W vs Z → More delicate for combined W+Z fit

Parton Distribution Functions



- **Good:** PDF sets are accompanied by uncertainty models with well defined correlations across phase space and between processes
- **Bad:** Different PDFs don't necessarily agree within their uncertainties
- Missing higher order uncertainties, resummation corrections in predictions usually not included
    - Partly mitigated by tolerance factors, etc

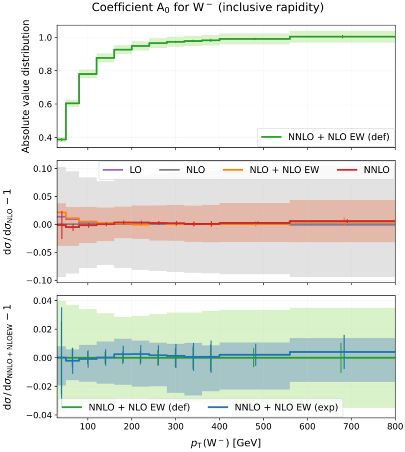
Parton Distribution Functions

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

- **Strategy:** Scale prefit PDF uncertainties to ensure consistency between sets for measured m_W value
- This procedure does **not** prove that e.g. NNPDF4.0 uncertainty is underestimated, only that it's too small to cover the central value of the other sets
- CT18Z is chosen as the nominal since it covers the others without scaling and with small uncertainty
    - But note that this set is amongst the largest in terms of nominal uncertainty

Angular Distributions

- Missing higher order uncertainties propagated to angular coefficients through variations of μ_r and μ_f in MiNNLOPS
- While MiNNLOPS predicts angular coefficients consistent with fixed order calculations, Pythia intrinsic k_T treatment actually modifies them somewhat
    - In particular A_1 and A_3 at low boson p_T due to isotropic smearing
- This effect may or may not be physical → propagate the full difference as an additional uncertainty



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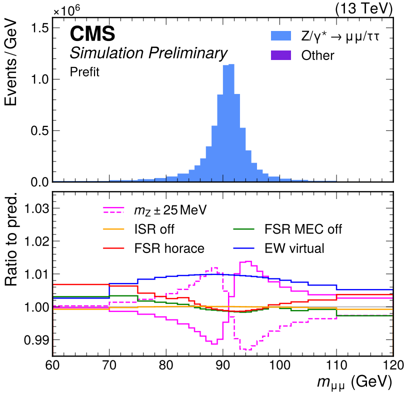
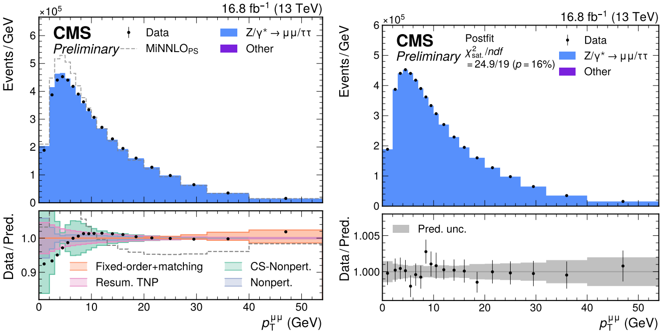
Electroweak Uncertainties



- Most important electroweak effect is from QED FSR, included in nominal MC prediction through PHOTOS
  - Includes higher order corrections and pair production
- Residual uncertainties for QED FSR (and ISR) very small, < 0.5MeV contribution for m_W
- Largest electroweak uncertainty from virtual corrections, $\sim$ 2MeV on m_W

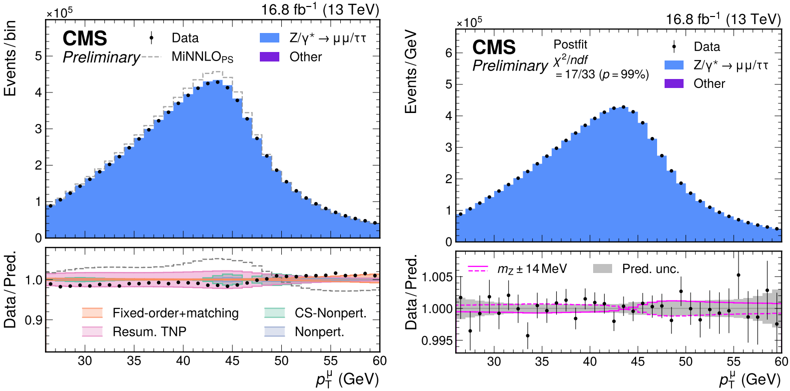
Validation of boson p_T modeling with $Z \rightarrow \mu\mu$



(a) prefit (b) postfit

- Fit theory model to dilepton p_T spectrum directly to validate that it can describe the data
- O(10%) level discrepancy due to untuned non-perturbative parameters at low p_T fully reabsorbed
- Postfit description of the spectrum at 0.1% level

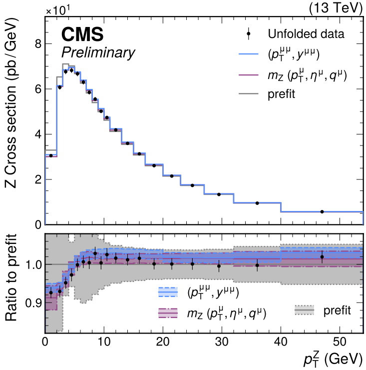
Validation of boson p_T modeling with W-like $Z \to \mu\mu$



