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Measurement of the W boson mass at CMS

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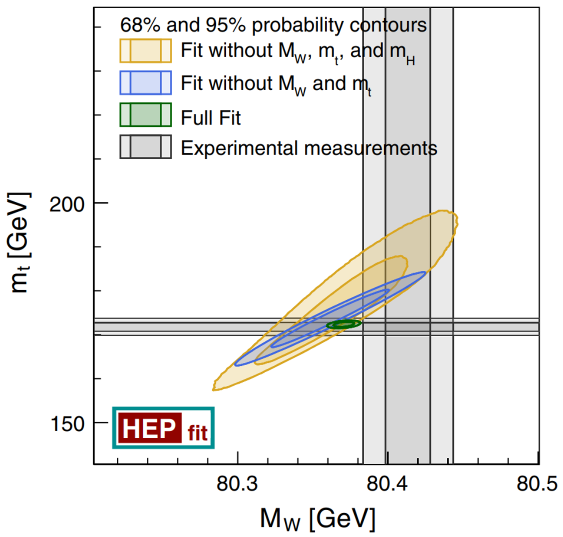
On behalf of CMS collaboration

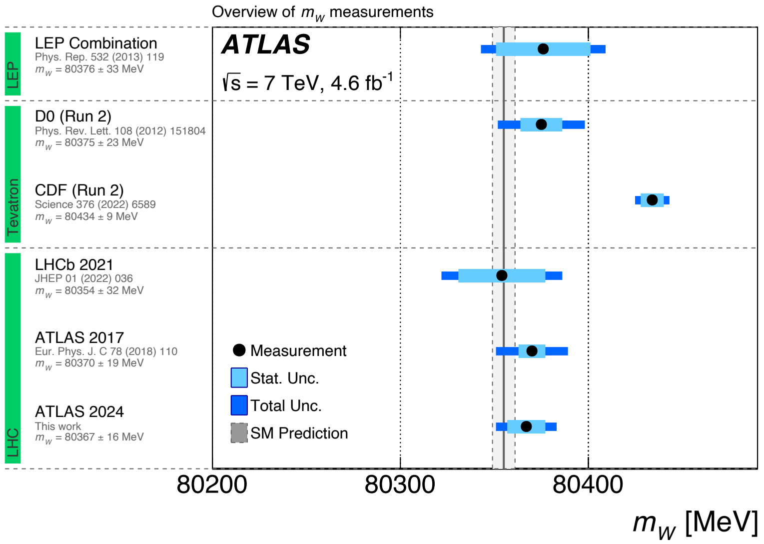
CMS-SMP-23-002

Overview

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



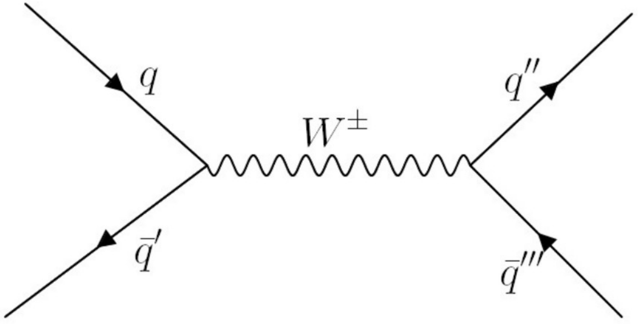
ATLAS W mass measuremnt, arXiv:2403.15085

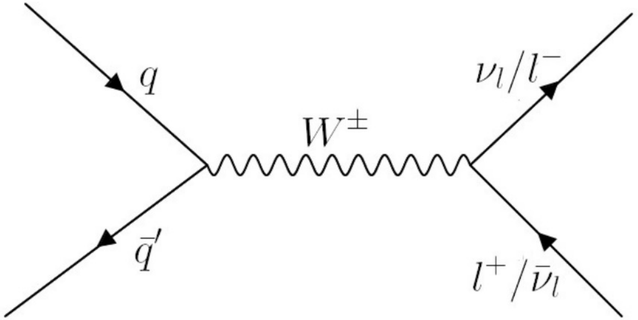


- m_W provides a stringent test of the internal consistency of the Standard Model (SM). The global Electroweak(EW) Fit allows for a precise prediction of m_W given m_H, m_t, etc.
  - m_W predicted by EW fit with $\Delta m_W = 6$ MeV (10^{-4}) uncertainty, ΔmW on PDG average in 2022 = 13 MeV
  - Last 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 decay channel not feasible due to huge QCD backgrounds/jet energy scale
- Focus on leptonic decay
    - Neutrino goes undetected in the detector, but can be inferred from the missing transverse momentum or p_T^{Miss}



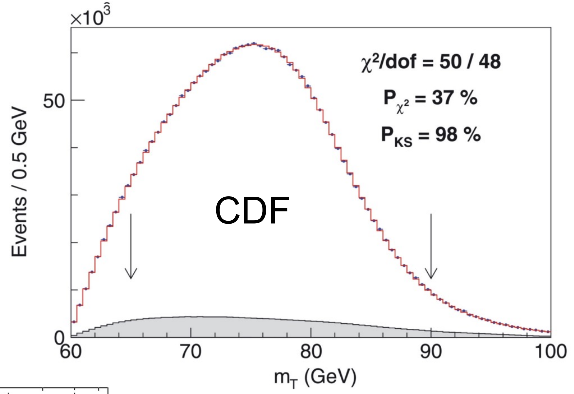


Measuring m_W at hadron colliders

- Traditionally, m_T is the preferred variable for the m_W measurement
  - More robust wrt theoretical calculations, but resolution limited at high pileup environments
- At LHC, due to higher pileup, p_T^l is more precise than m_T
  - Sensitive to theoretical uncertainties (PDFs and W p_T)
  - Can be measured very precisely experimentally

