35th Rencontres de Blois on Particle Physics and Cosmology, October 22nd, 2024

High-precision measurement of the W boson mass at CMS

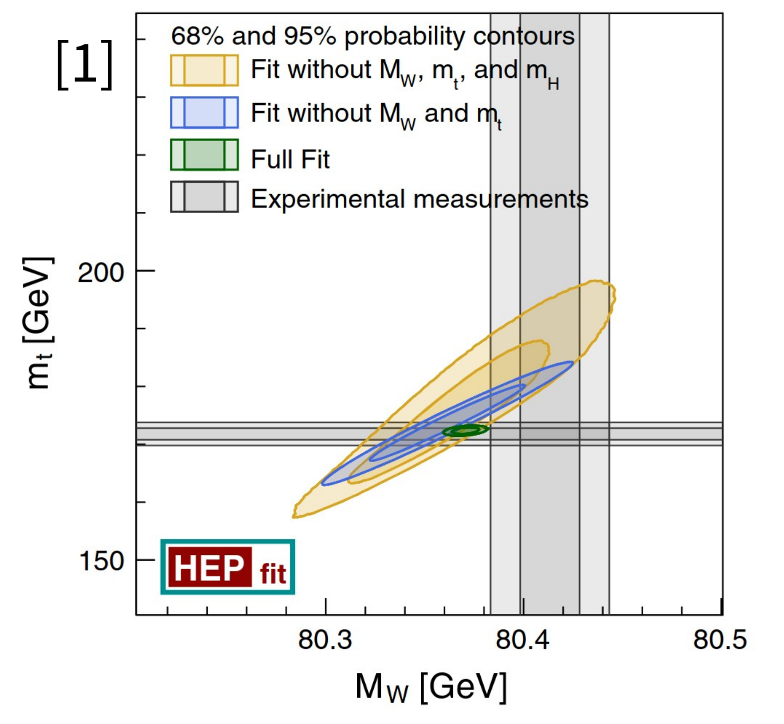
Davide Bruschini[1,2] on behalf of the CMS collaboration

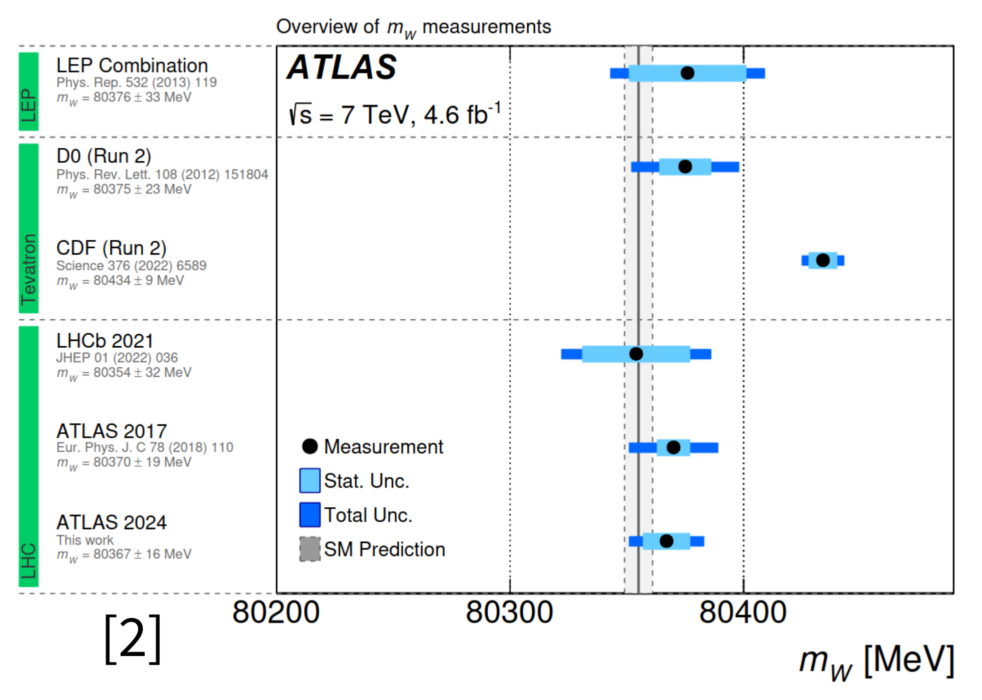
1: Scuola Normale Superiore, Pisa

2: INFN Sezione di Pisa

Overview

[1]





[2]

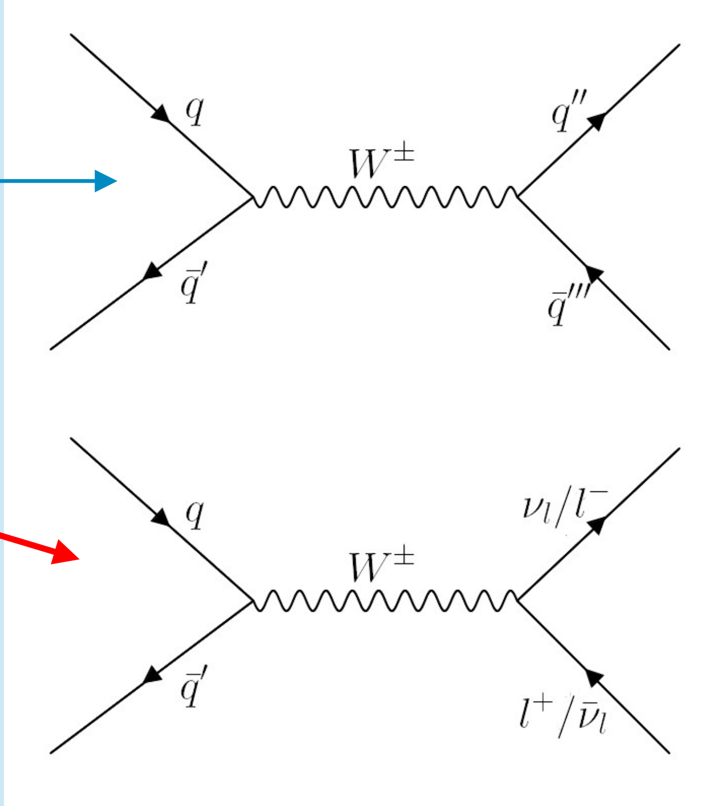
- m_W provides a stringent test of the internal consistency of the Standard Model. The global Electroweak Fit allows for a precise prediction of m_W given m_H, m_t, etc.
  - m_W predicted by EW fit with **Δm_W=6 MeV** (10^{-4} precision) uncertainty, **Δm_W on PDG average in 2022 = 13 MeV**
  - Last **CDF II** measurement in **strong tension with SM prediction and previous measurements**

W boson production and decay

- Production of W boson from quarks inside the colliding protons
- Hadronic channel not feasible due to huge QCD backgrounds/jet energy scale
- **Focus on leptonic decay**
  - Production of a neutrino which goes undetected
    - Loss of information on final state (particularly along collision axis)
    - Reconstruction of charged lepton
    - Neutrino inferred from missing transverse momentum, or p_T^{miss}, also used to define m_T

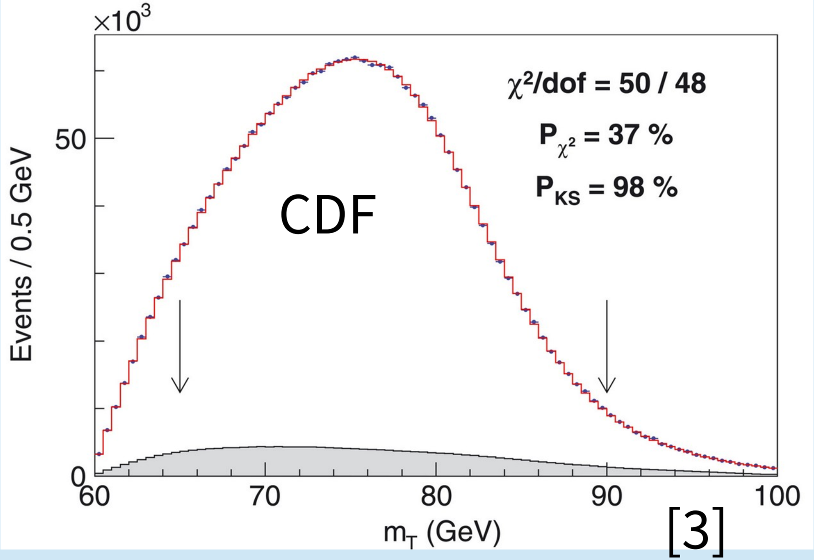
$$\vec{p}_T^{miss} = -\sum_{i=0}^{N_{rec}} \vec{p}_T$$

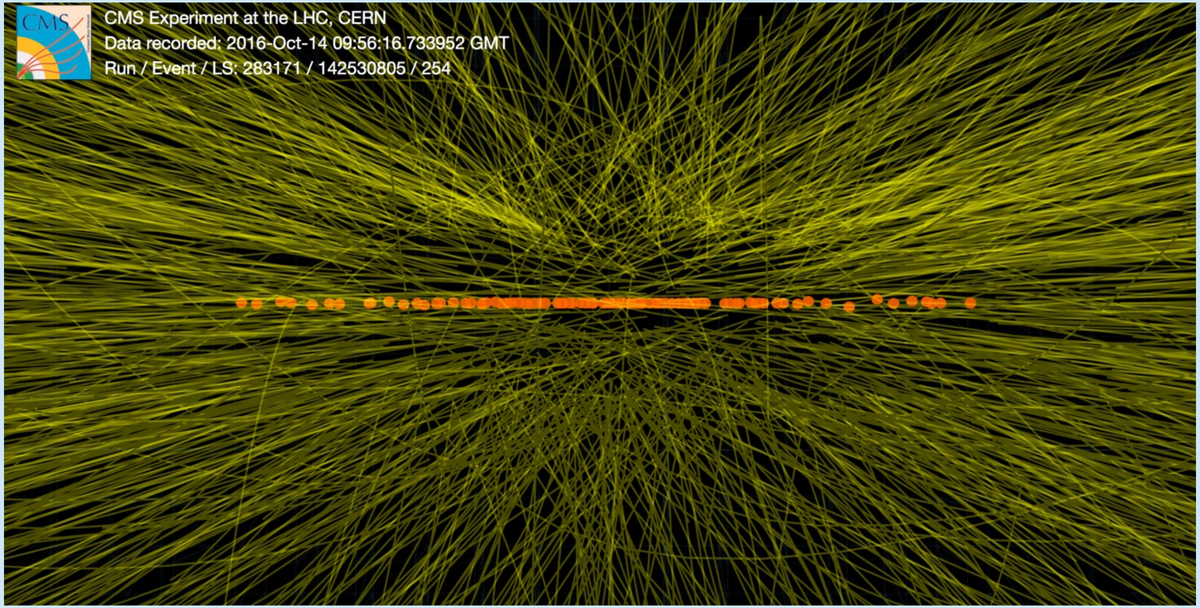
$$m_T = \sqrt{2 p_T^l p_T^{miss} \left(1 - \cos \Delta\phi_{p_T^l, p_T^{miss}}\right)}$$



Measuring m_W at hadron colliders

- M_W extracted from 1D template fits to m_T and/or p_T:
  - M_T more robust wrt theoretical calculations, but resolution limited at high pileup environments → **focus on p_T**





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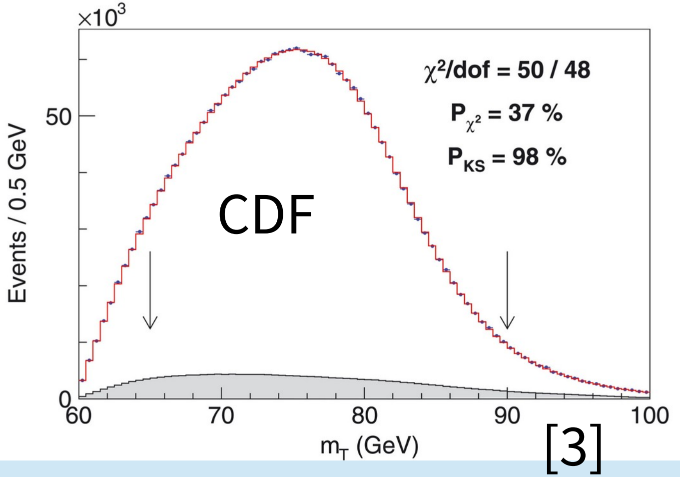
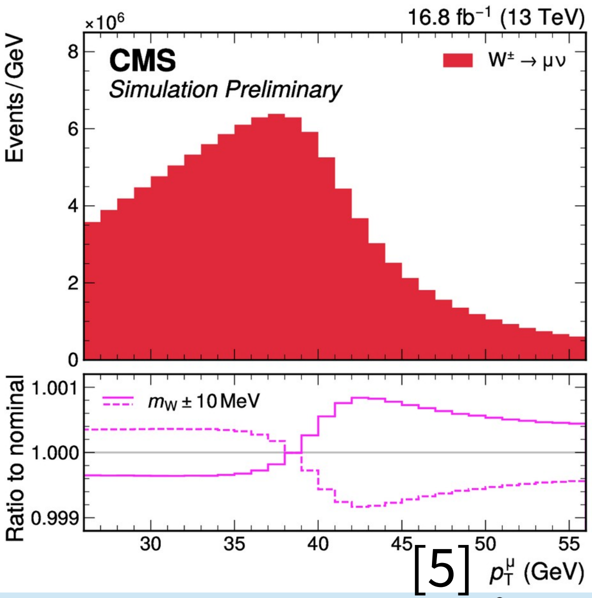
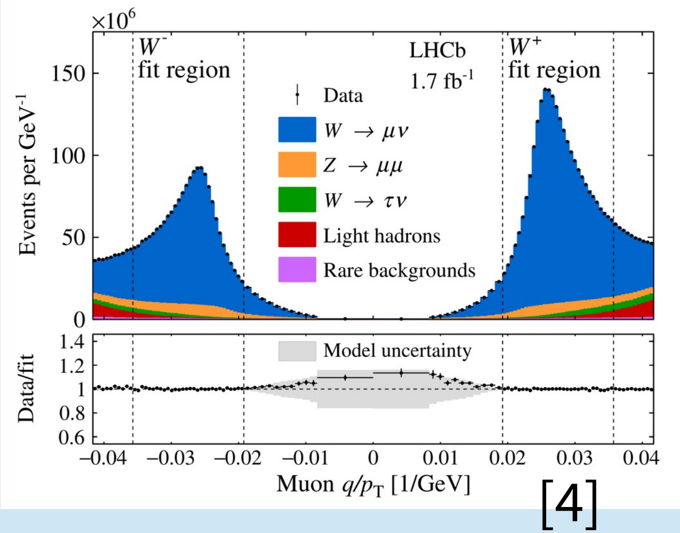






