High-precision measurement of the W boson mass with the CMS experiment

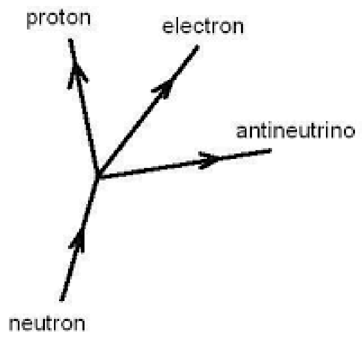
CMS-PAS-SMP-23-002

Lorenzo Bianchini
Università & INFN Pisa

Towards the W boson

- **E. Fermi** (1934): a theory of β-decay

$$G_F = 1.166 \times 10^{-5}\ \mathrm{GeV}^{-2}$$



FERMI BETA DECAY THEORY, 1934

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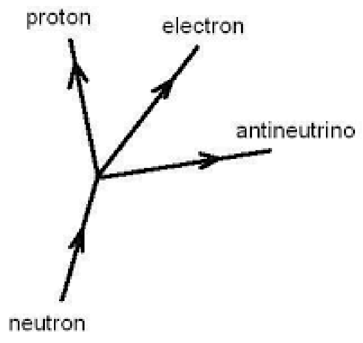

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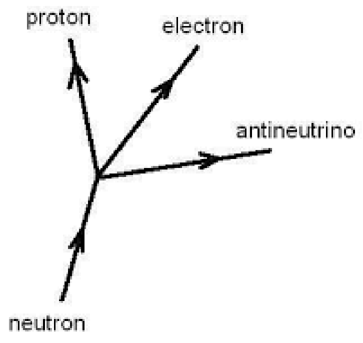

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$$\begin{cases} m_W^2 = \dfrac{\pi\,\alpha_{EM}}{\sqrt{2}G_F \sin^2\theta_W} \gtrsim (40\ \text{GeV})^2 \\ m_Z^2 = \dfrac{\pi\,\alpha_{EM}}{\sqrt{2}G_F \sin^2\theta_W \cos^2\theta_W} \gtrsim (80\ \text{GeV})^2 \end{cases}$$

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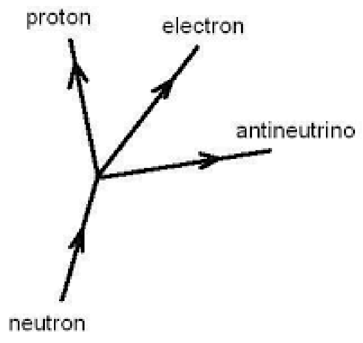

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- **GARGAMELLE** (1973): $\sin^2\theta_W \in [0.3, 0.4]$ ⇒

$$m_W \in [60,80]\ \mathrm{GeV}$$
$$m_Z \in [75,92]\ \mathrm{GeV}$$

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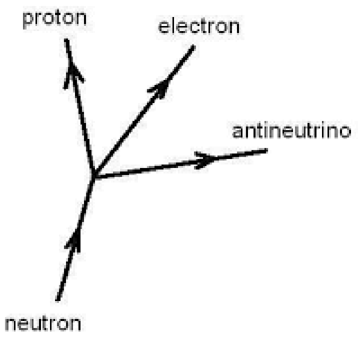

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- **GARGAMELLE** (1973): $\sin^2\theta_W \in [0.3, 0.4]$ ⇒ $m_W \in [60, 80]$ GeV, $m_Z \in [75, 92]$ GeV
- **C. Rubbia *et al.*** (1983): W, Z discovery ⇒ $m_W = \mathbf{80.2} \pm 1.5$ GeV, $m_Z = \mathbf{91.5} \pm 1.8$ GeV

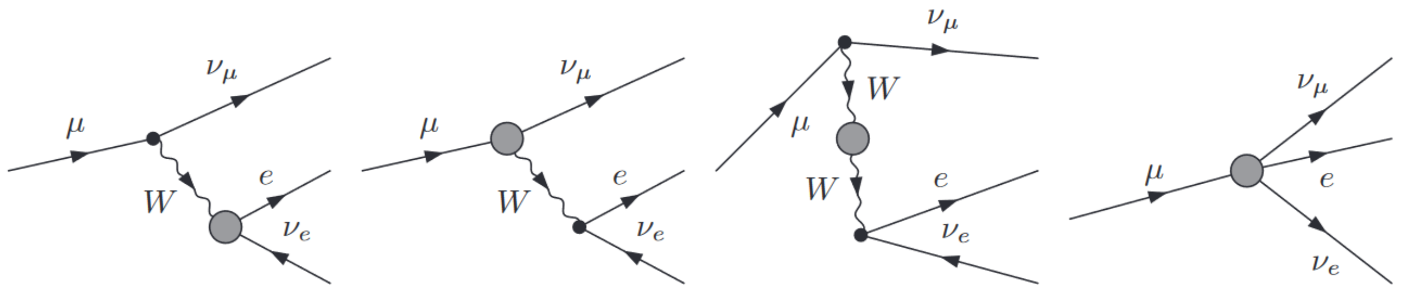
The SM prediction for m_W

$$m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{4\pi\,\alpha_{EM}}{\sqrt{2}G_F m_Z^2}}\right)$$

See e.g. JHEP 05 (2015) 154
W. Hollik's talk

The SM prediction for m_W

$$m_W^2 = \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\,\alpha_{EM}}{\sqrt{2}G_F m_Z^2}}\right) \Rightarrow \frac{m_Z^2}{2}\left(1+\sqrt{1-\frac{4\pi\,\alpha_{EM}}{\sqrt{2}G_F m_Z^2}(1+\Delta r)}\right)$$



$+ \ \ldots$

$$\Delta r = -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2\tan^2\theta_W} + \frac{11 G_F m_W^2}{24\sqrt{2}\pi^2}\ln\frac{m_H^2}{m_W^2} + \cdots$$

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$$\begin{cases} m_Z = 911880 \pm 2.0\ \text{MeV} \\ m_H = 125.20 \pm 0.11\ \text{GeV} \\ m_t = 172.57 \pm 0.29\ \text{GeV} \end{cases}$$

Full 2 loops + QCD/EWK
@ 3,4-loops

m_W = **80353 ± 6 MeV**
(75 ppm)

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BSM

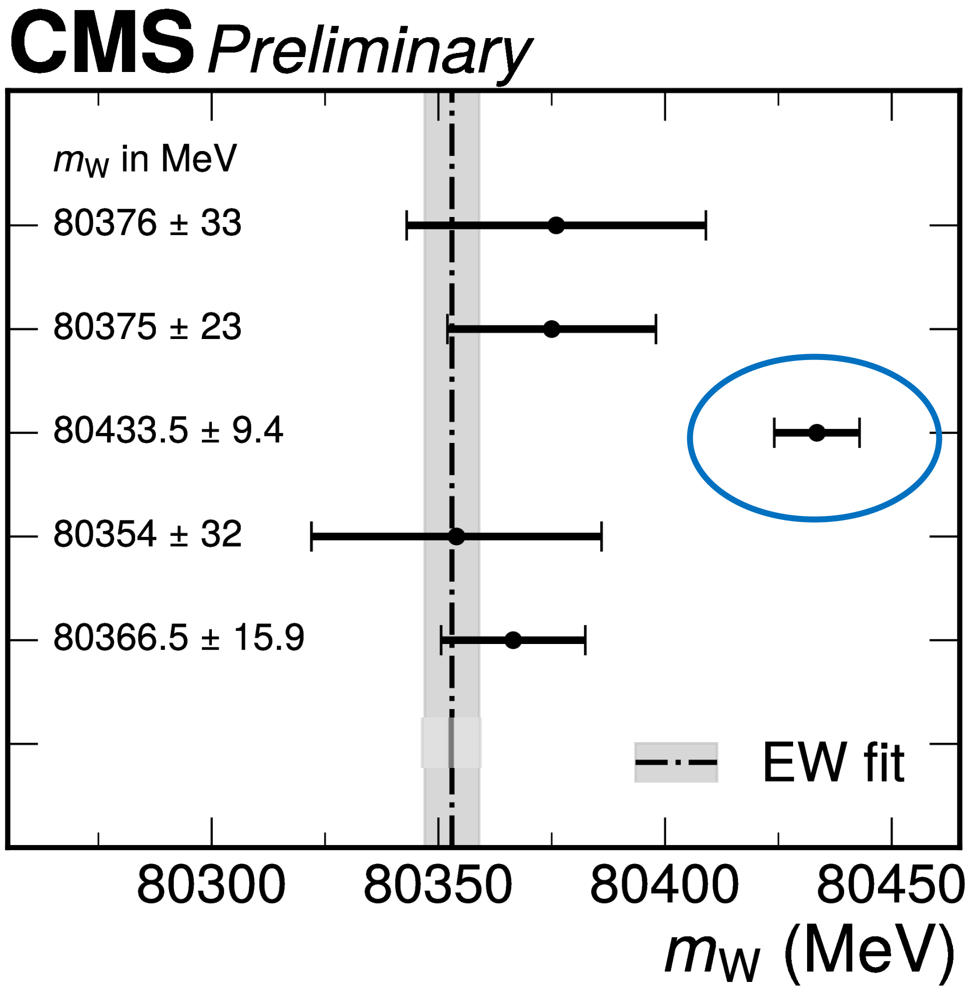
$T > \frac{1}{2}$ Higgs multiplets?

Extra $SU(2)$ doublets ?

Extra $U(1)'$?

The W mass puzzle (before Sept. 17th)

LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arxiv:2403.15085, subm. to EPJC

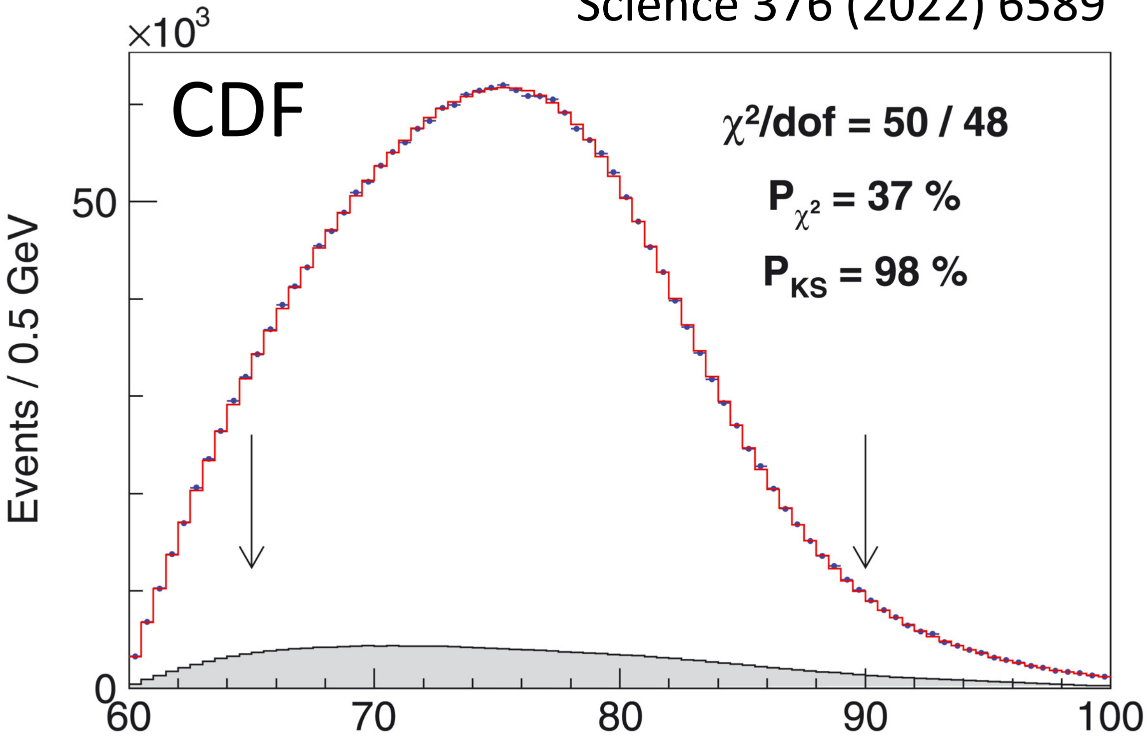


- Legacy CDF result **inconsistent with SM** (7σ)
  - Tension with other measurements ($\sim 4\sigma$)
- PDG 2024 (w/o CDF): $\mathbf{80369.2 \pm 13.3\ MeV}$
  - i.e. $\Delta m_W^{\mathrm{PDG}} \sim 2 \times \Delta m_W^{\mathrm{SM}}$

➔ This calls for a new measurement

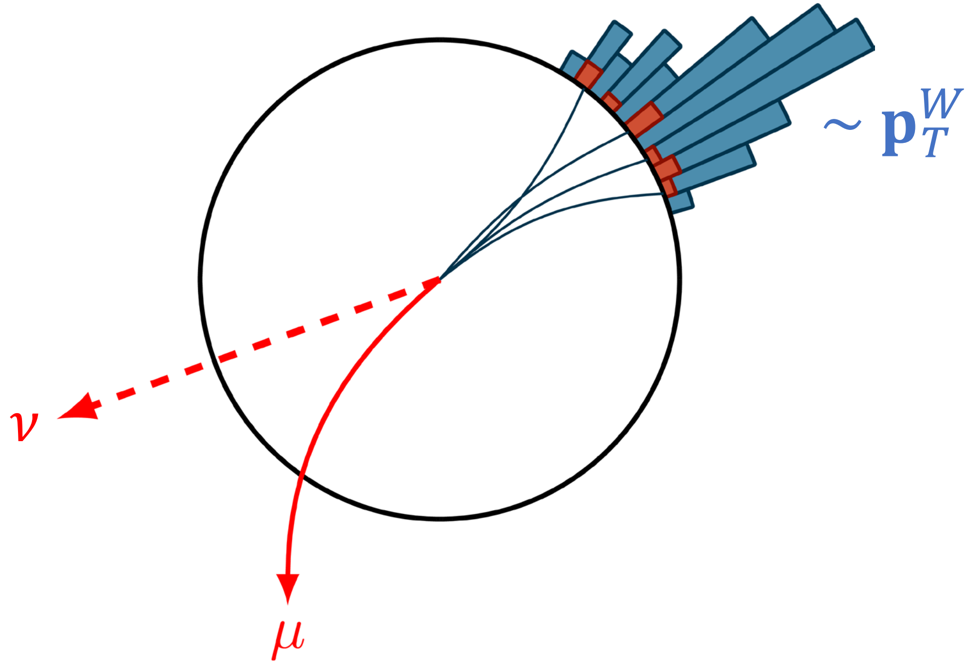
Measuring m_W at hadron colliders

Science 376 (2022) 6589



$W \to q\bar{q}$ not feasible

➔ focus on $W \to \ell\nu$ decay



$$m_T^{\ell\nu} = \sqrt{2(p_T^\ell|\mathbf{p}_T^\ell + \mathbf{p}_T^W| + p_T^{\ell\,2} + \mathbf{p}_T^\ell \cdot \mathbf{p}_T^W)}$$

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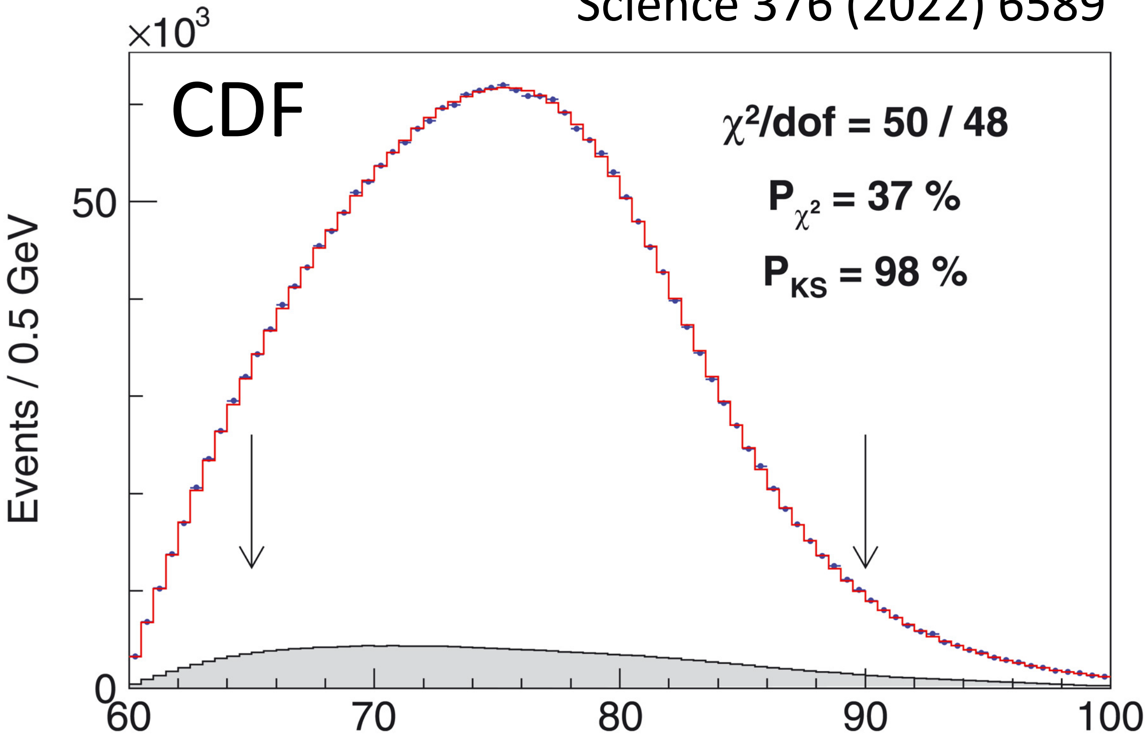

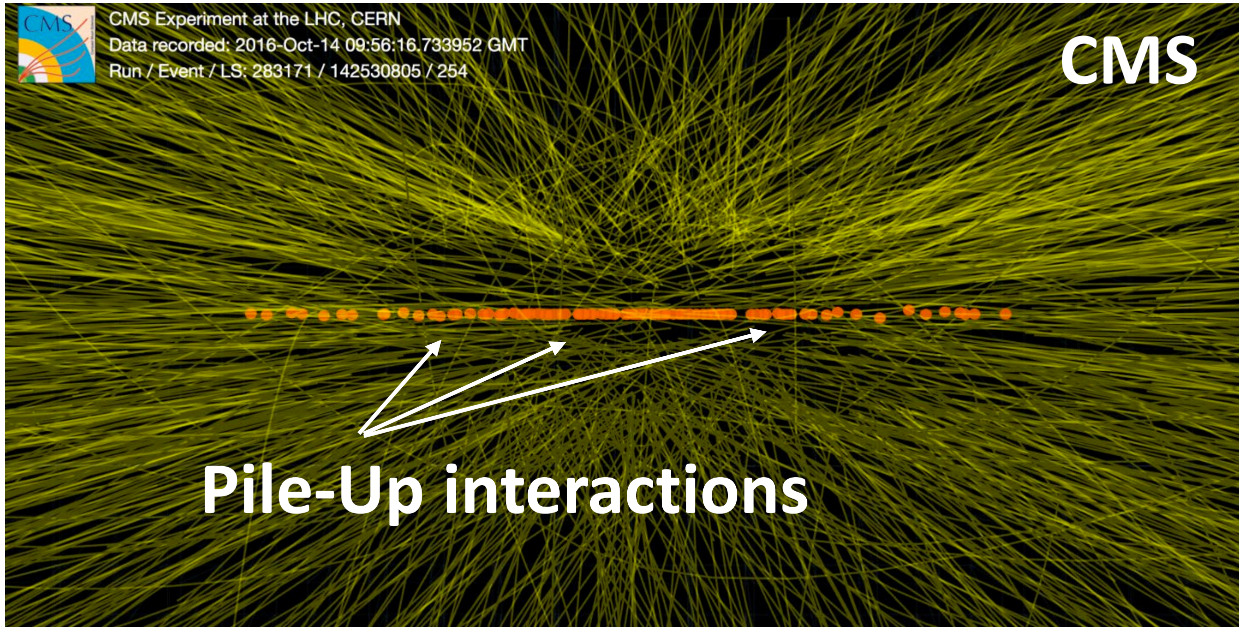

$$m_T^{\ell\nu} = \sqrt{2\left(p_T^\ell \left|\mathbf{p}_T^\ell + \mathbf{p}_T^W\right| + {p_T^\ell}^2 + \mathbf{p}_T^\ell \cdot \mathbf{p}_T^W\right)}$$

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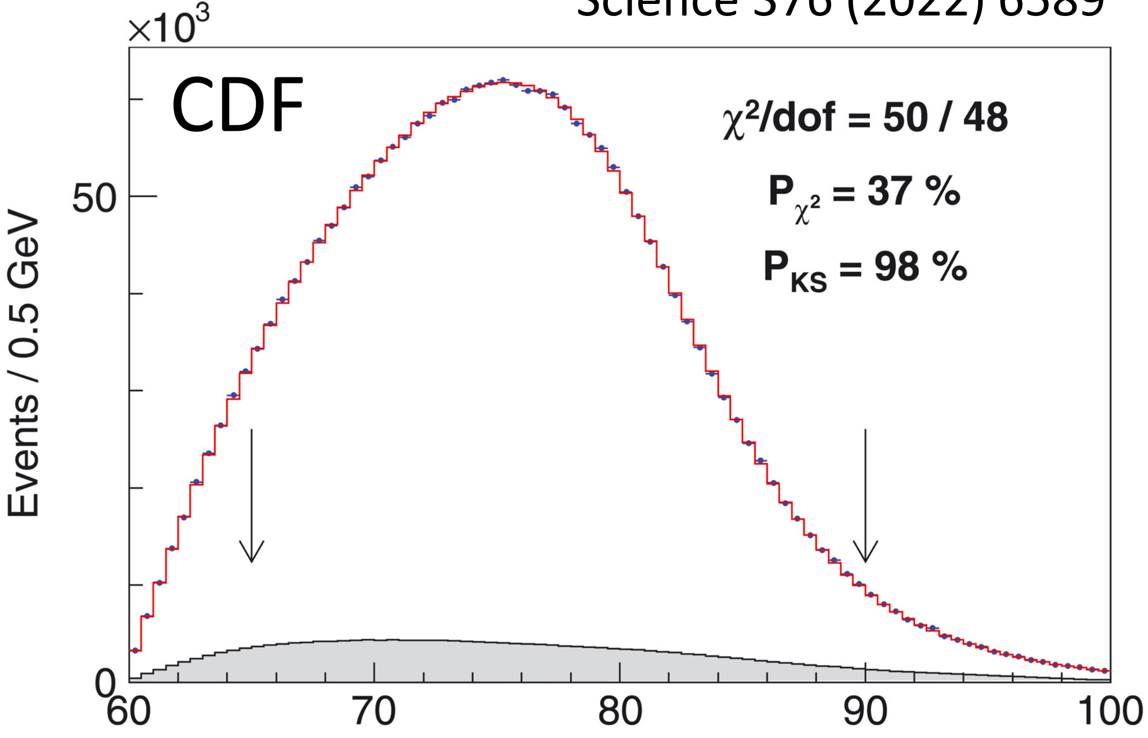
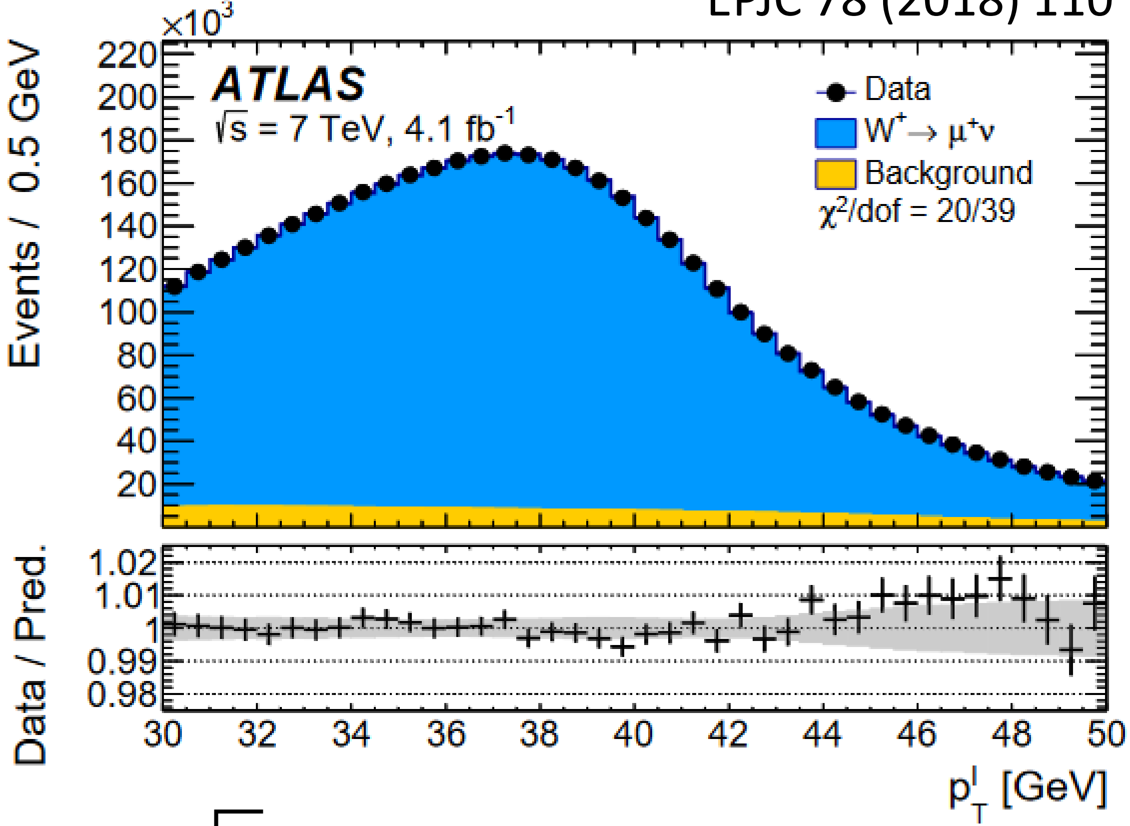
Science 376 (2022) 6589



EPJC 78 (2018) 110



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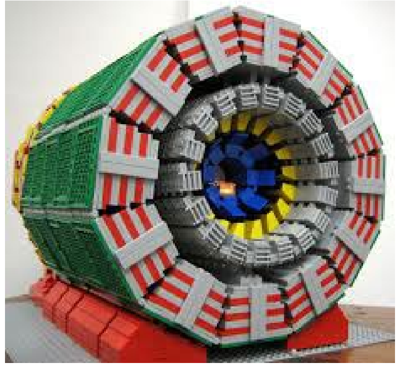
p_T^ℓ ➔

- Cleaner at the LHC
- But: **sensitive to $\boldsymbol{W}$ modeling**

Measuring m_W at hadron colliders

MC simulation
$pp \to W^{\pm} + X$
$\quad \hookrightarrow \ell^{\pm} + \nu_{\ell}$

$\otimes$



1) Build **templates of** $\boldsymbol{\frac{d\sigma}{dp_T^{\ell}}}$ **for different values of** $\boldsymbol{m_W}$