$$m_T^2 = 2 p_T^\ell p_T^\nu (1 - \cos\phi_{\ell\nu})$$

p_T^{miss}



Science 376 (2022) 6589

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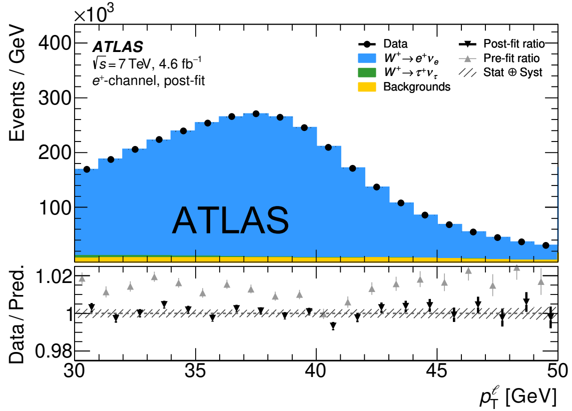
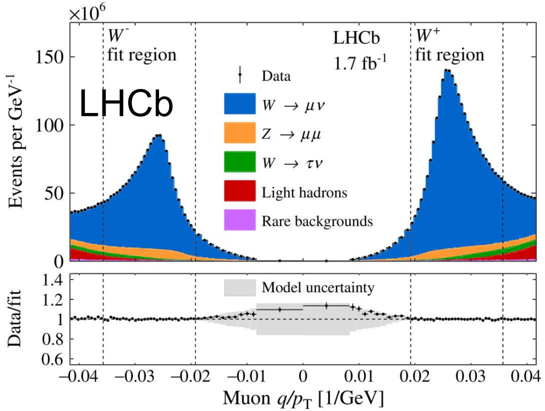
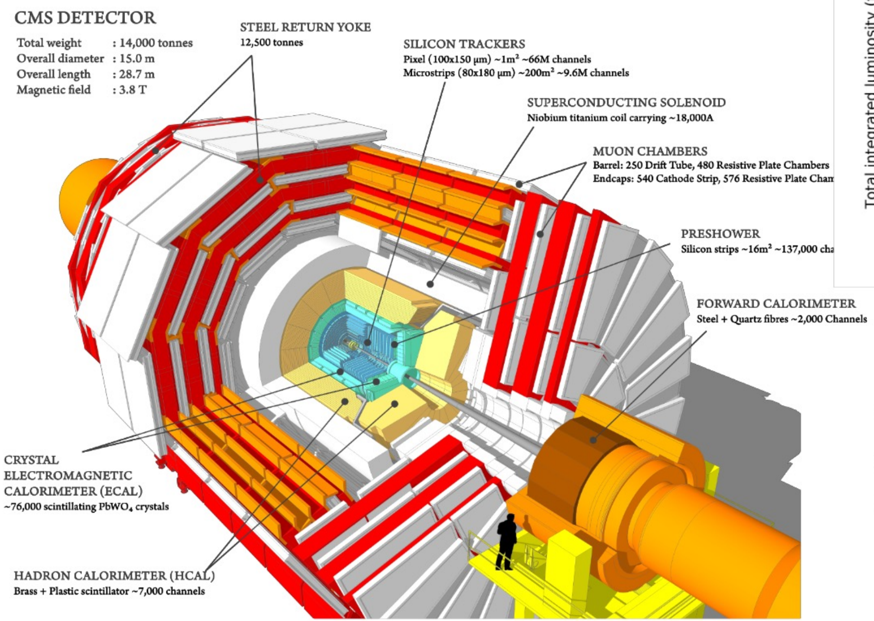
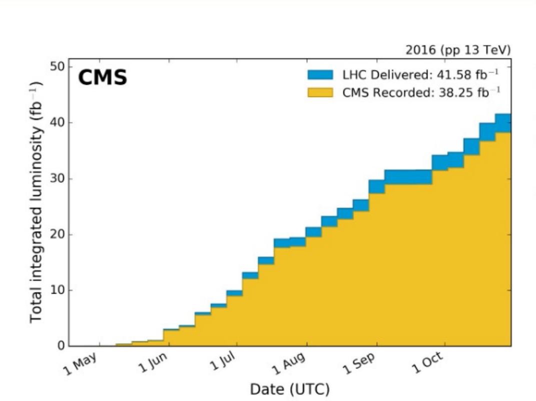




JHEP 01 (2022) 036

The CMS analysis

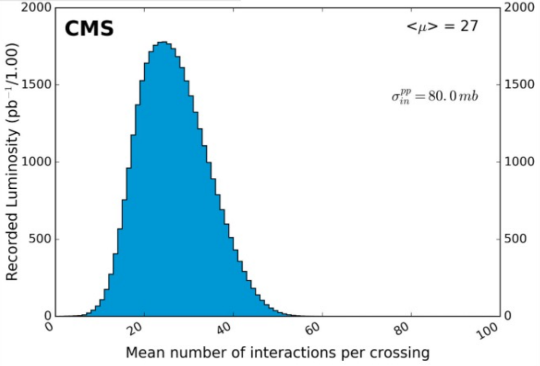




Use 2nd part of 2016 data set

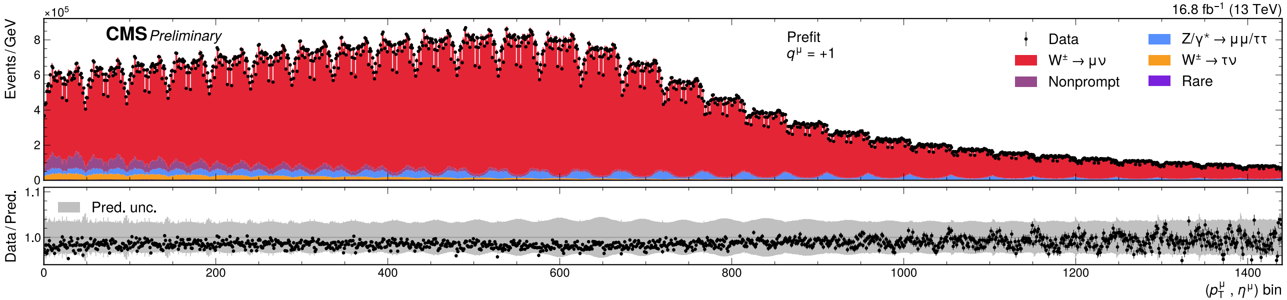
➔ $L = 16.8\ \mathrm{fb}^{-1}$

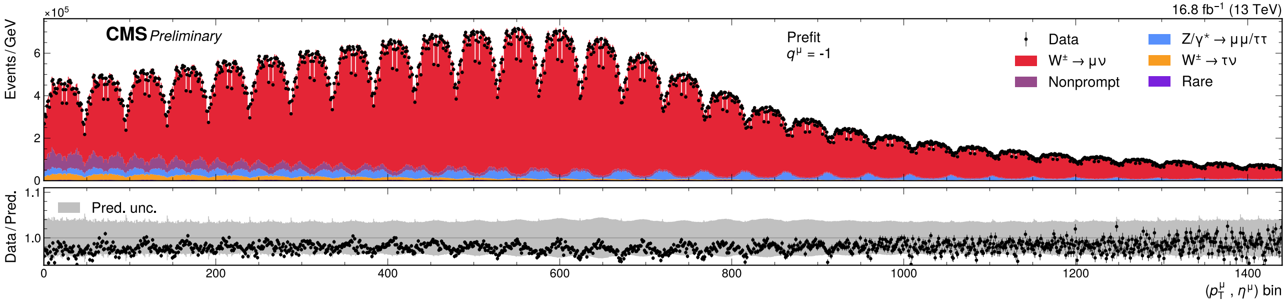
Avg. number of Pile-Up $\langle \mu \rangle = 27$