(a) prefit (b) postfit

- When running the full W-like fit to single muon (η, p_T, charge) the theory model is also able to accommodate the muon p_T distribution very precisely

Validation of boson p_T modeling with $Z \to \mu\mu$



(a) Unfolded $d\sigma^{U+L}/dp_T$

- Detector level fit results can be propagated to predictions for unfolded Z p_T spectrum
    - For both direct fit to $p_T^{\mu\mu}$ and W-like fit to single muon $(\eta, p_T, \text{charge})$
- Strong and **consistent** constraints from **both** fits, and in agreement with unfolded data
- Direct fit to $p_T^{\mu\mu}$ has stronger constraints but W-like fit is able to correctly disentangle m_Z from the Z p_T spectrum
- **m_W can be measured without tuning the p_T spectrum to the Z**

Helicity Cross Section Fit

- Theory model represents our best understanding of QCD and proton structure
- As an additional test of its validity, or in case of BSM physics in W production or decay, a less model-dependent measurement of m_W is useful
- **Basic strategy:** Parameterize theory uncertainty explicitly in terms of the 9 helicity cross sections $\sigma_i \equiv \sigma^{U+L} A_i$ instead of the PDF and non-perturbative models + perturbative uncertainty, and fit the helicity cross sections (double-differential in W rapidity and p_T) together with m_W
- In this way theoretical uncertainties are “traded” for larger statistical uncertainties

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}q_T^2\,\mathrm{d}y\,\mathrm{d}m\,\mathrm{d}\cos\theta\,\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}^3\sigma^{U+L}}{\mathrm{d}q_T^2\,\mathrm{d}y\,\mathrm{d}m}\Big[(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1\sin 2\theta\cos\phi$$
$$+\frac{1}{2}A_2\sin^2\theta\cos 2\phi + A_3\sin\theta\cos\phi + A_4\cos\theta + A_5\sin^2\theta\sin 2\phi + A_6\sin 2\theta\sin\phi + A_7\sin\theta\sin\phi\Big]$$

- With current data/observables not possible to simultaneously constrain all of the relevant helicity components, so cross sections are regularized via constraints to the nominal prediction
- Relevant theory uncertainties are retained since they have different correlations

Nuisance Parameters

Systematic uncertainties	W-like m_Z	m_W
Muon efficiency	3127	3658
Muon eff. veto	–	531
Muon eff. syst.	343	
Muon eff. stat.	2784	
Nonprompt background	–	387
Prompt background	2	3
Muon momentum scale	338	
L1 prefire	14	
Luminosity	1	
PDF (CT18Z)	60	
Angular coefficients	177	353
W MiNNLO$_{PS}$ μ_F, μ_R	–	176
Z MiNNLO$_{PS}$ μ_F, μ_R	176	
PYTHIA shower k_T	1	
p_T^V modeling	22	32
Nonperturbative	4	10
Perturbative	4	8
Theory nuisance parameters	10	
c, b quark mass	4	
Higher-order EW	6	7
Z width	1	
Z mass	1	
W width	–	1
W mass	–	1
$\sin^2\theta_W$	1	
Total	3750	4859

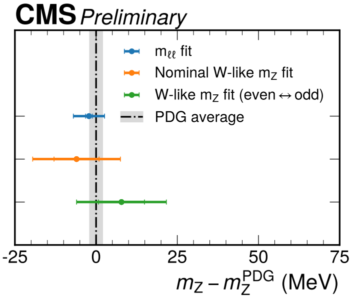
W-like m_Z result

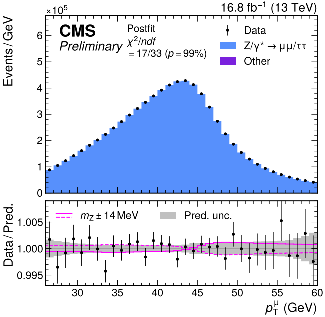
- Nominal W-like result:

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

- Even-odd event selection reversed (nearly statistically independent sample)

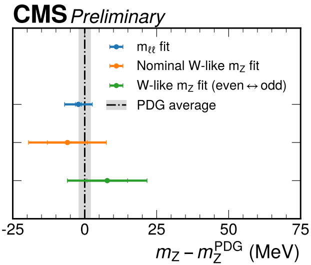
$$m_Z - m_Z^{\mathrm{PDG}} = 8 \pm 14\mathrm{MeV}$$





- All extracted m_Z values in agreement with the LEP/PDG value

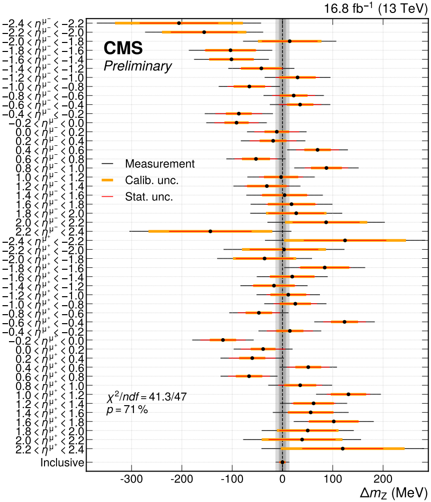
W-like m_Z result: Uncertainty Breakdown



Source of uncertainty	Impact (MeV) Nominal	Impact (MeV) Global
Muon momentum scale	5.6	5.3
Muon reco. efficiency	3.8	3.0
W and Z angular coeffs.	4.9	4.5
Higher-order EW	2.2	2.2
p_T^V modeling	1.7	1.0
PDF	2.4	1.9
Integrated luminosity	0.3	0.2
MC sample size	2.5	3.6
Data sample size	6.9	10.1
Total uncertainty	13.5	13.5