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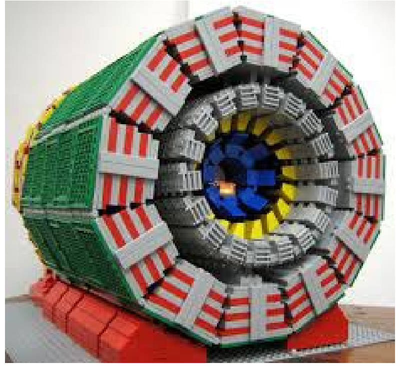
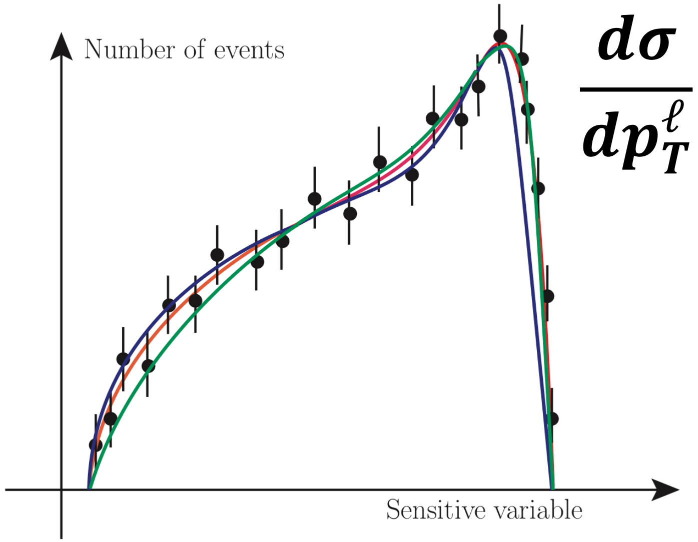


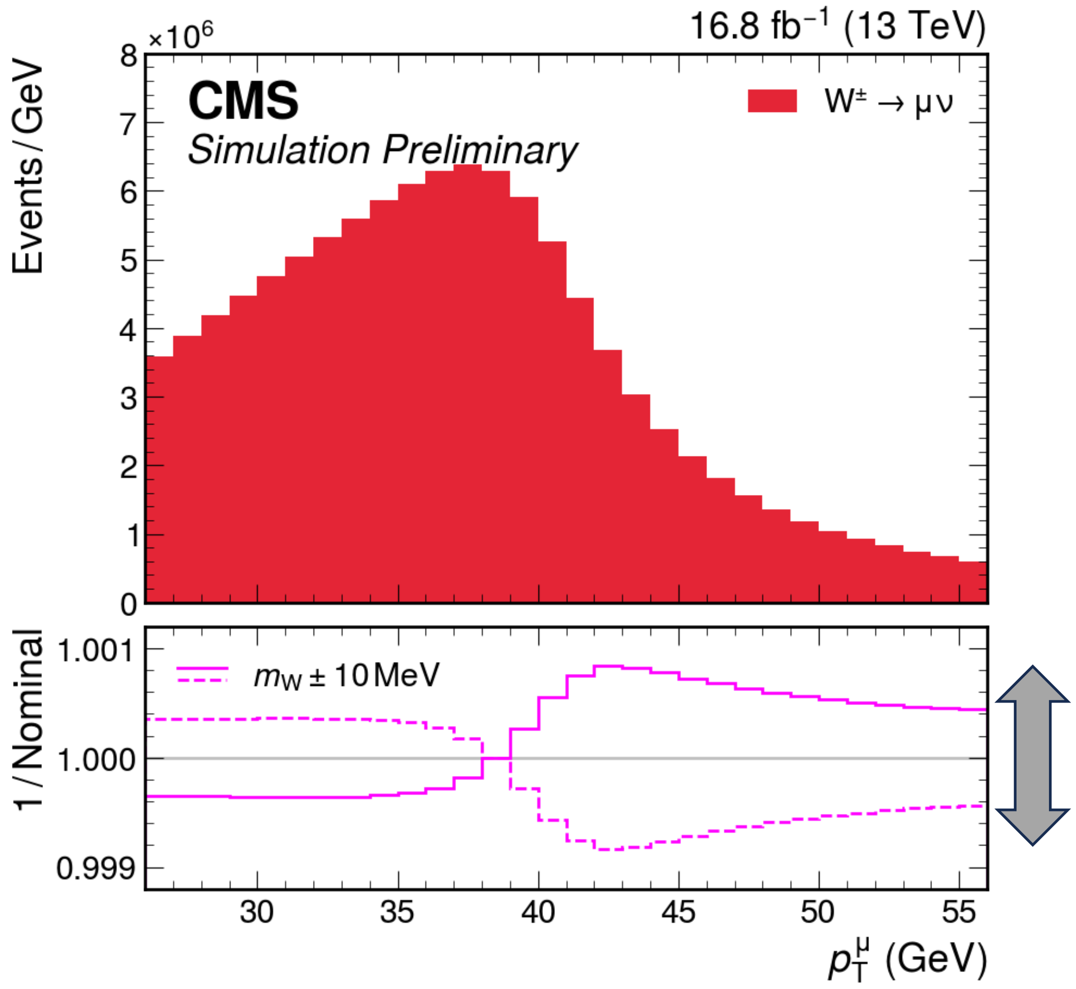


$\frac{d\sigma}{dp_T^{\ell}}(\hat{m}_W)$

1) Build **templates of** $\frac{d\sigma}{dp_T^{\ell}}$ for different values of m_W

2) Find $m_W = \hat{m}_W$ that **best fits the data**

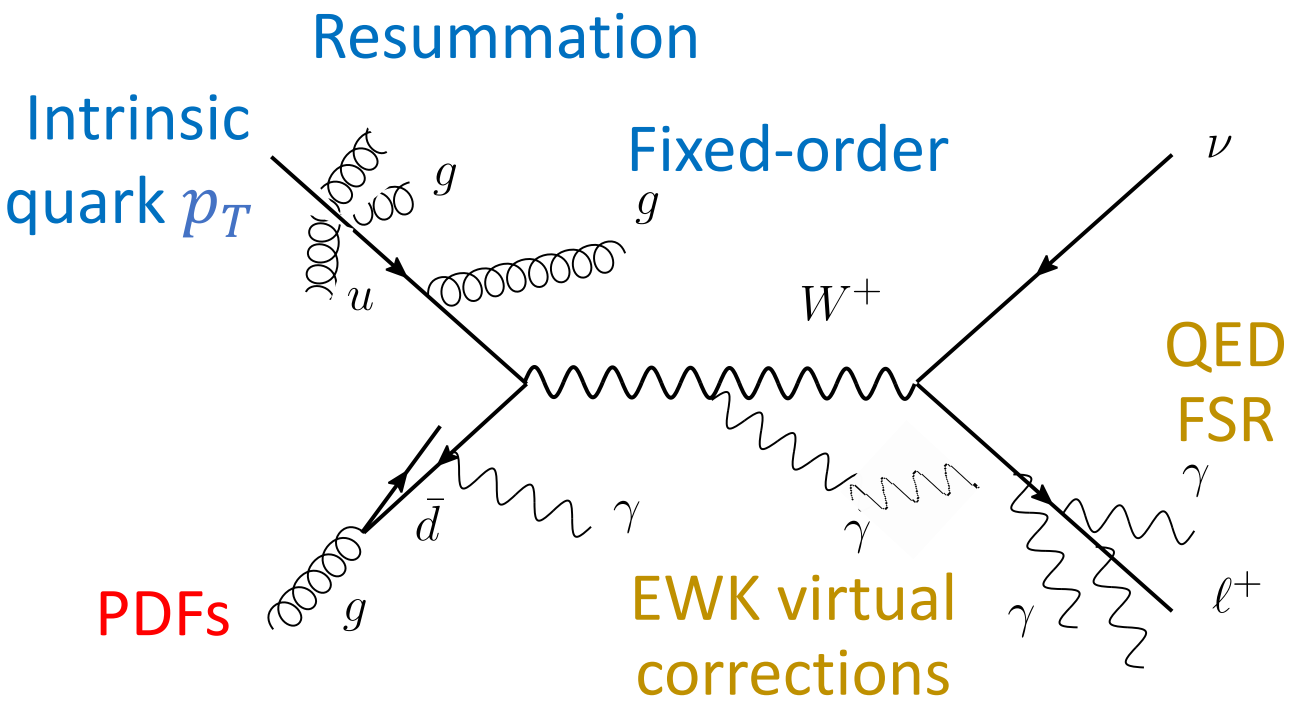
Measuring m_W at hadron colliders



$\Delta m_W = 10$ MeV

$\Longrightarrow$ **0.1% variation**

Monte Carlo simulation



see e.g. EPJC 77 (2017) 280

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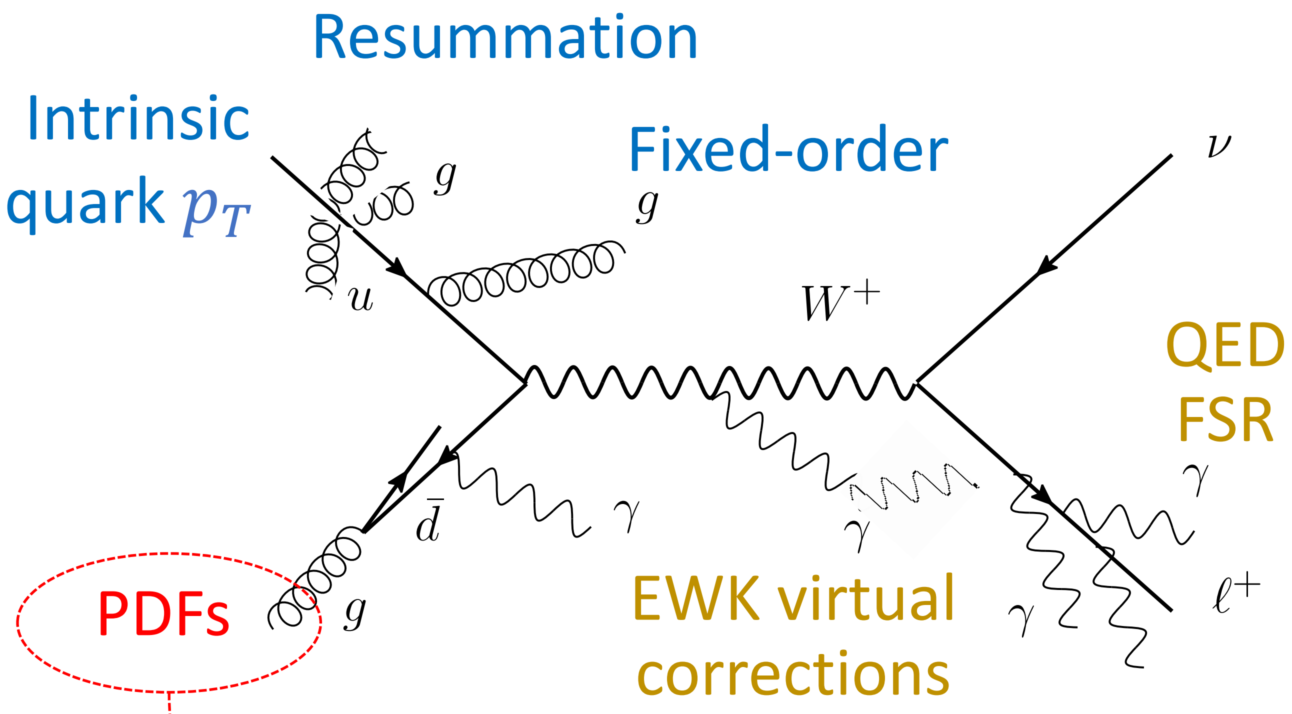

y^W, polarization $\Longrightarrow \langle p_T^\ell \rangle$

see e.g. EPJC 77 (2017) 280

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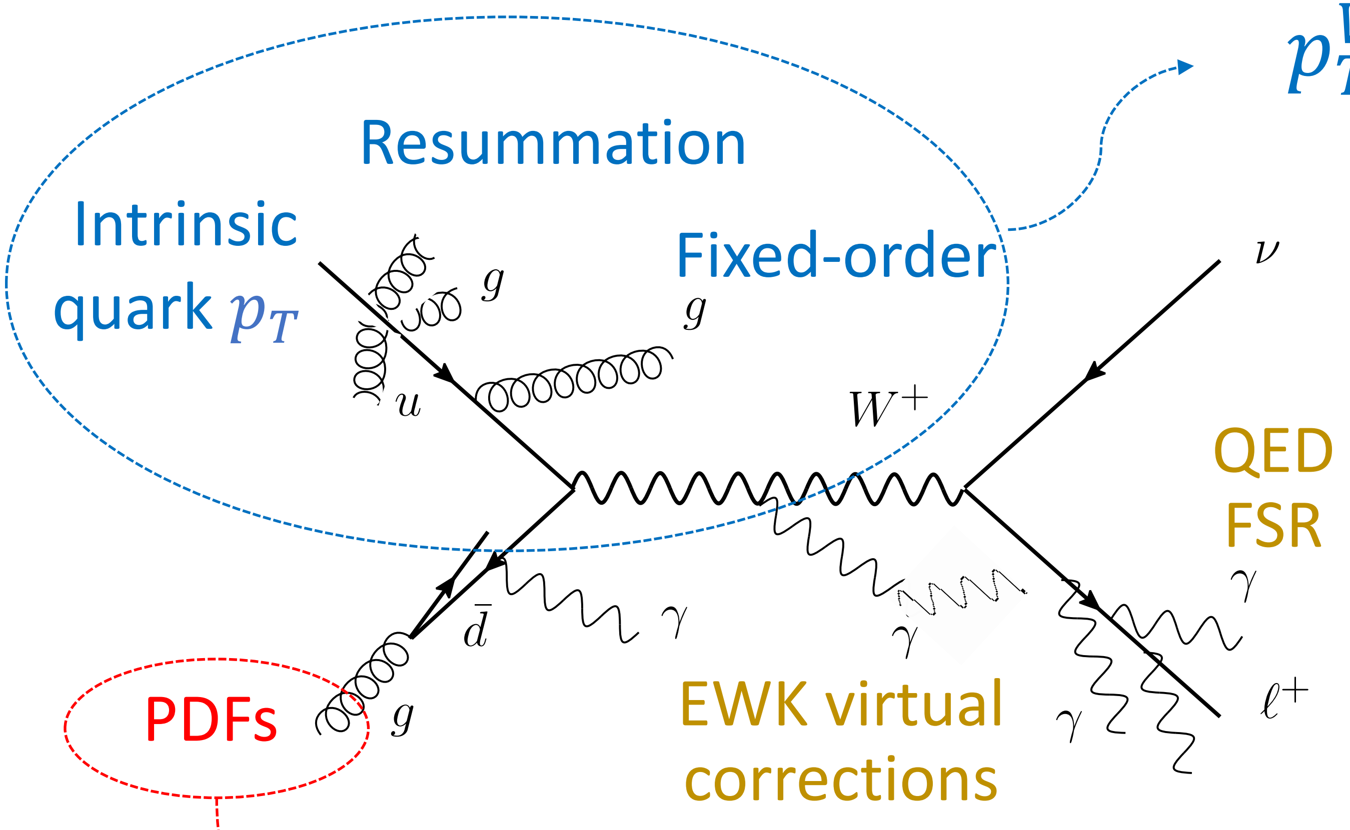

$p_T^W \Longrightarrow p_T^\ell$

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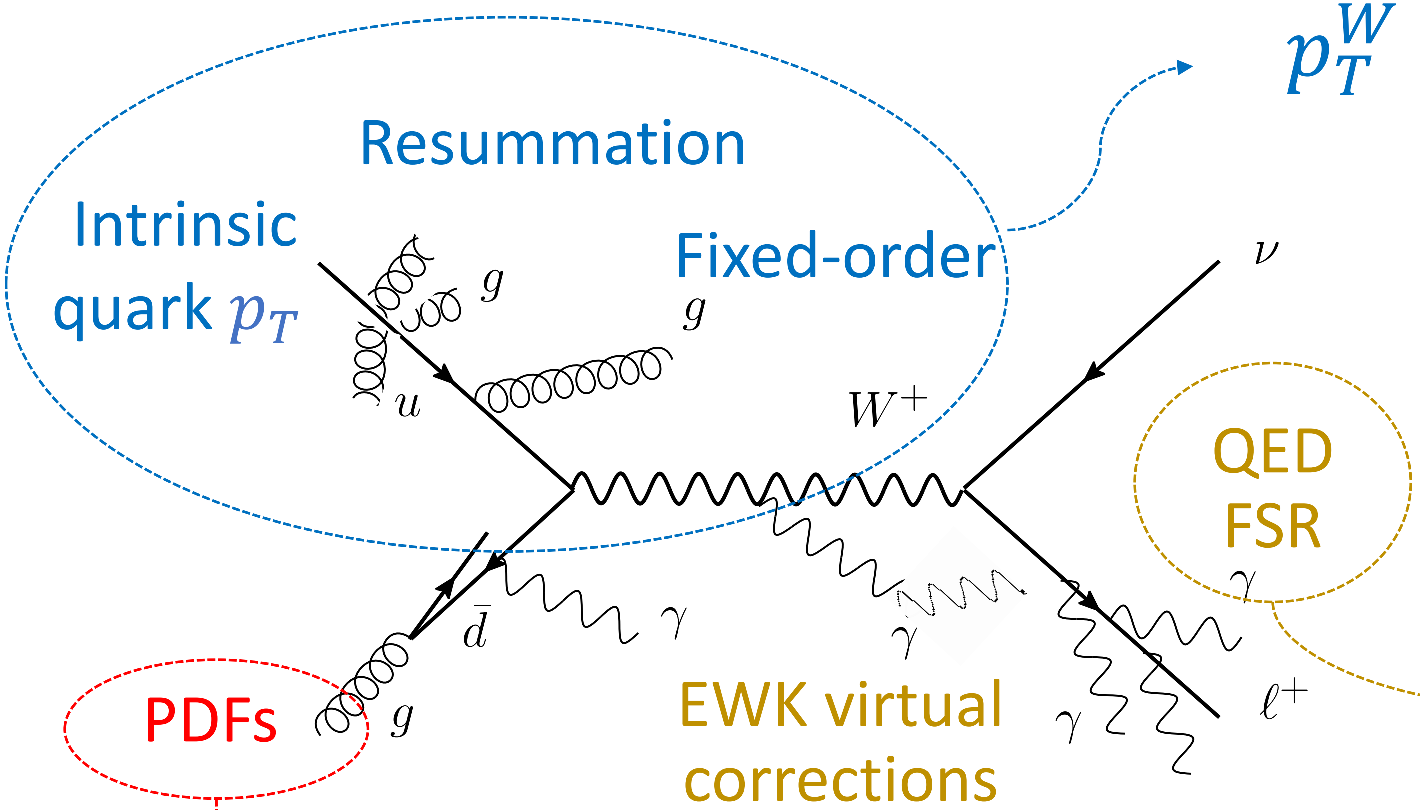

$p_T^W \Longrightarrow p_T^\ell$

$E_\ell^* \Longrightarrow p_T^\ell - \Delta p_T^\ell$

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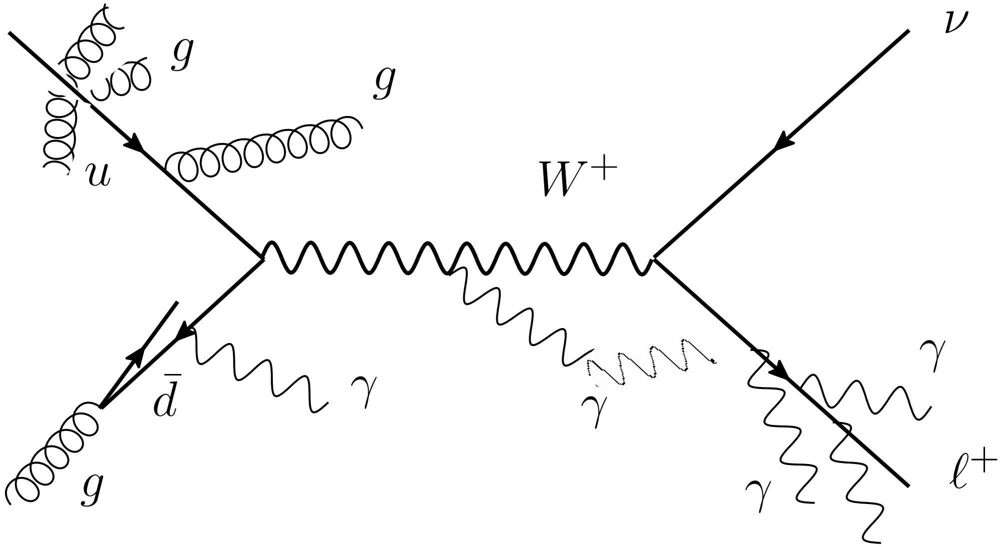
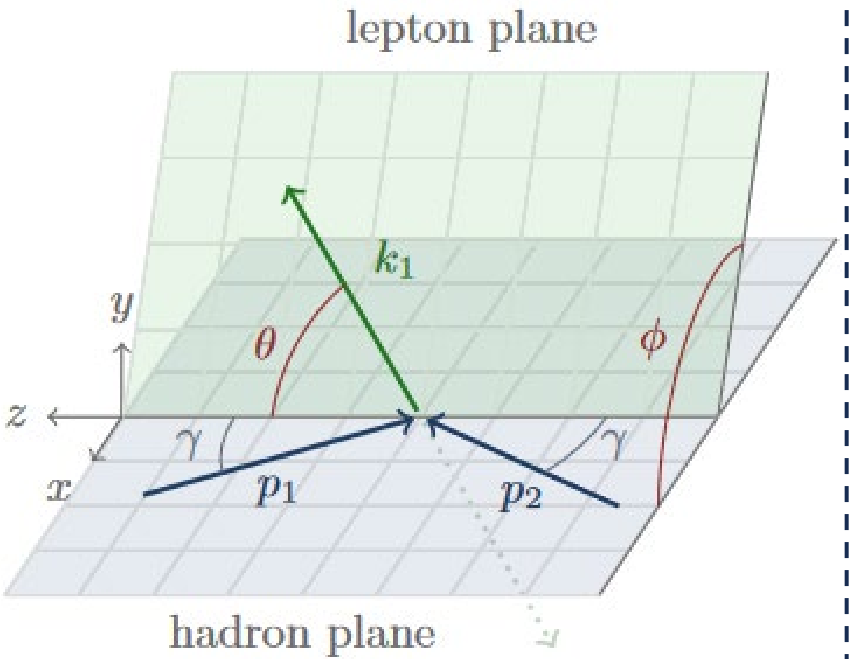
see e.g. EPJC 77 (2017) 280

Monte Carlo simulation

See e.g.JHEP11 (2017) 003



A_i = angular coefficients



$$\frac{d^6\sigma}{d\mathbf{\Phi}^{\ell^+}d\mathbf{\Phi}^{\ell^-}} \propto \frac{d^4\sigma_{\mathrm{UL}}}{d\mathbf{\Phi}^V} \times \left(\sum_{i=0}^{7} A_i(\mathbf{\Phi}^V) \times P_i(\theta^*,\varphi^*)\right)$$

Parton Density Functions

- Dominant systematics in the past
  - <u>Point of concern today</u>: spread of different **PDF fits** not always covered by their uncertainties

Eur. Phys. J. C (2010) 69: 379–397
DOI 10.1140/epjc/s10052-010-1417-0

Regular Article - Experimental Physics

$\Delta M_W \leq 10$ MeV/c^2 at the LHC: a forlorn hope?*

M.W. Krasny[1,a], F. Dvdak[2], F. Favette[1], W. Płaczek[3], A. Siódmok[1,3]

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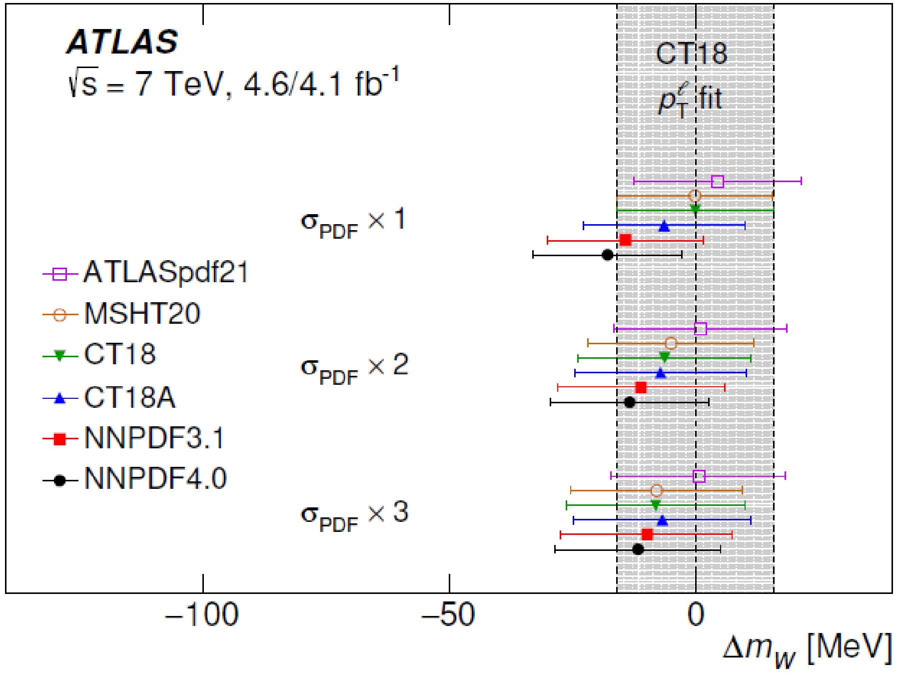

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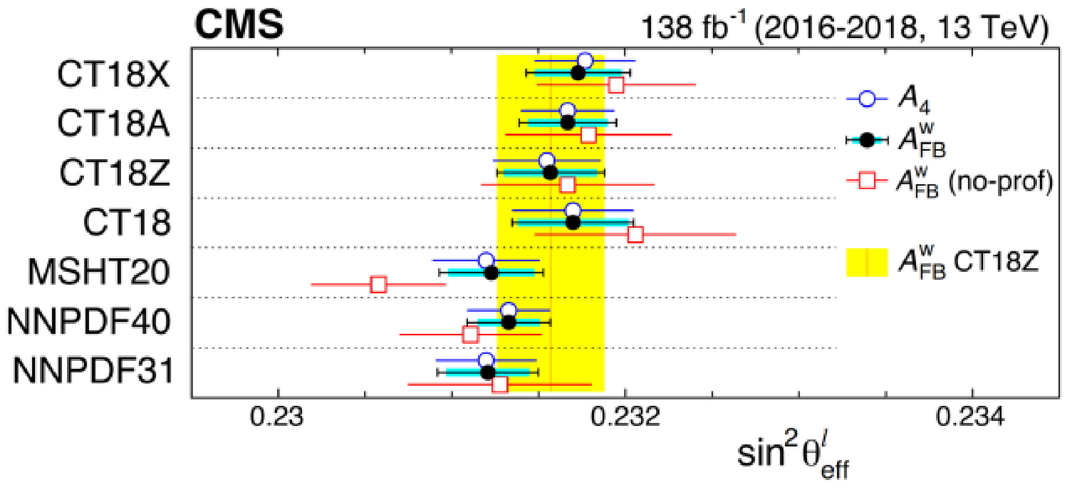

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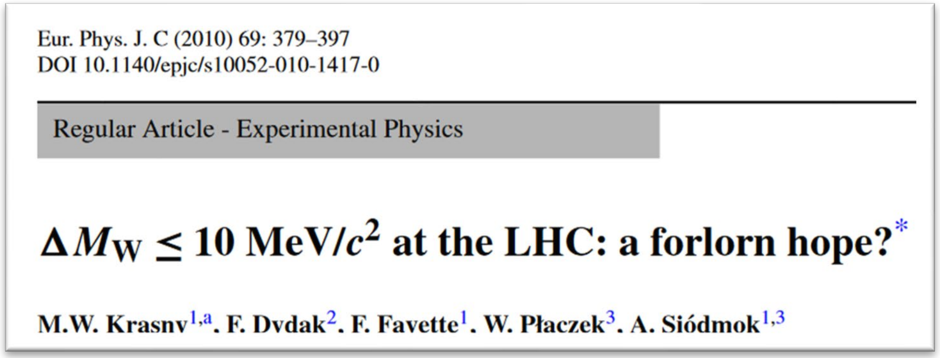