The CMS analysis

- Standard single-muon selection
- Simultaneous maximum likelihood fit to muon p_T- η distribution for W^+ and W^-
  - p_T^W: use theoretical model with large systematic uncertainties which are constrained in-situ:
    - Z kept as independent cross-check
  - PDFs: Constrain PDF uncertainties exploiting η (demonstrated in W helicity measurement Phys. Rev. D 102 (2020) 092012)



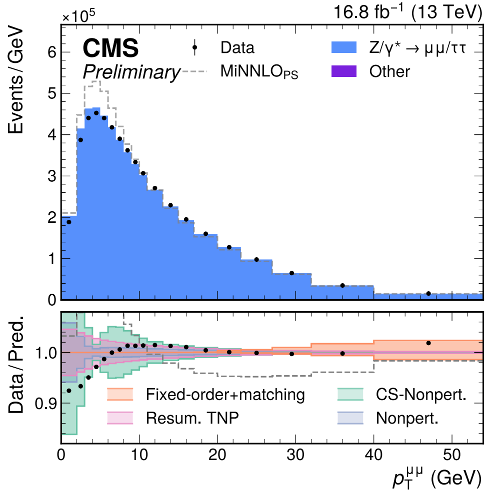


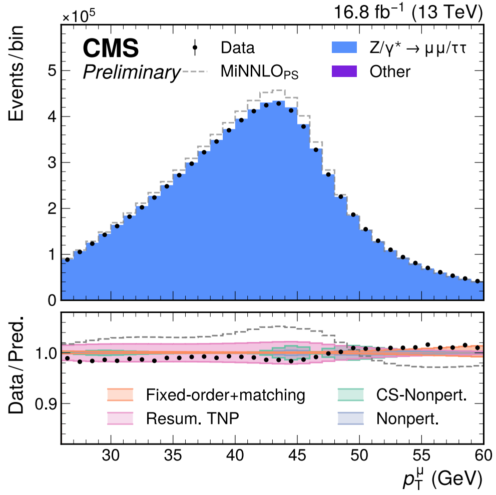
- 2880 bins
- O(5K) systematic variations
- 4.5B fully simulated events, > 100M selected W candidates

No electron or m_T for now, more challenging systematics, need additional works.

p_T^W modelling

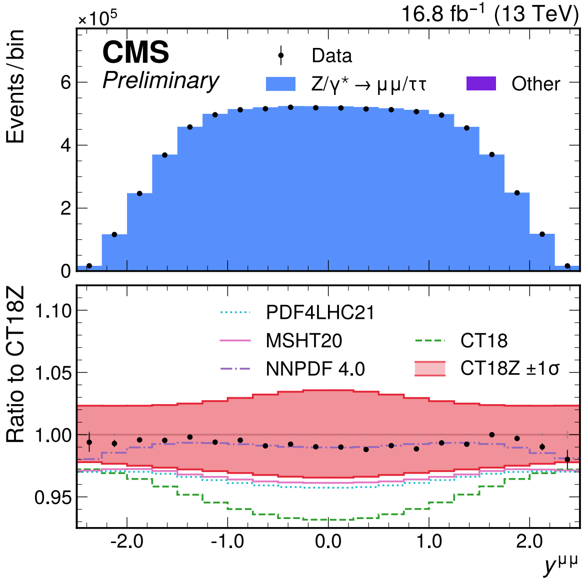
- Simulation of events using MiNNLO$_{PS}$ + Pythia8 + Photos (NNLO + LL in α_s)
- Reweighting to match predictions from SCETLib + DYTurbo (N3LL + NNLO)
- Uncertainties
  - Non-perturbative: Intrinsic momentum of partons (TMP PDF), non-perturbative uncertainties in resummation
  - Resummation (perturbative): "Theory Nuisance Parameters" corresponding to coefficients in resummed calculations
  - Matching: Variation in matching scale
  - Fixed order: Missing higher orders in α_s assessed through μ_r, μ_f variations





PDFs

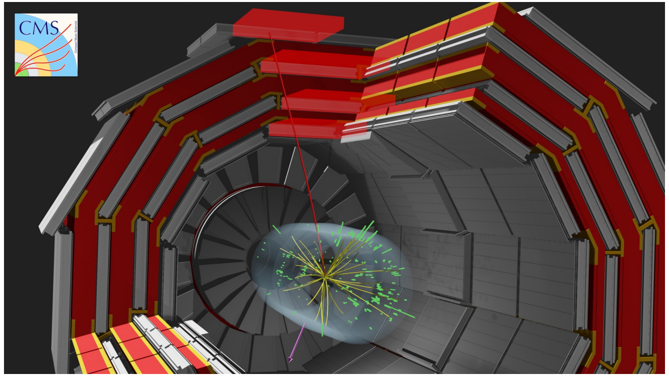
- Several modern sets are considered.
- Check compatibility between PDF sets:
  - Bias test with prediction from one PDF set as nominal and prediction from the other as pseudo-data, repeated changing the nominal PDF set
  - Inflate PDF uncertainties for “failing” sets
- CT18Z chosen as nominal set:
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

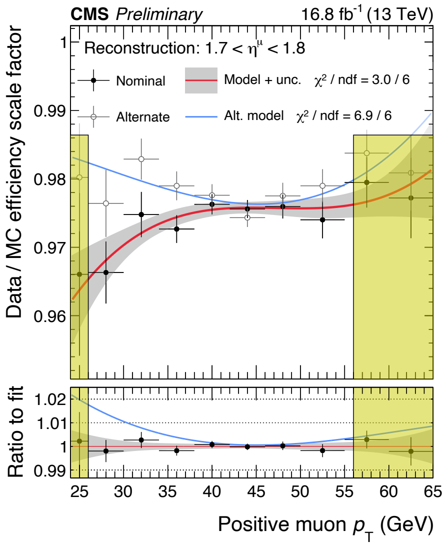


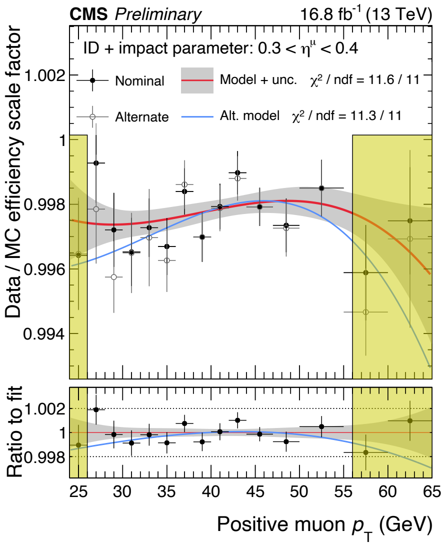
PDF set	Scale factor	Impact in m_W (MeV)	
		Original σ_{PDF}	Scaled σ_{PDF}
CT18Z	–	4.4	
CT18	–	4.6	
PDF4LHC21	–	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0