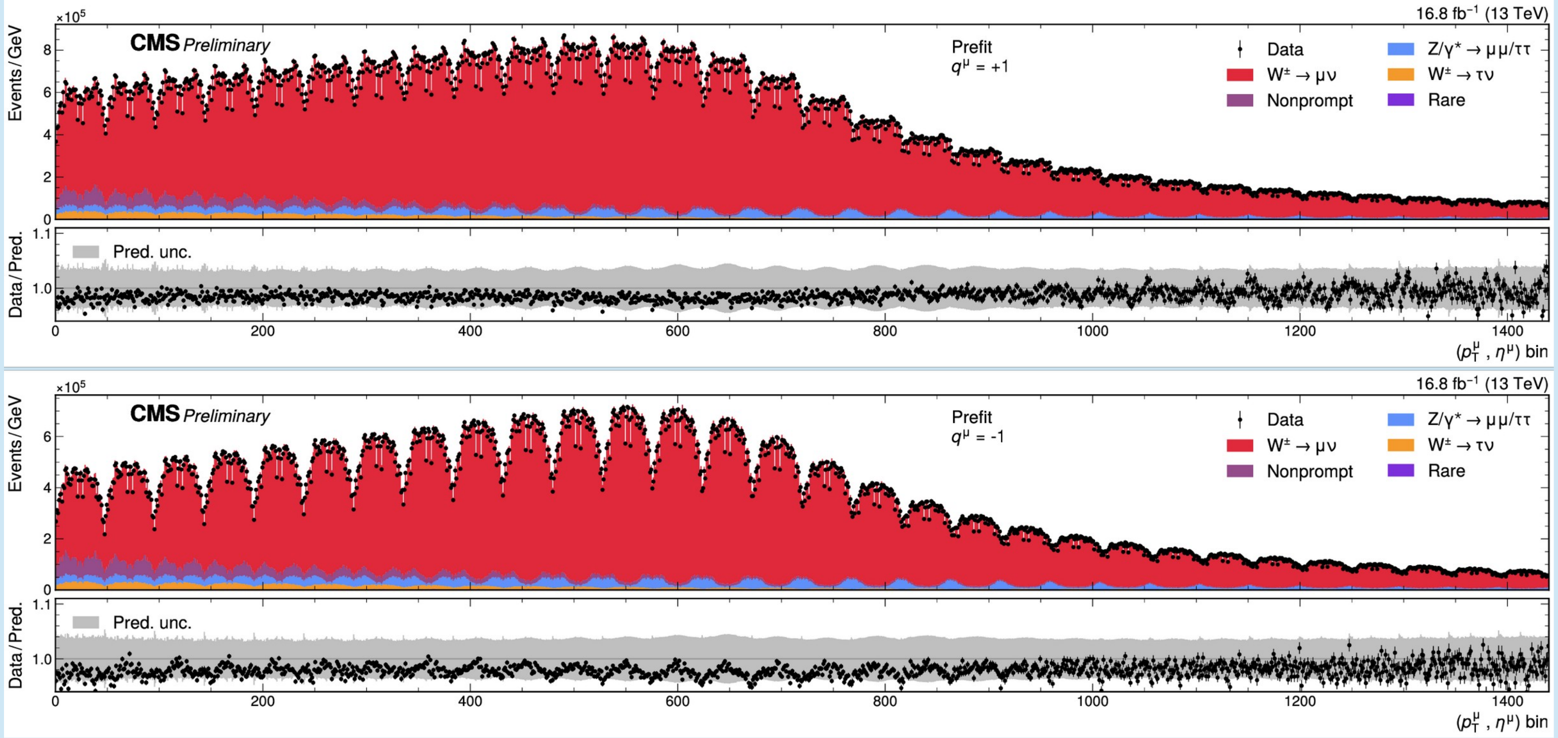
- **10 MeV shift of m_W modifies observables below permille level**
- Outstanding control of the W kinematics:
  - Theory: PDFs (Y_W), QCD/EW higher orders and non-perturbative effects (p_T^W, A_i's)
  - Experiment: detector calibration, efficiencies (+outstanding control of backgrounds)

CMS strategy [5]

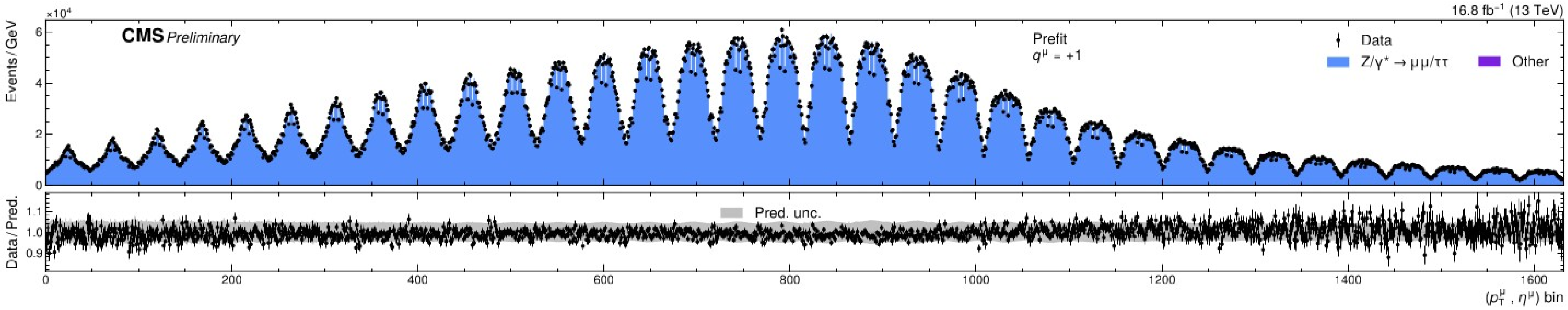
- Exploit larger **Run 2 data set** (albeit with higher pileup) compared to 7 TeV Run 1 dataset used for ATLAS measurements so far
- Use **well-understood subset** (16.8/fb for the later part of 2016):
  - Largest dataset ever used for m_W
- Focus on charged **lepton kinematics in 3D space of muon p_T-η-q:**
  - **P_T^W**: use theoretical model with **large systematic uncertainties which are constrained in-situ:**
    - **Z kept as independent cross-check**
  - **PDFs:** proven in W helicity and rapidity measurement [6] that these are significantly constrained
  - **Important:** P_T^W and PDF variations significantly different from m_W variations
- No electrons or m_T for now, more challenging systematics, additional work required

The analysis

- Simultaneous maximum likelihood fit to muon p_T-η distribution for W+ and W-:
  - **2880 bins**
  - **O(5k) systematic variations**
  - **4.5B fully simulated MC events, >100M selected W candidates**



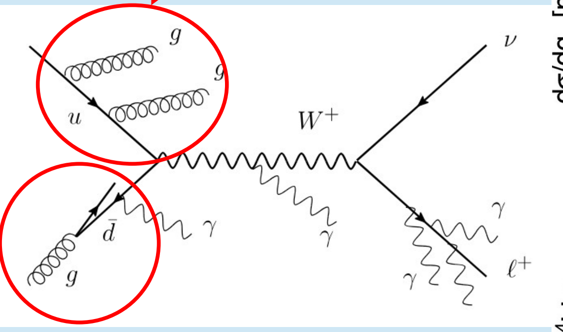
“W-like” selection of Z events



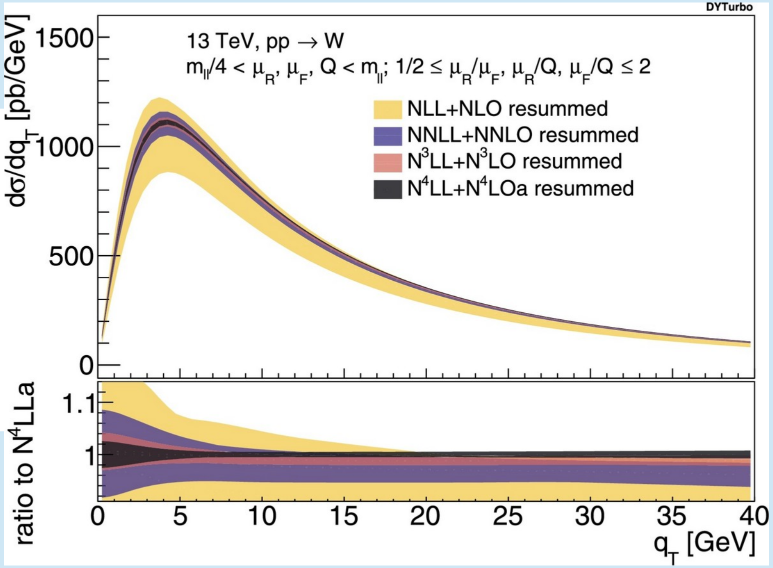
- $Z \rightarrow \mu\mu$ events are also selected with very similar selection
- One muon removed and treated as neutrino
- To avoid statistical correlations, split events in two. Positive (negative) muons for even (odd) numbered events are considered as muon in the analysis
- Z mass can be extracted from single muon (η, p_T, q) distribution as for W case
- Validates all aspects of the actual W measurement except for non-prompt and $Z \rightarrow \mu\mu$ background

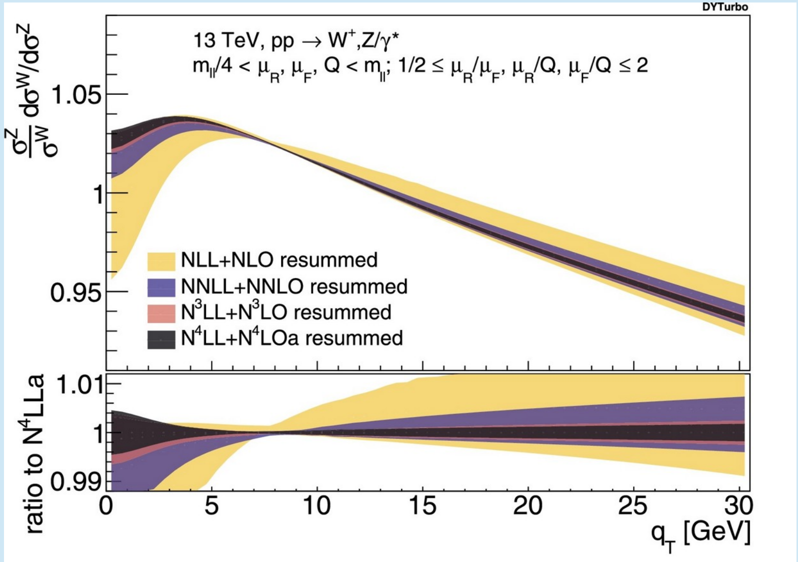
P_T^W modelling

- Conventional wisdom: estimate p_T^W using measured p_T^Z spectrum and rely on theoretical ratio of W/Z cross sections. Uncertainties expressed in terms of QCD scales decorrelated in bins of p_T^W and angular coefficients
  - **QCD scales don't capture non-perturbative effects**
  - Not physical parameters → **no statistical meaning if constrained**
  - large dependence of the uncertainty on the degree of correlation that is assumed between W and Z