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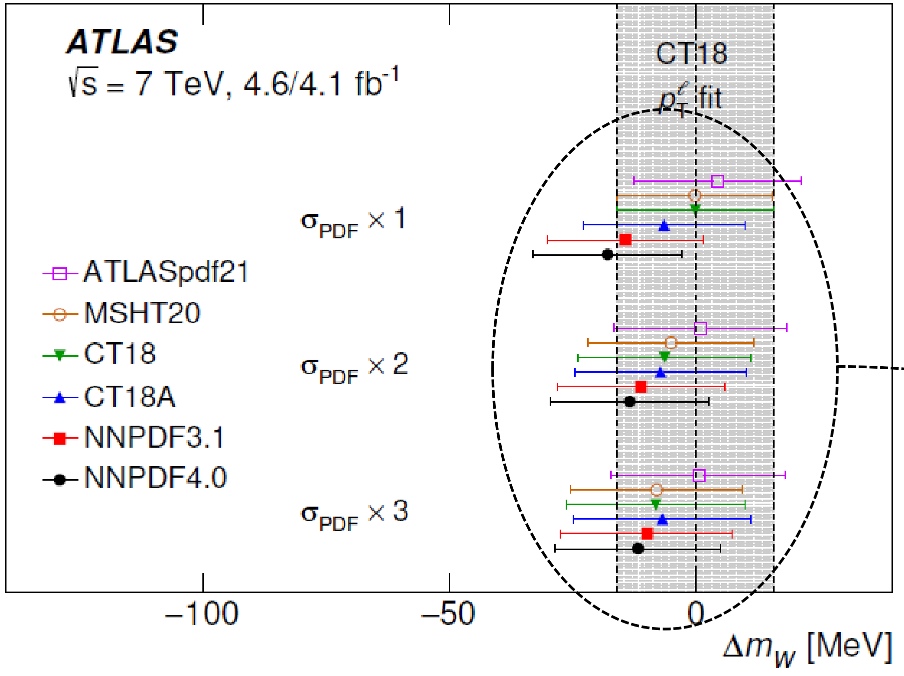

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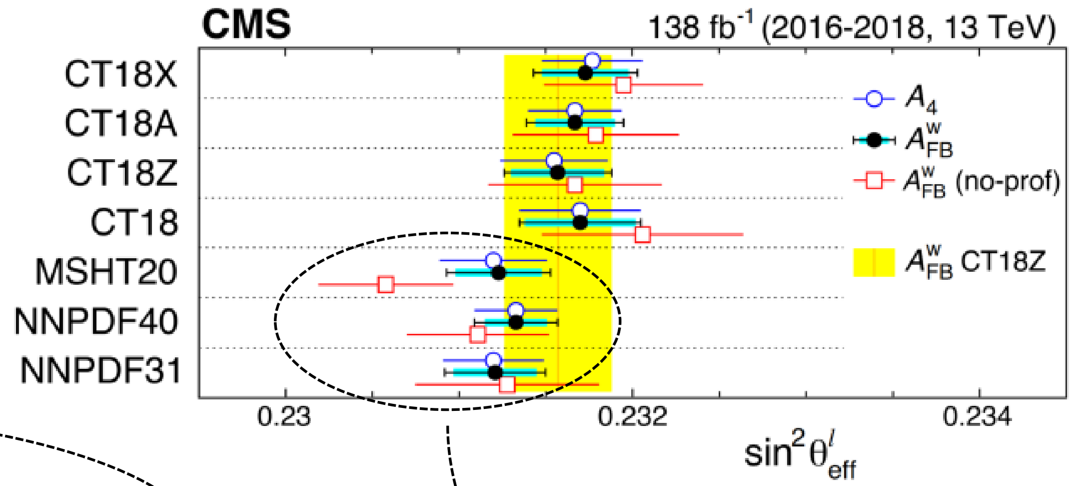

TAKE HOME MESSAGE:

Scatter can be reduced by *in situ* PDF profiling

p_T^W modeling

- <u>Conventional wisdom</u>: tune $\boldsymbol{p_T^W}$ **model** on precisely measured $\boldsymbol{p_T^Z}$ **data**

$$\left(\frac{1}{\sigma_W}\frac{d\sigma}{dp_T^W}\right)_{\text{predicted}} = \frac{\left(\frac{1}{\sigma_W}\frac{d\sigma}{dp_T^W}\right)_{\text{MODEL}}}{\left(\frac{1}{\sigma_Z}\frac{d\sigma}{dp_T^Z}\right)_{\text{MODEL}}} \times \left(\frac{1}{\sigma_Z}\frac{d\sigma}{dp_T^Z}\right)_{\text{measured}}$$

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- <u>Rationale</u>: **RATIO** better known than **spectrum**
  - But: cancellation of μ_R/μ_F relies on **correlation scheme**

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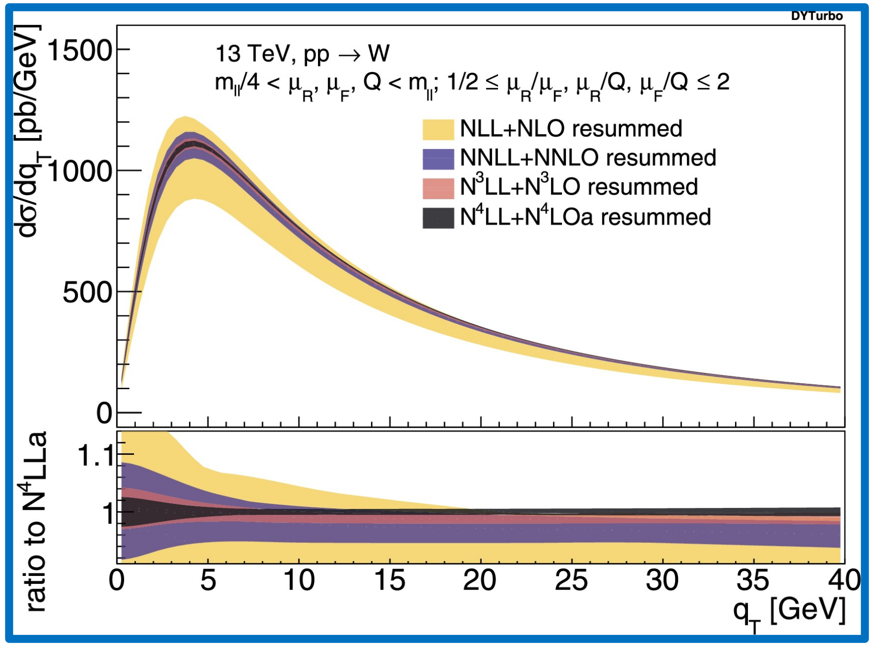
PLB 845 (2023) 138125



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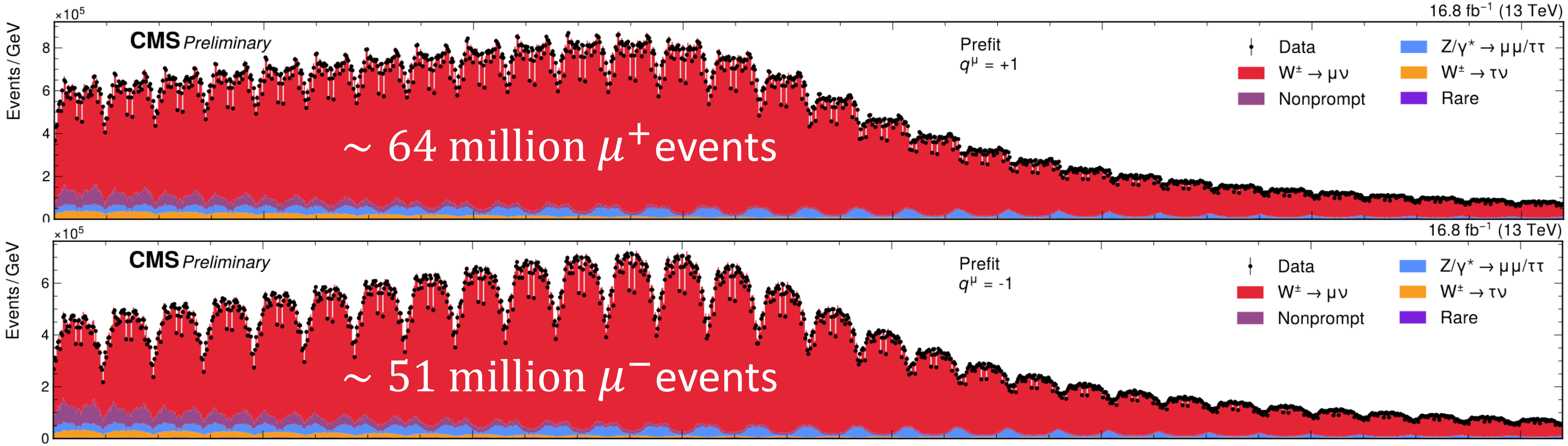
- Ideal case: a single **MODEL** prediction with **properly defined uncertainties**

The CMS paradigm

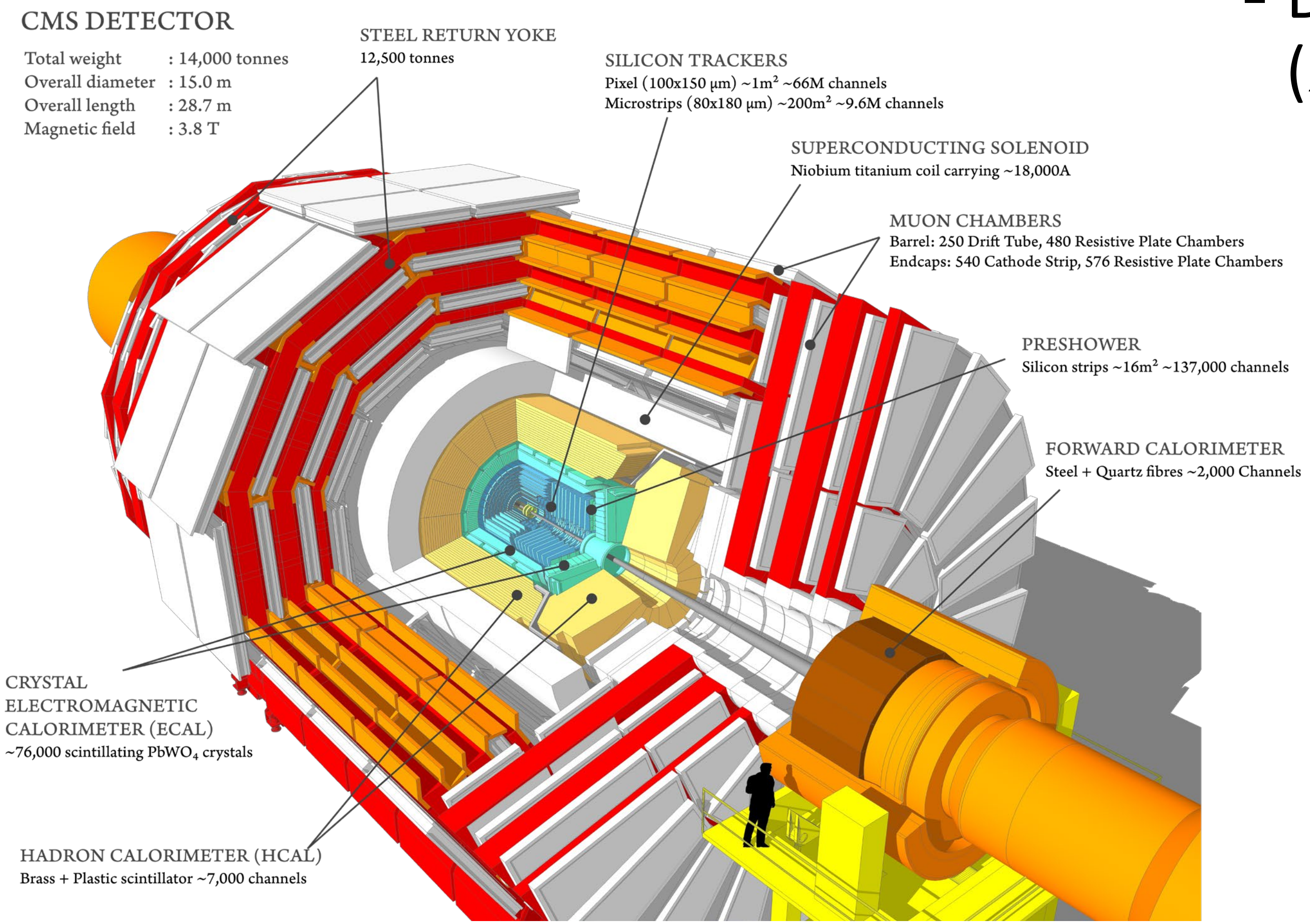
Z only for validation (i.e. <u>no tuning</u>)	State-of-the-art calculations	Constrain model uncertainties *in situ*

Large samples, high-granularity

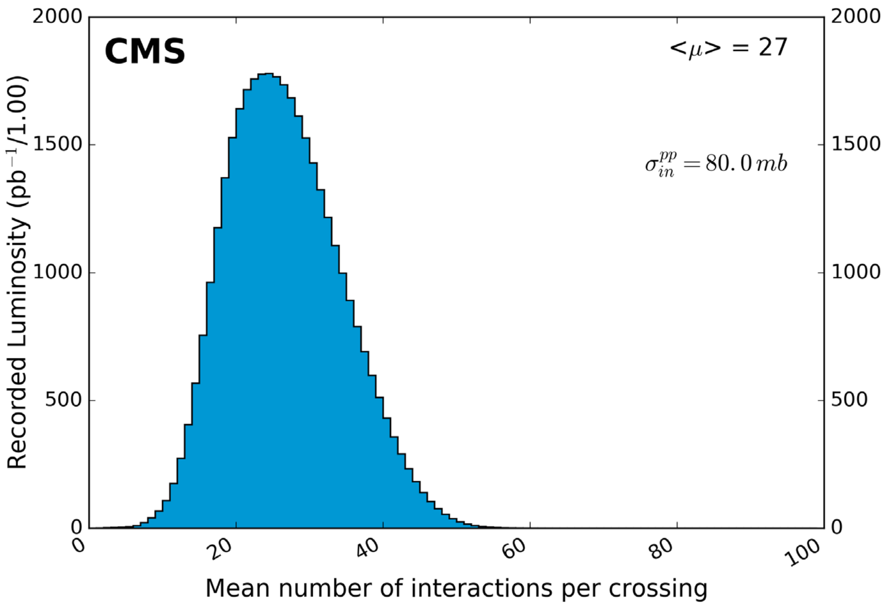
- Large samples → <u>high pile-up</u> LHC data → focus on **muon momentum** alone
- Analysis done in **finely grained 3D-space**: $(p_T^\mu \times \eta^\mu \times q^\mu) \rightarrow$ **2880 bins**
  - $26 < p_T^\mu < 56$ GeV, $-2.4 < \eta^\mu < 2.4$, $q^\mu = \pm 1$



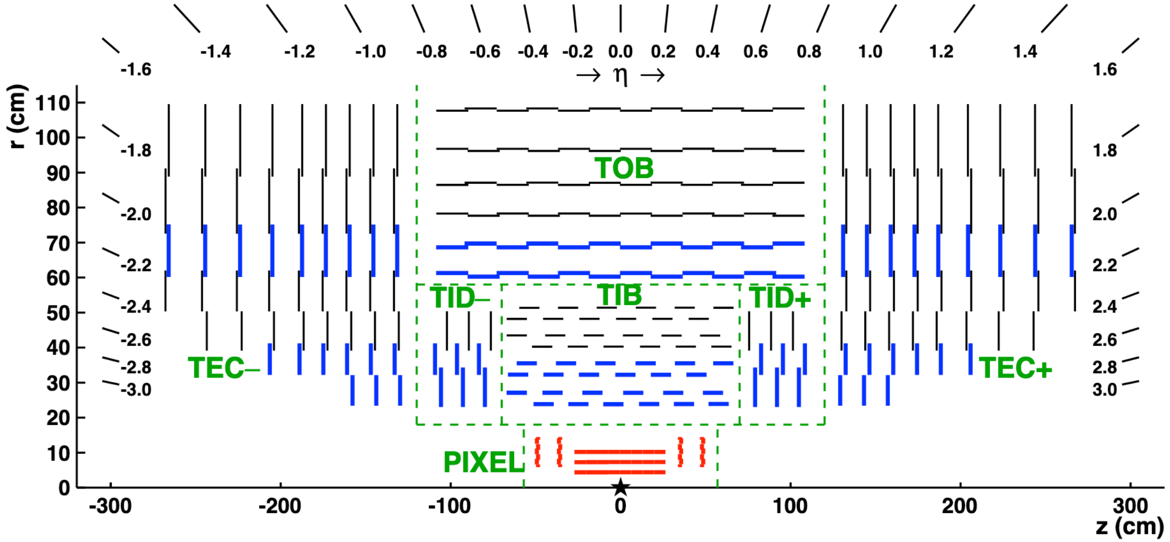
The CMS detector



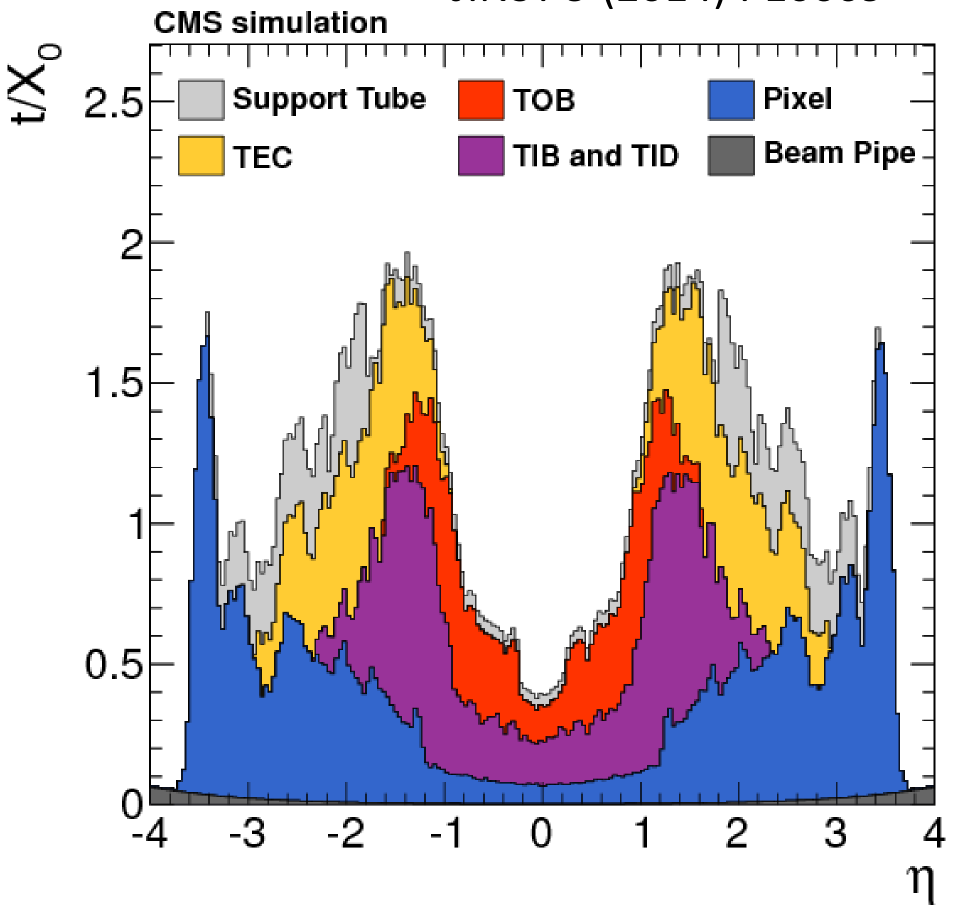
- Data from a **subset** $(\sim 10\%)$ **of Run2** $(L = 16.8\ \mathrm{fb}^{-1})$
  - 1st half of 2016 data discarded due to a Read-out problem in Si-strip tracker
  - Average pile-up: $\langle\mu\rangle = 25$



The CMS tracker



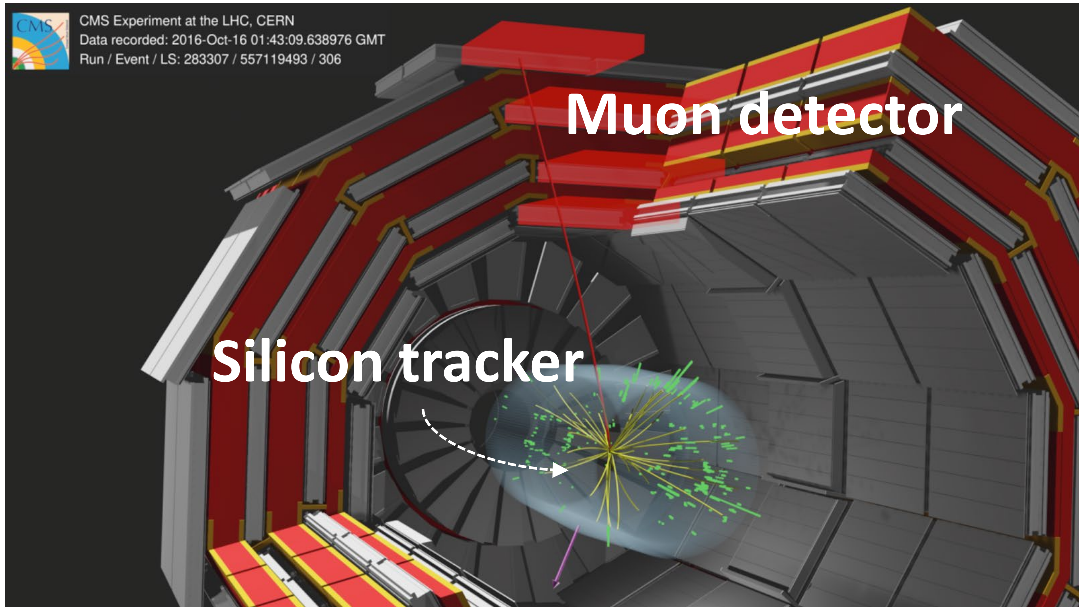
JINST 9 (2014) P10009



- Fully **silicon-based**
  - Up to 17 points per track ($9 \div 50\ \mu m$ resolutions)
- Up to **2 radiation lengths**

Muons in CMS

- Two-stage reconstruction
  - **Muon detector** → trigger and ID
  - **Tracker** → momentum at the IP



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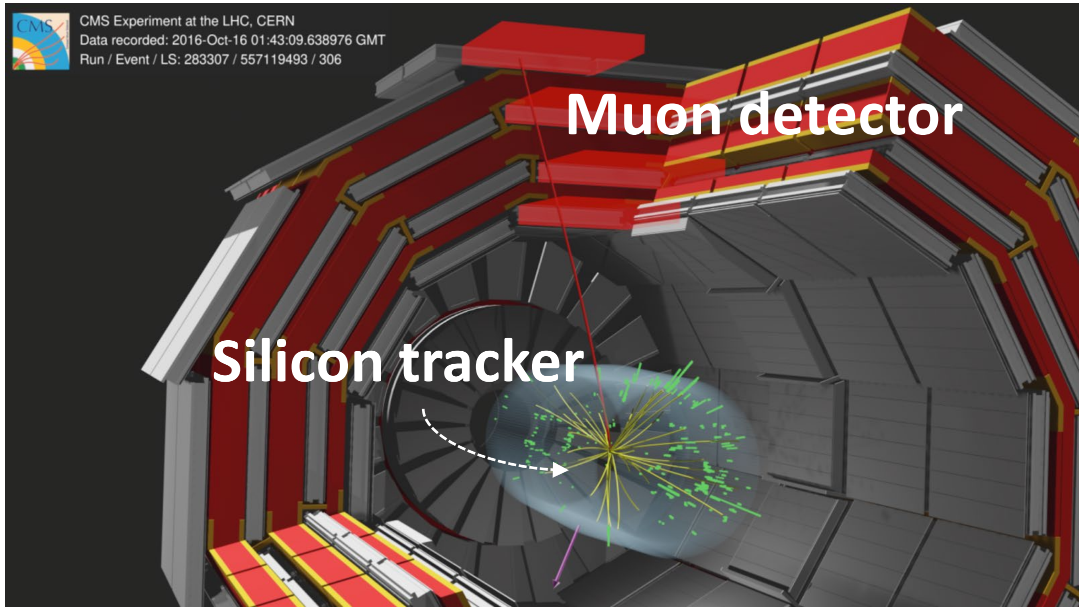
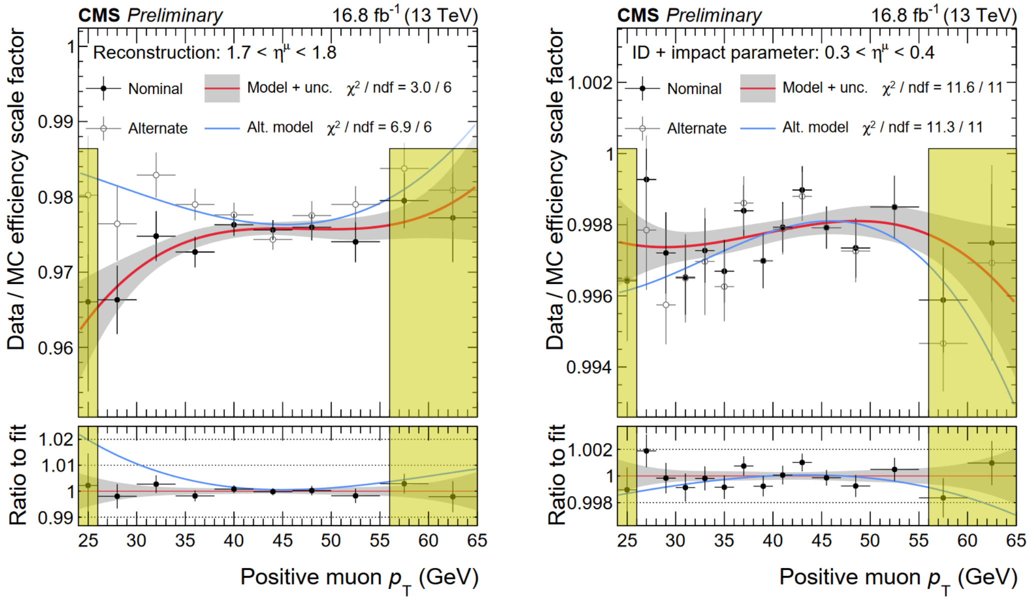
  - **Muon detector** → trigger and ID
  - **Tracker** → momentum at the IP



- Detector efficiency calibrated on $Z \to \mu\mu$
  - Uncertainties propagated through $O(3{,}000)$ nuisance parameters

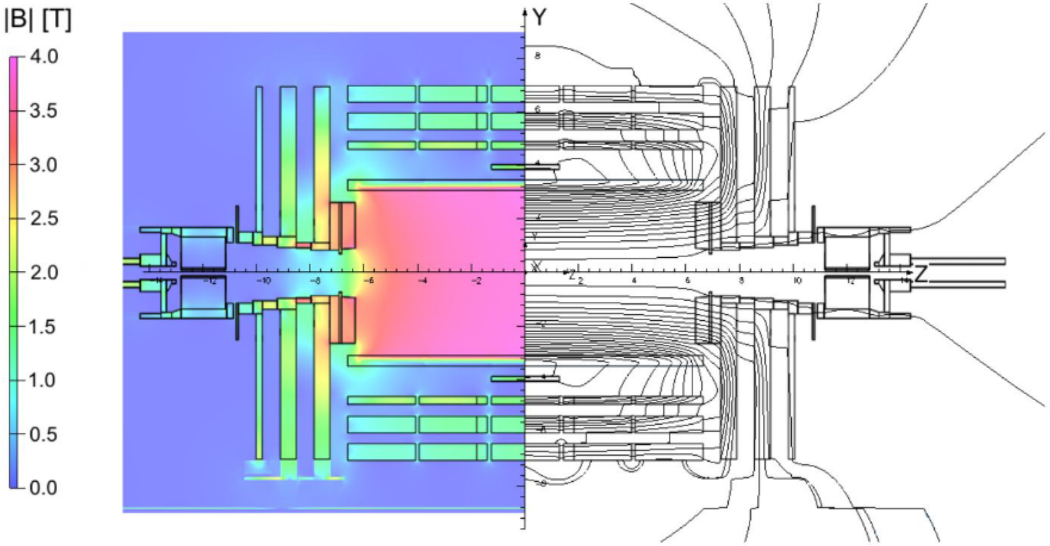


Impact on m_W → ~3 MeV

Magnetic field

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

- *B*-field inside tracker **mapped** in 2006
  1. at the **surface**,
  2. with **empty coil**
  3. with Hall probes calibrated to $\mathbf{3 \times 10^{-4}}$
  4. $\frac{\Delta B}{B} = \mathbf{-8 \times 10^{-4}}$ between map and *in situ* NMR survey