Muons in CMS

- Two-stage reconstruction
  - Tracker track matched with muon track
  - Additional identification criteria
- Efficiencies and scale factors are measured in Z → $\mu\mu$ events
  - With unprecedented level of granularity
  - Careful factorization of each reconstruction/identification step
  - Effect of hadronic recoil from W/Z boson is also taken into account for isolation and trigger efficiencies
- Uncertainties propagated through O(3000) nuisance parameters
  - Impact on m_W → ~3 MeV

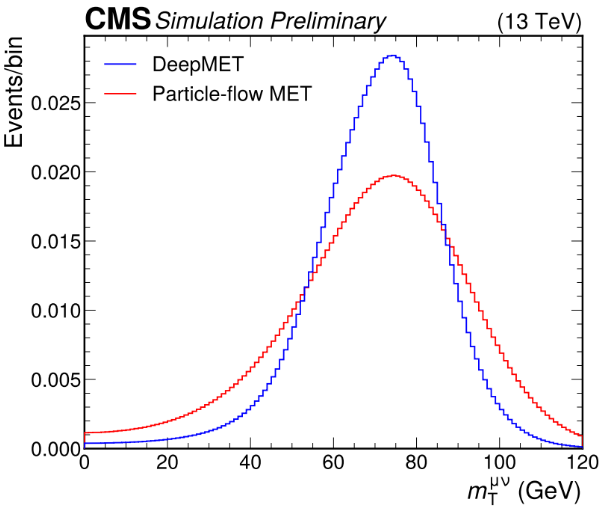


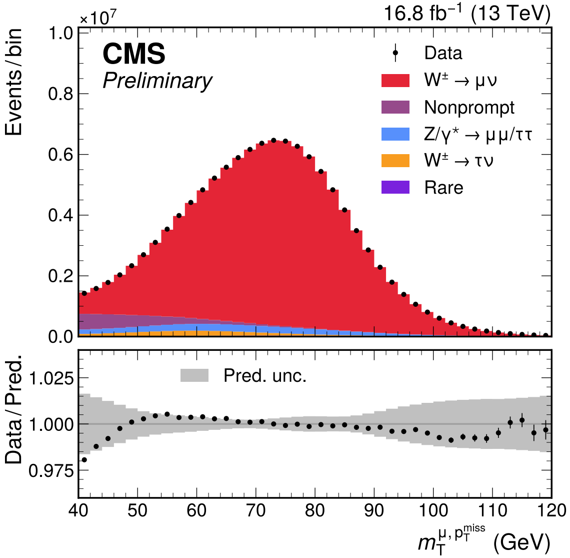




Hadronic Recoil

- Transverse mass is not directly used as a fit variable in the present analysis, but it’s used as a part of the event selection and non-prompt background estimation
- Hadronic recoil is constructed 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.

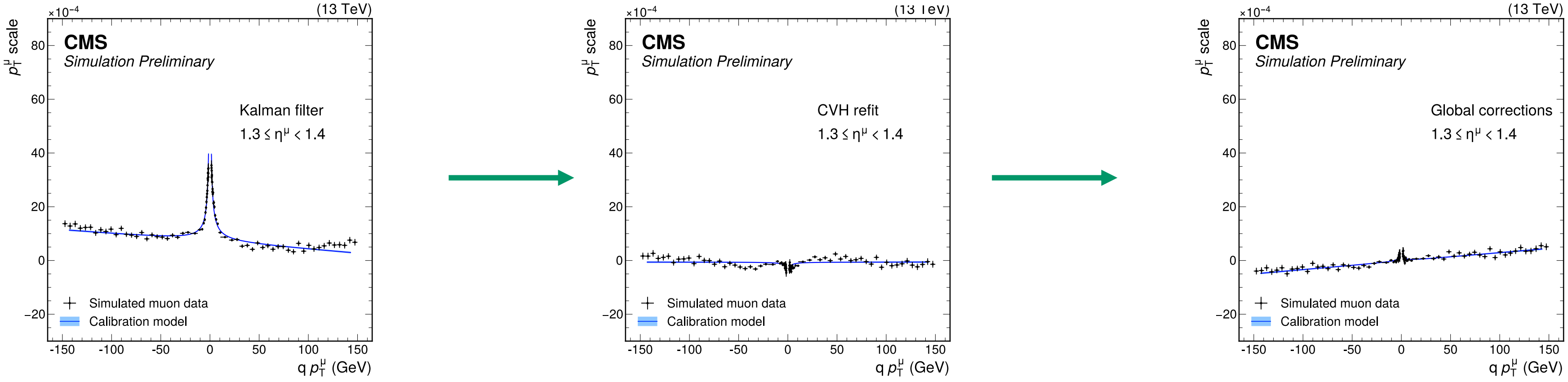




Muon Momentum Calibration

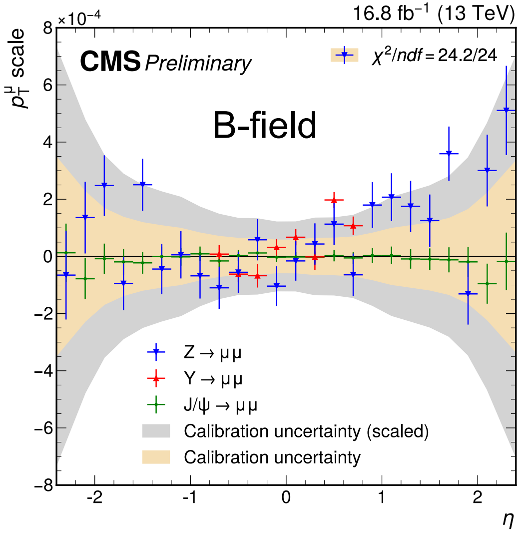
- Target is $\frac{\delta p_T{}^{\mu}}{p_T{}^{\mu}} \sim 10^{-4}$ for ~40 GeV muons (~ 8 MeV on m_W)
- With default muon reconstruction and calibration of CMS this can not be achieved
- Calibration performed in sequential steps
  - Tuning of parameters in CMS simulation
  - Track re-fit with improved B-field/material treatment based on Geant4e (Continuous Variable Helix or 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 (p_T^+, η^+, p_T^-, η^-) by fitting a parametric model