Peak at low p_T

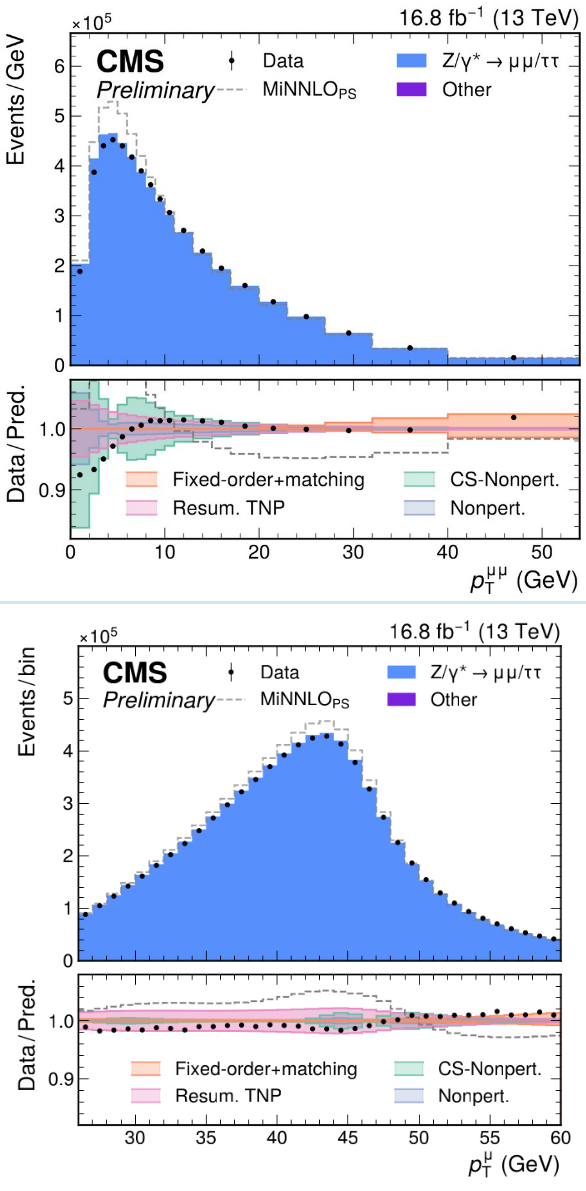




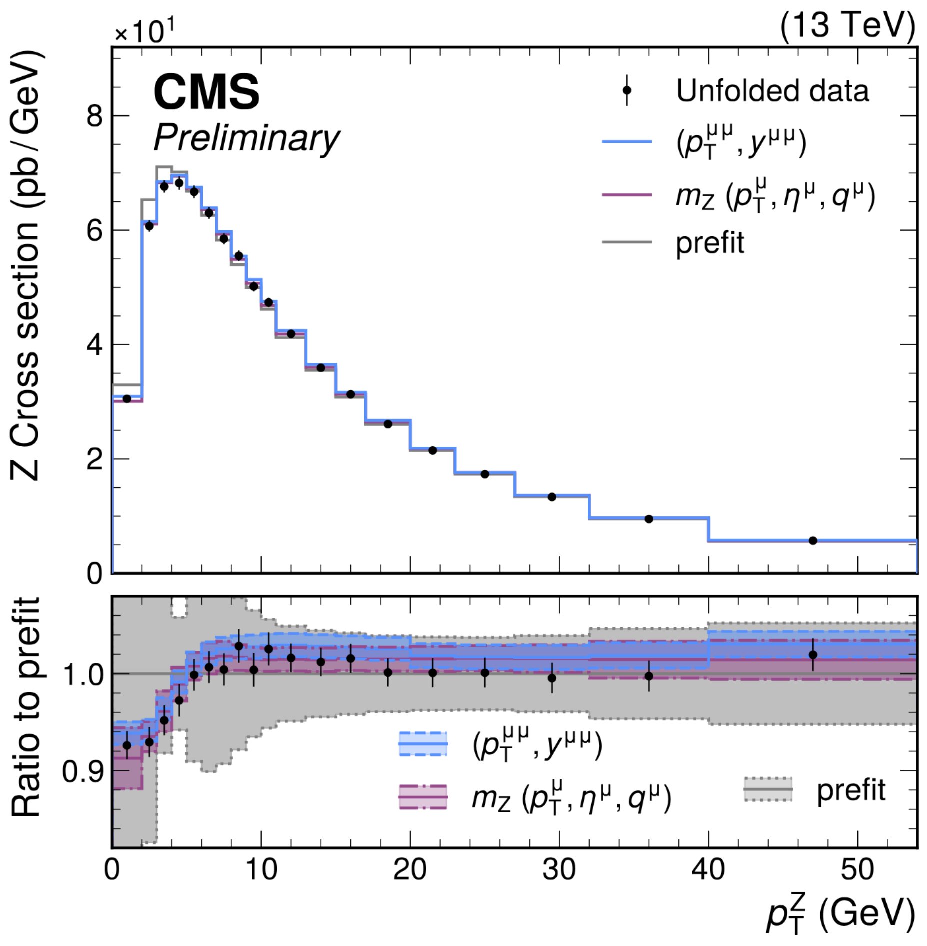
PLB 845 (2023) 138125

P_T^W modelling

- Simulation of events using **MiNNLO$_{PS}$ + Pythia8 + Photos (NNLO)**
- Reweighting to match predictions from **SCETLib + DYTurbo (N3LL + NNLO)**
- **Non-perturbative model and uncertainties inspired by TMD-PDFs**
- "Theory Nuisance Parameters" encoding missing higher orders in resummed calculations (details in [7], [8])
- **well defined physics meaning**, can then be used in a fit as any other nuisance parameter



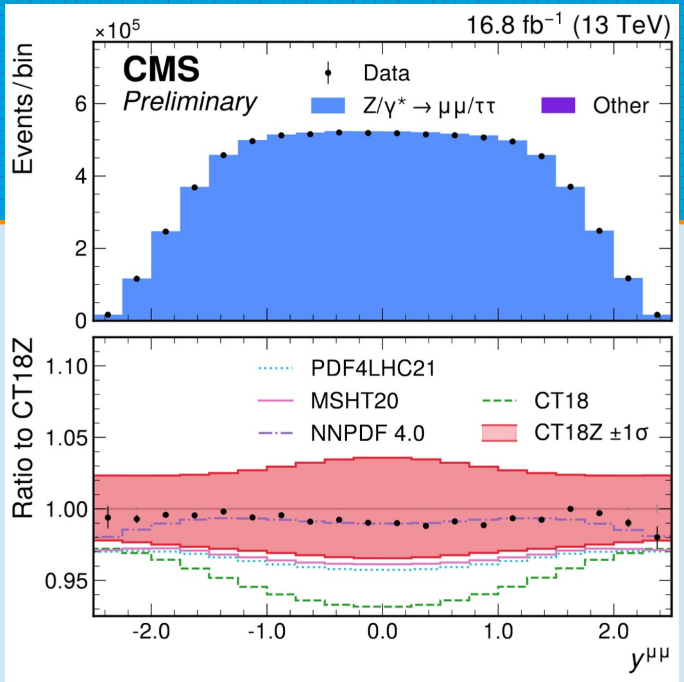
Model validation



- Comparison of p_T^{ll} unfolded at generator level with predictions from theory model
  - For both direct fit to $p_T^{\mu\mu}$ and W-like fit to single muon (η, p_T, q)
- **Agreement between unfolded data and postfit distributions**
- 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**

PDFs

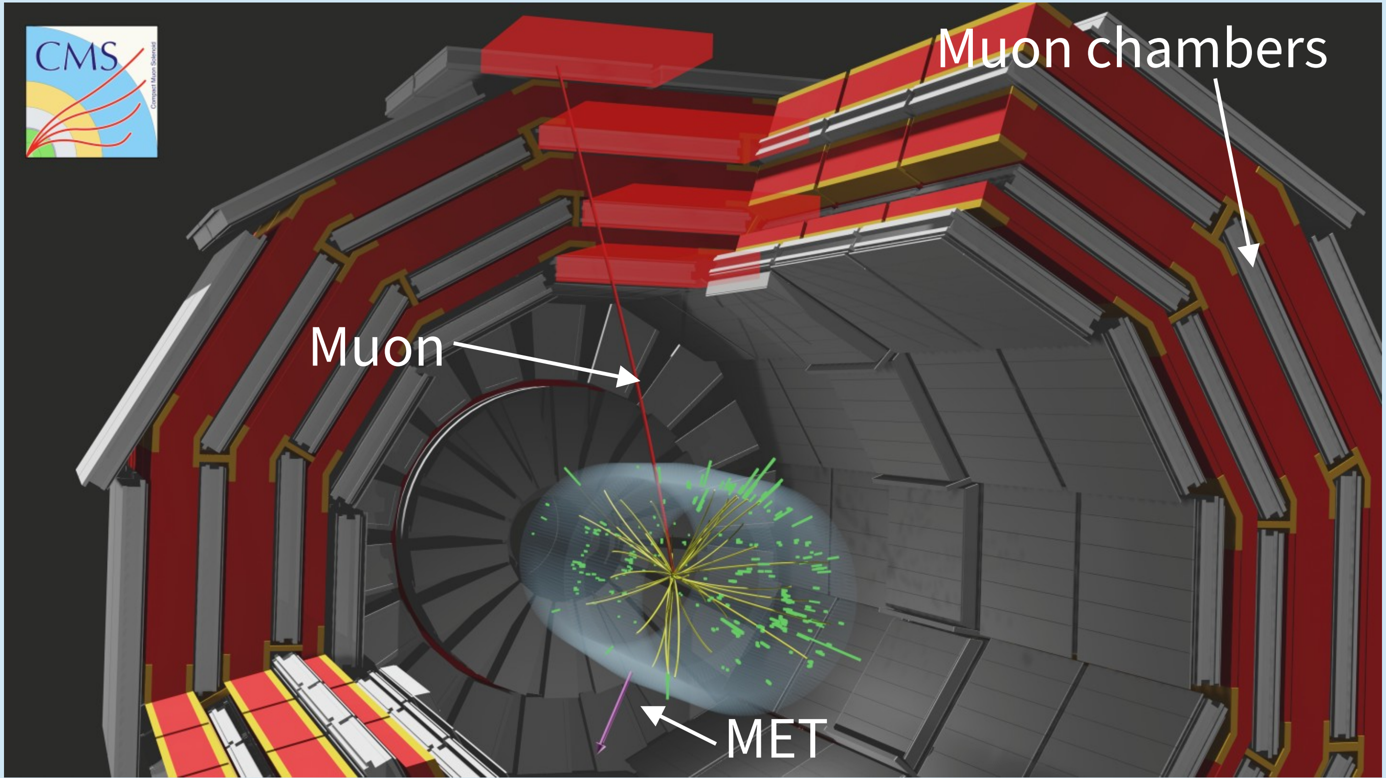
- Several modern sets considered
- Check compatibility between PDF sets:
  - **Bias test with prediction from one PDF set as nominal and prediction from the others as pseudodata**, repeated changing nominal PDF set
  - **Inflate PDF uncertainties for “failing” sets**
- **CT18Z** chosen as **nominal** set:
  - Among the largest unscaled impacts from PDFs
  - But doesn’t need inflation to cover other sets



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

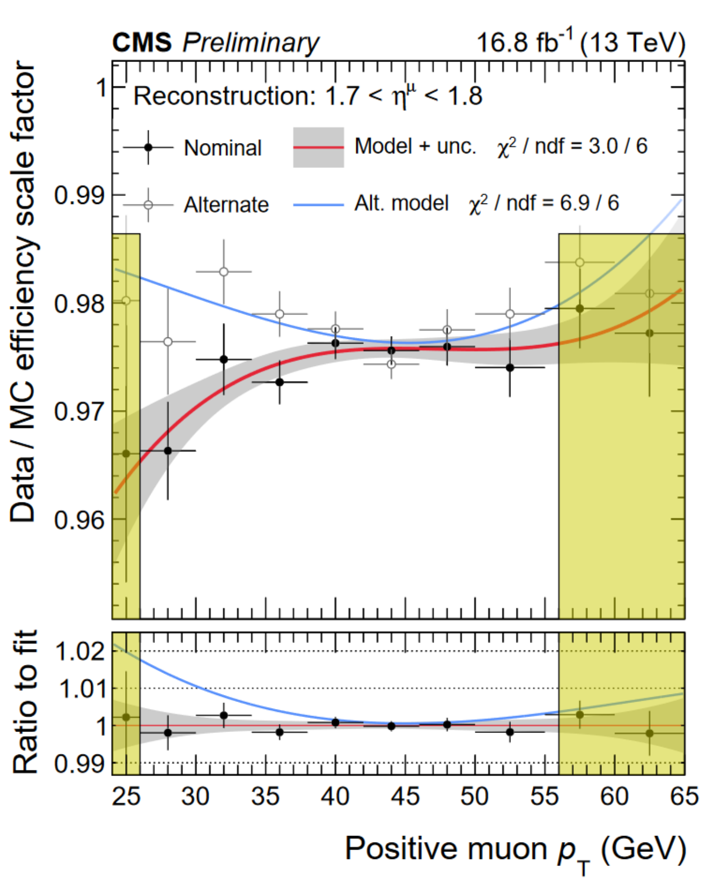
Muon reconstruction

- Our analysis uses global muons
  - Muon chambers only for trigger and ID
  - Tracker for kinematic properties



Muon Efficiencies

- **Fine-grained η-p_T scale factors** measured with tag-and-probe (TnP) from Z→μμ
  - Unprecedented level of granularity
- Our analysis uses global muons
  - Muon chambers only for trigger and ID
  - Tracker for kinematic properties
- Factorization into reconstruction and identification steps
- Isolation (and trigger) efficiencies also take into account contribution of hadronic recoil from W/Z boson



Muon calibration: validation with Υ and Z

- **Physics-motivated model** to predict bias on p_T scale, **parameters extracted from fits the J/Ψ data in 4D space (p_{T1},p_{T2},η_1,η_2)**
- For this to work, we implemented a **refined track refit** with a more accurate B-field map, energy loss modelling and alignment
- After the corrections from J/Ψ are derived:
  - New **invariant mass fits** in 4D space to extract the scale from **Υ(1S) and Z data**
  - Scale translated to **B-field-like** and **alignment-like** correction

$k = 1/p_T$

$$\frac{k_{rec}}{k_{gen}} = 1 + A - ek + \frac{qM}{k}$$

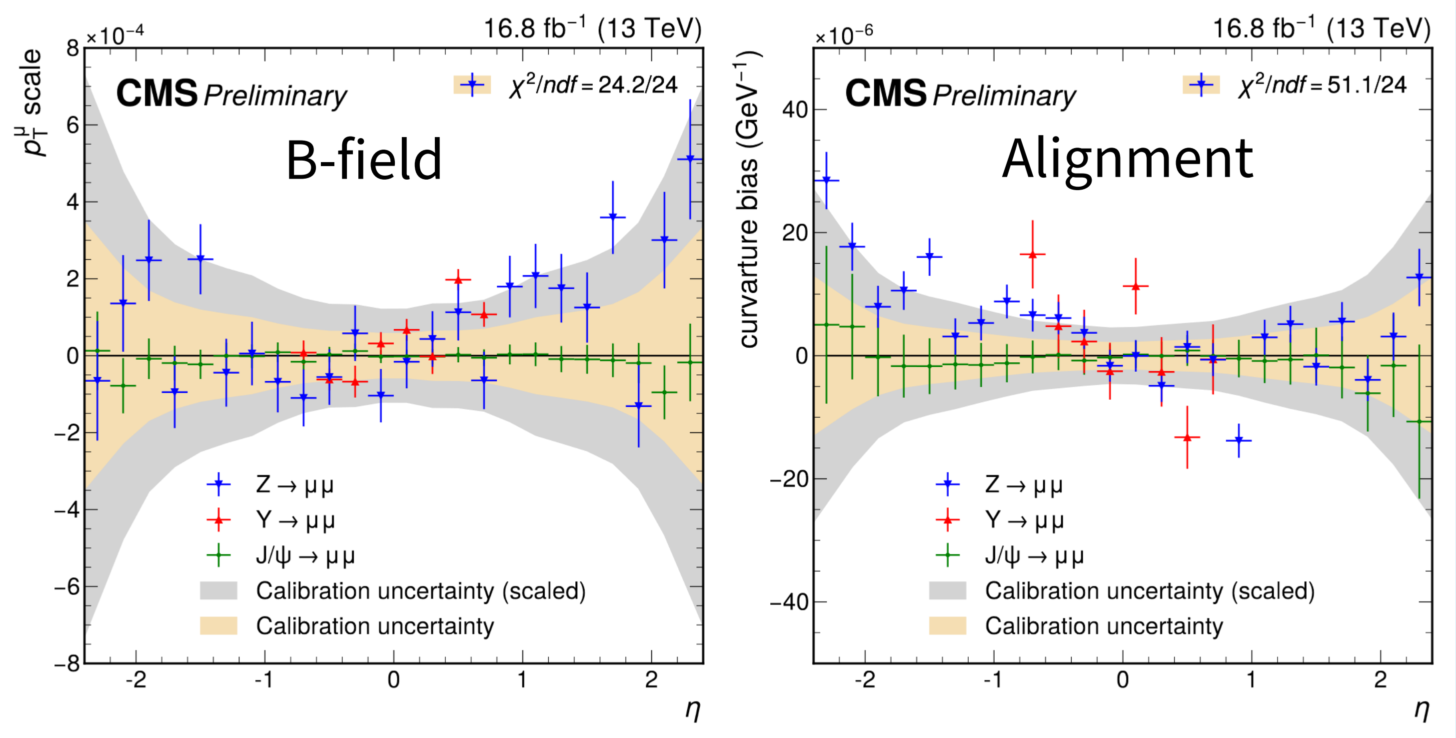
B-field (A)