A priori knowledge of *B*-field
not better than $\mathbf{10^{-3}}$

Magnetic field

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

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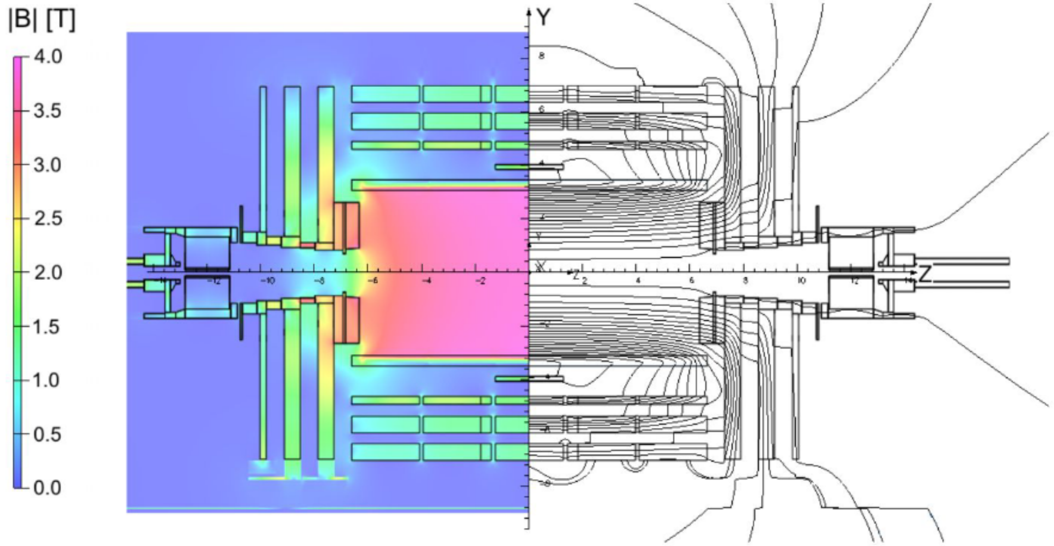


A priori knowledge of *B*-field **not better than $\mathbf{10^{-3}}$**

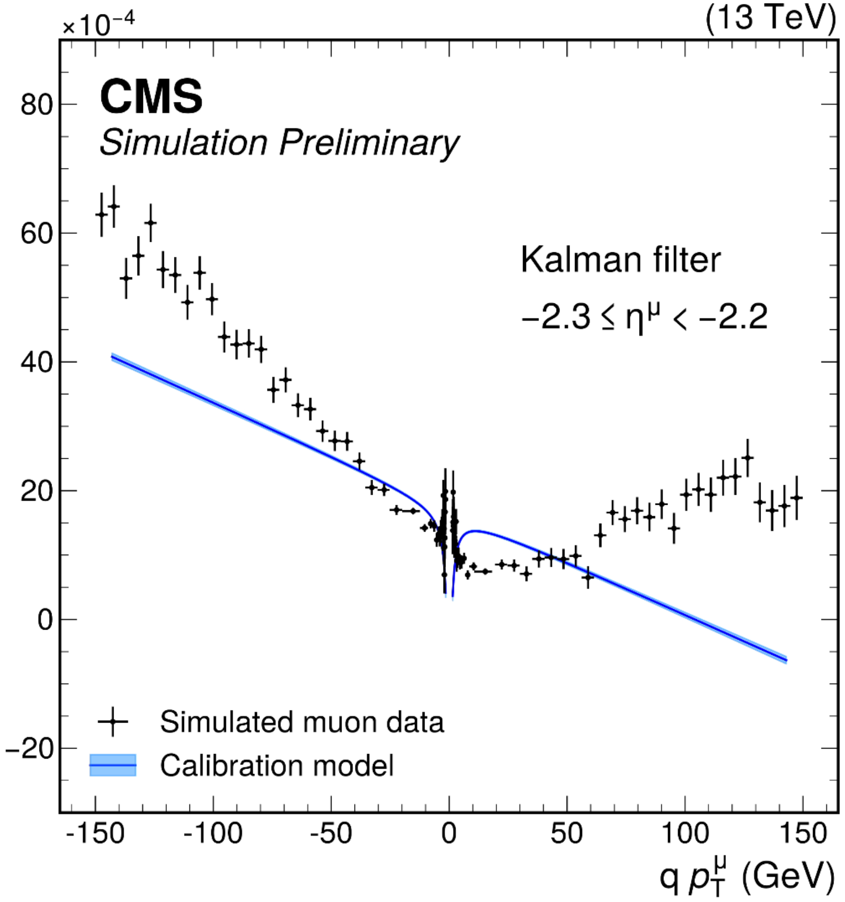
… in excess of the $\mathbf{10^{-4}}$ **target**

➔ **need for *in situ* calibration**

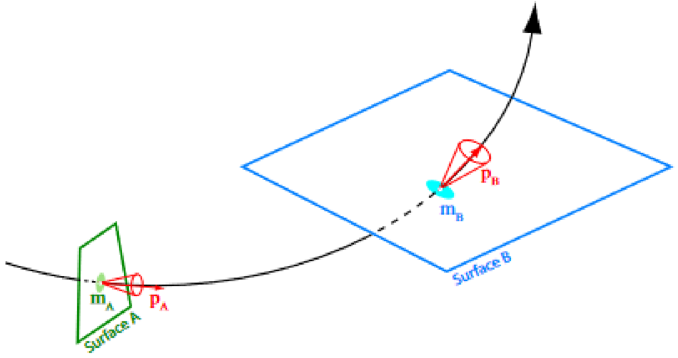
Muon momentum scale

- Observation: **up to 1% bias in scale** in **ideal simulation** (not expected/understood)

$$\left\langle \frac{p_T^{\text{reco}}}{p_T^{\text{gen}}} \right\rangle - 1$$

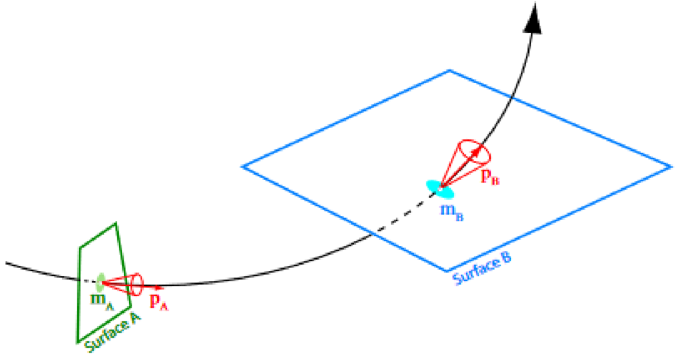


Muon momentum scale



1. **Fixes to standard CMS reconstruction**
   - ✓ **Tuning** of parameters in GEANT4 simulation
   - ✓ **Track re-fit** with improved treatment of *B*-field and material

Muon momentum scale



1. **Fixes to standard CMS reconstruction**
   - ✓ **Tuning** of parameters in GEANT4 simulation
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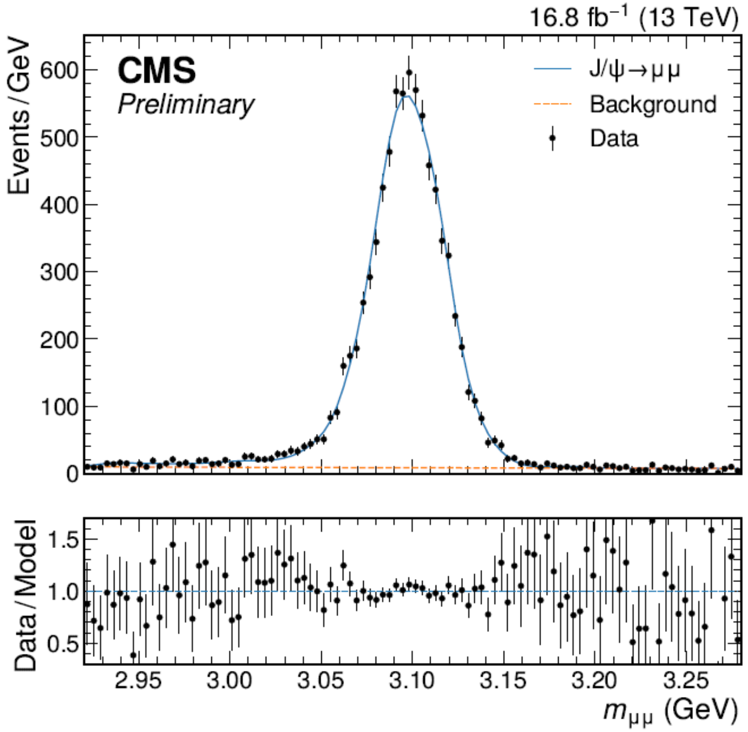
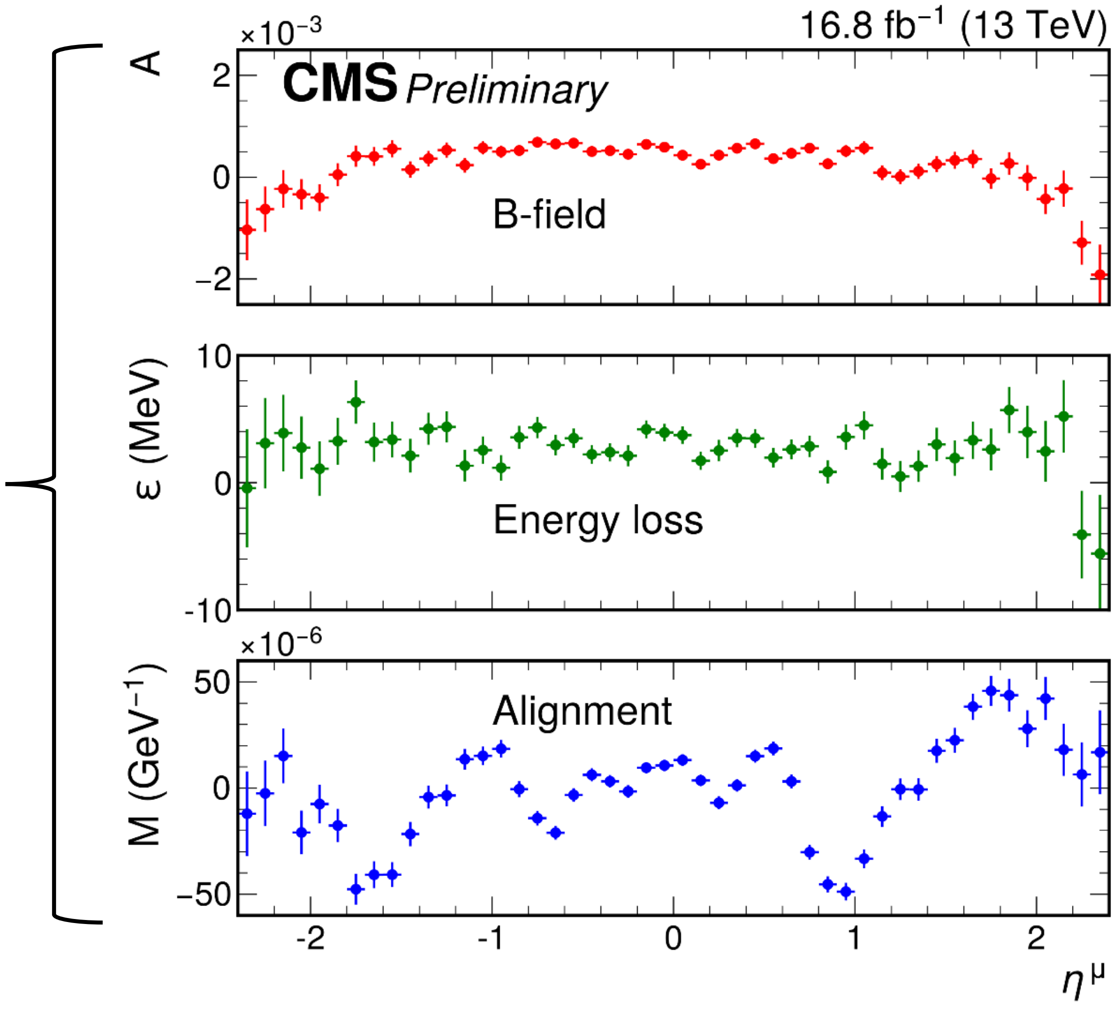
2. **Calibration on $\mathbf{J}/\boldsymbol{\Psi} \to \boldsymbol{\mu\mu}$** $\left(\frac{\Delta m_{\mathbf{J}/\boldsymbol{\Psi}}}{m_{\mathbf{J}/\boldsymbol{\Psi}}} \sim 10^{-6}\right)$
   - ✓ **Global alignment of tracker** (+ *B*-field + material)
   - ✓ **Fit** residual scale bias with **parametric model:**

$$\left(\frac{p_T^{\mathrm{corr}}}{p_T}\right)_{\pm} = 1 + A_{i\eta} - \frac{\varepsilon_{i\eta}}{p_T} \pm M_{i\eta} p_T$$



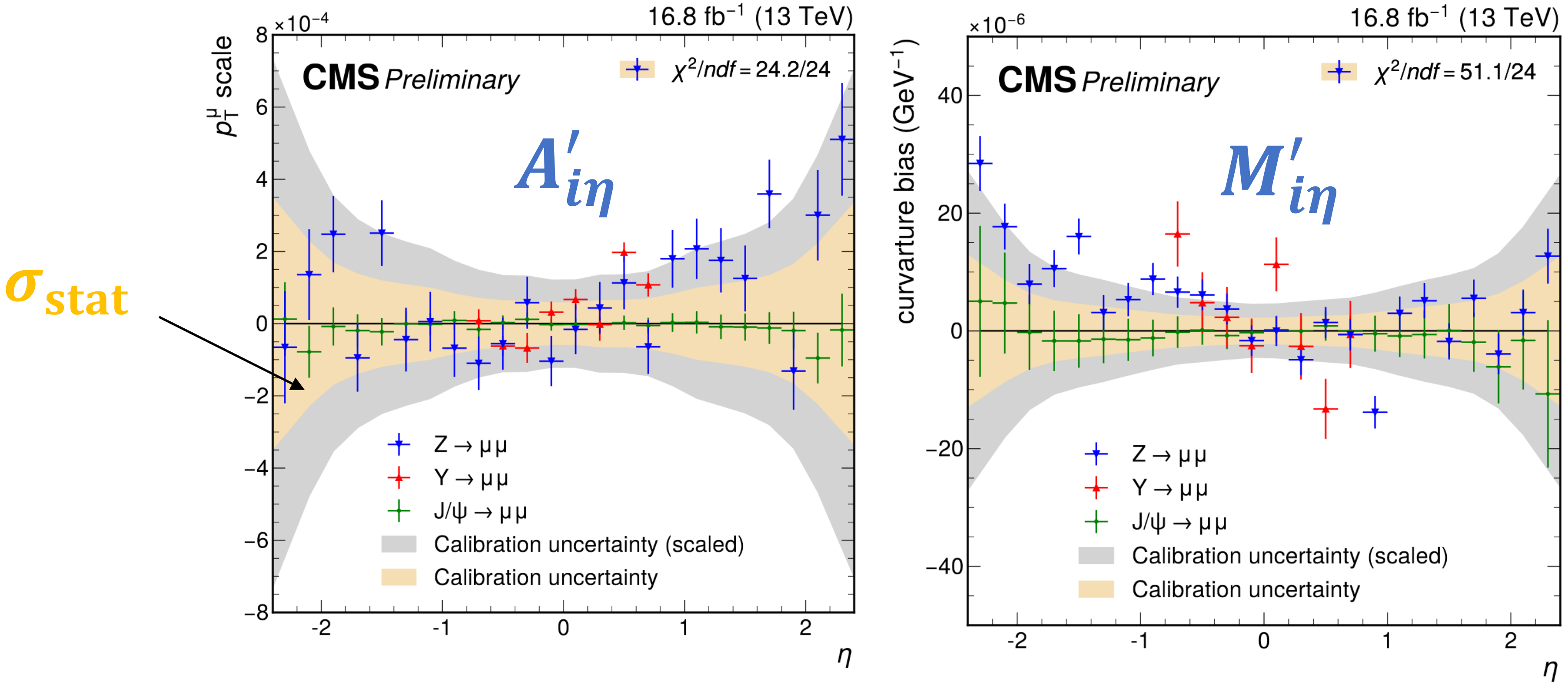
Parametrized scale corrections

Consistent with *a priori* expectation for ***B*-field** and **material**



Validation: Z-closure

- **J/Ψ-based calibrations** are applied to **all reconstructed muons**
  - Residual $A'_{i\eta}$, $M'_{i\eta}$ are derived using $Z \to \mu\mu$ ➔ should be $= 0$ for perfect calibration



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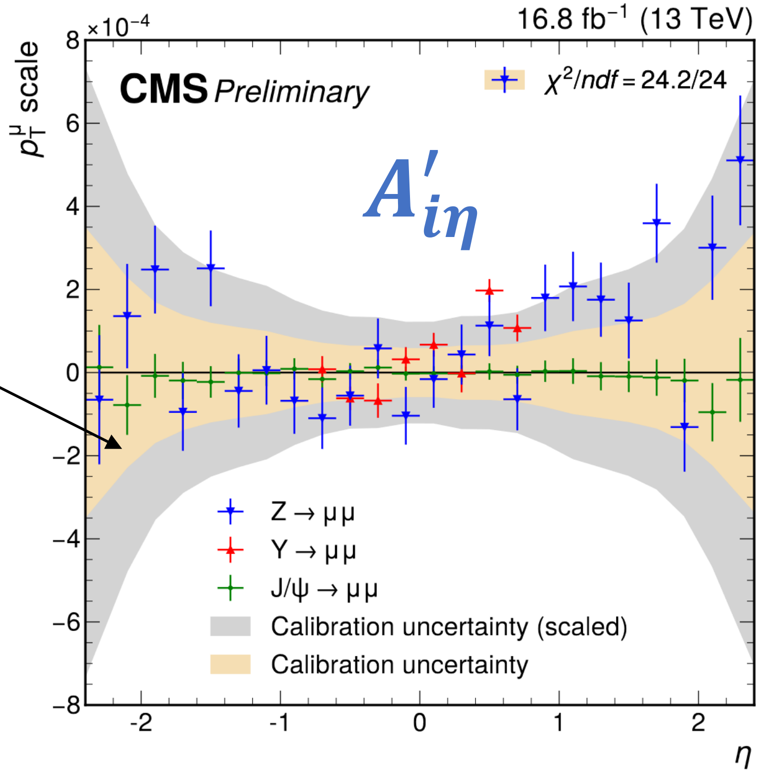
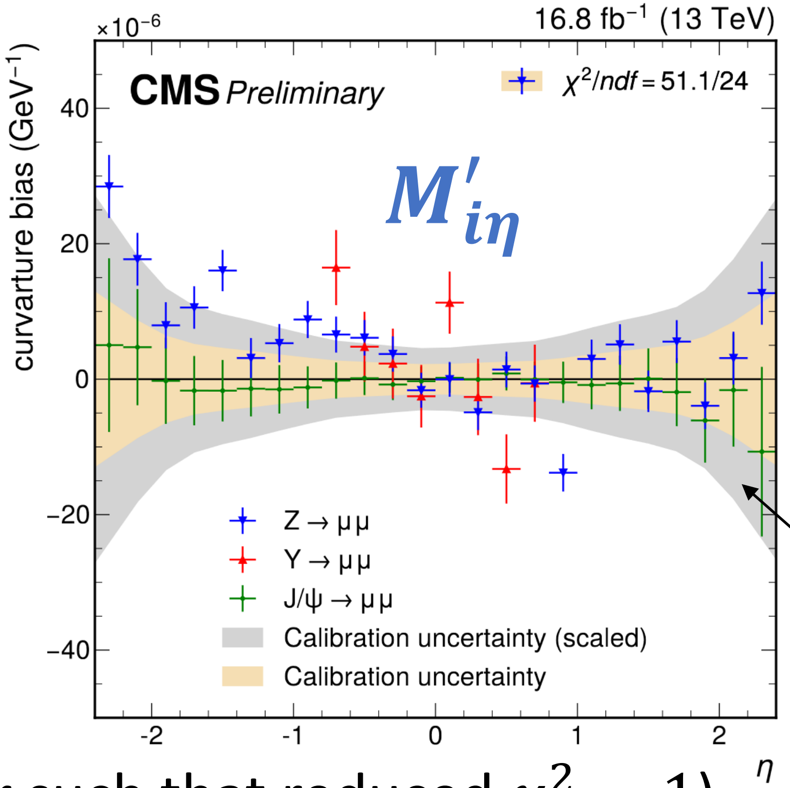
σ_{stat}





$2.1 \times \sigma_{\text{stat}}$

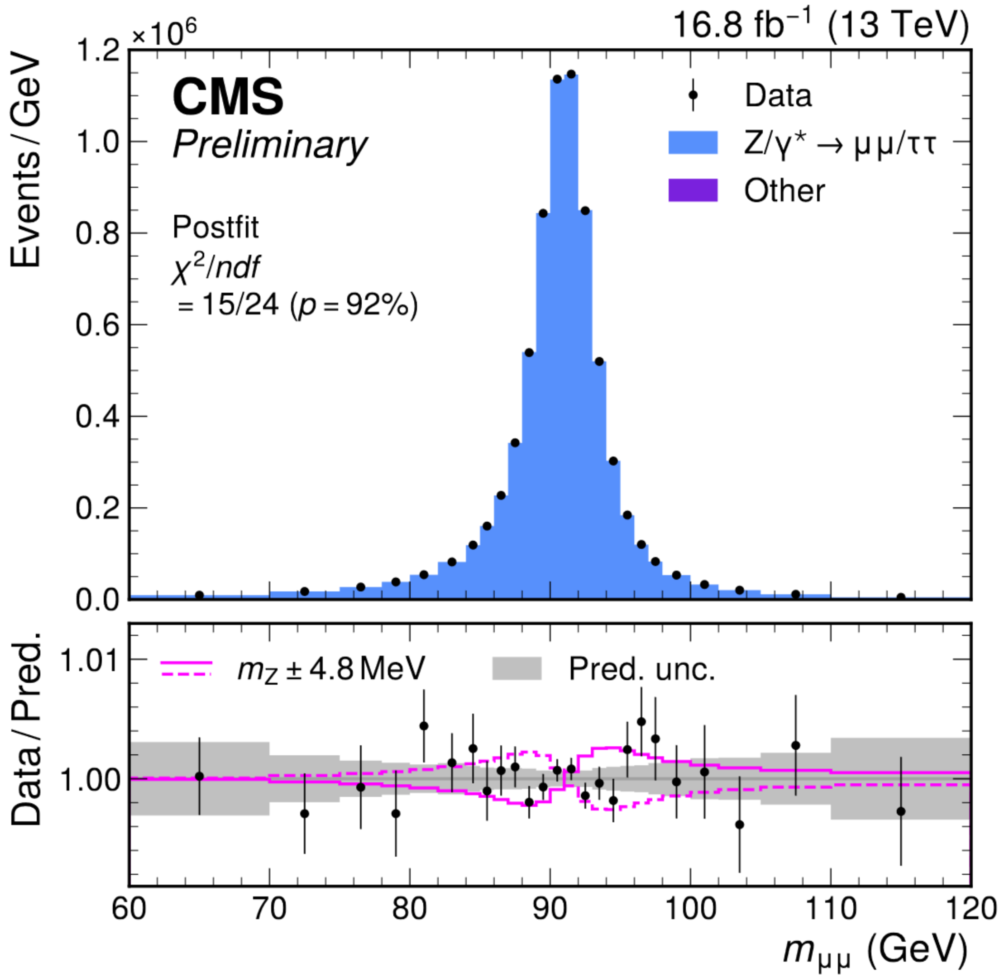
(2.1 = smallest scale-factor such that reduced $\chi^2 = 1$)

Uncertainties & closure test

- Uncertainties on **momentum scale**:
  - $(\mathbf{2.1}\ \times)\ \boldsymbol{\sigma}_{\mathbf{stat}}$ from J/Ψ
  - $\boldsymbol{\sigma}_{\mathbf{stat}}$ from $\mathrm{Z-closure}$
  - $\Delta \boldsymbol{m}_{\boldsymbol{Z}}^{\mathbf{LEP}}$

Impact on $\boldsymbol{m}_{\boldsymbol{W}}$ → $\mathbf{4.8}$ MeV

Uncertainties & closure test



- Uncertainties on **momentum scale**:
  - $(\mathbf{2.1}\ \times)\ \boldsymbol{\sigma}_{\mathbf{stat}}$ from J/Ψ
  - $\boldsymbol{\sigma}_{\mathbf{stat}}$ from $\mathrm{Z}-\mathrm{closure}$
  - $\Delta \boldsymbol{m}_{\boldsymbol{Z}}^{\mathbf{LEP}}$

Impact on m_W → 4.8 MeV

- Validation by fitting $\left(m^{\mu\mu}, \eta^{\mu-\mathrm{fwd}}\right)$ spectrum:

$$m_Z - m_Z^{\mathrm{PDG}} = -2.2 \pm 4.8\ \mathrm{MeV}$$
$$= -2.2 \pm 1.0\ (\mathrm{stat}) \pm 4.7\ (\mathrm{syst})\ \mathrm{MeV}$$

(not yet an independent measurement of m_Z)

W and Z modeling: p_T^V

EPJ+ 136 (2021) 214 F. Tackman's slides

JHEP07(2022)129 G. Marinelli's slides

arXiv:2411.16004 arXiv:2411.18606

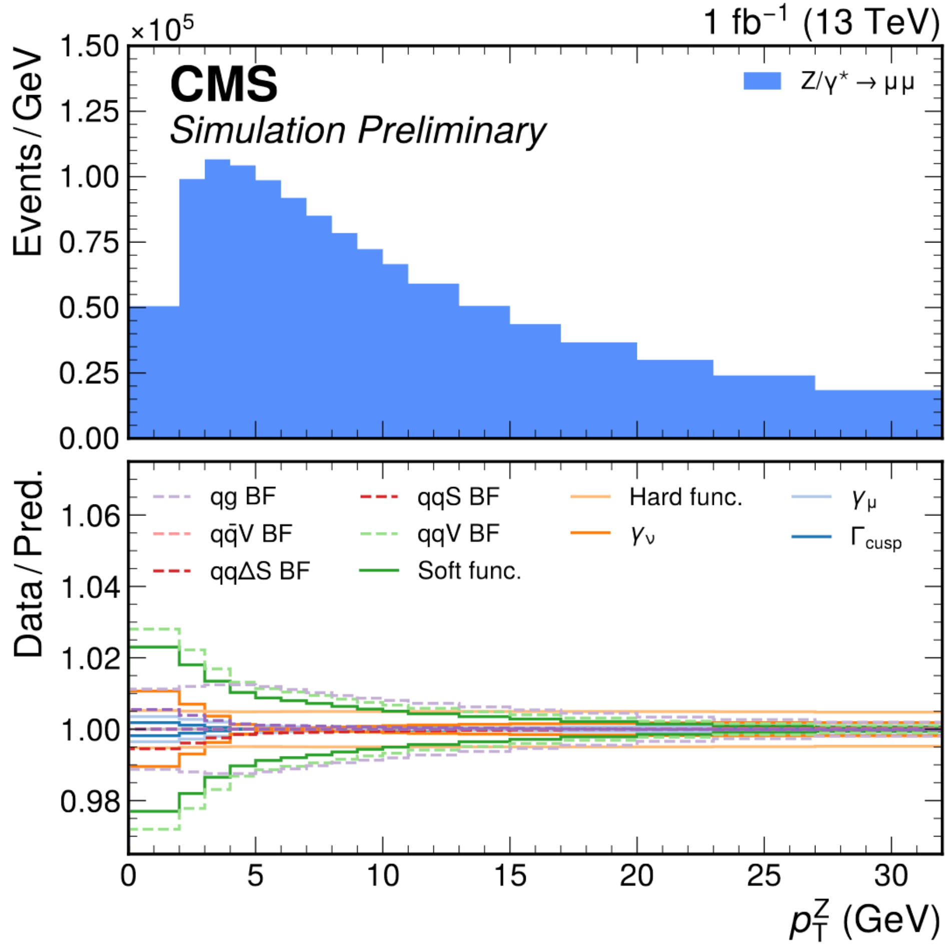
- **Resummation** (→ SCETLIB @N³LL)
  - "Theory Nuisance Parameters" approach based on **TMD-factorization theorem**

$$f^{\text{pred}}(\alpha) = f_0 + \alpha f_1 + \alpha^2 f_2 + \alpha^3 f_3(\theta_3) + \mathcal{O}(\alpha_S^4)$$