- Largest uncertainties are statistical, muon calibration, angular coefficients
- Total uncertainty is well defined, but several different ways of decomposing statistical and systematics uncertainties
- When uncertainties are constrained in-situ, “global” impacts (used e.g. for ATLAS 2024 m_W measurement) tends to count them as part of the statistical uncertainties

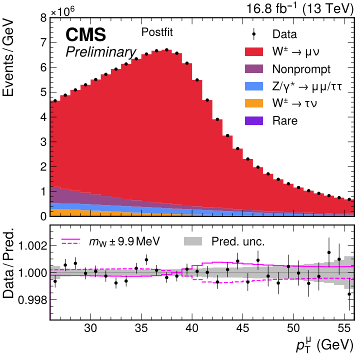
W-like m_Z result: Validation checks



- Consistent results when extracting 48 independent m_Z parameters split in charge and 24 η bins
- η-sign difference: $m_Z^{\eta>0} - m_Z^{\eta<0} = 35 \pm 20\text{MeV}$
- Charge difference: $m_Z^{+} - m_Z^{-} = 31 \pm 32\text{MeV}$
- Charge difference with reversed even-odd event selection: $m_Z^{+} - m_Z^{-} = 6 \pm 32\text{MeV}$

m_W Measurement

- Now with all elements in place, on to the m_W measurement:

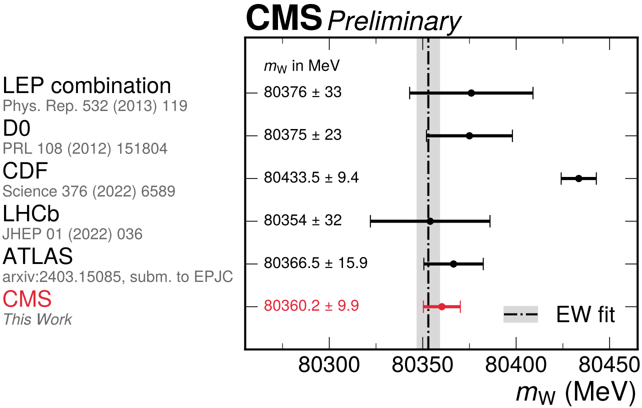


Source of uncertainty	Impact (MeV) Nominal	Impact (MeV) Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
p_T^V modeling	2.0	0.8
PDF	4.4	2.8
Nonprompt background	3.2	1.7
Integrated luminosity	0.1	0.1
MC sample size	1.5	3.8
Data sample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

- For the nominal measurement, total uncertainty is 9.9MeV
- Most precise measurement at the LHC and comparable to CDF precision

m_W result

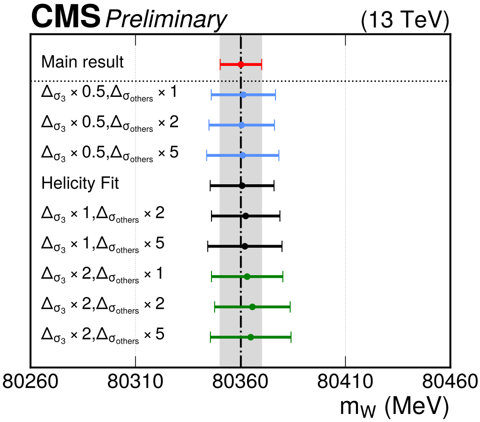
$$\mathbf{m_W = 80360.2 \pm 9.9 MeV}$$



- Compatible with the Standard Model expectation and with other measurements
- In clear tension with the CDF measurement

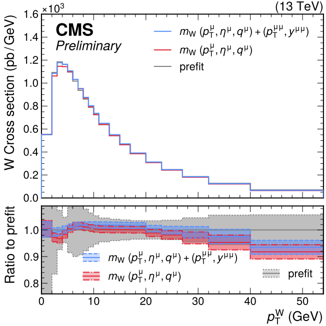
Helicity Cross Section Fit m_W result

Helicity Fit Result: $m_W = 80360.8 \pm 15.2\text{MeV}$



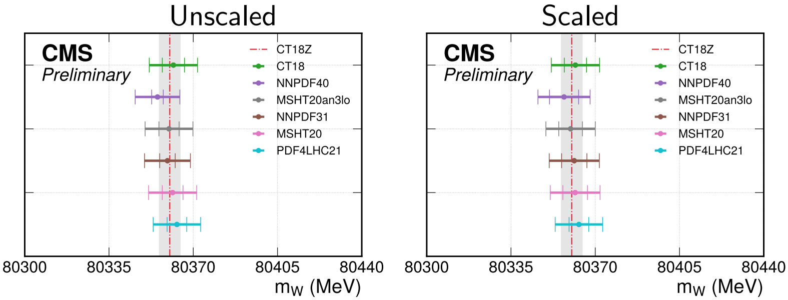
- Helicity cross section fit result very compatible with the nominal, with somewhat larger uncertainties as expected
- Result is very stable with looser or tighter initial constraints on the helicity cross sections