Energy loss (ek)

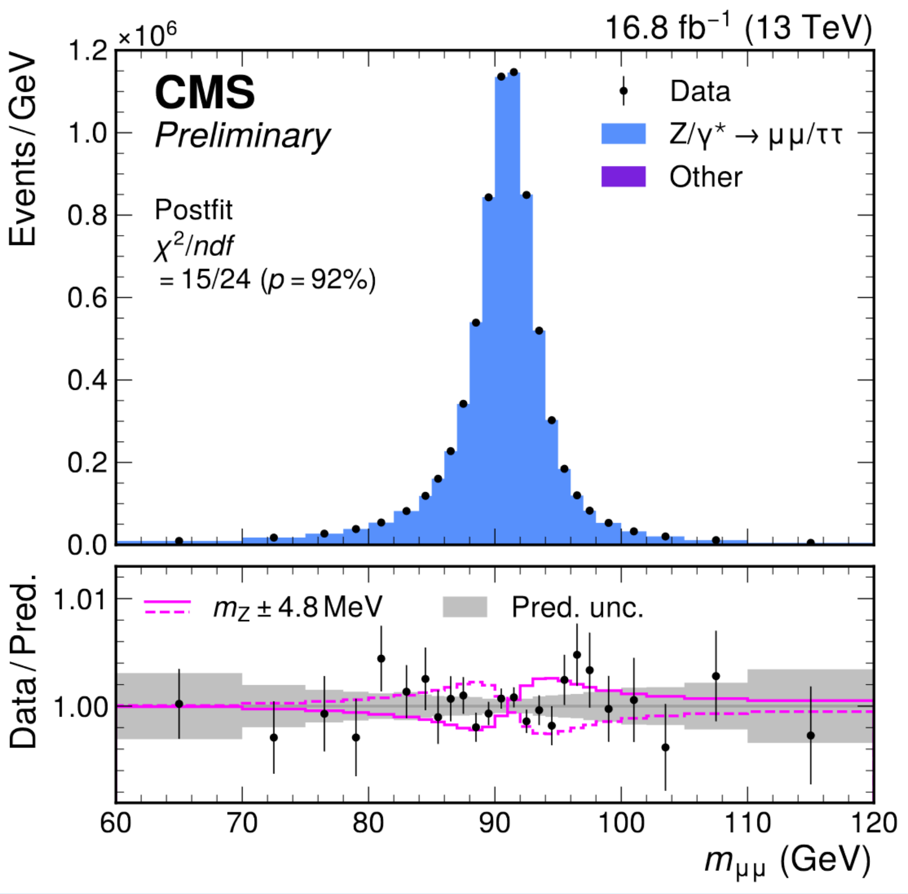
Alignment ($\frac{qM}{k}$)

Muon calibration: validation with Υ and Z

- **Check compatibility of additional corrections with 0 → Χ²/ndof test**
  - **Inflation** of J/Ψ stat. uncertainty by a factor **2.1**
  - Stat. uncertainty from Z added to uncertainty model, together with PDG uncertainty



Z→μμ mass fit

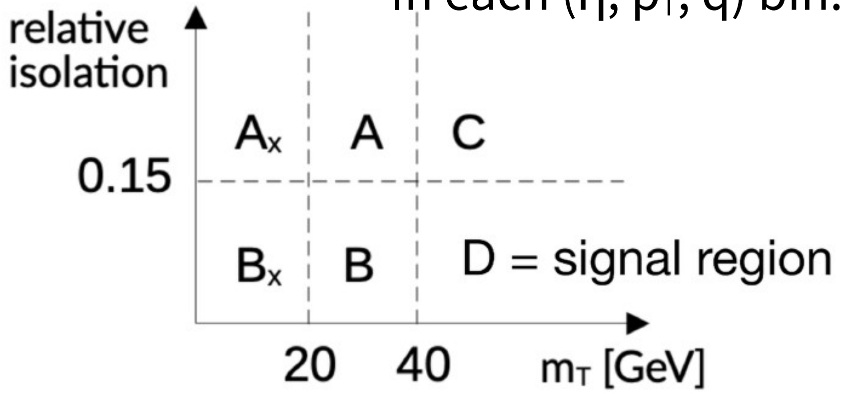


- Validation of the whole calibration procedure
- **$m_{Z,CMS}$-$m_{Z,PDG}$ = -2.2 ± 1.0 (stat) ±4.7 (syst) MeV = -2.2 ± 4.8 MeV**
- Since J/ψ vs Z closure was used to tune calibration and enters the uncertainty model, **not (yet) a fully independent measurement** for inclusion in world average

M_W: Non-prompt background

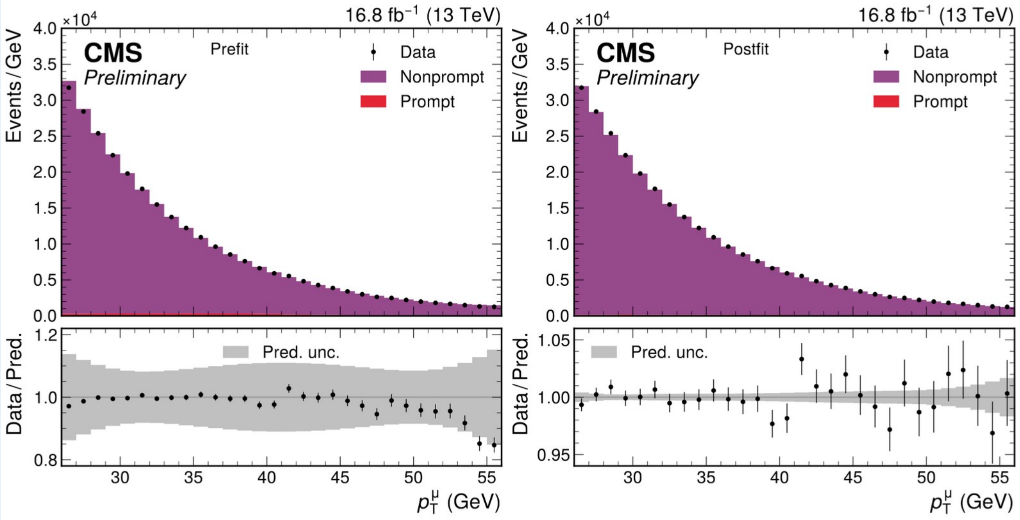
- Mostly muons from B/C hadron decays (~85%)
- Data-driven estimation using an extended ABCD method based on (iso,m_T)
  - Validated with QCD simulation and SV-sideband
  - 15% normalization correction applied (consistent between SV-sideband and QCD MC)

In each (η, p_T, q) bin:

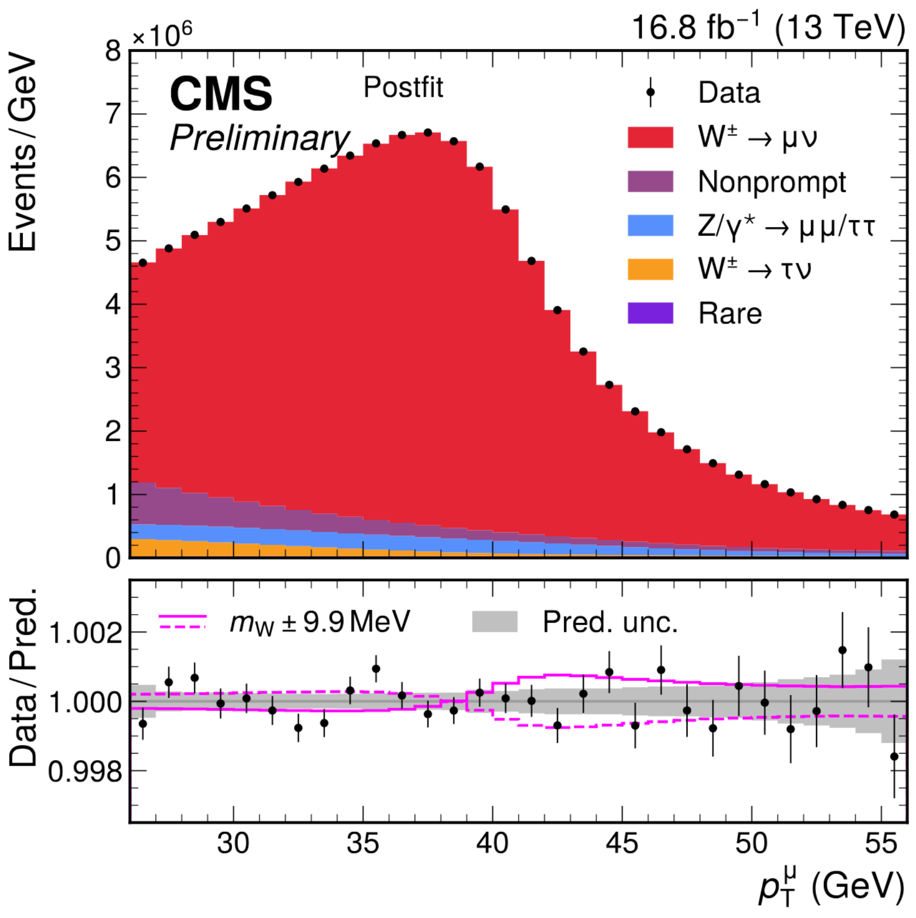


$$D = C\,\frac{A_x B^2}{B_x A^2}$$

Smoothing in each region with an exponential of a polynomial



Unblinding the W fit



- **M_W = 80360.2 ± 9.9 MeV**
- **In agreement with the SM**

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

Helicity cross-section fit

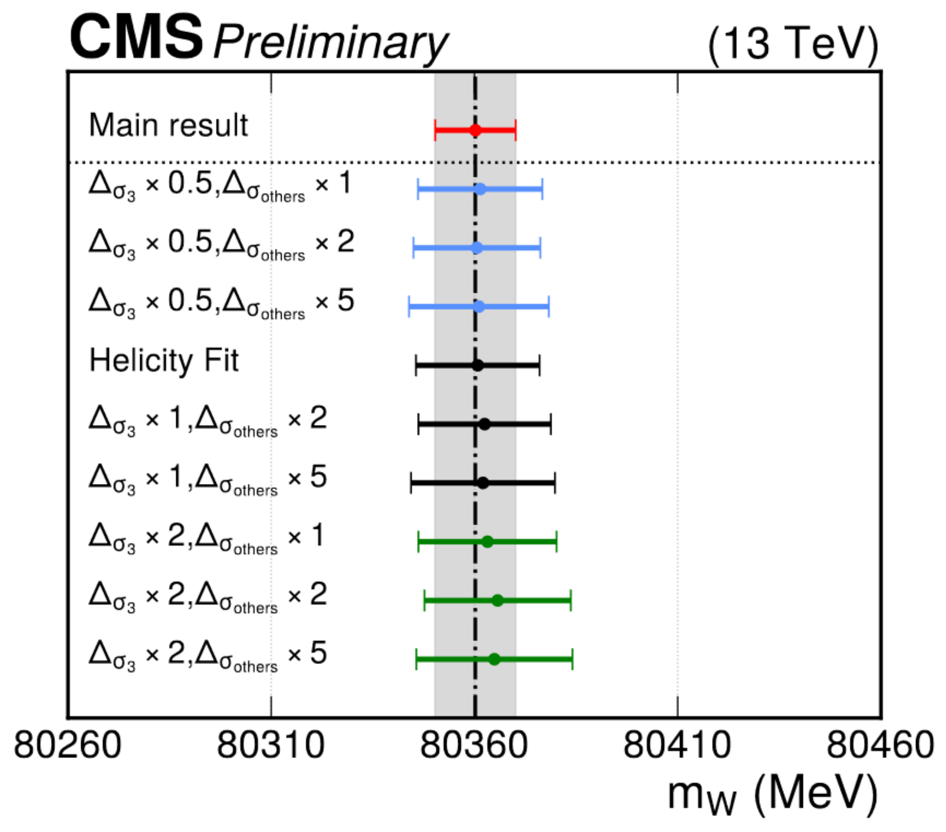
- Implementation of a less model dependent measurement:
  - Additional test of the QCD model, BSM physics in W production or decay, etc.
- **Basic strategy**: Measure the terms of the 9 helicity cross sections $\sigma_i \equiv \sigma_{UL} x A_i$ double-differentially in W rapidity and p_T (instead of using predictions and uncertainties from PDFs and QCD) together with m_W

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

- **Trade systematic uncertainties for larger statistical uncertainties**

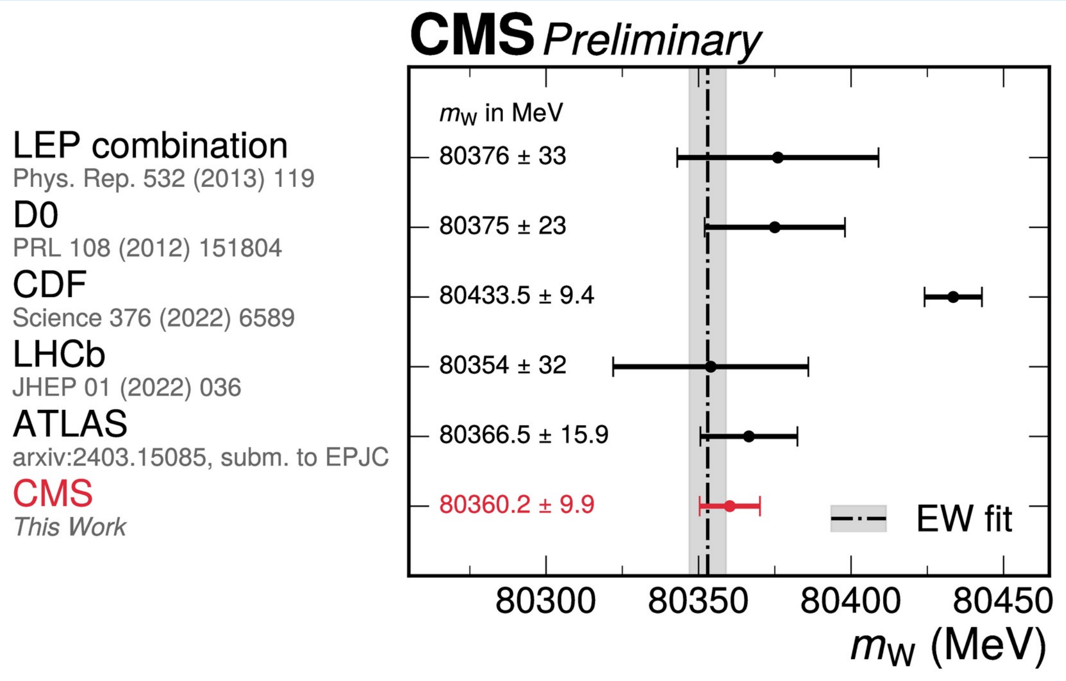
Helicity cross-section fit

- 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**
  - Uncertainties are increased wrt nominal prediction
- Results for different constraints to the nominal predictions are shown
- **Agreement with the main result**