→ **7** params. for *boundary conditions*

3 params. for *anomalous dimensions*

  - Uncertainties from variation of **last known term** (→ N^{3+0}LL scheme)



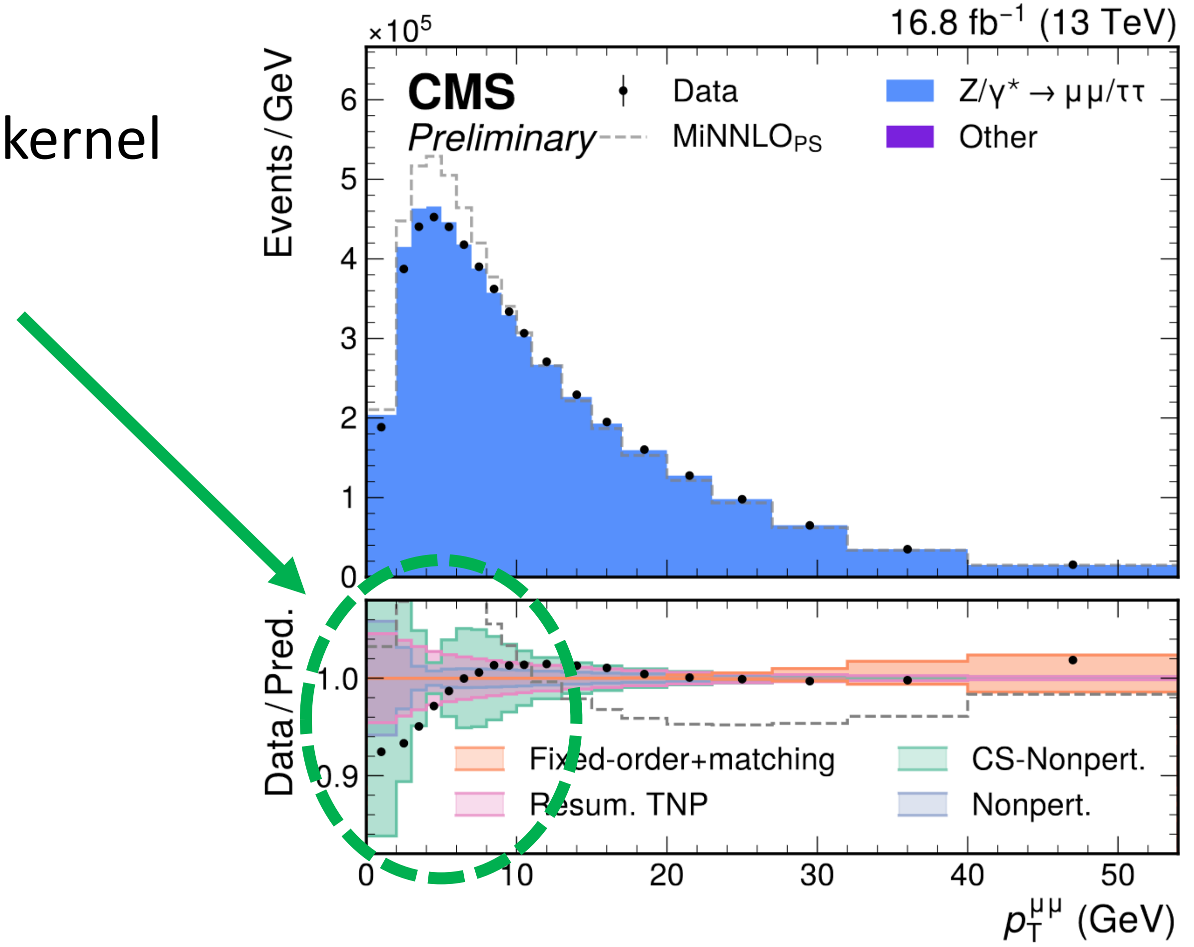
W and Z modeling: p_T^V

EPJ+ 136 (2021) 214 F. Tackman's slides

JHEP07(2022)129 G. Marinelli's slides

arXiv:2411.16004 arXiv:2411.18606

- **Non-perturbative** (→ SCETLIB)
  - $\Lambda_{\mathrm{QCD}}/p_T^V$ power corrections to the C.S. kernel
  - $|y|$-dependent Gaussian smearing in b_T



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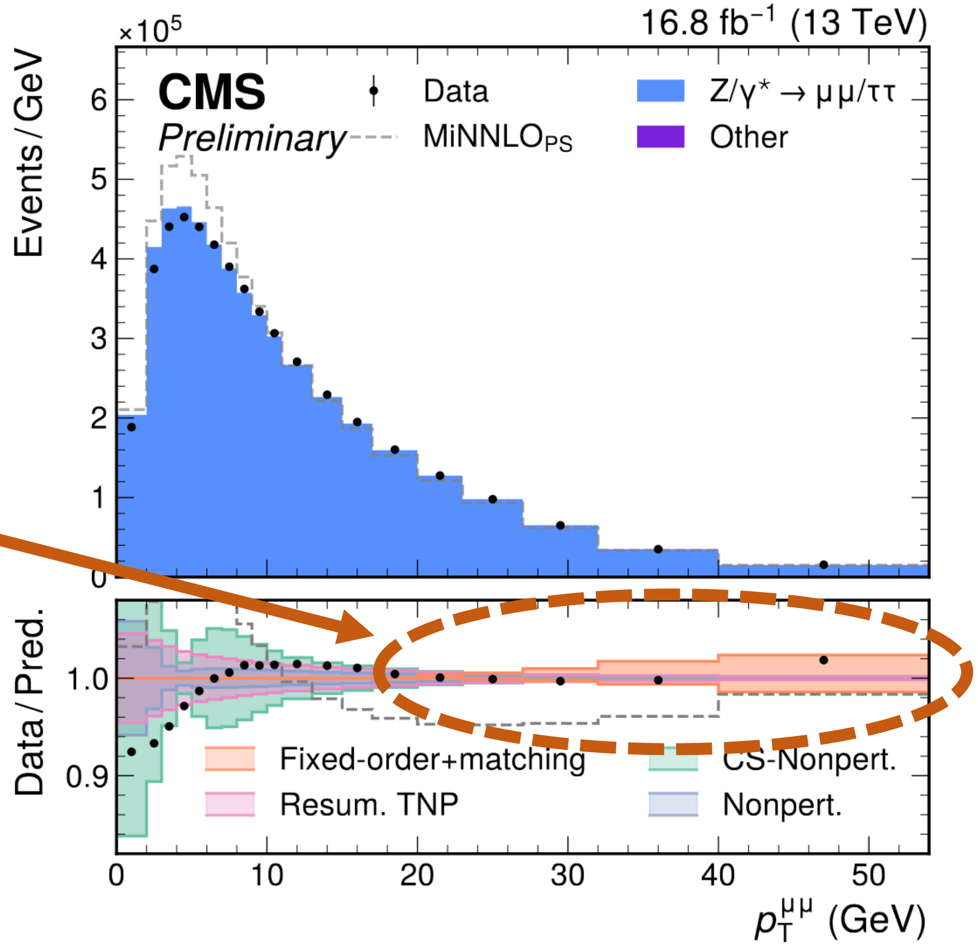
- **Matching to F.O.** (→ DYTURBO @NNLO)
  - Variations μ_R/μ_F scale and transition-point



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EPJ+ 136 (2021) 214 F. Tackman's slides

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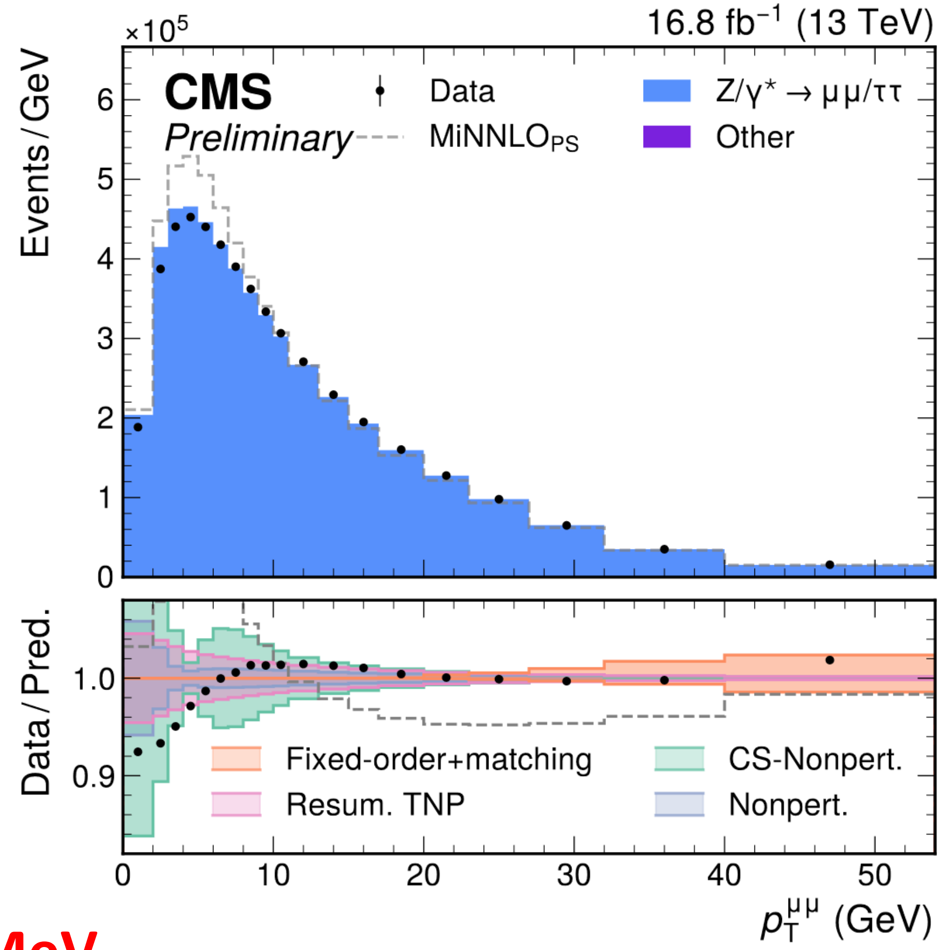
- **Matching to F.O.** (→ DYTURBO @NNLO)
  - Variations μ_R/μ_F scale and transition-point
- **b/c quark-masses** (→ MSHT20)
  - variation of heavy quark thresholds in PDFs



TOTAL Impact on m_W → ~2 MeV

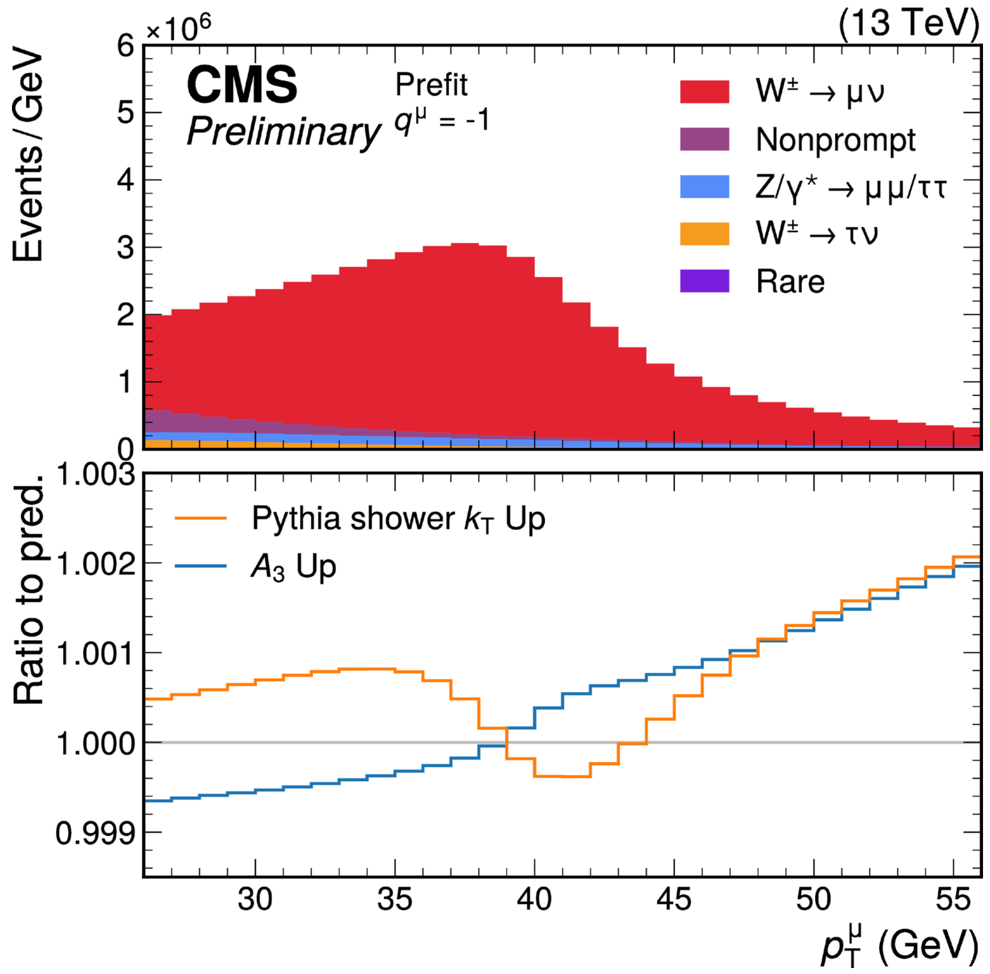
W and Z modeling: $\boldsymbol{A_i}$

- **Angular coefficients** (→ MiNNLO$_{PS}$ @NLO)
  - Envelope of 7-point scale variations in bins of p_T^V
  - Full difference

  MiNNLO$_{PS}$ *vs.* **MiNNLO$_{PS}$ + PYTHIA**

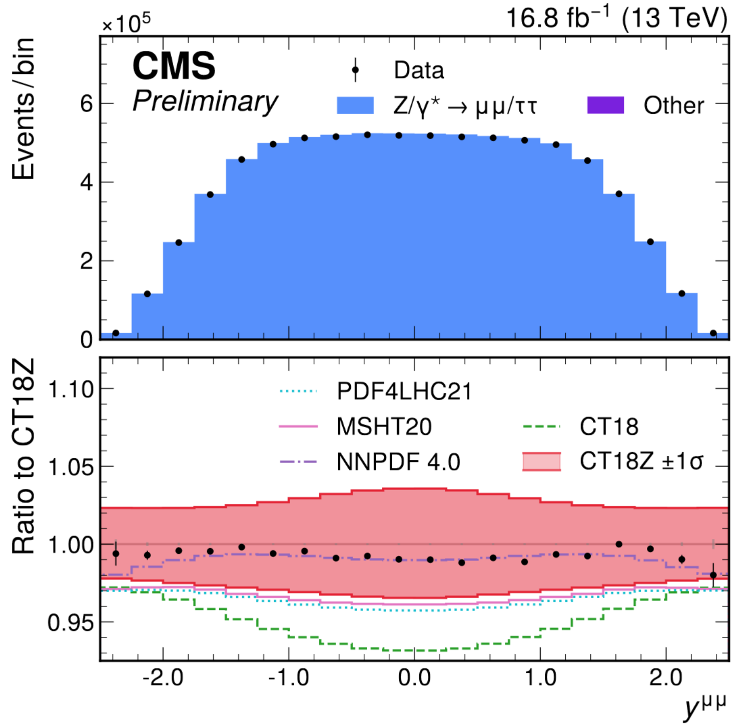
  (due to PYTHIA parton shower/intrinsic k_T)

Impact on m_W → $\sim$3.3 MeV



PDFs

<u>REMINDER</u>: large *in situ* constraint of PDFs expected thanks to **eigenvectors profiling**



- We chose **CT18Z** as nominal PDF set because:
  - good **pre-fit agreement** on y^Z, η^ℓ with relatively **large** uncertainty
  - it **covers** alternate PDF sets, i.e.

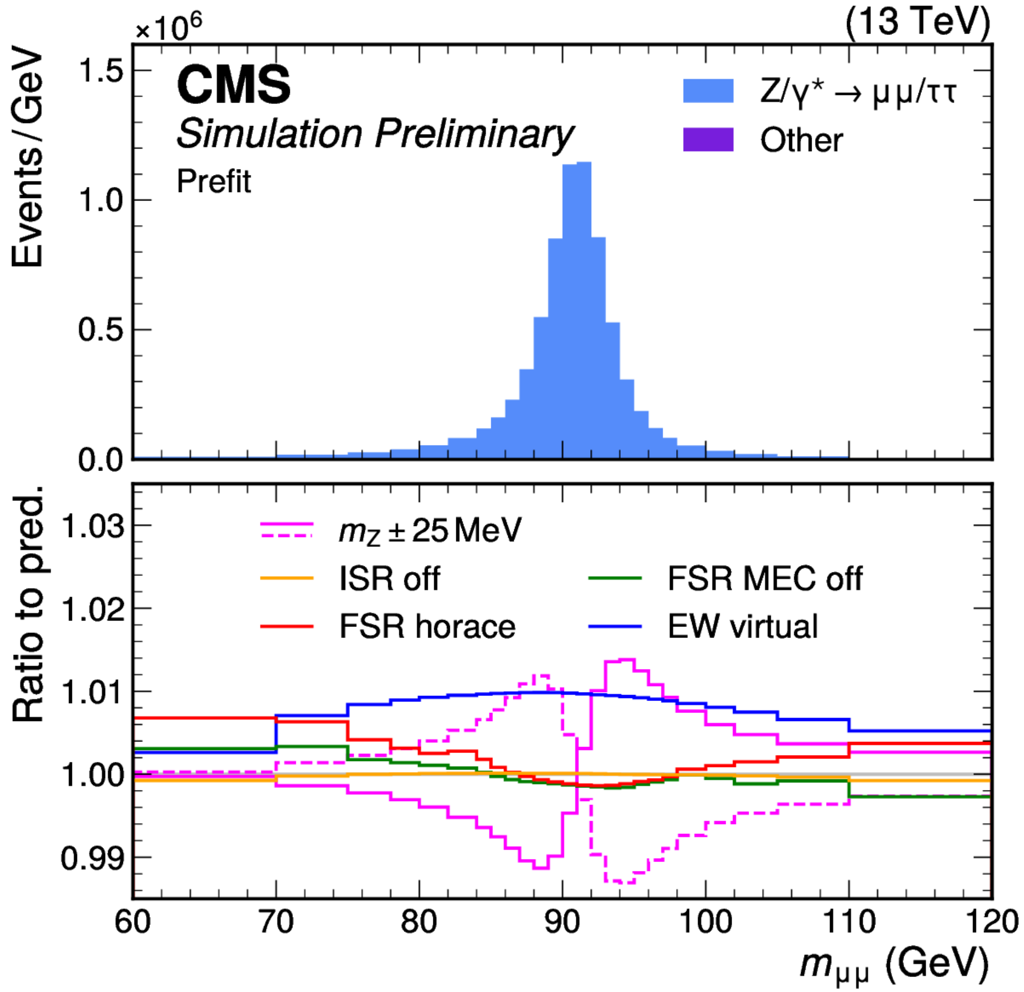
$$|m_W^{\text{alt.PDF}} - m_W^{\text{nom. PDF}}| \leq \sigma_{\text{nom. PDF}}$$

Impact on m_W → $\sim$4.4 MeV

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

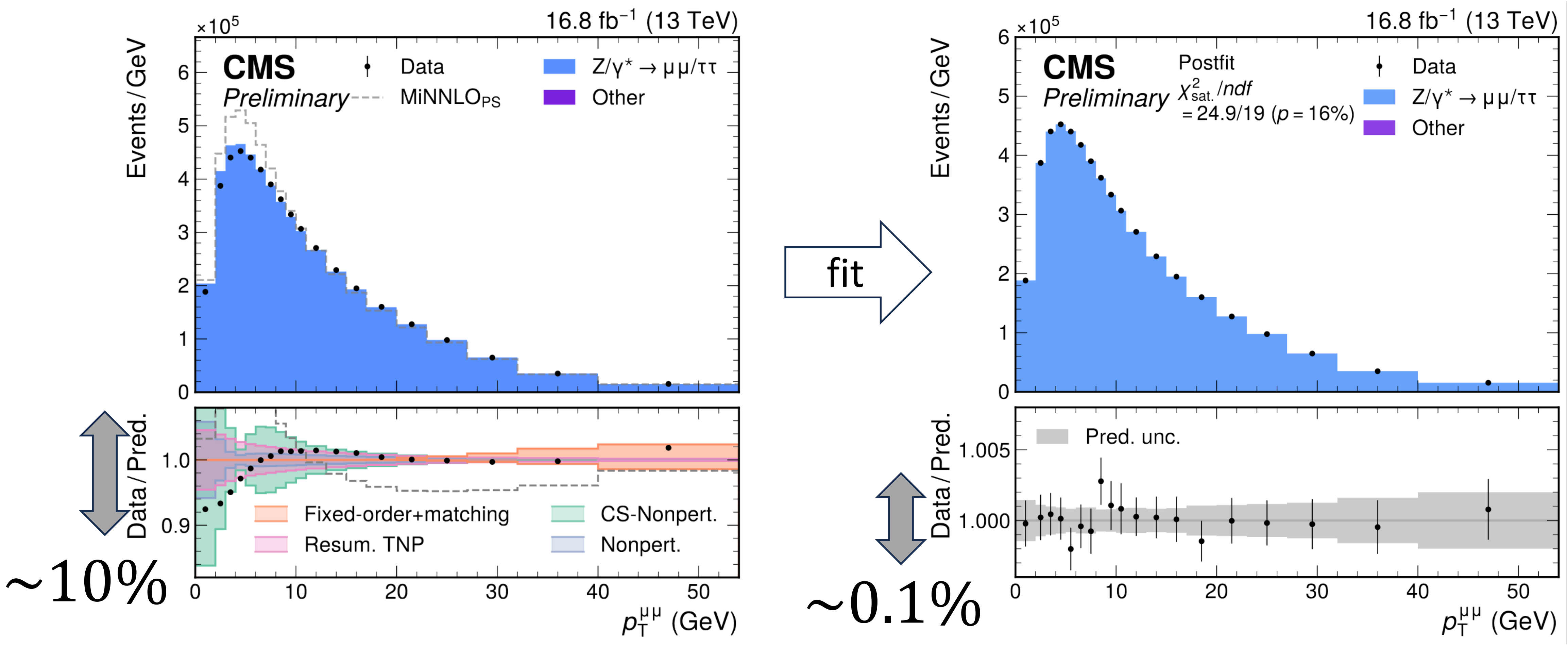
EWK uncertainties

- **FSR** (→ PHOTOS++ @LL+MEC)
  - uncertainty from switching on/off the MEC and from full difference with HORACE
- **ISR** (→ PYTHIA8 @LL)
  - uncertainty from switching on/off
- **Virtual EWK** (→ not included in nominal MC)
  - External calculations from:
    - RENESANCE (for W)
    - POWHEG-BOX-V2 (for Z)
  - NLO/LO ratio taken as a systematic

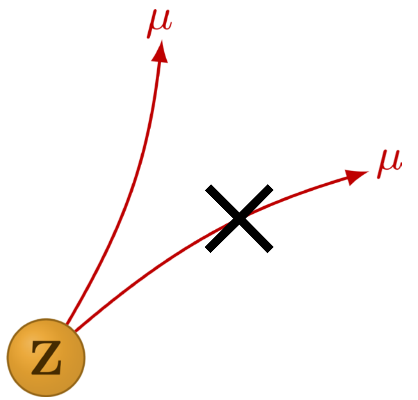


Impact on m_W → 1.9 MeV

Model validation: $(p_T^{\mu\mu}, y^{\mu\mu})$ spectrum



Model validation: W-like



- Proof-of-principle: mimic a $(\boldsymbol{p_T^\mu},\ \boldsymbol{\eta^\mu},\ \boldsymbol{q^\mu})$**-only fit** using $Z \to \mu\mu$:

Model validation: W-like

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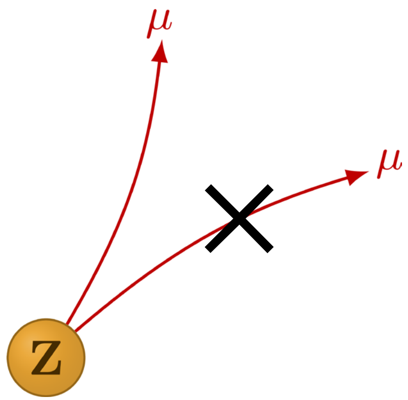
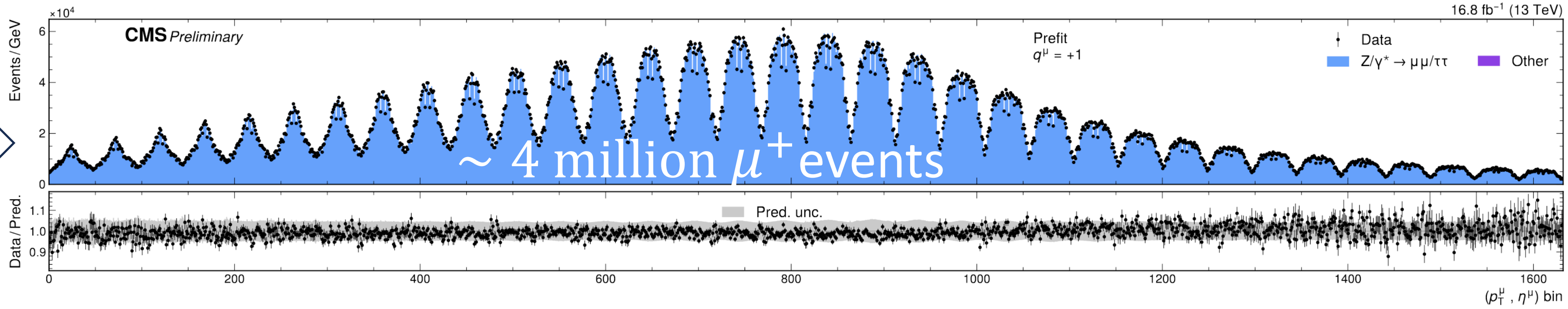


μ^+ in **even-numbered** events



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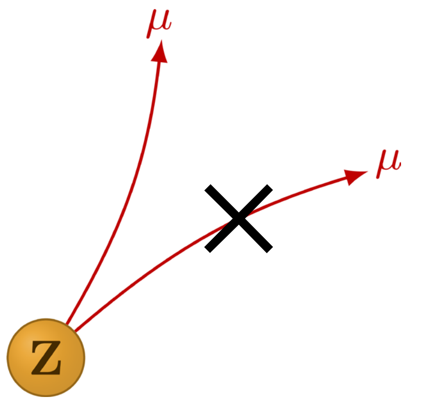