Validation: Simultaneous dilepton+W fit



- Nominal result is from fit to muon (η, p_T, charge) for W candidates alone
- Interesting to compare with simultaneous fit to $p_T^{\mu\mu}$ distribution from Z events
- Fit results propagated to inclusive W p_T distribution as for Z case shown previously
- **Postfit W p_T distribution broadly consistent and with strong constraints from data**
- $\Delta m_W = +0.6$ MeV with respect to nominal, uncertainty would decrease to 9.6 MeV
- But additional complications for W/Z correlations, so the nominal W only fit is more robust and is the nominal result

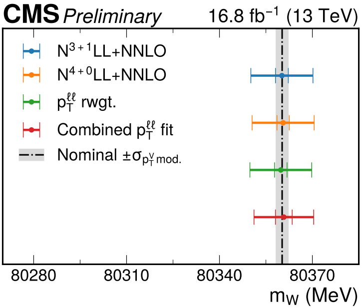
PDF Dependence of Result



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

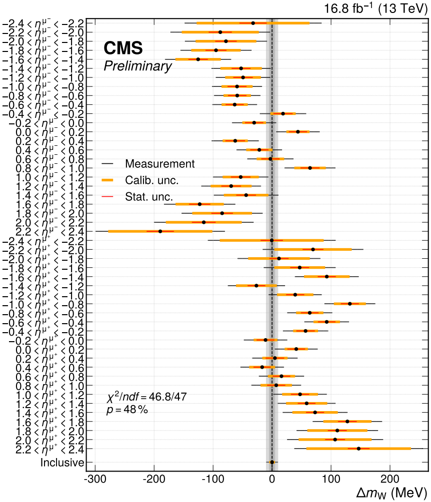
- Scaling of prefit PDF uncertainties reduces the dependence on PDF set and brings the variations within the quoted PDF uncertainties

Additional Theory Cross Checks



- Result is stable under variations of the TNP model and not very sensitive to changes in the initial prediction within the uncertainties

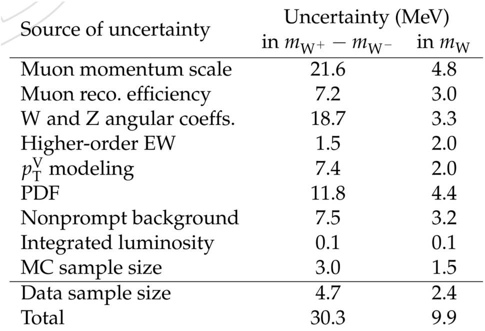
m_W result: Validation checks



- Consistent results when extracting 48 independent m_W parameters split in charge and 24 η bins
- η-sign difference: $m_W^{\eta>0} - m_W^{\eta<0} = 5.8 \pm 12.4\text{MeV}$
- Charge difference: $m_W^{+} - m_W^{-} = 57 \pm 30\text{MeV}$

m_W result: Closer look at charge difference

- $m_W^+ - m_W^- = 57 \pm 30$MeV, p-value 6.0%
- Uncertainty on charge difference much larger than nominal m_W uncertainty
- Strong anti-correlations due to experimental uncertainties (alignment) and theory uncertainties related to W polarization (opposite-parity coupling of W to μ^+ and μ^-)
- Correlation between charge difference and m_W itself is only 2%



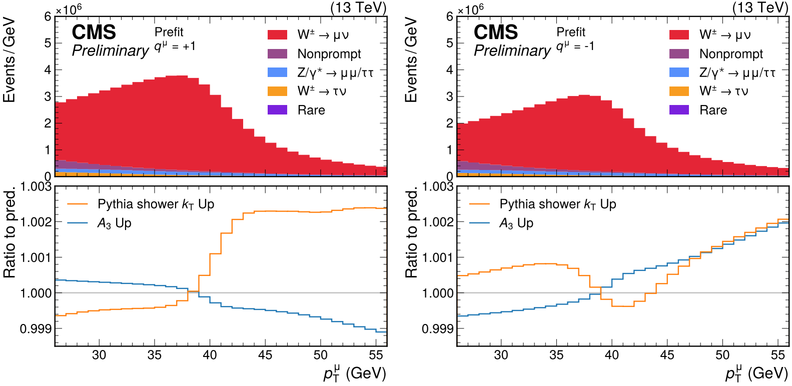
Source of uncertainty	Uncertainty (MeV) in $m_{W^+} - m_{W^-}$	in m_W
Muon momentum scale	21.6	4.8
Muon reco. efficiency	7.2	3.0
W and Z angular coeffs.	18.7	3.3
Higher-order EW	1.5	2.0
p_T^V modeling	7.4	2.0
PDF	11.8	4.4
Nonprompt background	7.5	3.2
Integrated luminosity	0.1	0.1
MC sample size	3.0	1.5
Data sample size	4.7	2.4
Total	30.3	9.9

m_W result: Closer look at charge difference

Configuration	$m_W^+ - m_W^-$ (MeV)	Δm_W (MeV)
nominal	57 ± 30	0
Alignment $\sim$1 sigma up	38 ± 30	< 0.1
LHE A_i as nominal	48 ± 30	-0.5
A_3 one sigma down	49 ± 30	0.4
Alignment and A_i shifted as above	21 ± 30	0.1
Alignment $\sim$ 3 sigma up	-5 ± 30	0.6