Conclusions

- **First measurement** of m_W by CMS
- **Most precise** measurement at the LHC
  - Approaching the precision of CDF
- Good **agreement with the SM** prediction and other measurements, except CDF
- Measurement is performed with ~ 10% of Run 2 data
  - Large room for improvement
- More precision measurements coming from CMS



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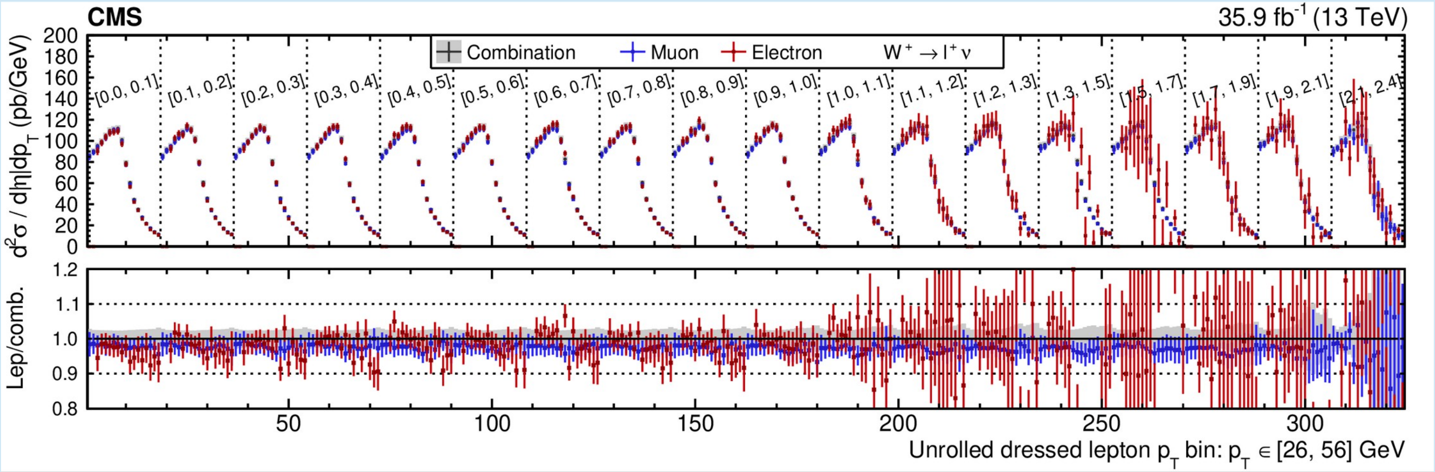
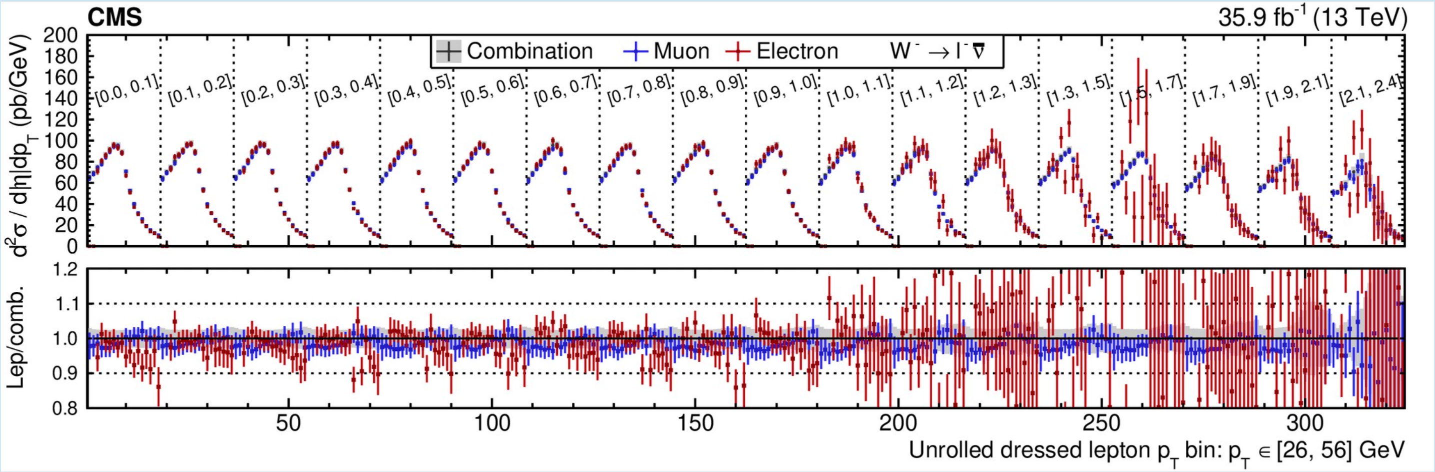
References

- [1]: Impact of the Recent Measurements of the Top-Quark and W-Boson Masses on Electroweak Precision Fits, J. De Bias et al., Phys. Rev. Lett. 129, 271801
- [2]: Measurement of the W-boson mass and width with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 7$ TeV, ATLAS Collaboration, arXiv:2403.15085
- [3]: High-precision measurement of the W boson mass with the CDF II detector, CDF Collaboration, Science 376, 170–176 (2022)
- [4]: Measurement of the W boson mass, LHCb Collaboration, JHEP 01 (2022) 036
- [5]: Measurement of the W boson mass in proton-proton collisions at $\sqrt{s} = 13$ TeV, CMS Collaboration, CMS-PAS-SMP-23-002
- [6]: Measurements of the W boson rapidity, helicity, double-differential cross sections, and charge asymmetry in pp collisions at $\sqrt{s}$=13 TeV, CMS Collaboration, Phys. Rev. D 102 (2020) 092012
- [7]: Theory uncertainties and correlations from theory nuisance parameters, F.J. Tackmann, in SCET 2024: XXI annual workshop on Soft-Collinear Effective Theory
- [8]: Beyond Scale Variations Theory Uncertainties from Nuisance Parameters, F. J. Tackmann, in Les Houches, June 14, 2019

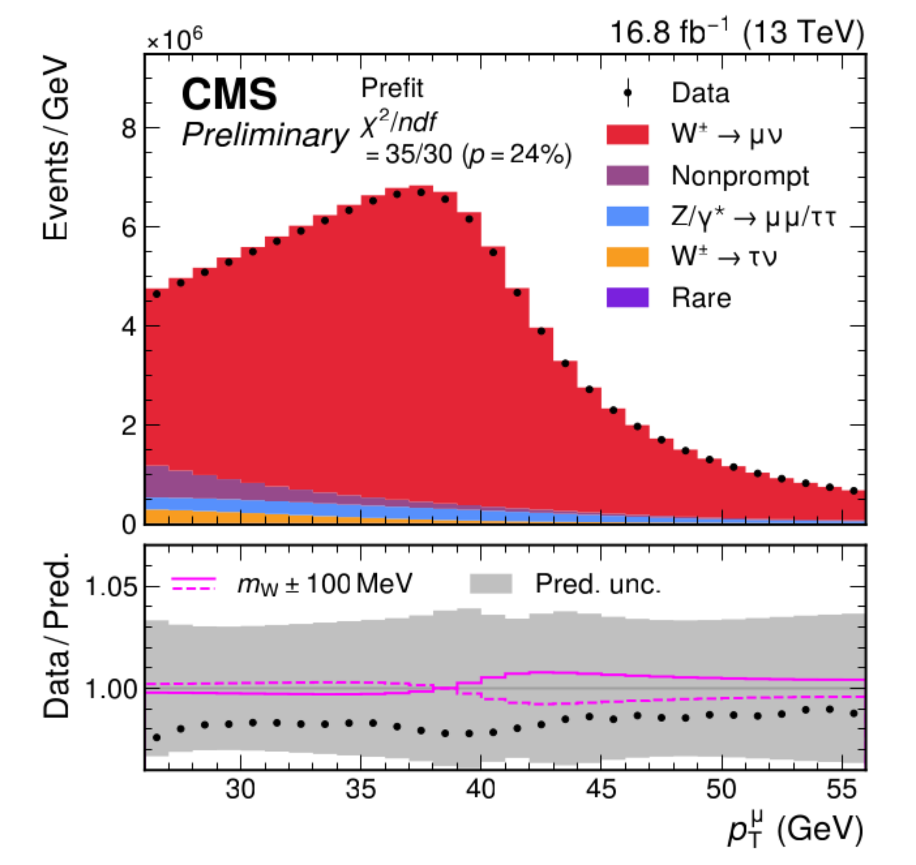
BACKUP

Muon vs electrons [6]





Event selection

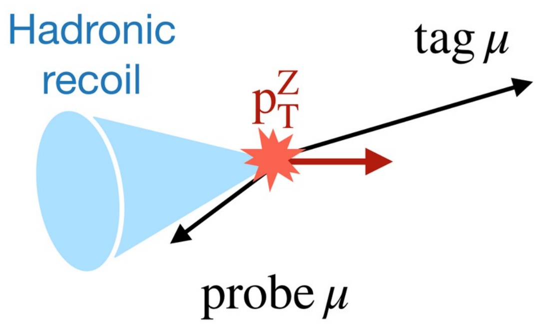


- Straightforward single muon selection: global muons, strict track criteria, medium ID, $|d_{xy}BS|<0.05$ cm, trigger matched, isolated.
  - We require $m_T>40$ GeV
- Selected events are about 90% W → μν
- Nonprompt background from data-driven estimate
  - Mostly from B and D decays with smaller contribution from π or K decay-in-flight
- Prompt backgrounds from simulation with all relevant corrections/uncertainties
  - W → τν, Z → μμ (mostly with one muon out-of-acceptance), Z → τ τ , top, diboson

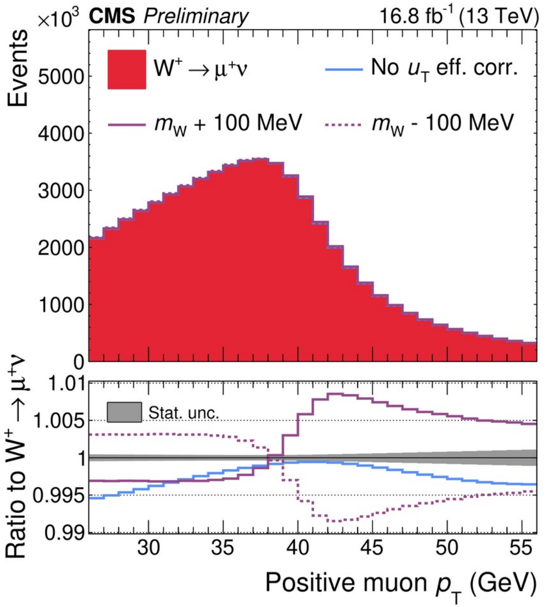
With materials from J. Bendavid's seminar

Muon isolation

- **Problem: tag-and-probe isolation efficiency sensitive to magnitude and direction of recoil**
  - Enhanced by tag η-p_T selection. Low p_T probe more likely sent in opposite direction with respect to Z
    - Results in smaller isolation efficiency
    - Also effects trigger, since HLT applies isolation
- **W is not the same as Z, different u_T spectrum and no "tag" selection**
  - Would result in ~7 MeV bias on m_W
- **Solution: we measure isolation/trigger efficiencies in 3D vs η-p_T-u_T**
  - Smoothing independently in each η bin as a function of p_T and u_T

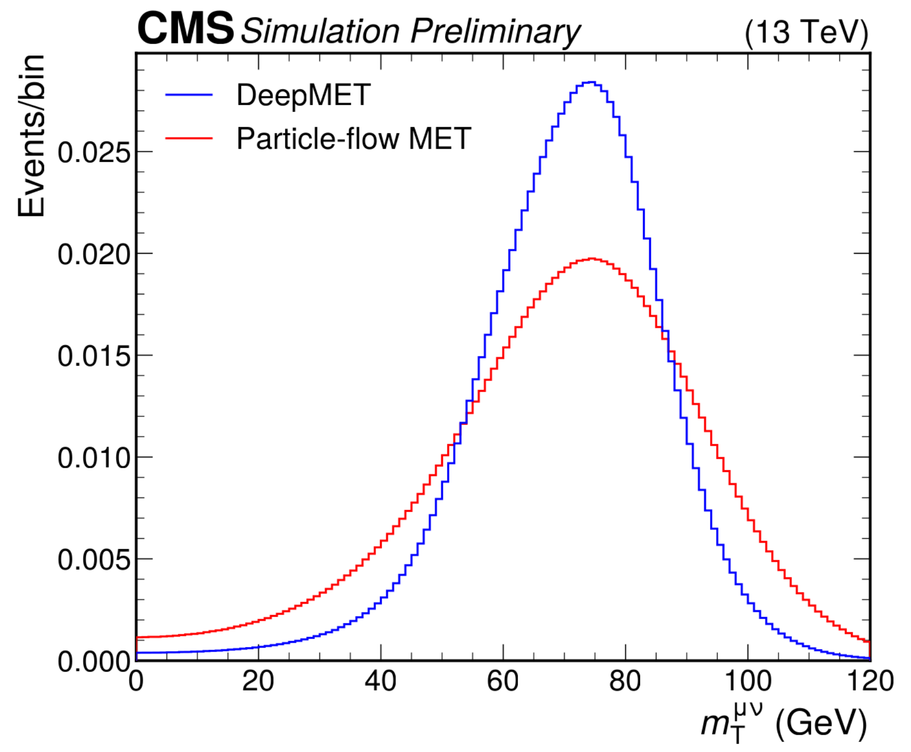


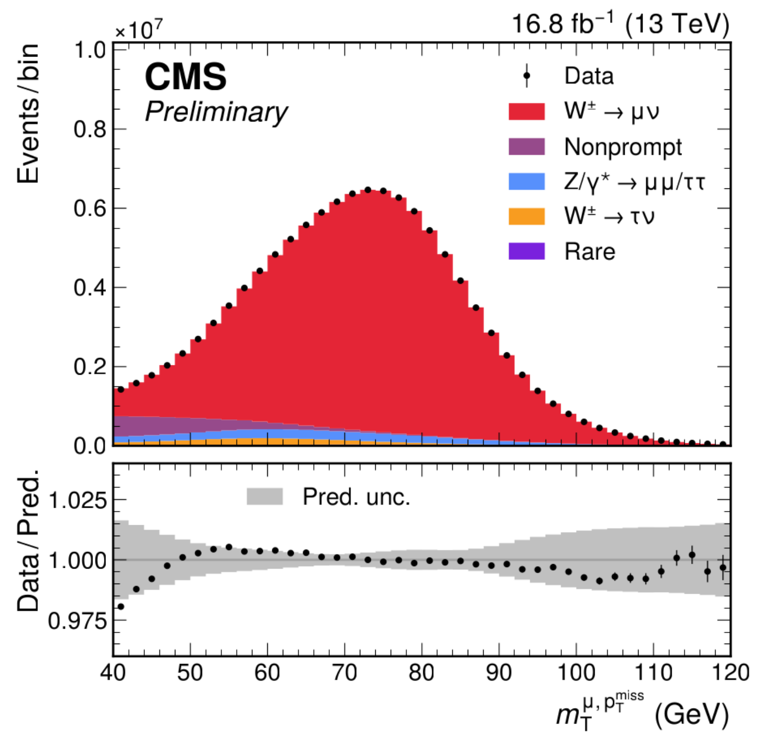
$$u_T = \frac{\vec{p}_T^{\,Z} \cdot \vec{p}_T^{\,\mu}}{|\vec{p}_T^{\,\mu}|}$$