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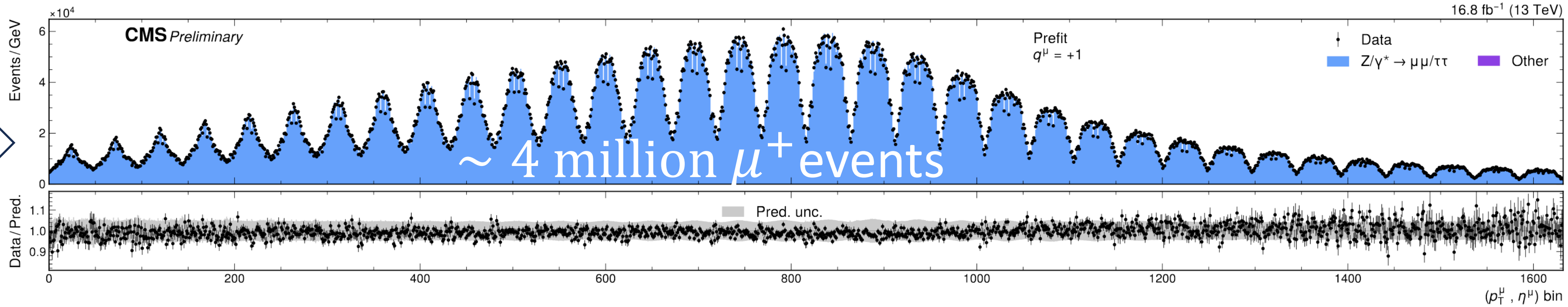
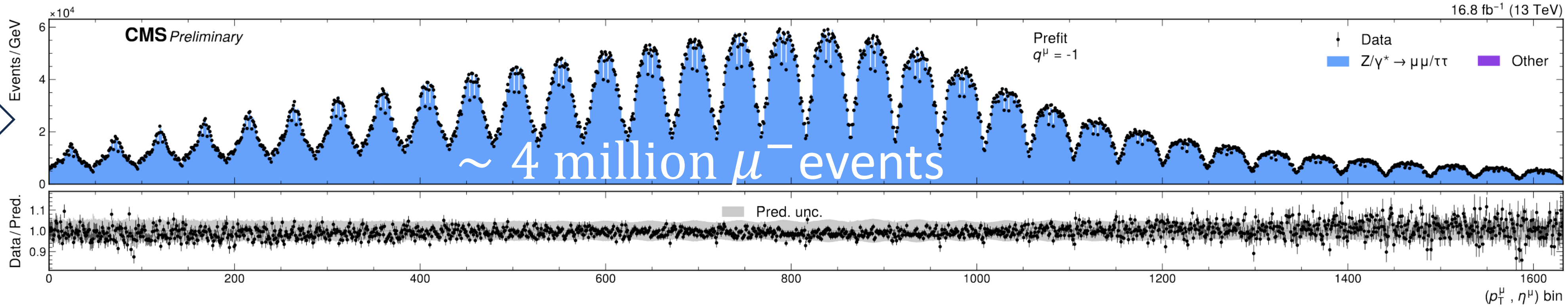
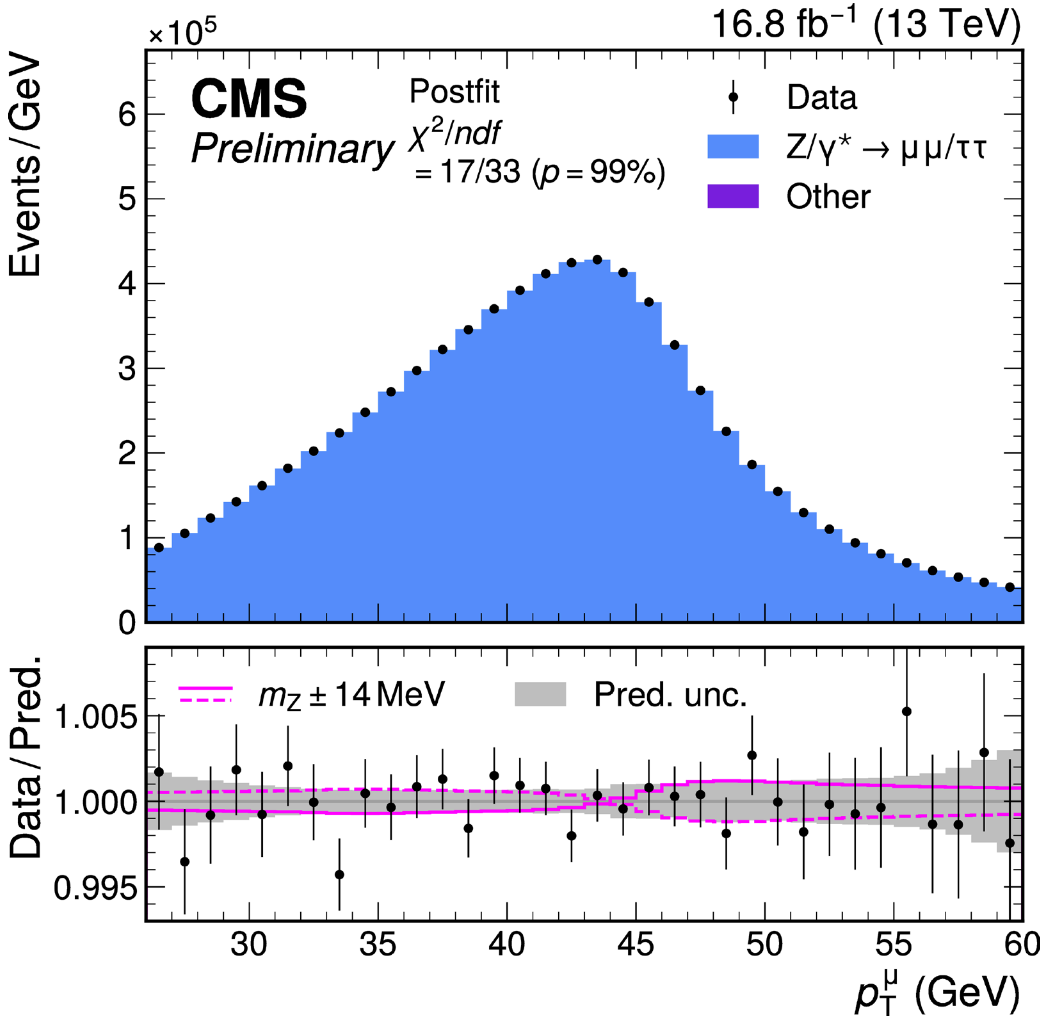


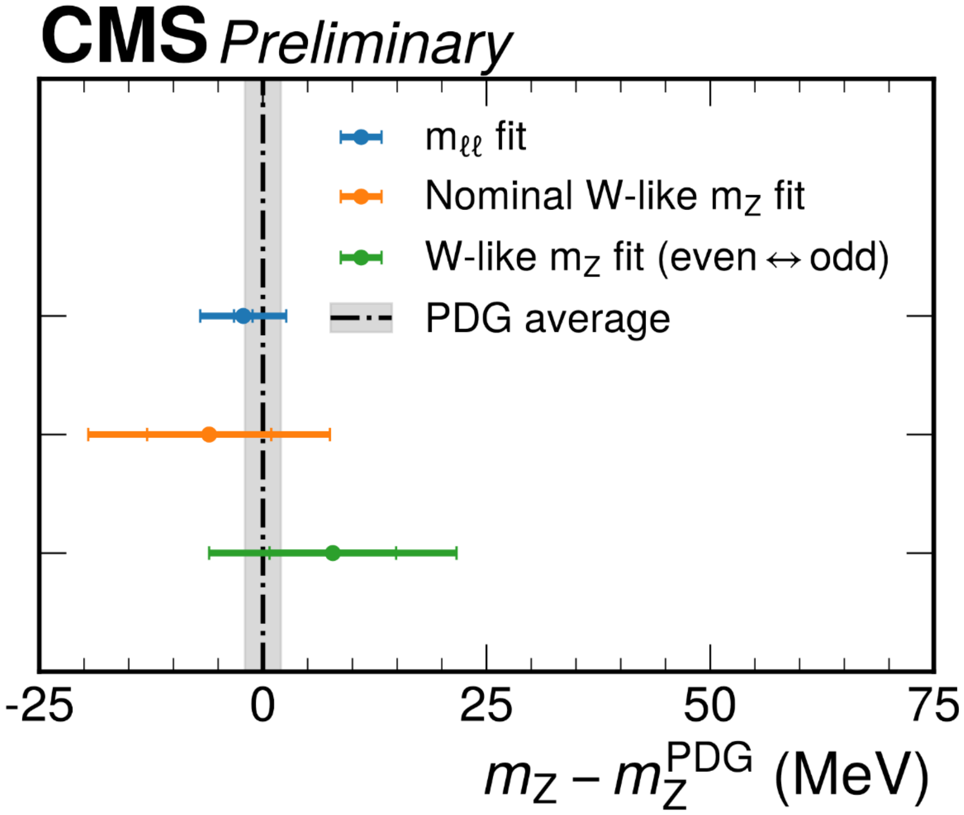
μ^- in **odd-numbered** events



W-like: results



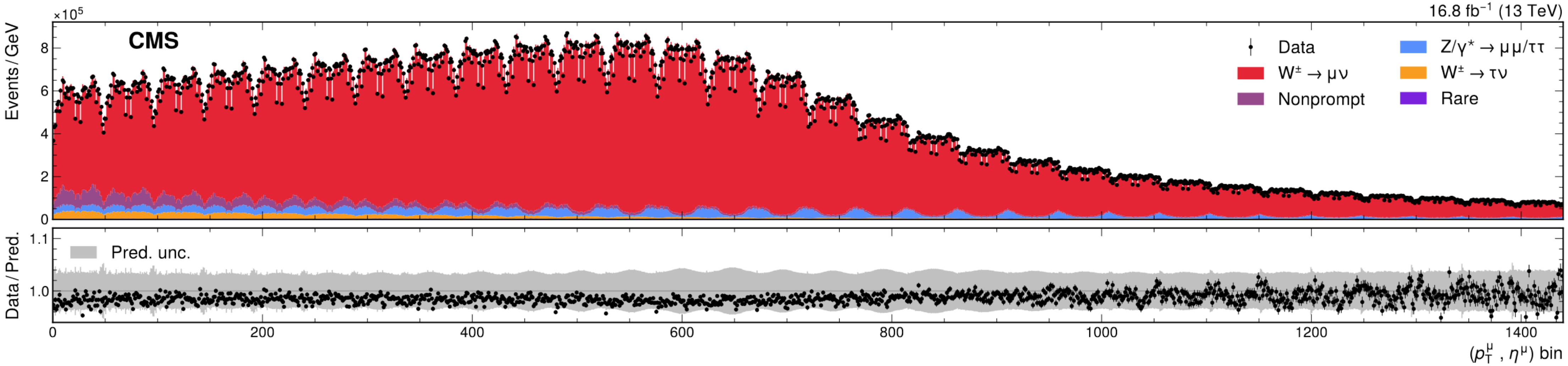
- Total uncertainty on m_Z is **13.5 MeV**
  - Muon scale (5.6), A_i (4.9), muon eff. (3.8)



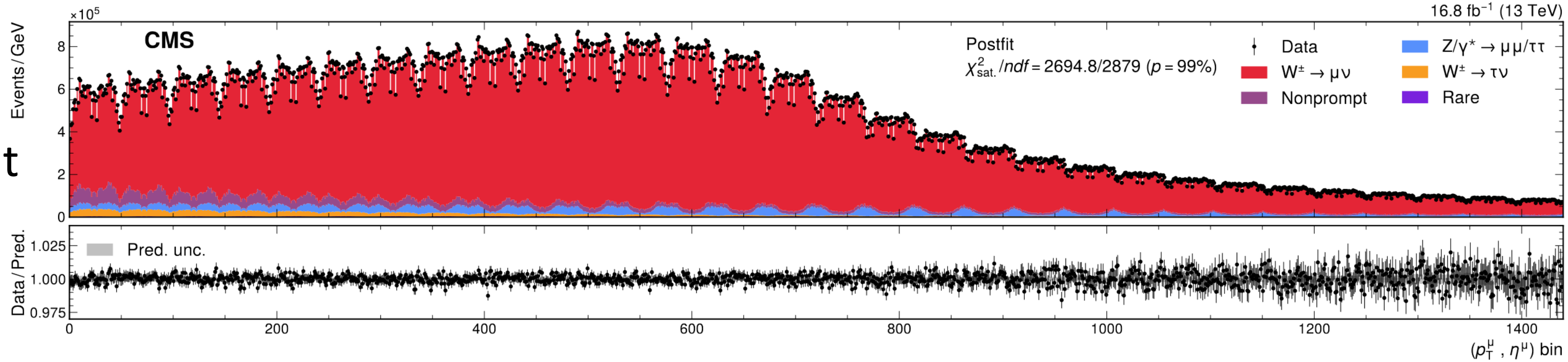
Moving to the W

$O(5{,}000)$ nuisance parameters
(with $\mathcal{N}(0,1)$ constraints)

Pre-fit

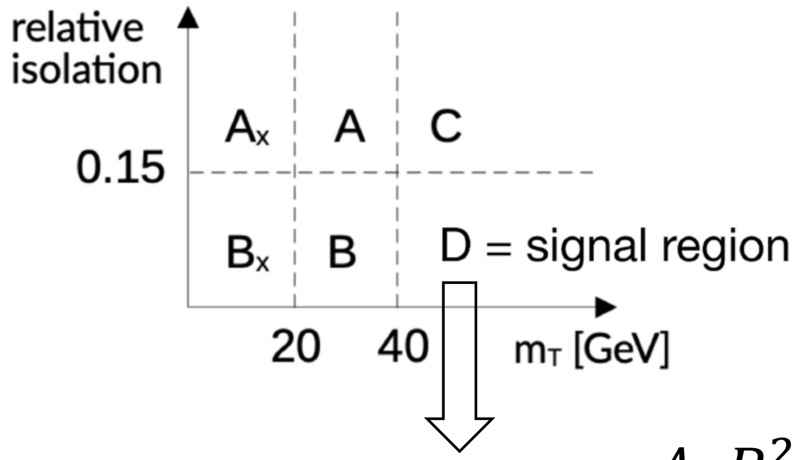


Post-fit

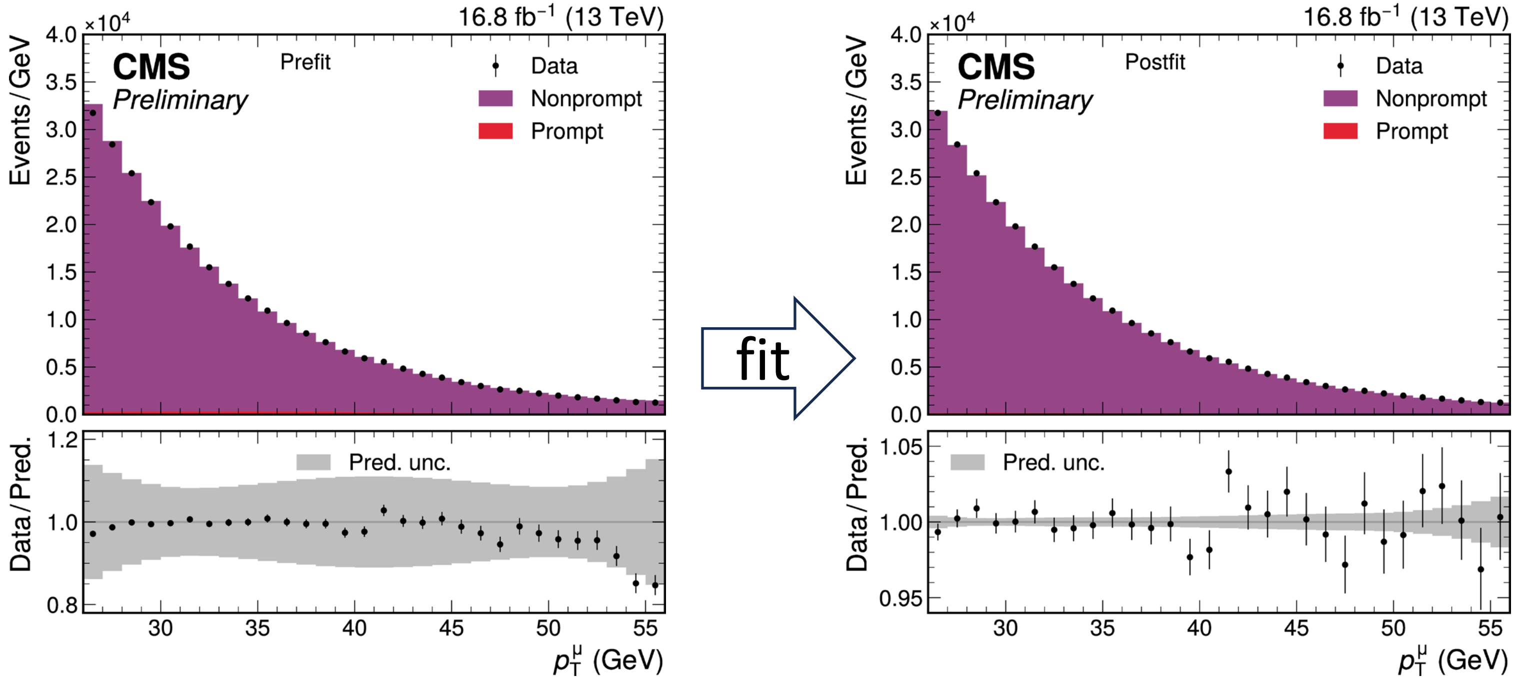


Non-prompt background

- Mostly muons from $\boldsymbol{B/C}$ **hadron decay**
- Extended "ABCD" method based on $\textbf{isolation} : \boldsymbol{m_T}$
  - Validated on MC simulation and data sidebands



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

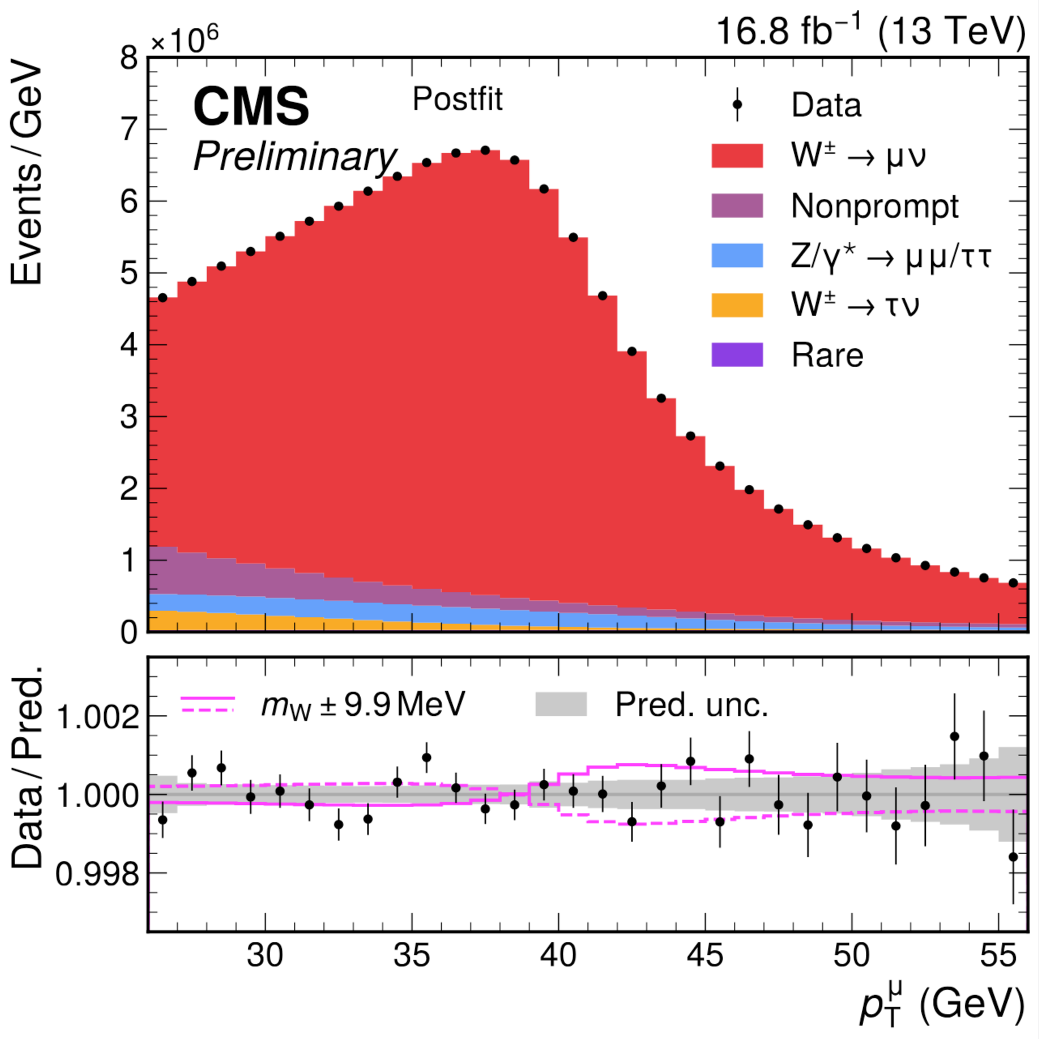


Enforcing analytic p_T spectrum:

$$f_i(p_T) \propto e^{-(a_i p_T^3 + b_i p_T^2 + c_i p_T)}$$

Impact on m_W → ~3 MeV

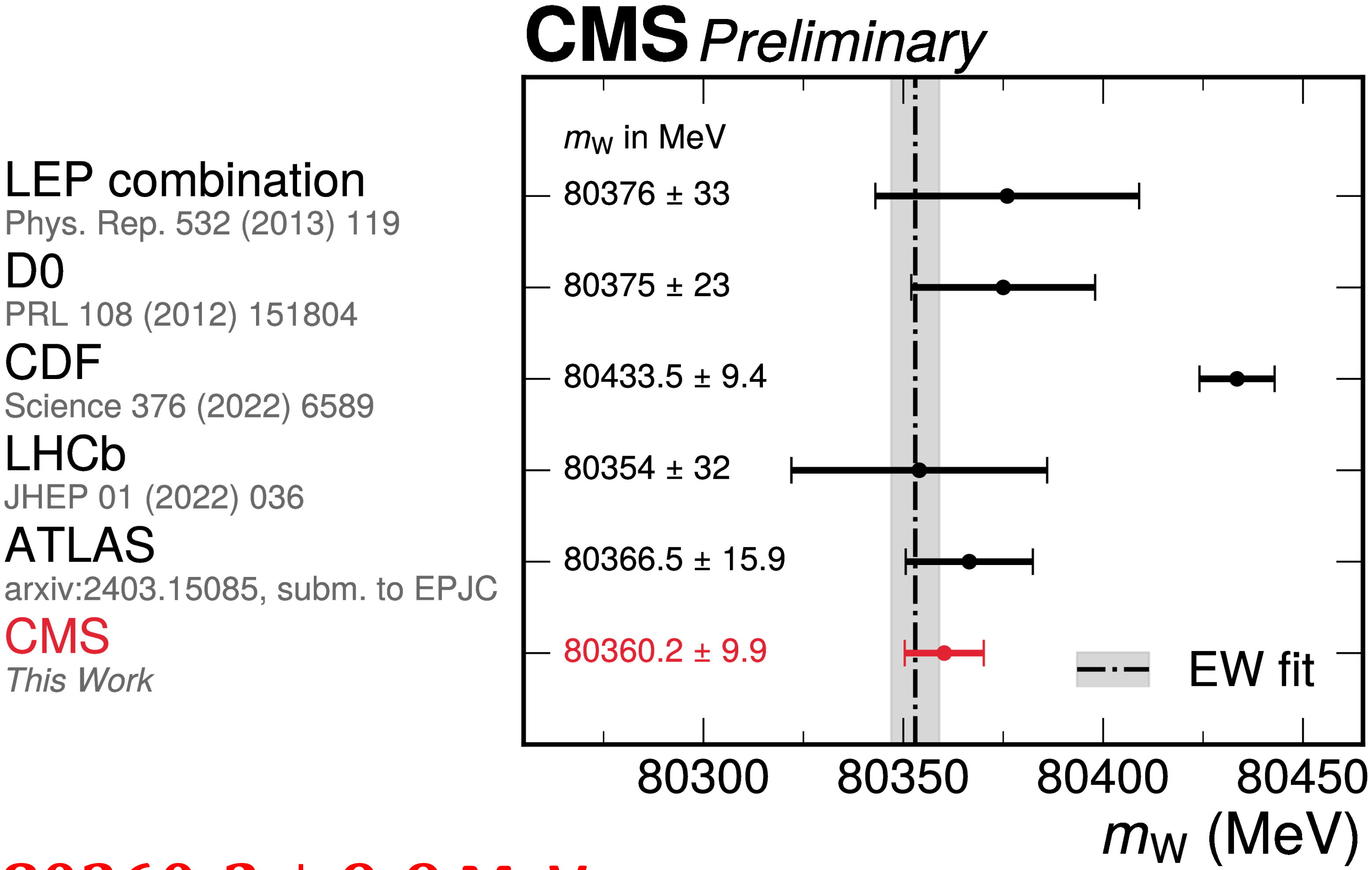
Unblinding the W fit



- Total uncertainty on m_W is **9.9 MeV**
  - m_W **blinded** until all check completed

Source of uncertainty	Nominal in m_Z	in m_W
Muon momentum scale	5.6	4.8
Muon reco. efficiency	3.8	3.0
W and Z angular coeffs.	4.9	3.3
Higher-order EW	2.2	2.0
p_T^V modeling	1.7	2.0
PDF	2.4	4.4
Nonprompt background	–	3.2
Integrated luminosity	0.3	0.1
MC sample size	2.5	1.5
Data sample size	6.9	2.4
Total uncertainty	13.5	9.9