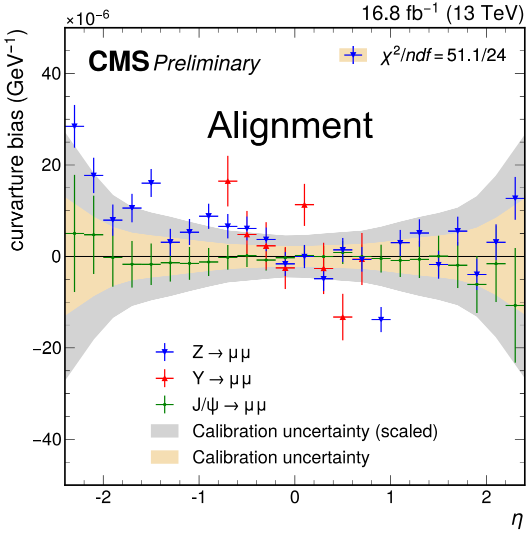
$$\left(\frac{\delta p_T}{p_T}\right)_{\pm} = A_\eta - \frac{\varepsilon_\eta}{p_T} \pm M_\eta p_T$$



Muon Momentum Calibration: Validation with Υ and Z

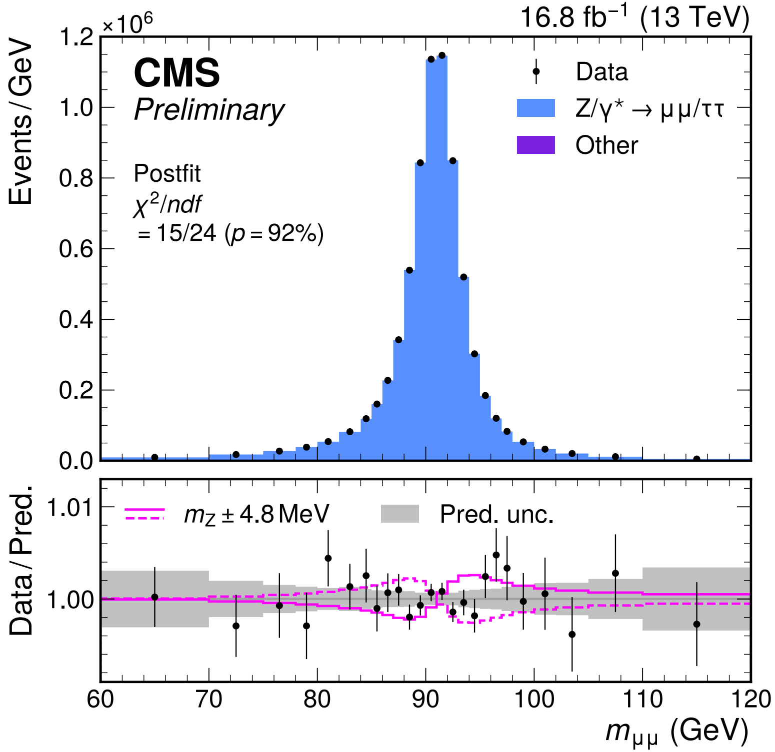
- Parametric corrections from J/ψ applied to Υ,Z → $\mu\mu$ events
  - Repeat last step to derive the residual scales for B-field and alignment
- Check the compatibility by a χ^2 test
  - Inflation of J/ψ stat. uncertainty by a factor 2.1
  - Stat. uncertainty from Z added to uncertainty model, together with PDG uncertainty





Z → $\mu\mu$ mass fit

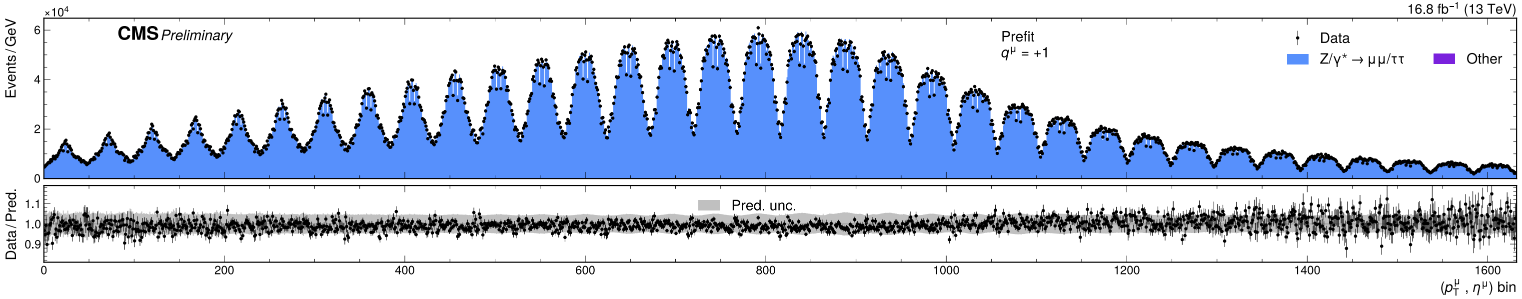
- Validation of the scale calibration by fitting the ($m^{\mu\mu}$, $\eta^{\mu}{}_{fwd}$) distribution
- $m_z^{CMS} - m_Z^{PDG} = -2.2 \pm 1.0$ (stat) $\pm$ 4.7 (syst) MeV
  $= -2.2 \pm 4.8$ MeV
- Though only J/ψ events are used as input for the muon momentum calibration
  - Z events are used to check the consistency of the derived result
  - J/ψ vs Z closure also used in the uncertainty model
- **Hence, can not be considered as an independent Z mass measurement**