Missing energy and transverse mass

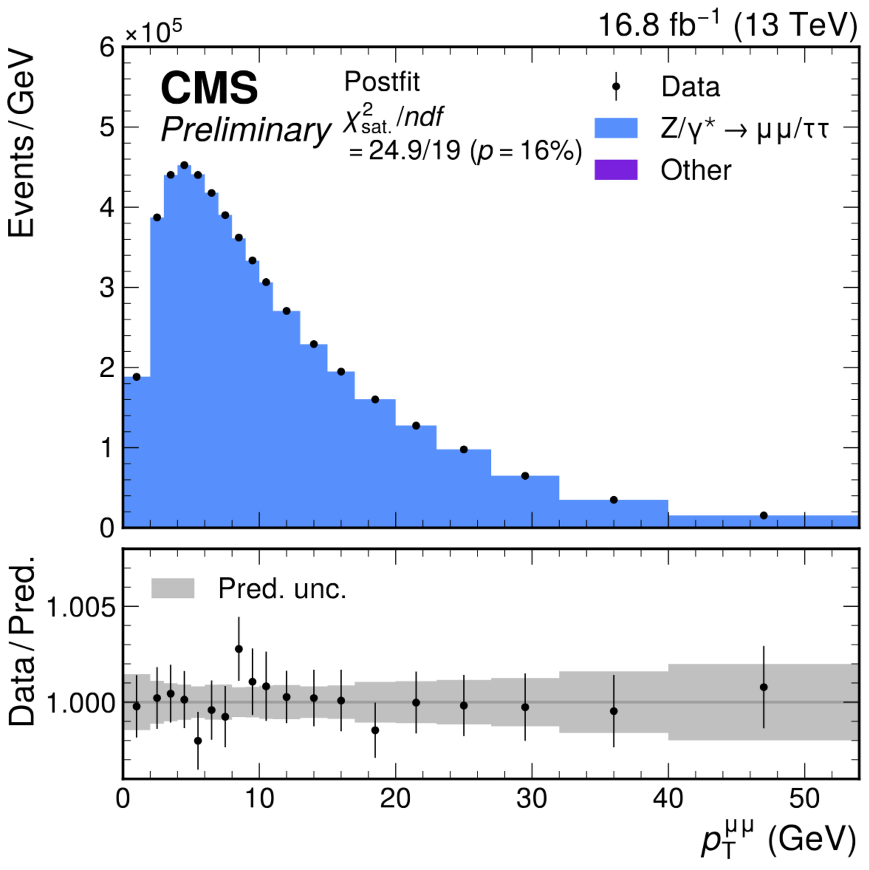
- DeepMET only used indirectly to select signal region (m_T > 40 GeV) and control regions for non-prompt background estimation through ABCD method
- Recoil response is calibrated using Z→ μμ events
- Good agreement for m_T after recoil calibration → maybe usable for future measurements



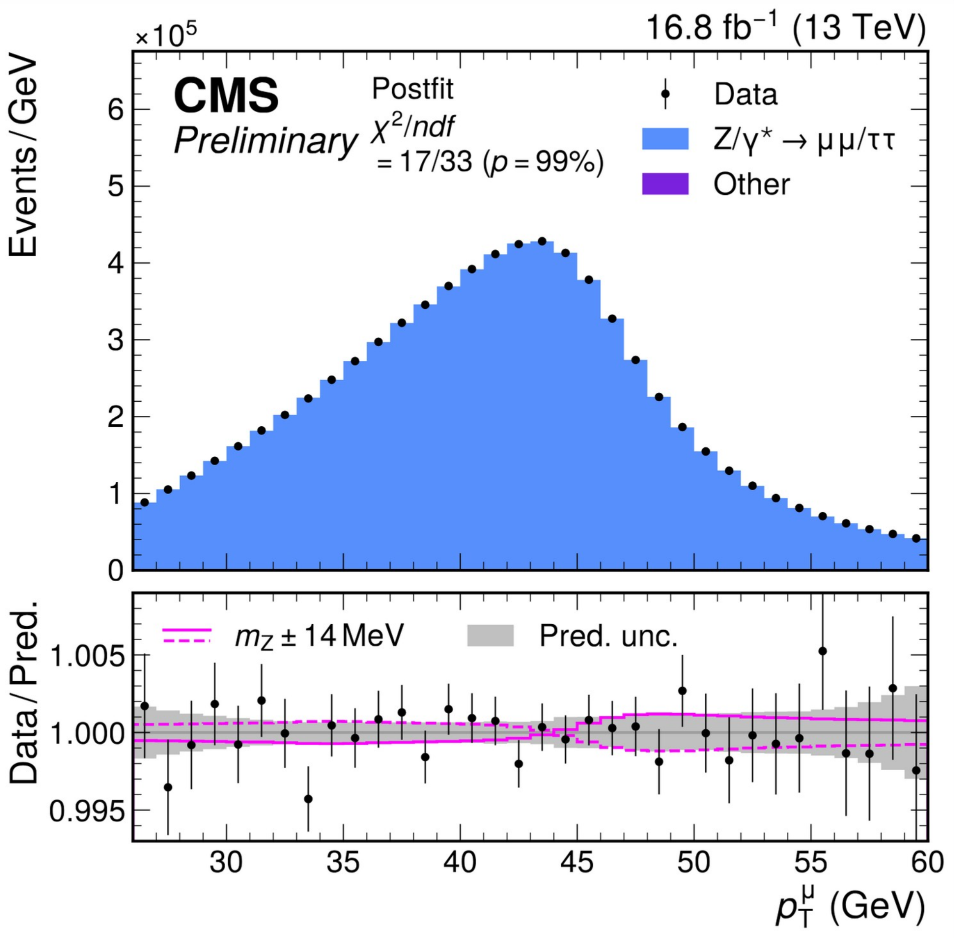


Model validation

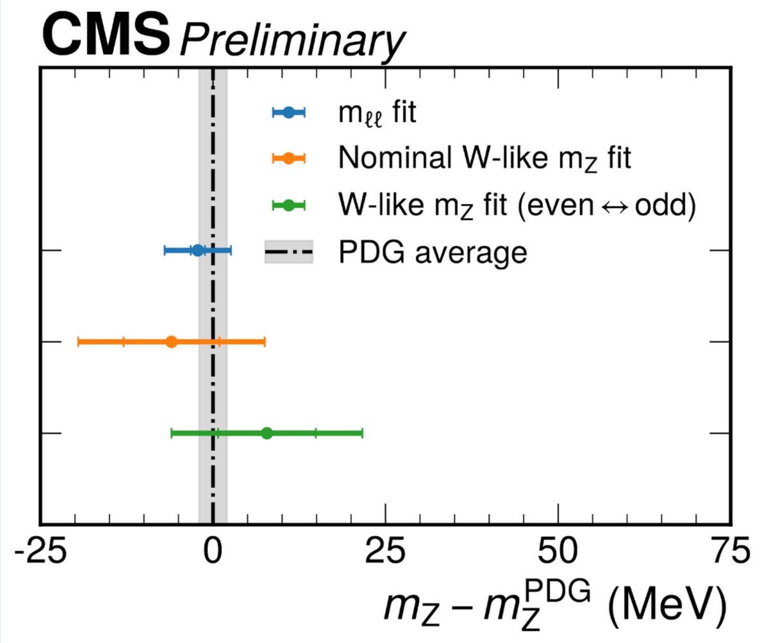
- Theory model validated by fitting (p_T^Z,y^Z) spectrum
  - **Agreement at the permille level**
- Model is flexible enough to **accomodate actual p_T^Z spectrum**, at least from dilepton data:
  - Can this be extracted from the p_T-η-q? Try this on the W-like



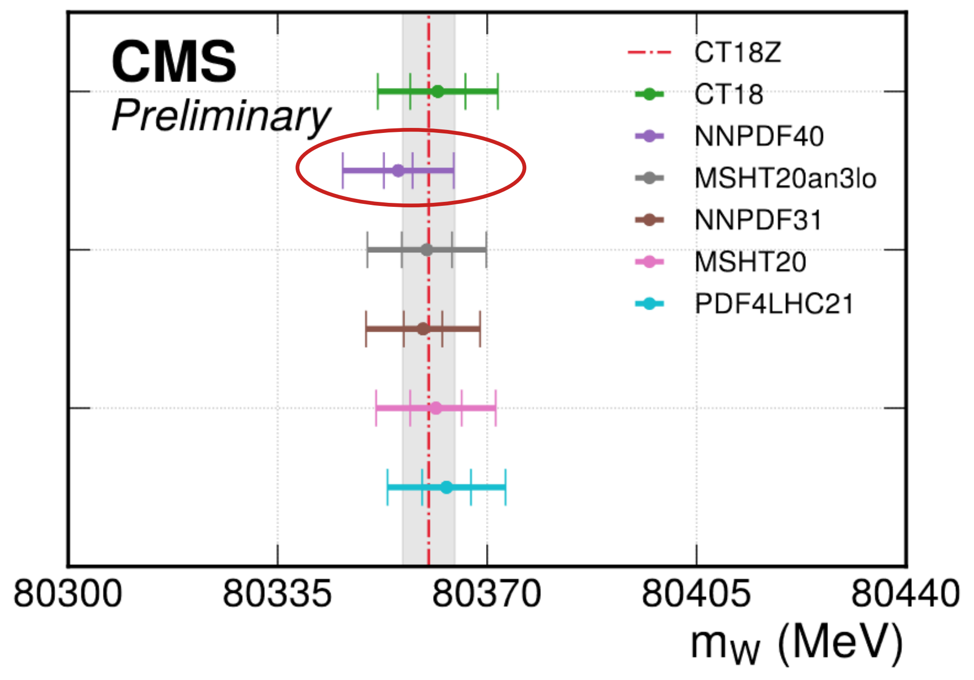
W-like results



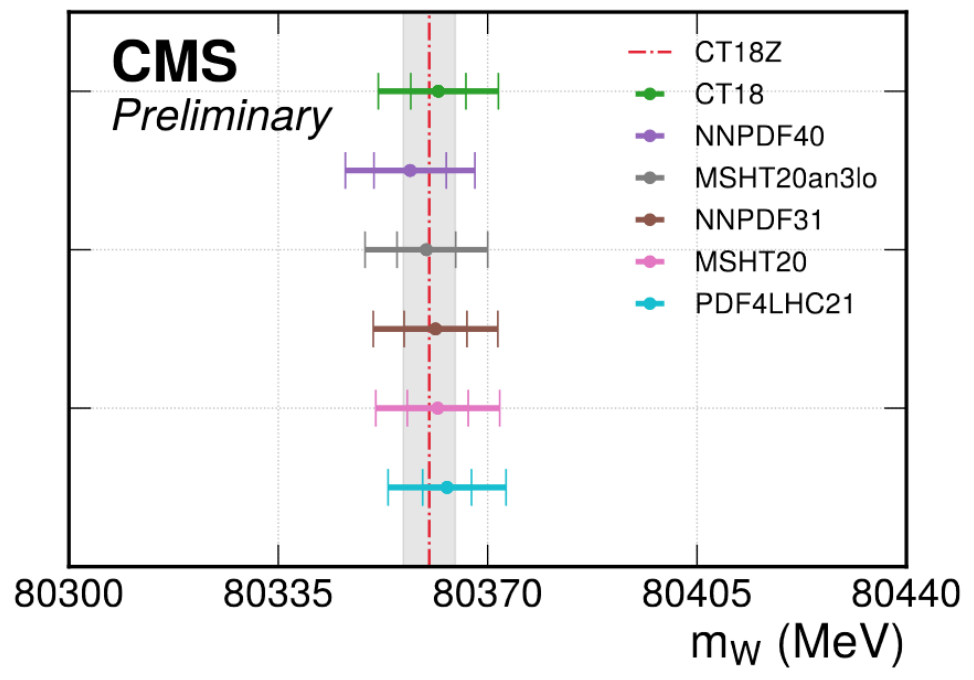
- Total uncertainty on m_Z is 13.5 MeV
  - Muon scale (5.6), angular coeff. (4.9), muon reco (3.8)