Results

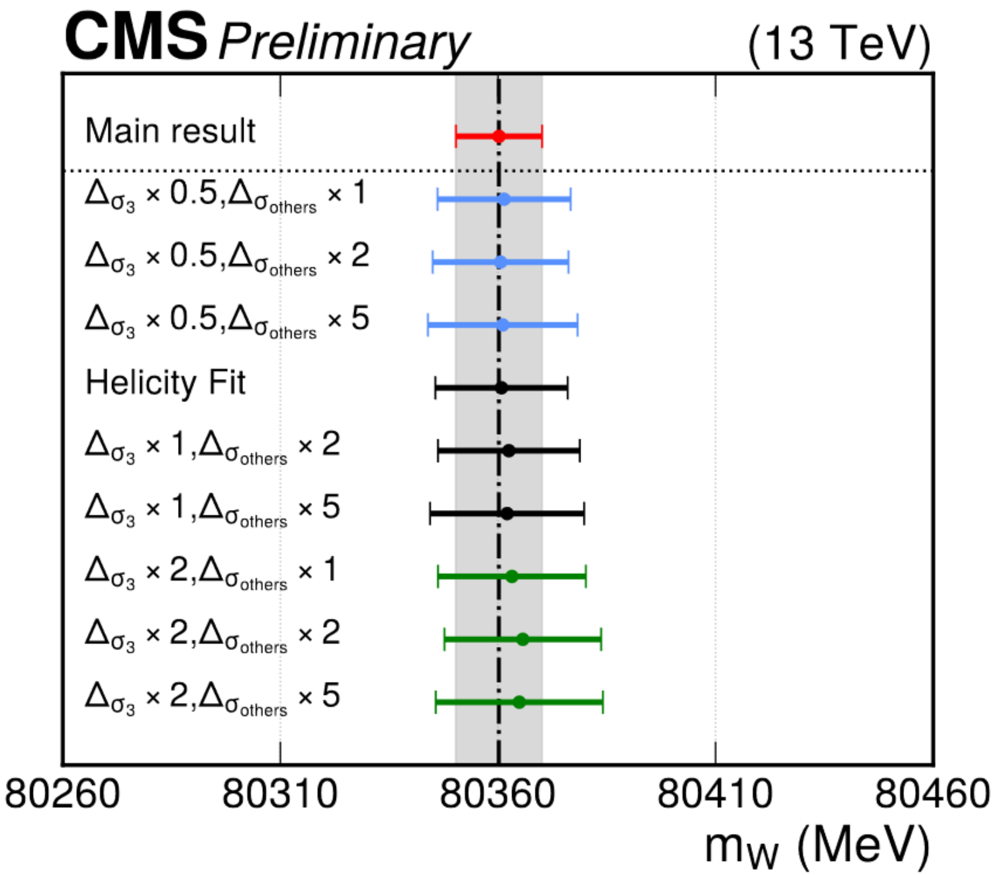


$$m_W^{\mathbf{CMS}} = \mathbf{80360.2 \pm 9.9\ MeV}$$

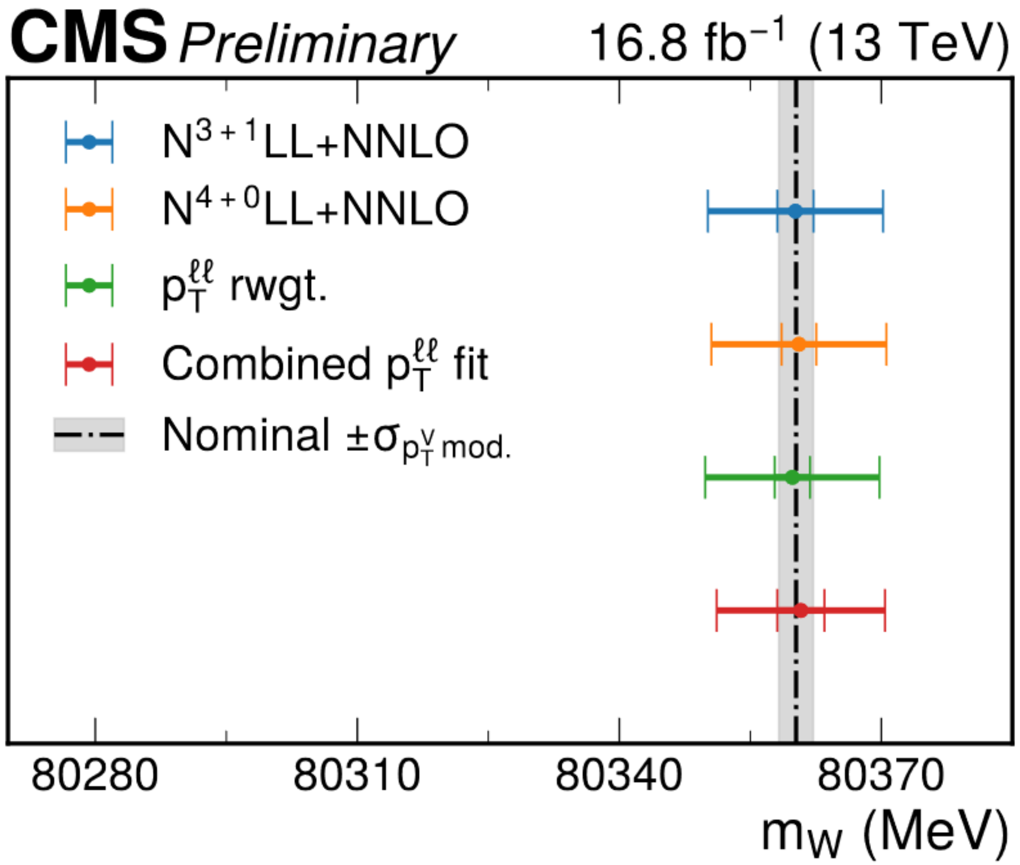
Test of model dependence

- Impact of loosening model-dependence by assigning additional priors on **helicity cross sections** $\boldsymbol{\sigma_i \equiv \sigma_{\mathrm{UL}} \times A_i}$

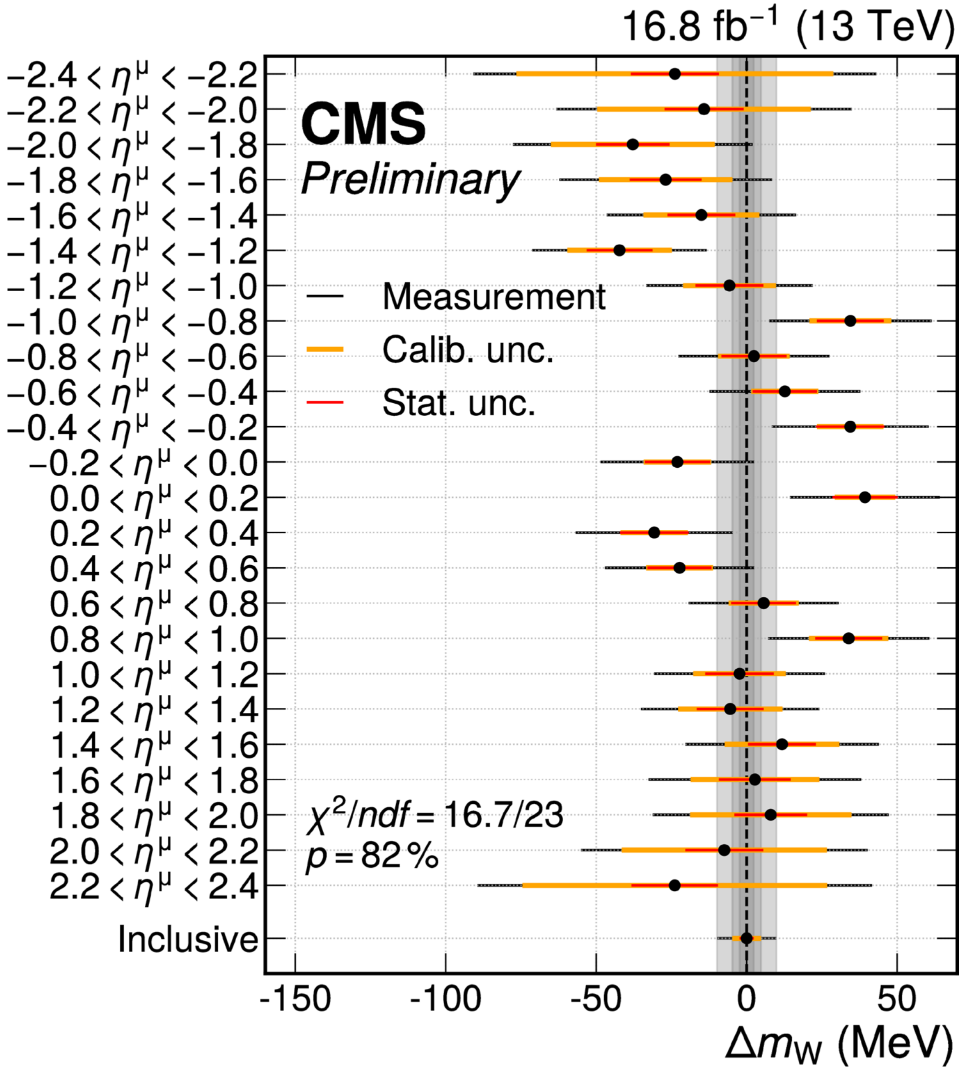
- **Stability** of best-fit m_W tested for increasingly looser priors
  → no evidence of tension or trends



Test of model dependence



→ Different p_T^W **uncertainty models**

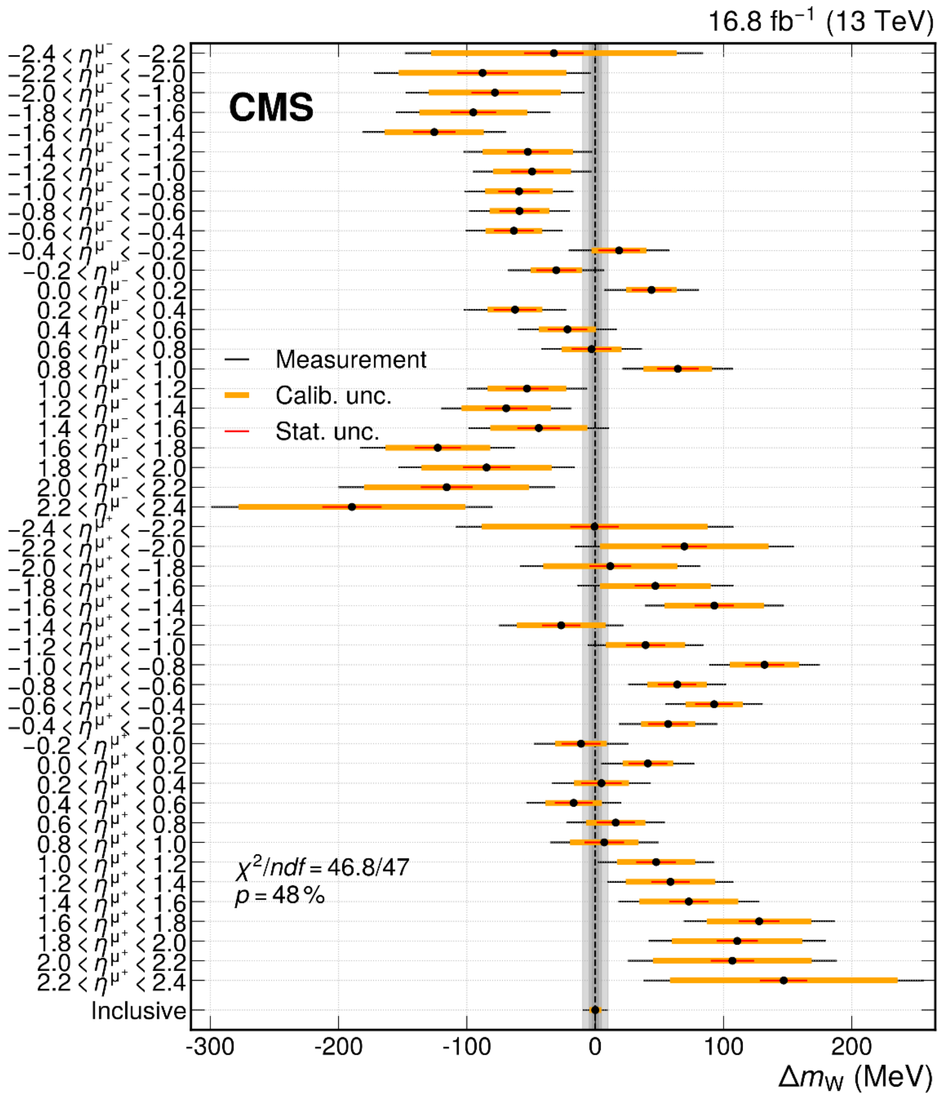


→ Different **detector** regions

Charge asymmetry

- $\boldsymbol{m_{W^+} - m_{W^-} = 57 \pm 30}$ **MeV** (p-value = 6%)
  - Correlation with **avg. mass** ~ 0.02

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



- Likely, a combination of alignment/theory NP's consistently pulled by $\sim 1\sigma$
  - no significant shift in **avg.** $\boldsymbol{m_W}$ even for generous shifts of pre-fit NP

Comparison with ATLAS

arXiv:2403.15085

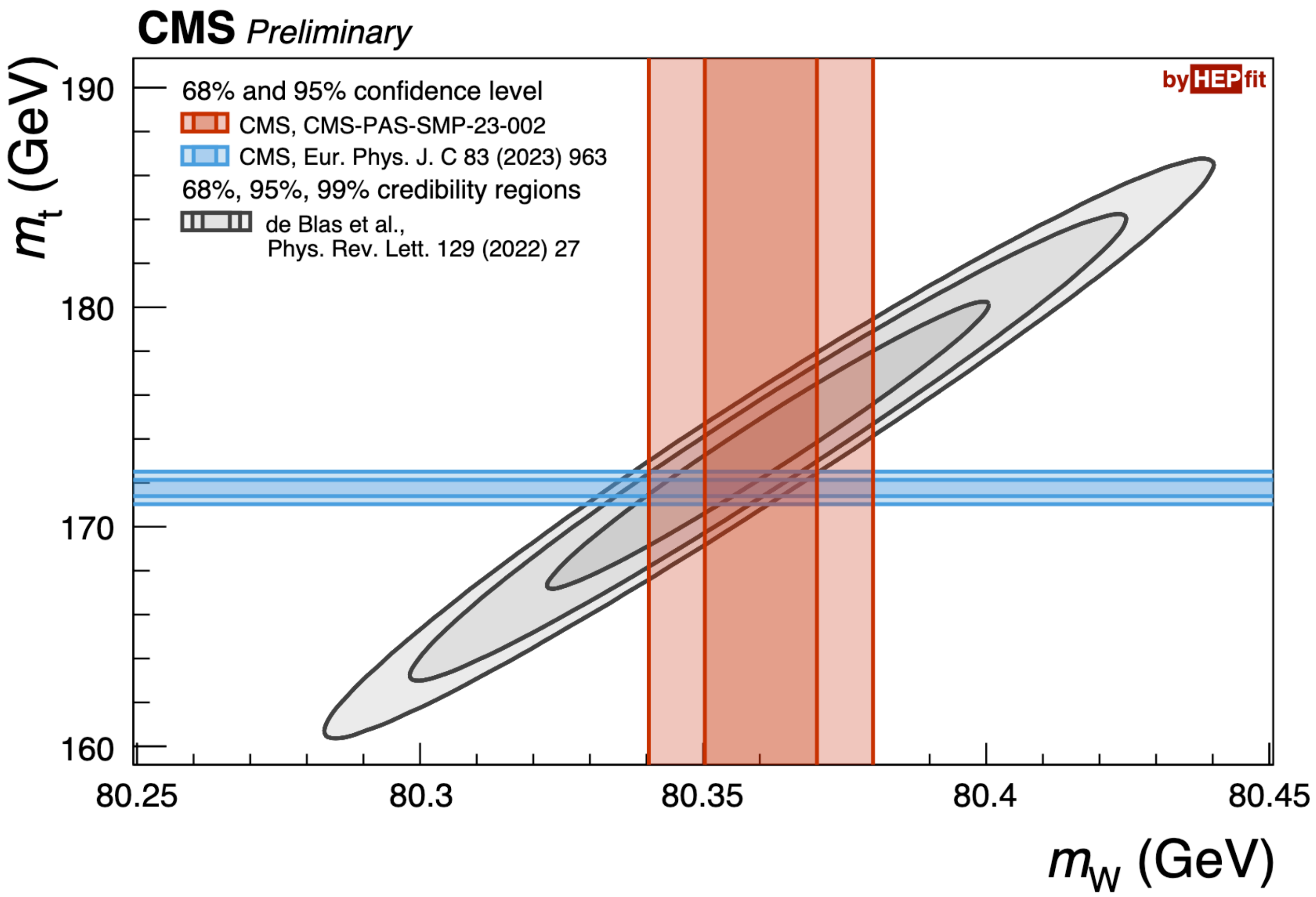
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5

For "global" impacts see arXiv:2307.04007

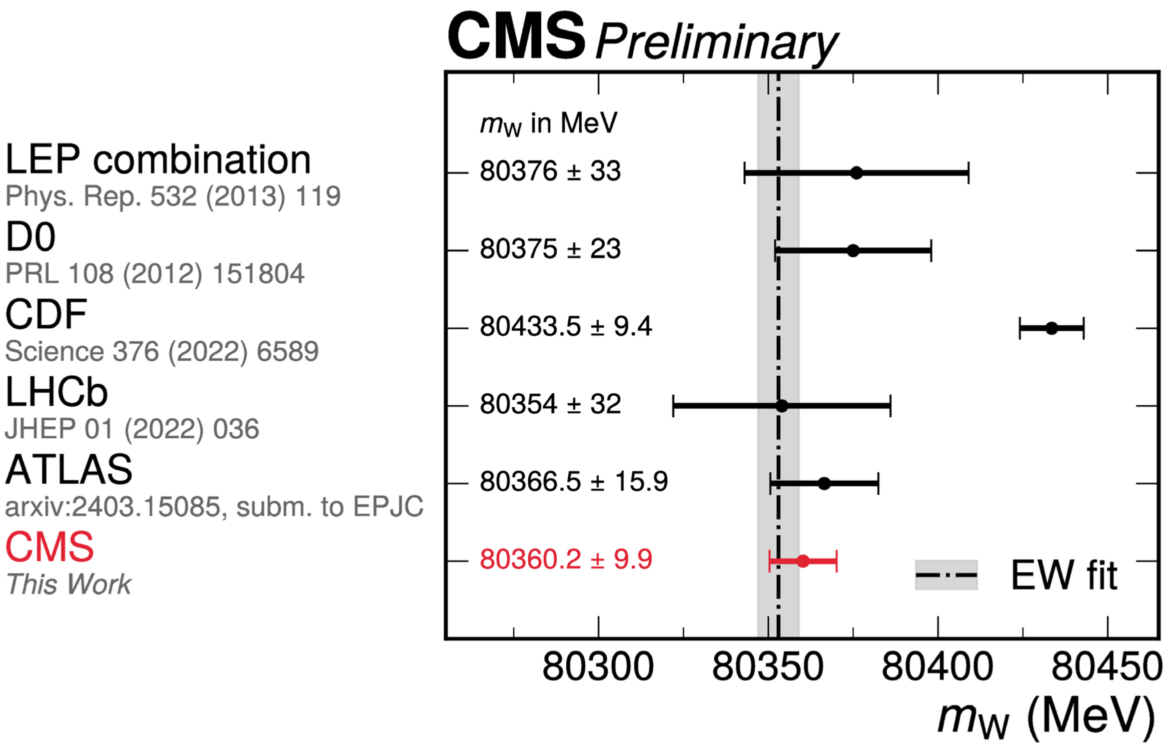
Source of uncertainty	Impact (MeV) Nominal in m_Z	Nominal in m_W	Global in m_Z	Global in m_W
Muon momentum scale	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt background	–	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

CMS-PAS-SMP-23-002

The EWK fit and direct CMS (m_t, m_W)



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 with the PDG average
- The **first in a line** of new precision EWK measurements by CMS

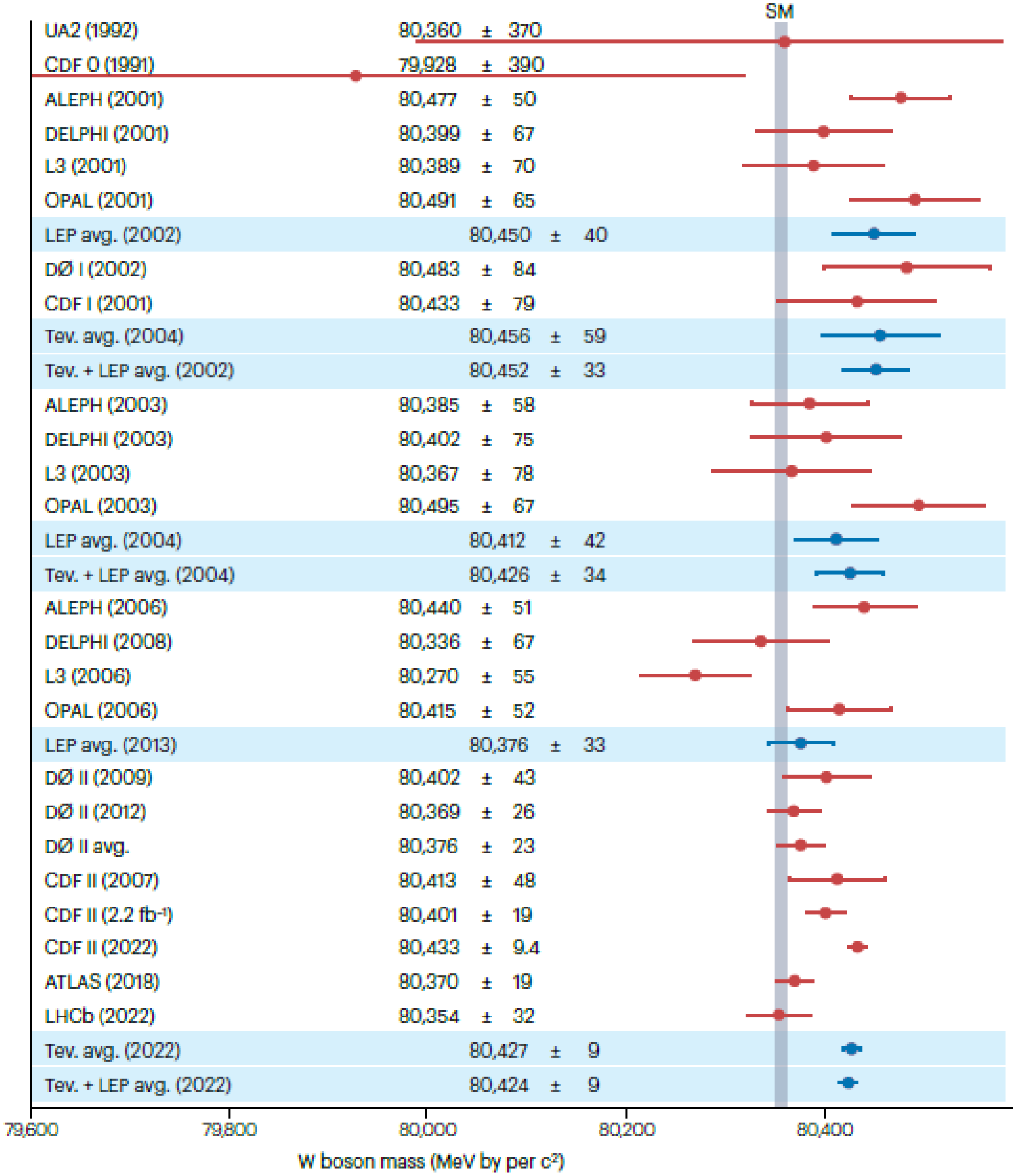
Grazie per l’attenzione!

Backup

Nature Reviews Physics **6** (2024) 180

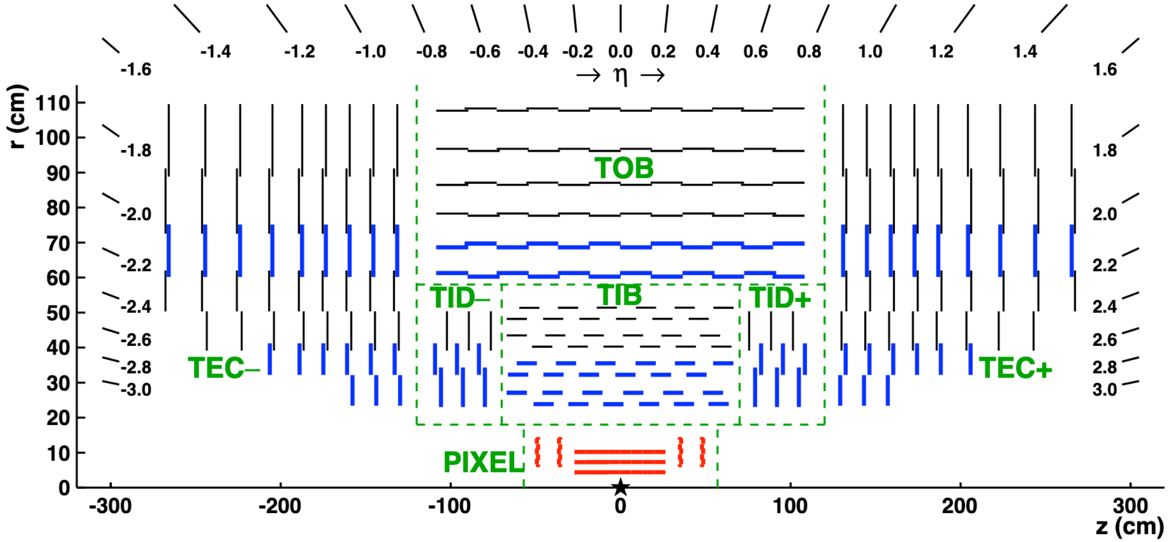
~500 MeV

~10 MeV

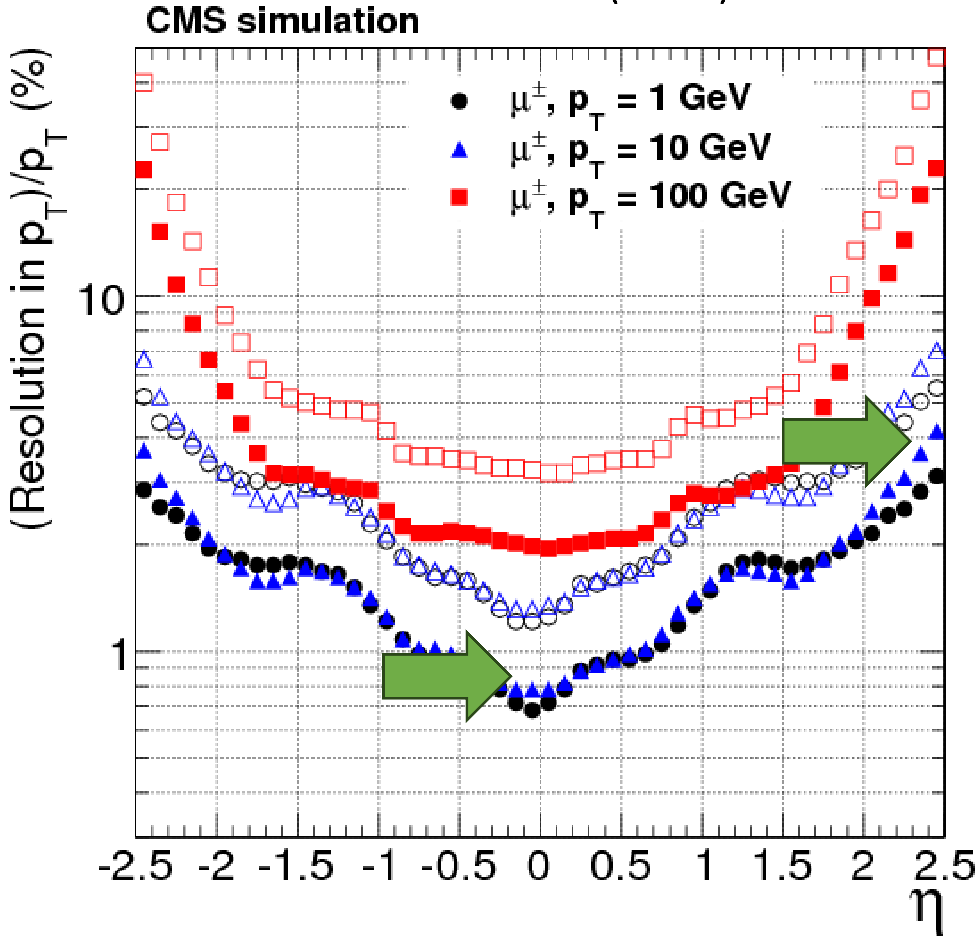


+2 new results in 2024

The CMS tracker



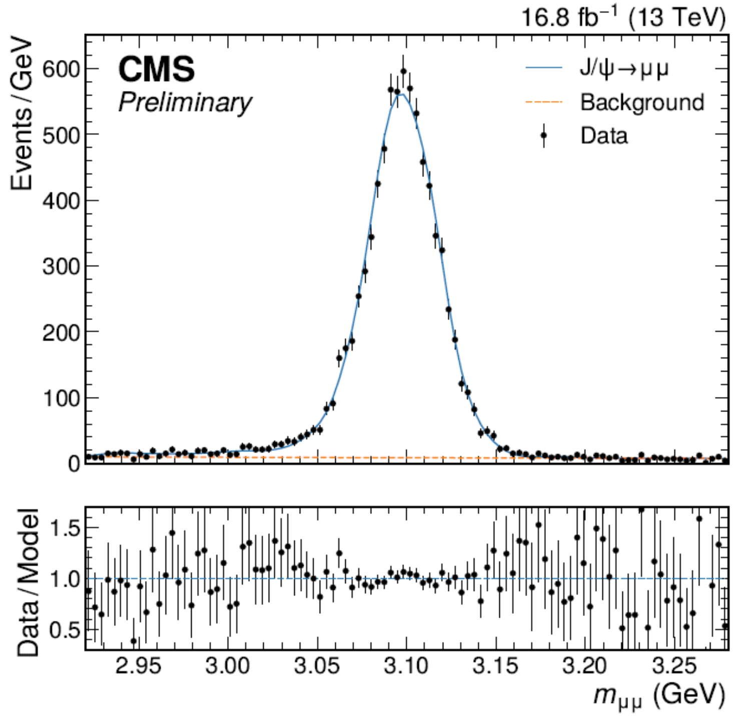
JINST 9 (2014) P10009



- Fully silicon-based
- Up to 17 points per track ($9 \div 50$ μm resolutions)
- Up to **2 radiation lengths**
  - p_T^{μ} resolution from multiple scattering: $\mathbf{1} \div \mathbf{3}\%$