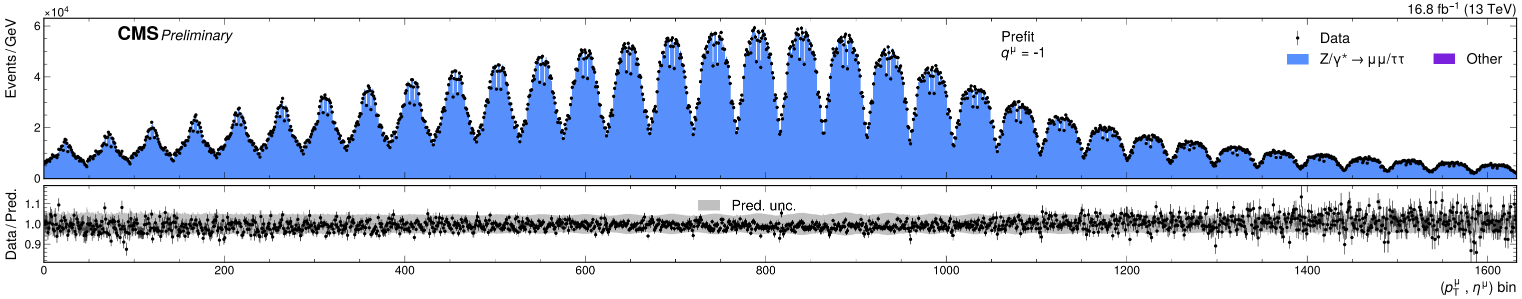
Validation : W - like

- Select Z → $\mu\mu$ events and treat one muon at the time as a neutrino

μ^+ in even numbered events

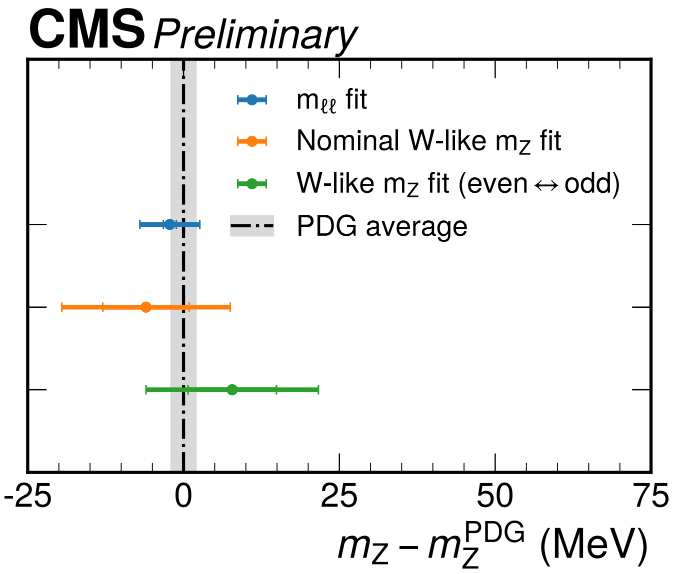


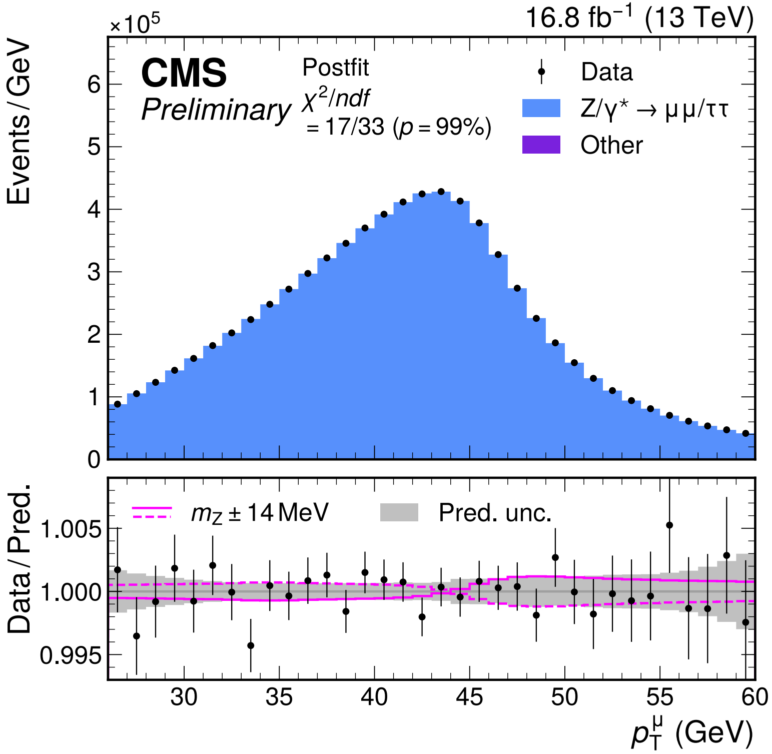
μ^- in odd numbered events



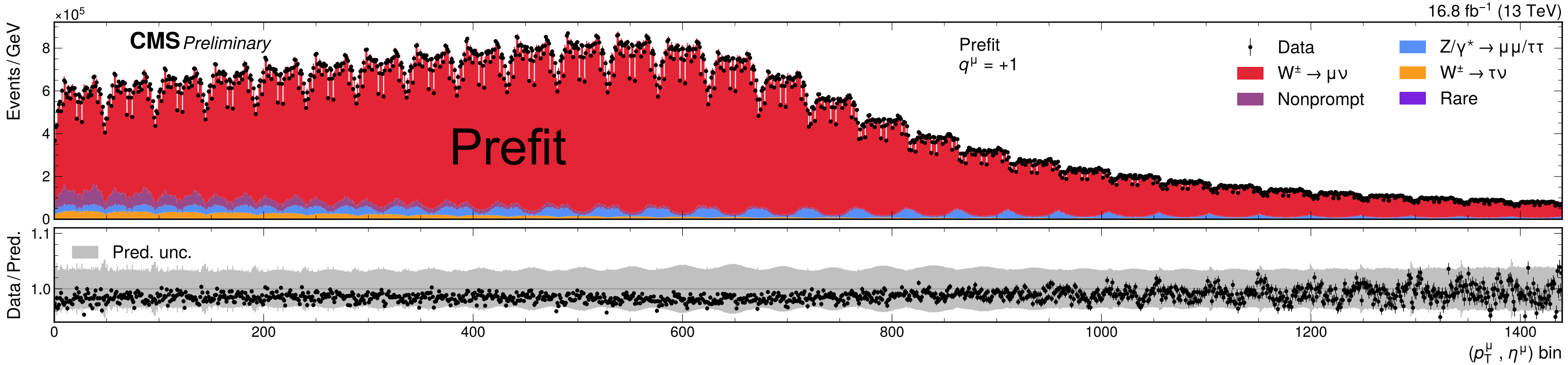
W – like results

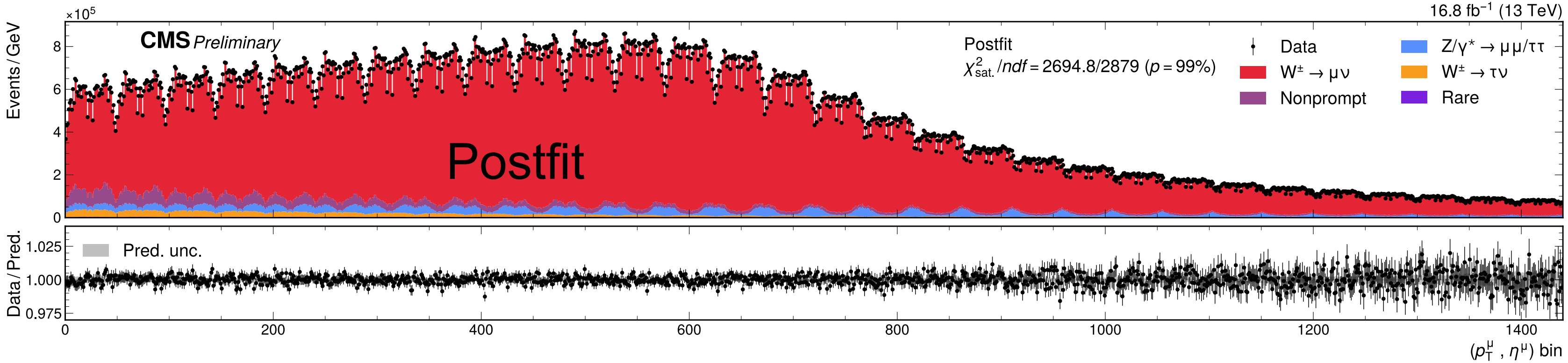
- Total uncertainty on m_Z is 14 MeV
  - Muon scale (5.6), angular coeff (4.9). Muon reco (3.8)
  - m_Z kept blind until all checks completed