PDF dependence



WITHOUT INFLATION



WITH INFLATION

Comparison with ATLAS

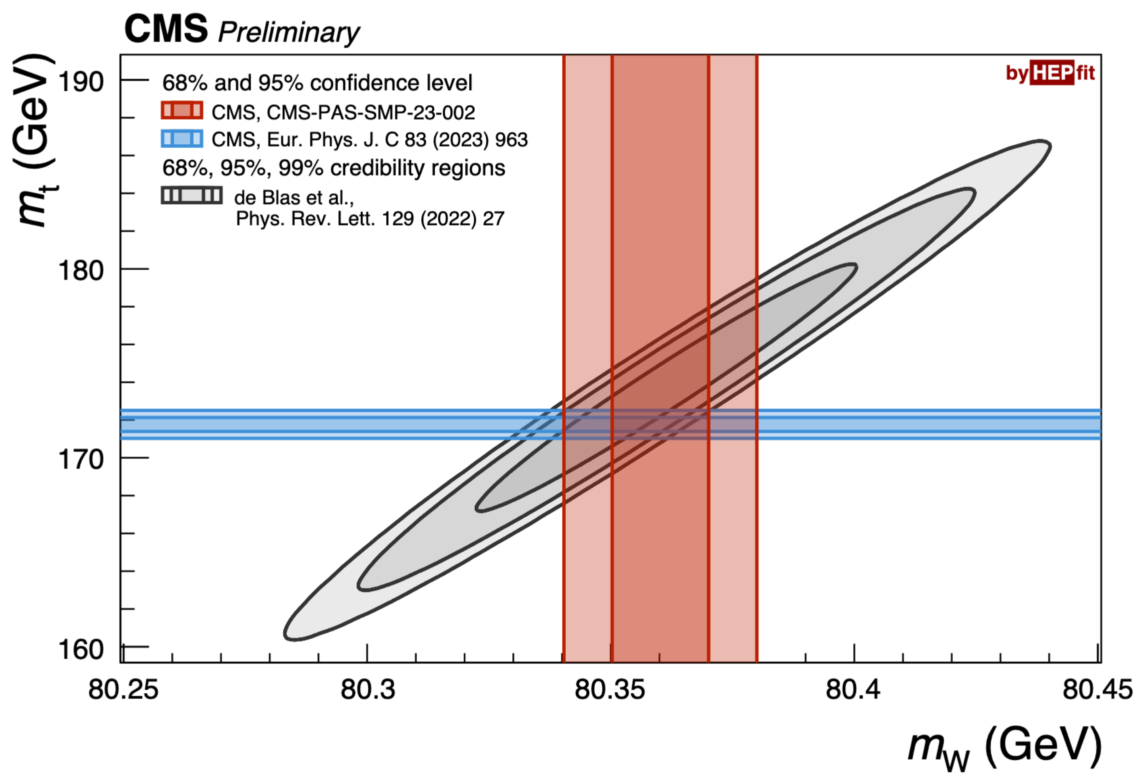
arXiv:2403.15085

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

For "global" impacts see arXiv:2307.04007

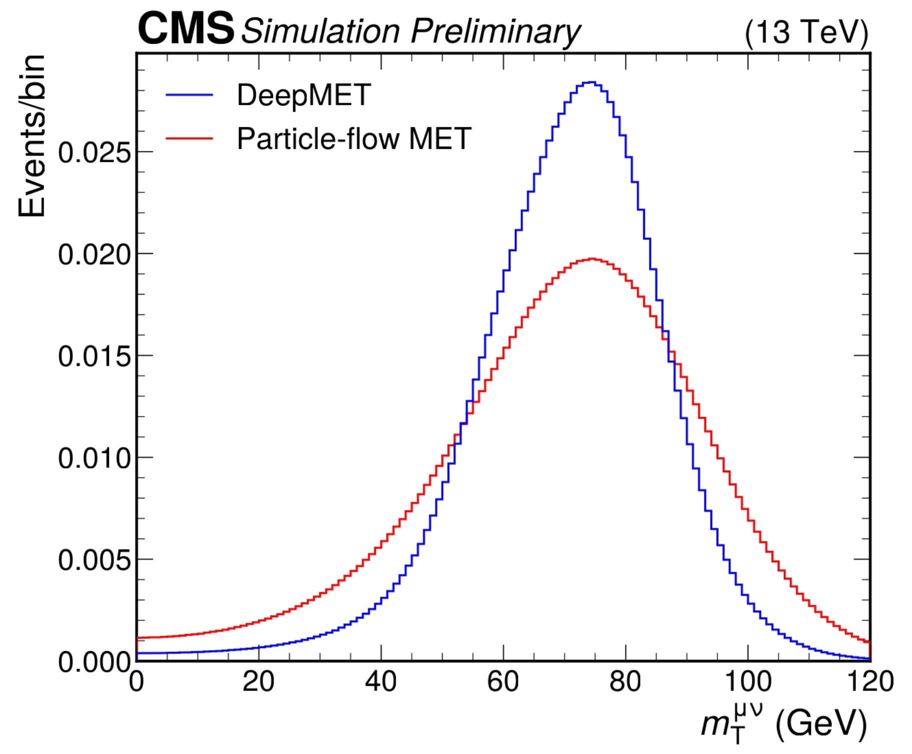
Source of uncertainty	Impact (MeV) Nominal in m_Z	Nominal in m_W	Global in m_Z	Global in m_W
Muon momentum scale	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt background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

Comparison of CMS result with EW fit



Future measurements

- More luminosity → smaller uncertainty due to in-situ constraints (6 MeV out of 9.9 MeV from stat)
  - Together with improvements from the theory side
  - **Theory agnostic approach: extract from fit parameters related to production mechanism**
    - trade systematic uncertainties from the theoretical modelling with statistical uncertainties
- Potential further **improvements in missing transverse energy** reconstruction:
  - Directly as fitting variable (potentially also for Γ_W)
  - Break degeneracy between m_W and Ai → improvement on theory agnostic approach
- Electrons (lower priority)



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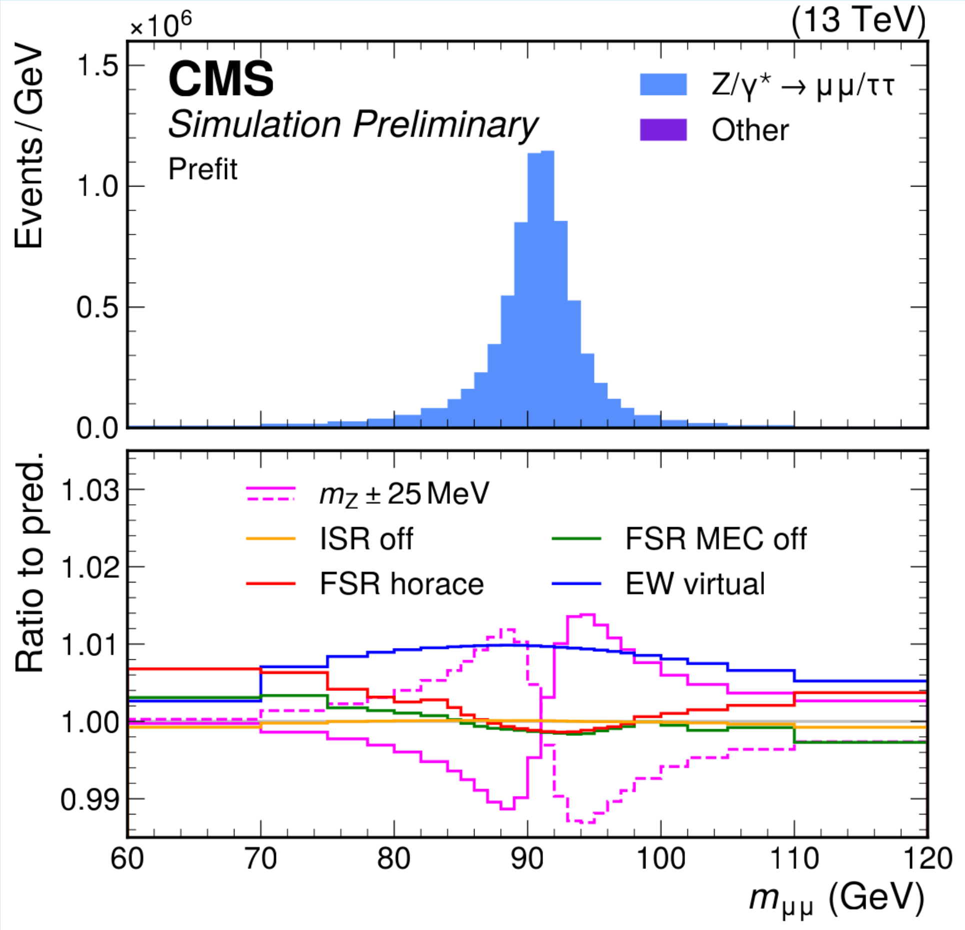
Electroweak uncertainties



- 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

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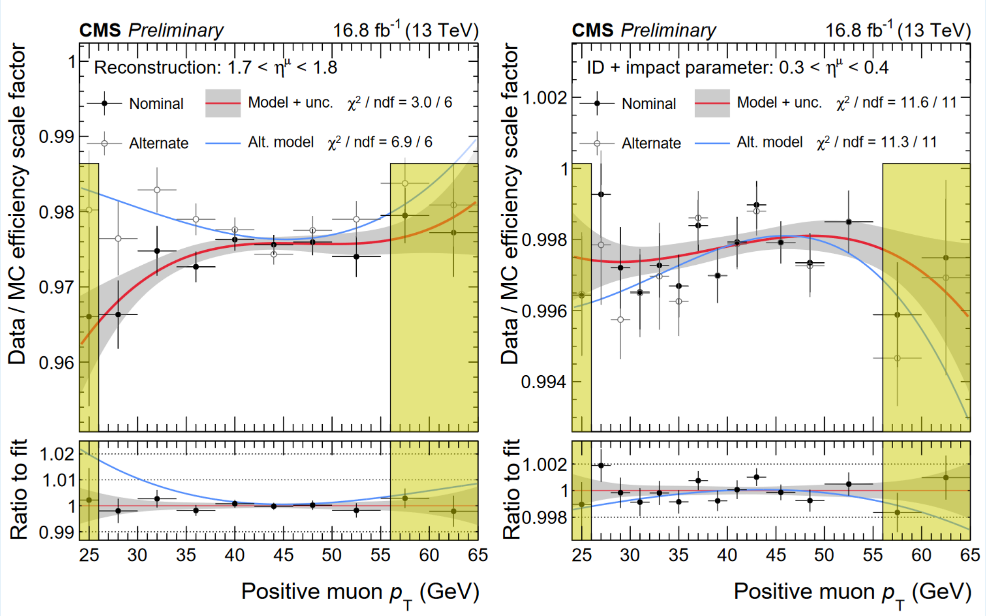
Muon Efficiencies

- **Fine-grained η-p_T scale factors** measured with tag-and-probe (TnP) from Z→μμ
  - Unprecedented level of granularity
- Our analysis uses global muons
  - Muon chambers only for trigger and ID
  - Tracker for kinematic properties
- Factorization into reconstruction and identification steps
- Isolation (and trigger) efficiencies also take into account contribution of hadronic recoil from W/Z boson



Muon scale calibration

- **Physics-motivated model** to predict bias on p_T scale (10^{-4} translates into $\delta m_W \approx 8$ MeV)

K = 1/p_T

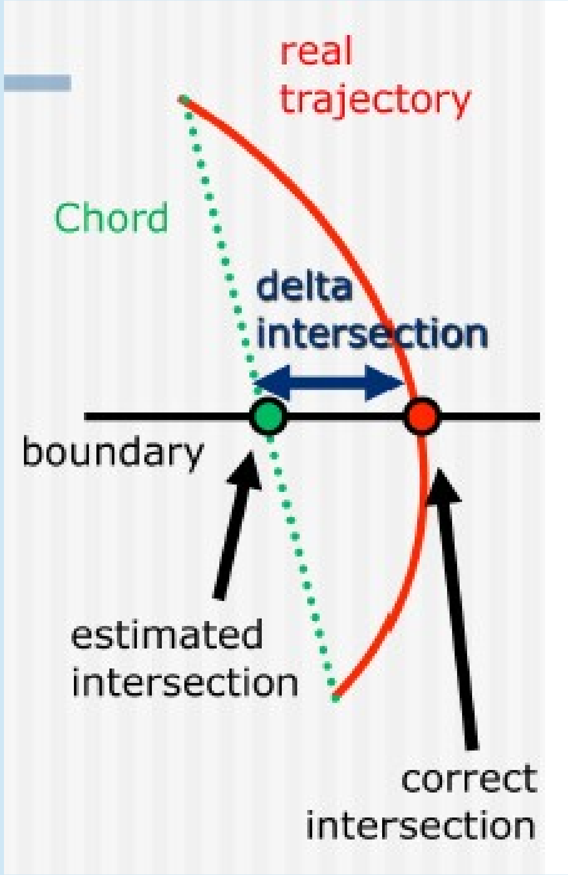
$$\frac{k_{rec}}{k_{gen}} = 1 + A - ek + \frac{qM}{k}$$

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

- A: Magnetic field mismodelling
- e: Energy loss (material) mismodelling
- M: Misalignment
- a: Multiple Scattering (material)
- c: Hit resolution

Muon scale calibration

- **Physics-motivated model** to predict bias on p_T scale (10^{-4} translates into $\delta m_W \approx 8$ MeV)
- Several limitations in standard CMS Kalman Filter tracking:
  - We started by **fixing/improving nominal SIM precision**, then



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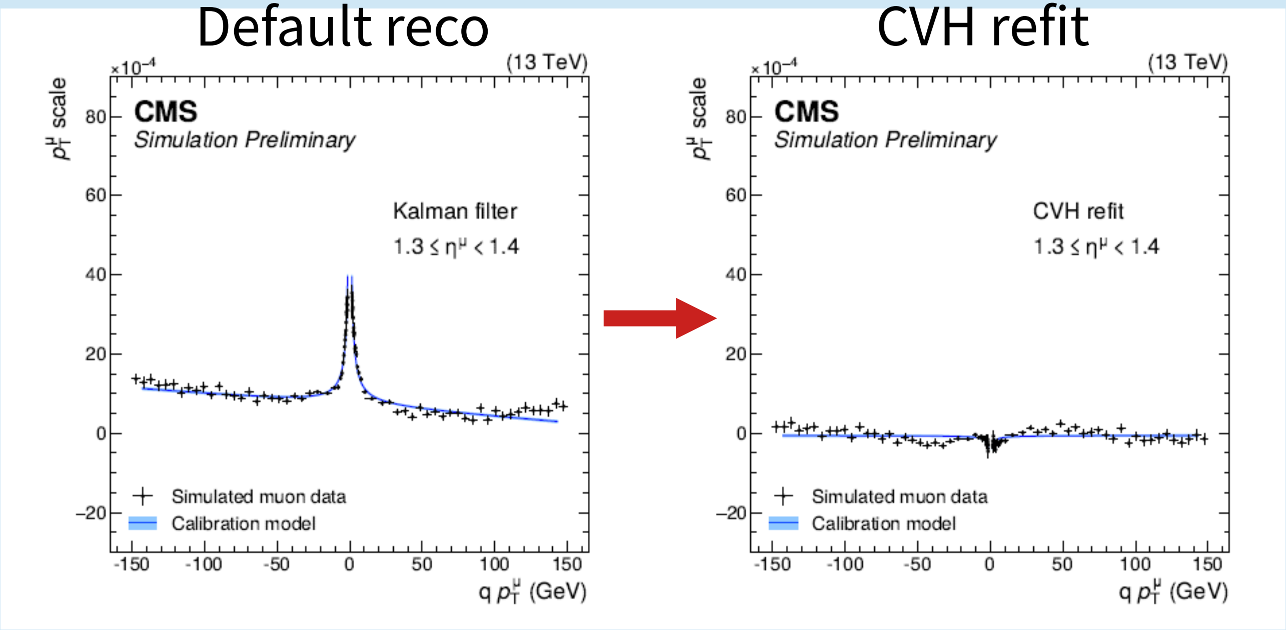