- Reminder: For W-like m_Z fit:
  $m_Z^+ - m_Z^- = 31 \pm 32$ MeV (nominal)
  $m_Z^+ - m_Z^- = 6 \pm 32$ MeV (reversed even-odd event selection)
- No conclusive evidence for a systematic problem ($< 2\sigma$)
- Statistical fluctuations from finite data and MC samples at the level of 16 MeV for $m_W^+ - m_W^-$
- Even extreme variations of the related systematics lead to small variations in m_W ($<$ 1MeV), within associated uncertainties
- Possible/plausible scenario: $\sim 1\sigma$ off on alignment and A_i's plus $\sim 1\ \sigma$ statistical fluctuation corresponds to totally negligible effect on m_W (0.1MeV)

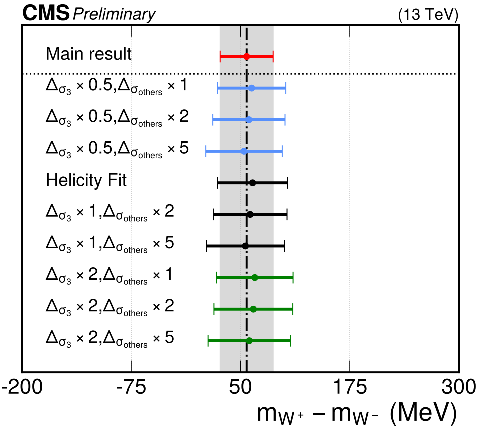
A_3 Variations By Charge



(a) W$^+$ (b) W$^-$

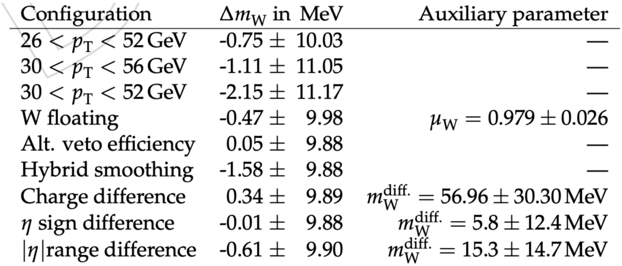
- A correlated variation of A_3 between W^+ and W^- produces an anti-correlated variation for the charged lepton kinematics
- The variation corresponding to switching off pythia intrinsic k_T for the angular coefficients mixes effects from A_1 and A_3

Charge Difference with Helicity Fit



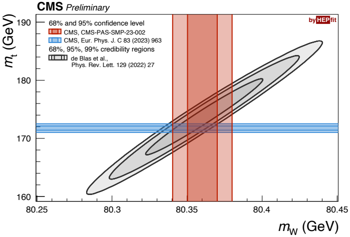
- Charge difference also very similar between nominal and helicity fit, and stable under changes in prefit uncertainties for the helicity cross sections

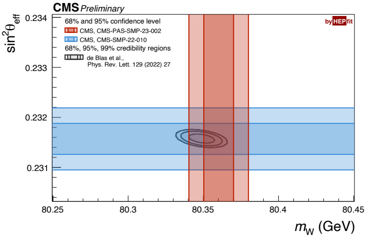
Additional Stability/Consistency Tests



Configuration	Δm_{W} in MeV	Auxiliary parameter
$26 < p_{\mathrm{T}} < 52\,\mathrm{GeV}$	-0.75 ± 10.03	—
$30 < p_{\mathrm{T}} < 56\,\mathrm{GeV}$	-1.11 ± 11.05	—
$30 < p_{\mathrm{T}} < 52\,\mathrm{GeV}$	-2.15 ± 11.17	—
W floating	-0.47 ± 9.98	$\mu_{\mathrm{W}} = 0.979 \pm 0.026$
Alt. veto efficiency	0.05 ± 9.88	—
Hybrid smoothing	-1.58 ± 9.88	—
Charge difference	0.34 ± 9.89	$m_{\mathrm{W}}^{\mathrm{diff.}} = 56.96 \pm 30.30\,\mathrm{MeV}$
η sign difference	-0.01 ± 9.88	$m_{\mathrm{W}}^{\mathrm{diff.}} = 5.8 \pm 12.4\,\mathrm{MeV}$
$\lvert\eta\rvert$range difference	-0.61 ± 9.90	$m_{\mathrm{W}}^{\mathrm{diff.}} = 15.3 \pm 14.7\,\mathrm{MeV}$

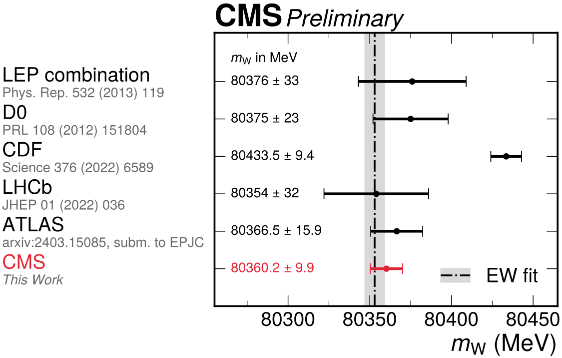
Towards the Electroweak Fit Precision





Conclusions

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

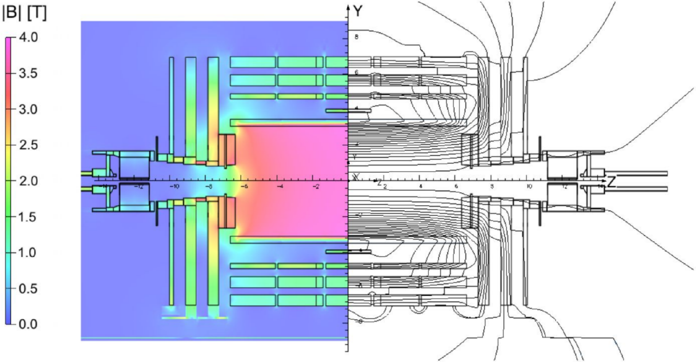


- This is the first m_W measurement from CMS
- Measurement is performed with ~ 10% of Run 2 data
- Major advances in experimental and theoretical techniques form the basis for further improved precision and additional measurements in the future