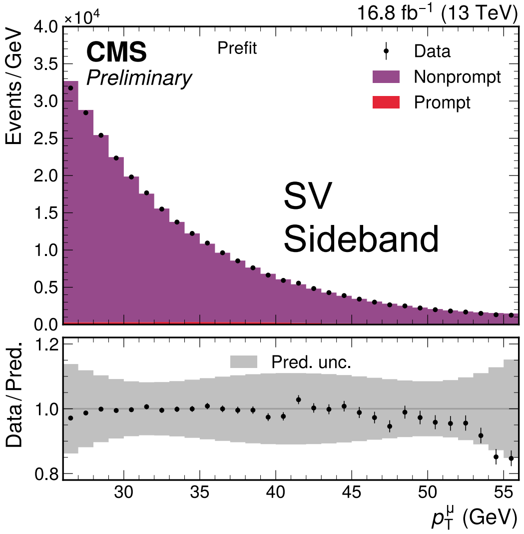
Moving to the W mass measurement

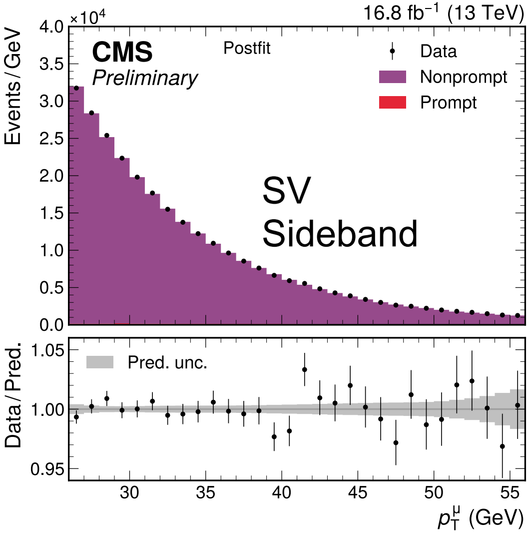




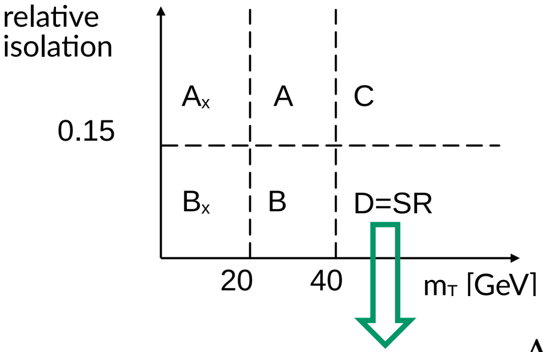
Non-prompt background

- Mostly muons from B/C hadrons decay (~85%)
- Data-driven estimation using an extended ABCD method based on iso : m_T
    - Validated with QCD simulation and data from control region with muons from secondary vertices (SV sideband region)





In each (η, p_T bin:)

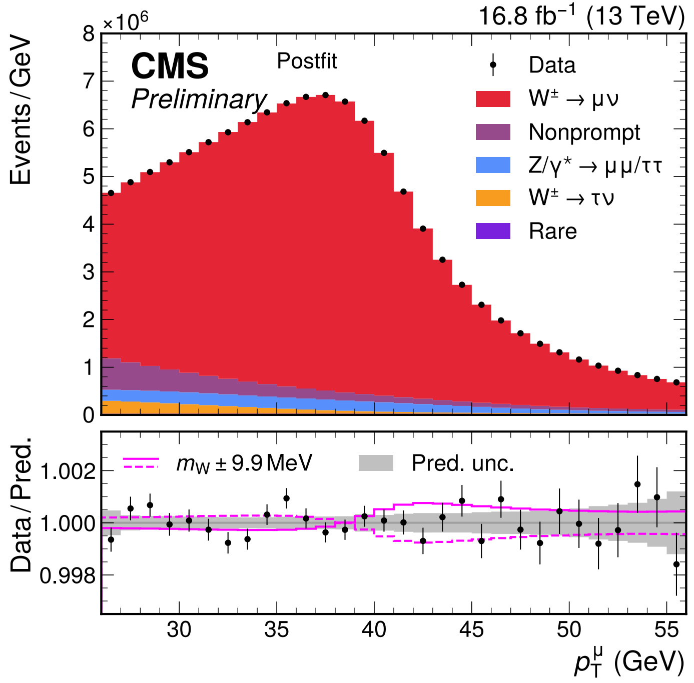


$$D = C \cdot \frac{A_x B^2}{B_x A^2}$$

Impact on $m_W \rightarrow$ ~ 3MeV

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

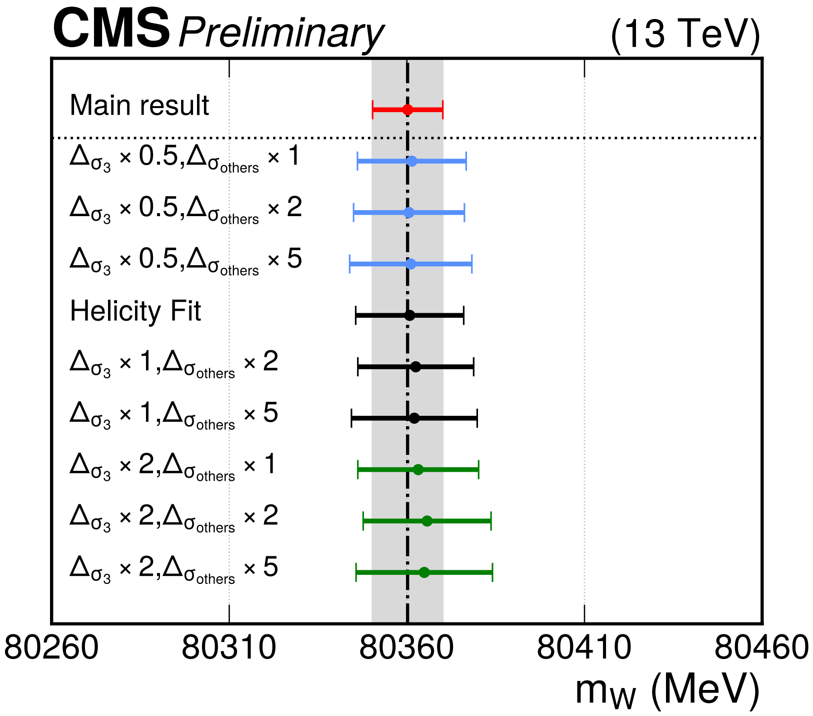
- Implementation of less model dependent measurement
  - Additional test of the QCD model, BSM physics in W production or decay, etc.
- Basic strategy: Measure the terms of the 9 helicity cross sections $\sigma_i \equiv \sigma_{UL} \times Ai$ double differentially in W rapidity and p_T(relying less on theoretical 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