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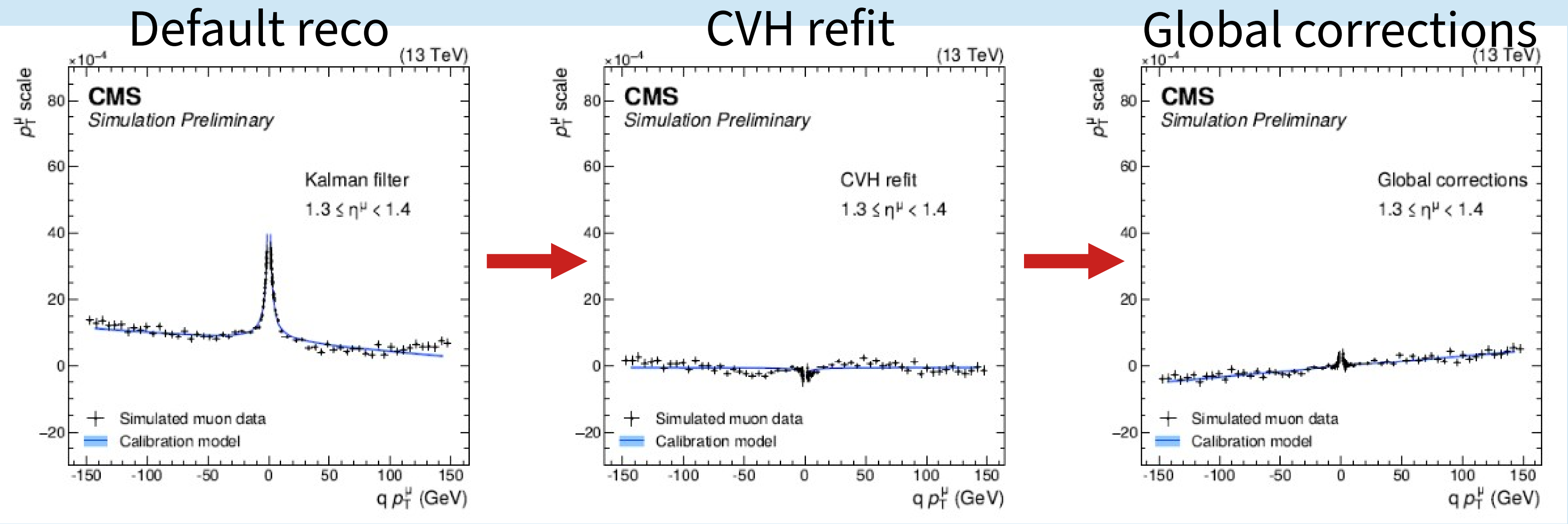
    - **Global correction** of alignment/B-field/material at the per-module level using J/Ψ events



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- Several limitations in standard CMS Kalman Filter tracking:
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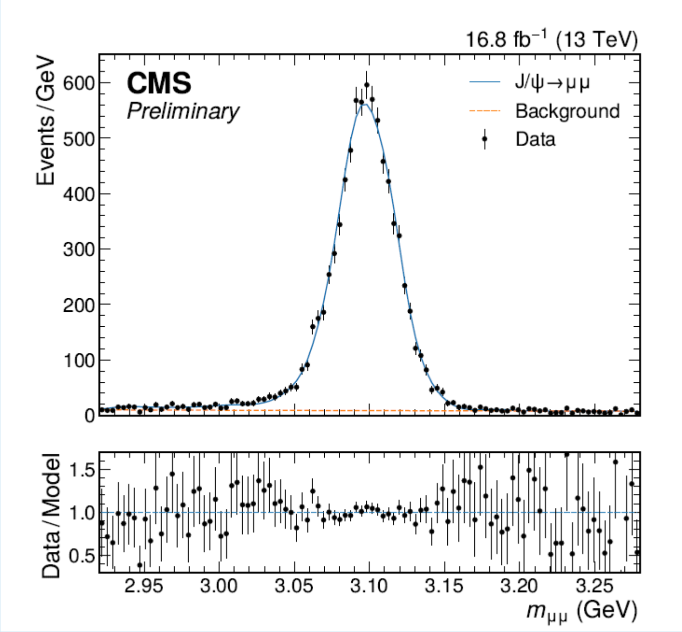
    - Track re-fit with improved B-field/material treatment based on *Geant4e* (**CVH refit**)
    - **Global correction** of alignment/B-field/material at the per-module level using J/Ψ events
    - **Residual scale bias measured on J/Ψ events in a fine-grained 4D space**, resolution corrections extracted from Z data

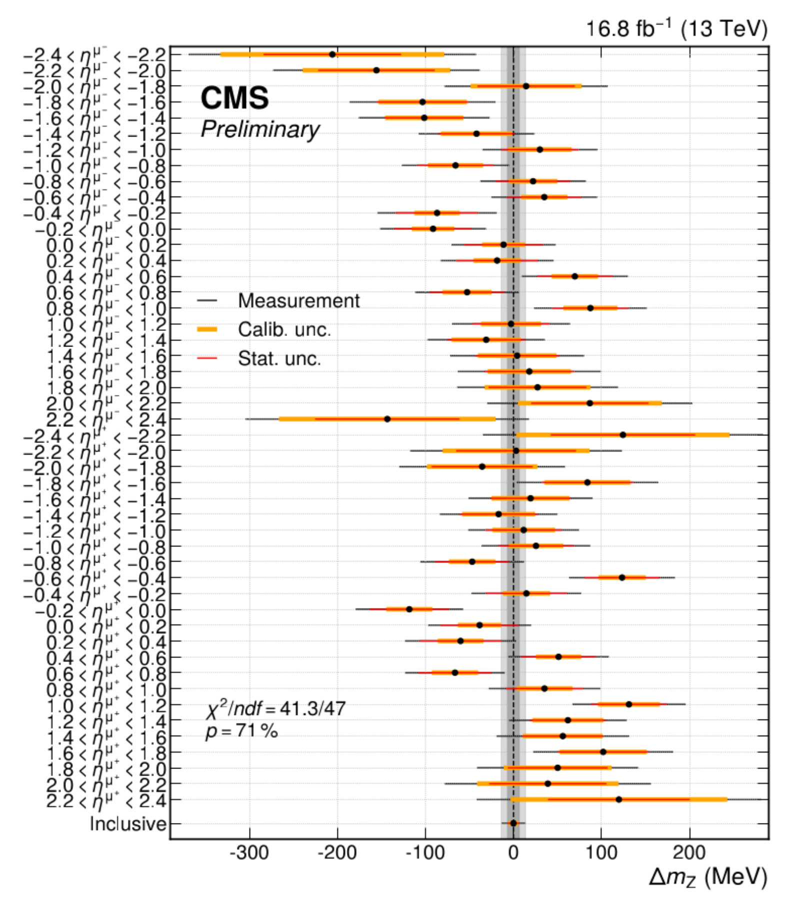
$$\frac{k_{rec}}{k_{gen}} = 1 + A - ek + \frac{qM}{k}$$

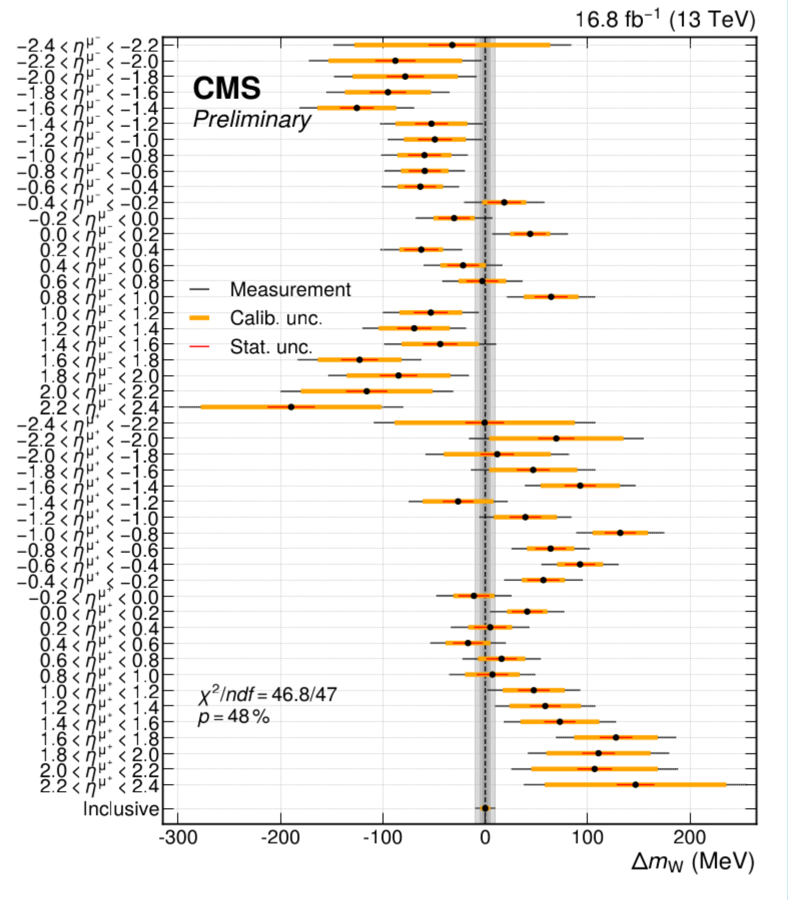
$$\left(\frac{\sigma_{p_T}}{p_T}\right)^2 = a^2 + c^2 \cdot p_T^2 + \frac{b^2}{1 + \frac{d^2}{p_T^2}}$$



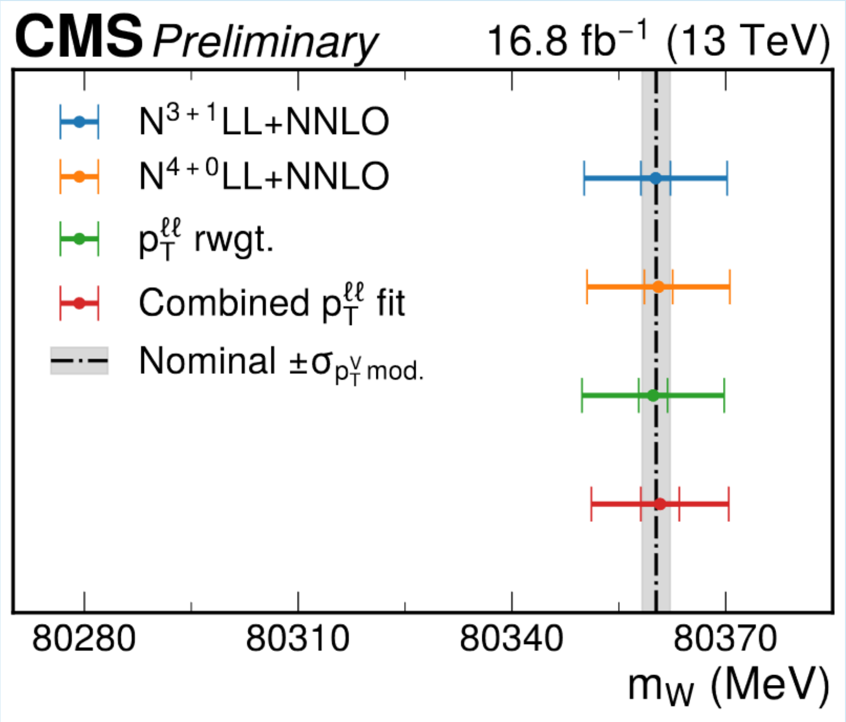
Calibration cross-checks

- Several were performed. Observed that **m_{W+}-m_{W-} = 57 ± 30 MeV**, m_Z^+-m_Z^- = 31 ± 32 MeV

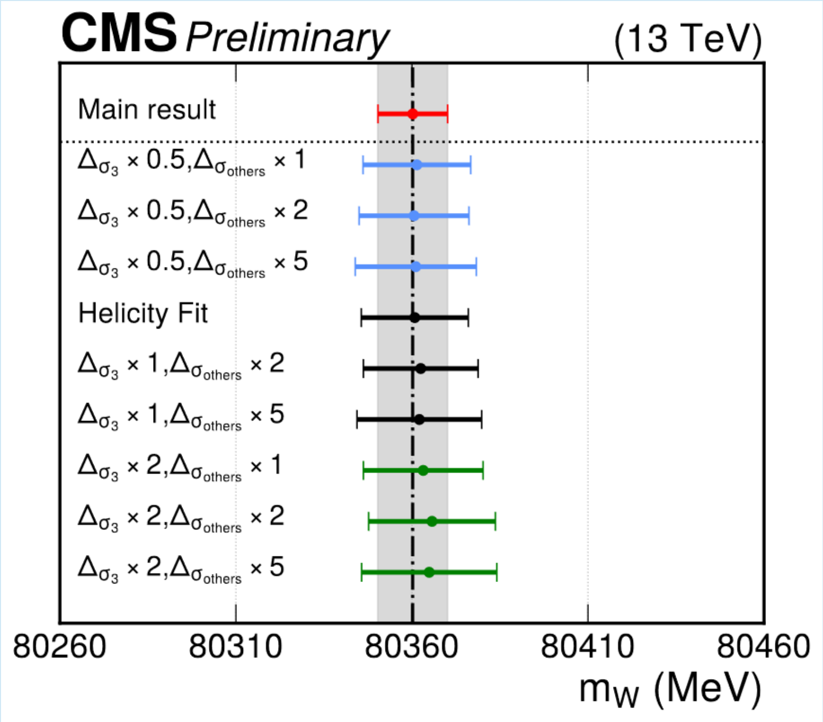




Test of model dependence



Different p_T^V uncertainty models



Helicity cross-section fit

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

- No conclusive evidence for a systematic problem (<2σ)
- 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

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m_W result: Closer look at charge difference

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

m_W result: Closer look at charge difference

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