Backup

JINST 5:T03021,2010
Symmetry 14 (2022) 169

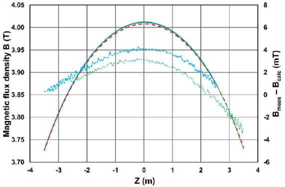
Magnetic Field Model



Magnetic Field Model

JINST 5:T03021,2010
Symmetry 14 (2022) 169

- High granularity (33,840 space points) 3D field map taken in 2006 (but on the surface and without much of the detector)
    - NMR probes with relative accuracy better than 5e-5 and calibrated hall probes with accuracy of ~3e-4
- TOSCA model+parameterization used for track reconstruction reproduces field map data to +-0.1% with some variation vs z
- Possible future improvement: use the (interpolated) field map data directly
- Several NMR probes inside the solenoid (but outside the tracking volume) for monitoring
- **Magnetic field in tracking volume known to 0.1% a priori**
    - Residual corrections at this level not-unexpected
    - Uniformity could possibly be improved with direct use of field map data



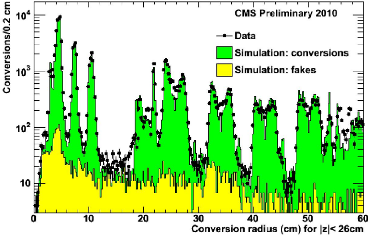
Model vs field map data at R = 0.1m (surface)

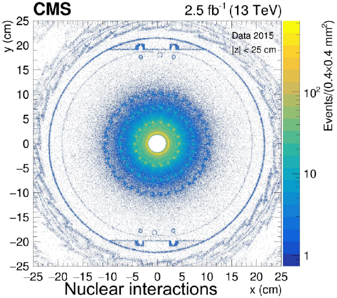
Source	Field	Δ (rel.)
Surface NMR (2006)	3.9176T	-8e-4
In-situ NMR (2008)	3.9206T	0
In-situ Model Prediction	3.9181T	-6e-4

Model vs NMR Measurements at R = 2.91m, z = -0.01m

CMS-TRK-10-003, CMS DP-2019/001

Material Model

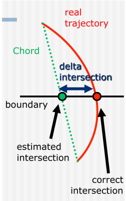


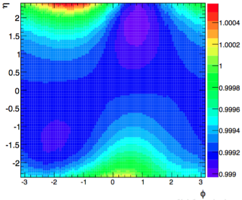


- Material model in simulation is correct at the O(10%) level
- Additional corrections may be needed due to the infinitesimal plane approximation in the tracking

Muon Momentum Calibration

- Tune simulation parameters to remove small biases
  - Increase Geant4 surface surface intersection precision to avoid small, charge-dependent, accumulating biases in the propagation
- Refit muon tracks to remove small biases and improve B-field and material modeling
  - Continuous Variable Helix fit developed for this measurement which extends Generalized Broken Line fit with quasi-continuous energy loss and multiple scattering using Geant4e propagator
  - Avoids infinitesimal-plane approximation for material since full simulation geometry is used
  - Higher accuracy B-field map from full 3d field-survey





Muon Momentum Calibration

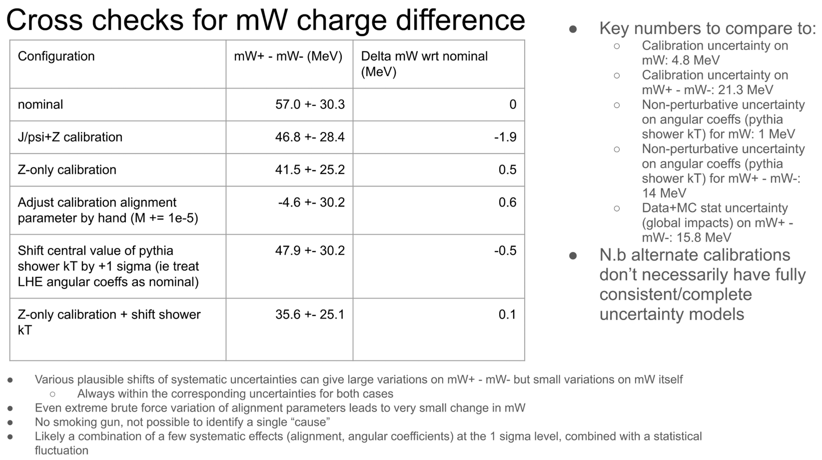
- Correct for local biases in B-field, material and alignment between data and reconstruction model
    - Generalization of global alignment procedure with additional parameters for local magnetic field and material corrections
    - Parameters determined from $J/\psi \rightarrow \mu\mu$ events
    - Sufficient to correct local biases, but limitations in Gaussian mass constraint leave significant weak modes remaining
- Final corrections for residual scale differences between data and simulation
    - High accuracy determination of residual B-field, material (energy loss) and alignment biases using mass fits in $J/\psi \rightarrow \mu\mu$ events
    - Parameterized using "simple" functional form since local biases have been removed or corrected
    - Residual resolution corrections from J/ψ and $Z \rightarrow \mu\mu$ using corresponding parameterization for hit resolution, multiple scattering and correlation terms