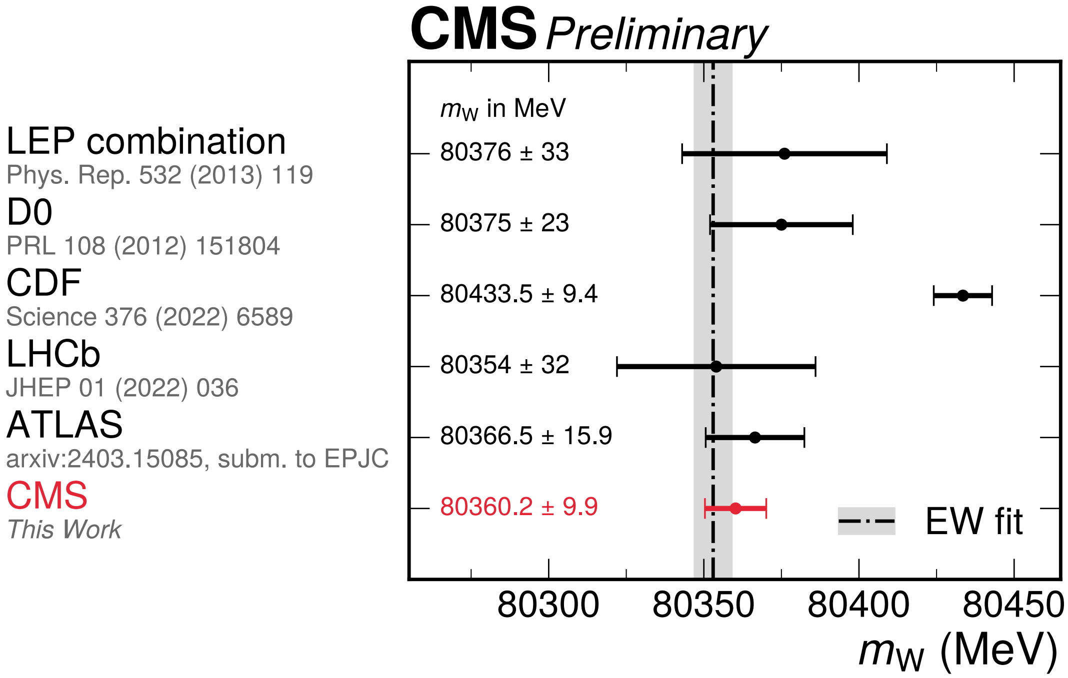
Helicity cross-section fit

- Current data/observables are not sufficient to constrain all the relevant helicity components
- Cross sections are regularized via constraints to the nominal prediction
  - Uncertainties are increased with respect to the 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



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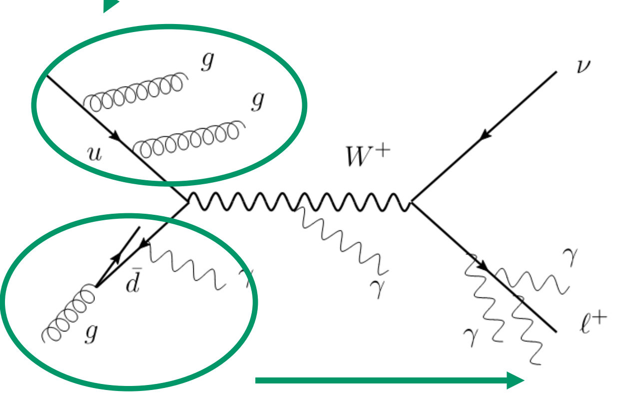
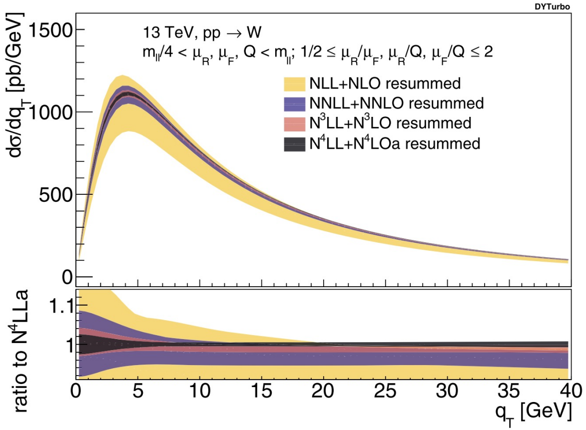
Backup

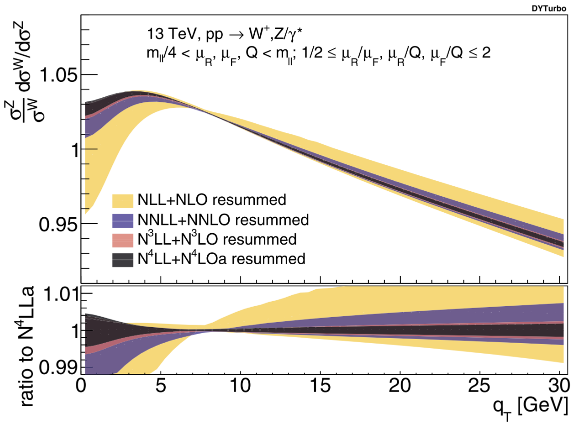
p_T^W modelling

- Conventional wisdom: estimate p_T^W using measured p_T^Z sprectrum and rely on theoretical ration 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

Model validation

- Comparison of p_T^{ll} unfolded at generator level with predictions from theoretical modelling
  - 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 from TNPs
- Direct fit to $p_T^{\mu\mu}$ has stronger constraints but W-like fit is able to correctly dientagle m_Z from from the Z p_T spectrum
- m_W can be measured without tuning the p_T spectrum to the Z