Parton Distribution Functions

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

- **Strategy:** Scale prefit PDF uncertainties to ensure consistency between sets for measured m_W value
- Scaling factors are determined with analysis still blind by using pseudodata generated from each PDF set and fitting with every other PDF set and its uncertainty
- n.b. symmetrization procedure is applied for asymmetric uncertainties which tends to increase the uncertainty for CT18 and MSHT
- This procedure does **not** prove that e.g. NNPDF4.0 uncertainty is underestimated, only that it's too small to cover the central value of the other sets
- CT18Z is chosen as the nominal since it covers the others without inflation and small uncertainty

Additional checks related to charge diff



Cross checks for mW charge difference

Configuration	mW+ - mW- (MeV)	Delta mW wrt nominal (MeV)
nominal	57.0 +- 30.3	0
J/psi+Z calibration	46.8 +- 28.4	-1.9
Z-only calibration	41.5 +- 25.2	0.5
Adjust calibration alignment parameter by hand (M += 1e-5)	-4.6 +- 30.2	0.6
Shift central value of pythia shower kT by +1 sigma (ie treat LHE angular coeffs as nominal)	47.9 +- 30.2	-0.5
Z-only calibration + shift shower kT	35.6 +- 25.1	0.1

- Key numbers to compare to:
  - Calibration uncertainty on mW: 4.8 MeV
  - Calibration uncertainty on mW+ - mW-: 21.3 MeV
  - Non-perturbative uncertainty on angular coeffs (pythia shower kT) for mW: 1 MeV
  - Non-perturbative uncertainty on angular coeffs (pythia shower kT) for mW+ - mW-: 14 MeV
  - Data+MC stat uncertainty (global impacts) on mW+ - mW-: 15.8 MeV
- N.b alternate calibrations don't necessarily have fully consistent/complete uncertainty models

- Various plausible shifts of systematic uncertainties can give large variations on mW+ - mW- but small variations on mW itself
  - Always within the corresponding uncertainties for both cases
- Even extreme brute force variation of alignment parameters leads to very small change in mW
- No smoking gun, not possible to identify a single "cause"
- Likely a combination of a few systematic effects (alignment, angular coefficients) at the 1 sigma level, combined with a statistical fluctuation

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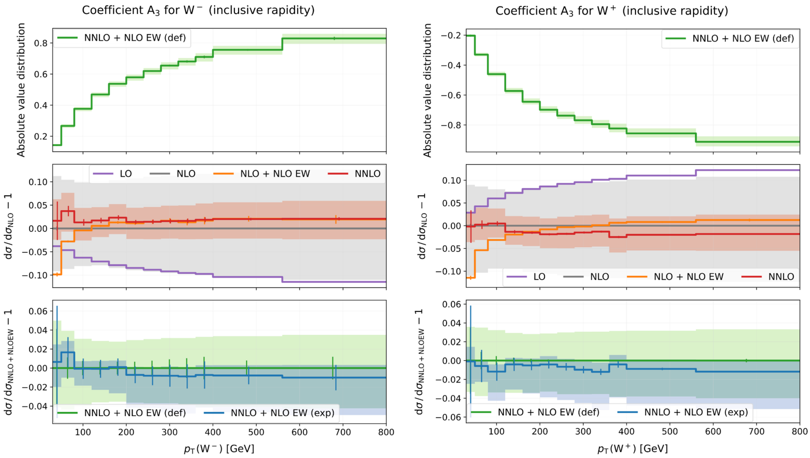
Higher order corrections for A_3



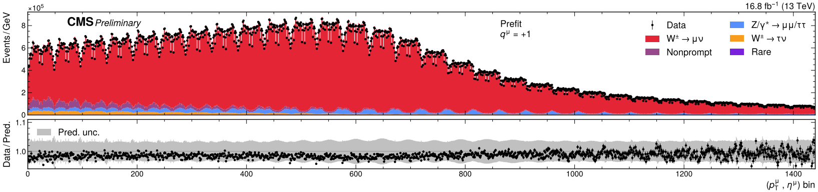
Charge Difference Impacts: Nominal

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

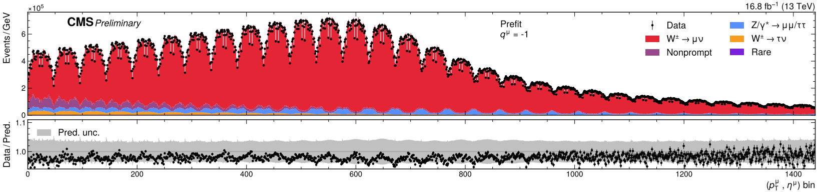
Charge Difference Impacts: Global

Source of uncertainty	Global impact (MeV) in $m_{Z^+} - m_{Z^-}$	in m_Z	in $m_{W^+} - m_{W^-}$	in m_W
Muon momentum scale	21.2	5.3	20.0	4.4
Muon reco. efficiency	6.5	3.0	5.8	2.3
W and Z angular coeffs.	13.9	4.5	13.7	3.0
Higher-order EW	0.2	2.2	1.5	1.9
p_T^V modeling	0.4	1.0	2.7	0.8
PDF	0.7	1.9	4.2	2.8
Nonprompt background	–	–	4.8	1.7
Integrated luminosity	< 0.1	0.2	0.1	0.1
MC sample size	6.4	3.6	8.4	3.8
Data sample size	18.1	10.1	13.4	6.0
Total uncertainty	32.5	13.5	30.3	9.9

Prefit

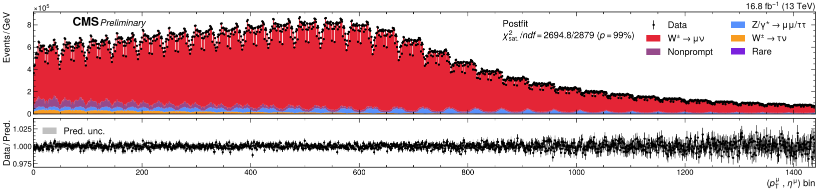


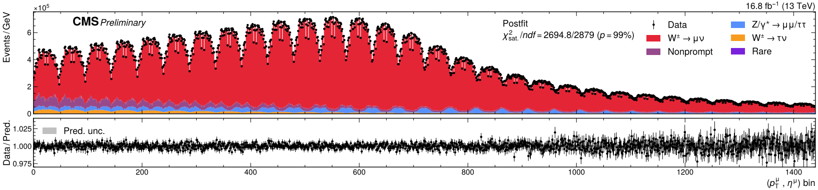
×10^5
16.8 fb^-1 (13 TeV)
CMS Preliminary
Prefit
q^μ = +1
Data
W± → μν
Nonprompt
Z/γ* → μμ/ττ
W± → τν
Rare
Events / GeV
0
2
4
6
8
Pred. unc.
Data / Pred.
1.0
1.1
0
200
400
600
800
1000
1200
1400
(p_T^μ , η^μ) bin



×10^5
16.8 fb^-1 (13 TeV)
CMS Preliminary
Prefit
q^μ = -1
Data
W± → μν
Nonprompt
Z/γ* → μμ/ττ
W± → τν
Rare
Events / GeV
0
2
4
6
Pred. unc.
Data / Pred.
1.0
1.1
0
200
400
600
800
1000
1200
1400
(p_T^μ , η^μ) bin

Postfit

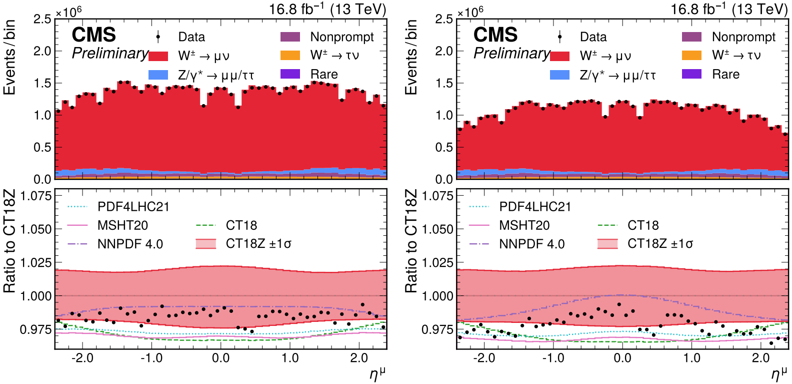

×10⁵
16.8 fb⁻¹ (13 TeV)
CMS Preliminary
Postfit
$\chi^2_{\mathrm{sat.}}/ndf = 2694.8/2879$ ($p = 99\%$)
Data
W± → μν
Nonprompt
Z/γ* → μμ/ττ
W± → τν
Rare
Events / GeV
0
2
4
6
8
Data / Pred.
Pred. unc.
1.025
1.000
0.975
0
200
400
600
800
1000
1200
1400
(p_T^μ, η^μ) bin


×10⁵
16.8 fb⁻¹ (13 TeV)
CMS Preliminary
Postfit
$\chi^2_{\mathrm{sat.}}/ndf = 2694.8/2879$ ($p = 99\%$)
Data
W± → μν
Nonprompt
Z/γ* → μμ/ττ
W± → τν
Rare
Events / GeV
0
2
4
6
Data / Pred.
Pred. unc.
1.025
1.000
0.975
0
200
400
600
800
1000
1200
1400
(p_T^μ, η^μ) bin

PDF Compatibility with Data

PDF set	Nominal fit		Without PDF+α_s unc.		Without theory unc.	
	χ^2/ndf	p-val. (%)	χ^2/ndf	p-val. (%)	χ^2/ndf	p-val. (%)
CT18Z	100.7/116	84	125.3/116	26	103.8/116	78
CT18	100.7/116	84	153.2/116	1.0	105.7/116	74
PDF4LHC21	97.7/116	89	105.5/116	75	104.1/116	78
MSHT20	97.0/116	90	107.4/116	70	98.8/116	87
MSHT20aN3LO	99.0/116	87	122.8/116	31	101.9/116	82
NNPDF3.1	99.1/116	87	105.5/116	75	115.0/116	51
NNPDF4.0	99.7/116	86	104.3/116	77	116.7/116	46

PDF Compatibility with Data



Comparisons

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

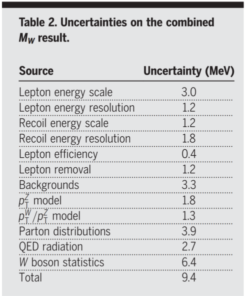


Table 2. Uncertainties on the combined M_W result.

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

Source of uncertainty	Impact (MeV) Nominal	 Global
Muon momentum scale	4.8	4.4
Muon reco. efficiency	3.0	2.3
W and Z angular coeffs.	3.3	3.0
Higher-order EW	2.0	1.9
$p_{\mathrm{T}}^{\mathrm{V}}$ 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