Muon momentum scale: workflow

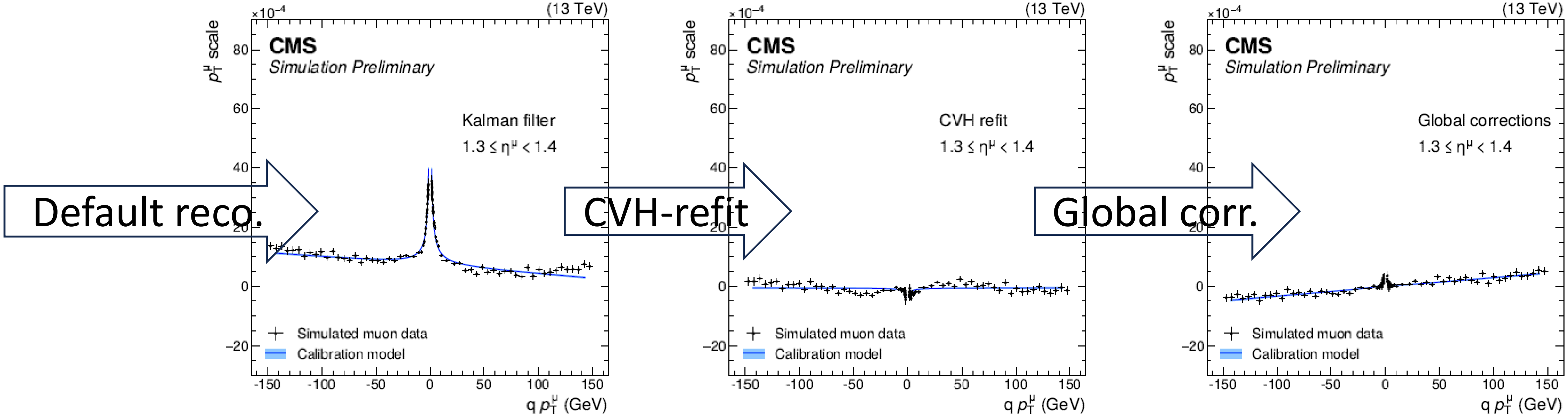
1. **Tuning** of parameters in CMS simulation.
2. **Track re-fit** with improved B-field/material treatment in track propagation.
3. **Module-level correction** of alignment, B-field, and material by minimizing $J/\Psi \rightarrow \mu\mu$ track residuals.
   → Scale in ideal MC is **now unity** within a few 10^{-5}
   → Residual mis-modeling can be **parametrized** as:



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

4. $(A_{i\eta}, \varepsilon_{i\eta}, M_{i\eta})$ from likelihood fits to **J/Ψ mass** binned in $(p_T^+, \eta^+, p_T^-, \eta^-)$

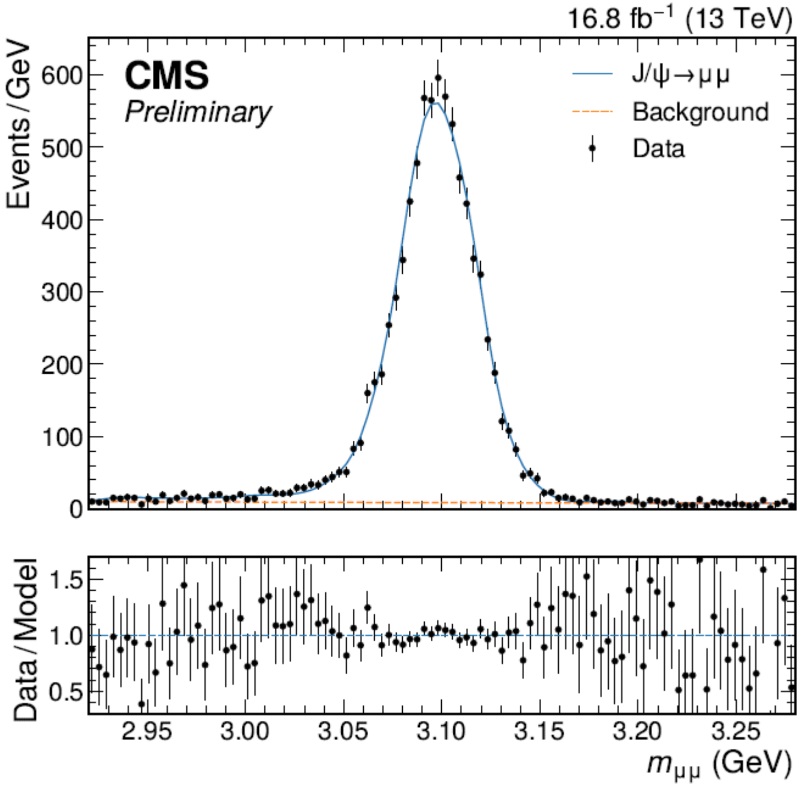
Muon momentum scale



Muon momentum scale

4. **Removal of residual data/MC scale bias** using J/Ψ events in a fine-grained 4D space $(p_T^+, \eta^+, p_T^-, \eta^-)$

$O(10{,}000)$
Mass spectra



- Fit a **scale shift $\boldsymbol{\Sigma}$** in each 4D bin
- Finally, do a χ^2 fit of $(A_\eta, \varepsilon_\eta, M_\eta)$ from all bins

$$\sum_{ijkl} \frac{\left(\Sigma_{ijkl}^2 - \left(\boldsymbol{A_j} - \frac{\boldsymbol{\varepsilon_j}}{p_{T,i}} + \boldsymbol{M_j} p_{T,i}\right)\left(\boldsymbol{A_l} - \frac{\boldsymbol{\varepsilon_l}}{p_{T,k}} + \boldsymbol{M_l} p_{T,k}\right)\right)^2}{\mathrm{Var}\left[\Sigma_{ijkl}^2\right]}$$

Impact on m_W

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

PDF

- Fitting simultaneously eta_mu and yZ

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

Further checks

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

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

Fit model

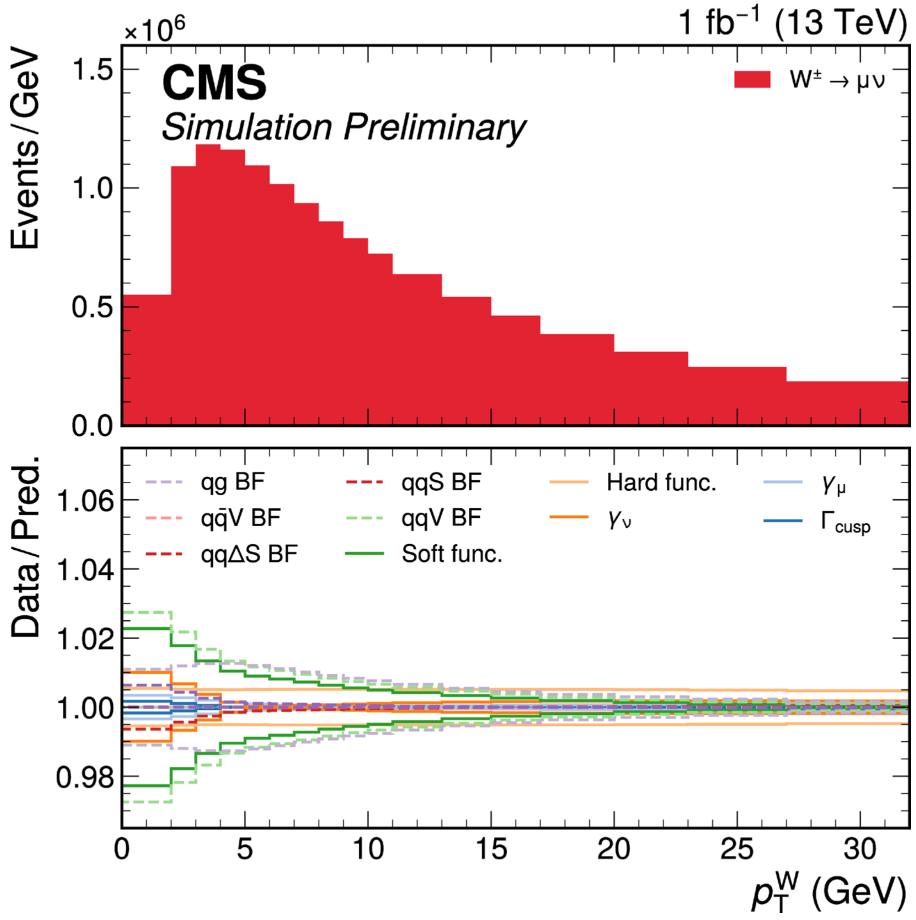
- m_W extracted from binned maximum-likelihood fit
  - Systematic uncertainties → **nuisance parameters (NP)** with Gaussian constraints
- RDataFrame → multi-dimensional Boost Histogram's
  - Nominal × **systematic variations**
- Likelihood calculation and minimization based on Tensorflow library

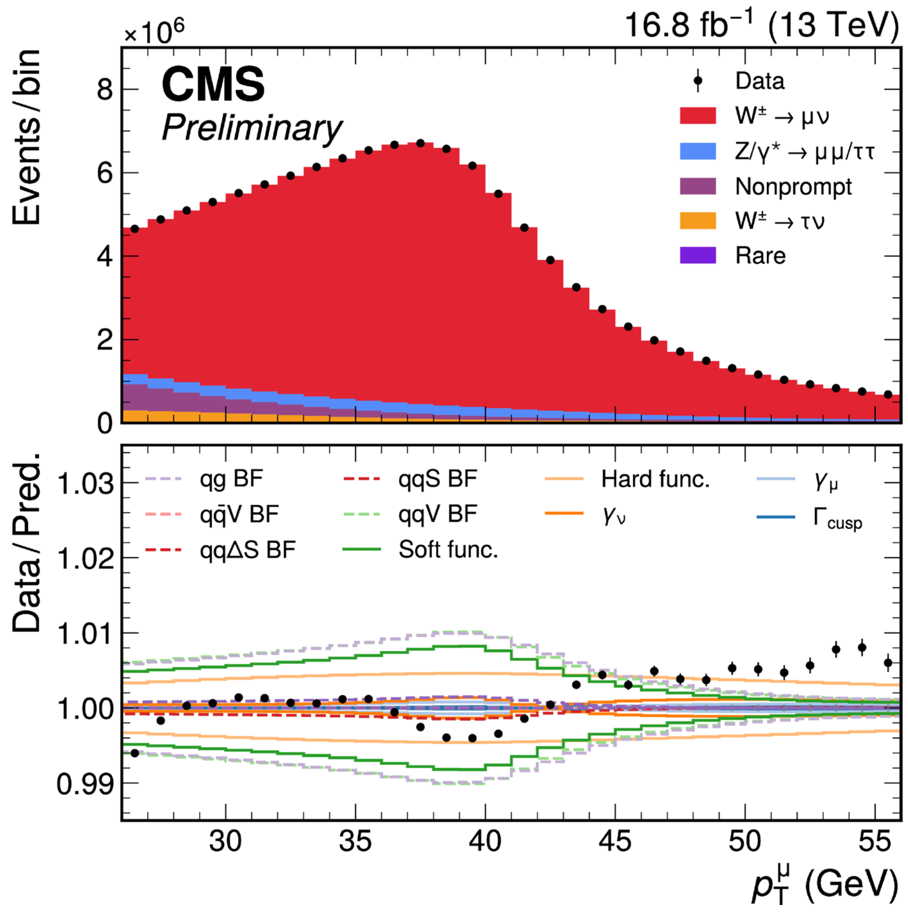
<table>
<tr><th>Systematic uncertainties</th><th>W-like m_Z</th><th>m_W</th></tr>
<tr><td>Muon efficiency</td><td>3127</td><td>3658</td></tr>
<tr><td>Muon eff. veto</td><td>–</td><td>531</td></tr>
<tr><td>Muon eff. syst.</td><td colspan="2">343</td></tr>
<tr><td>Muon eff. stat.</td><td colspan="2">2784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

D. Walter's slides

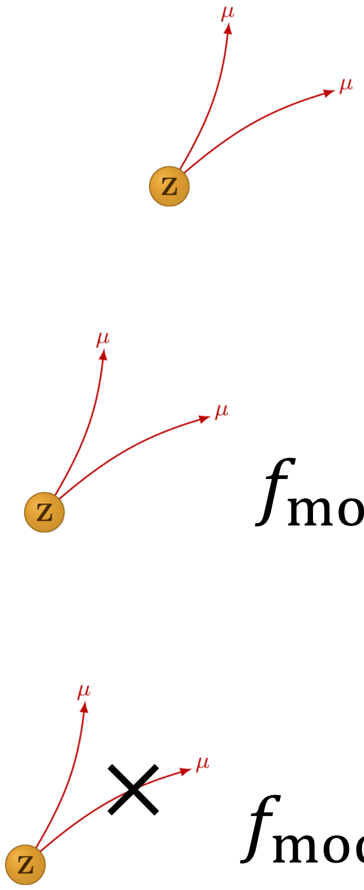
TNP

[F. Tackman's slides]





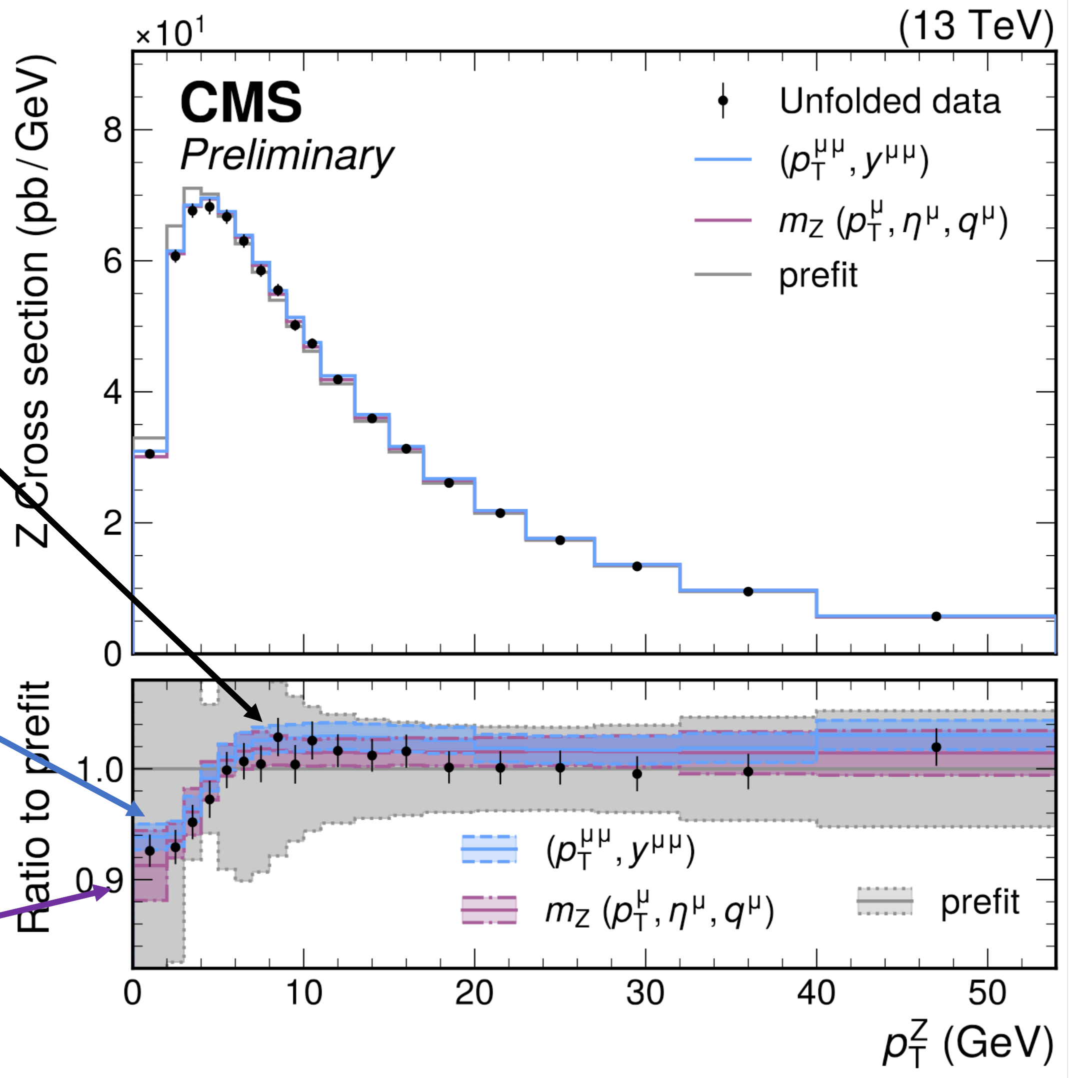
W-like: p_T^Z modeling



$$f_{\text{unfold}} = U_{\text{reco|gen}}^{-1} f_{\text{reco}}$$

$$f_{\text{model}}(p_T^Z \mid \theta_{(p_T^{\mu\mu}, y^{\mu\mu})})$$

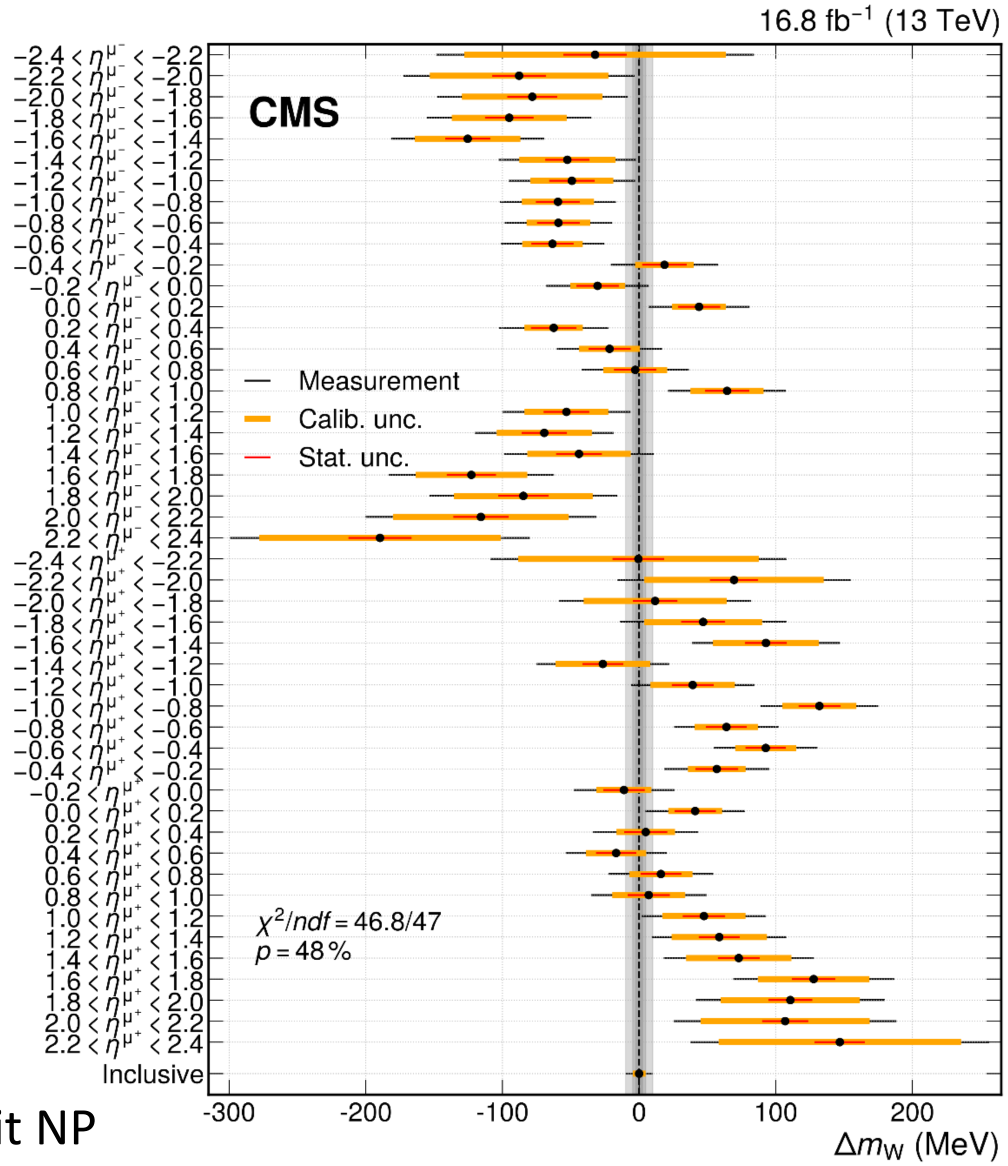
$$f_{\text{model}}(p_T^Z \mid \theta_{(q^{\mu}, p_T^{\mu}, \eta^{\mu})})$$



Charge asymmetry

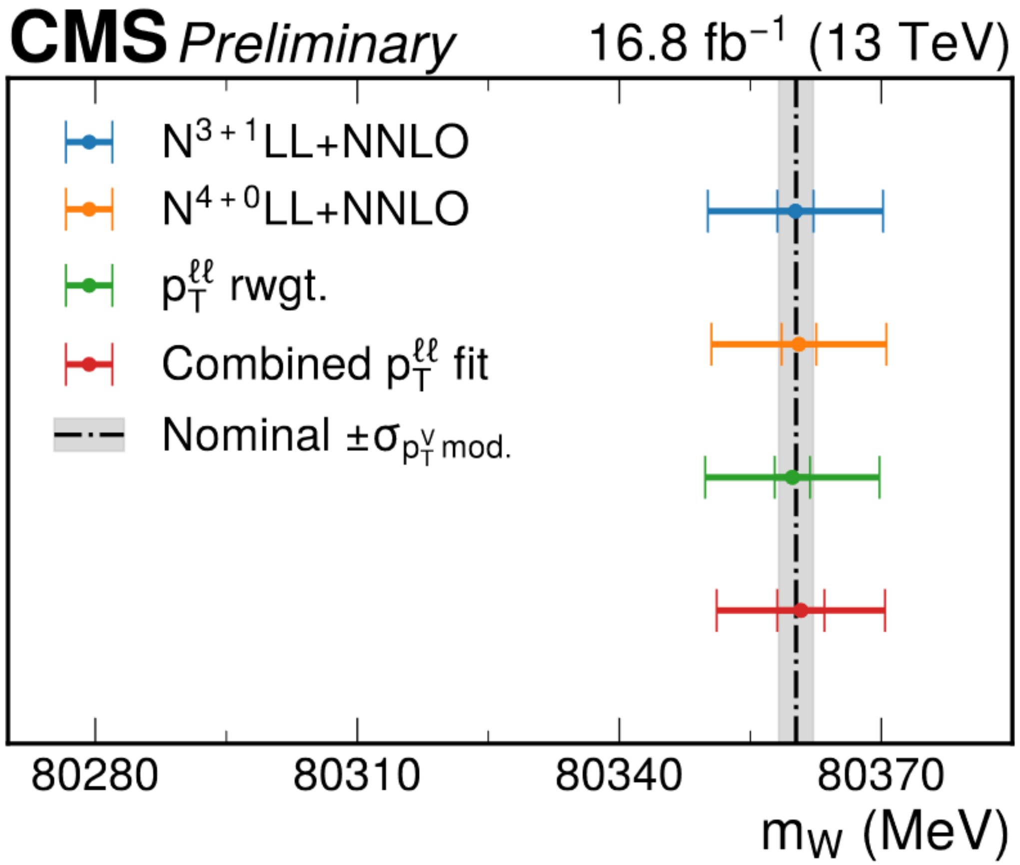
- $\boldsymbol{m_{W^+} - m_{W^-} = 57 \pm 30}$ **MeV**
  - *p*-value = 6%

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

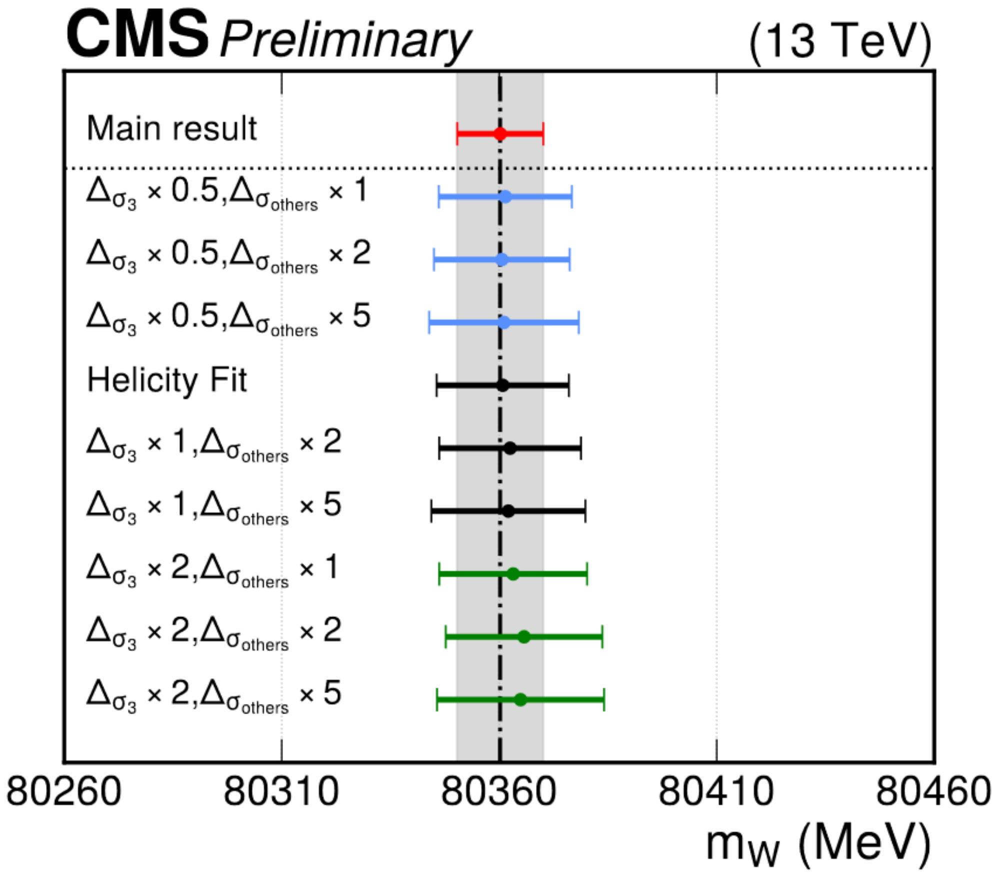


- Likely, a combination of alignment/theory nuisances consistently pulled by $\sim 1\sigma$
  - no significant shift in m_W even for generous shifts of pre-fit NP

Test of model dependence

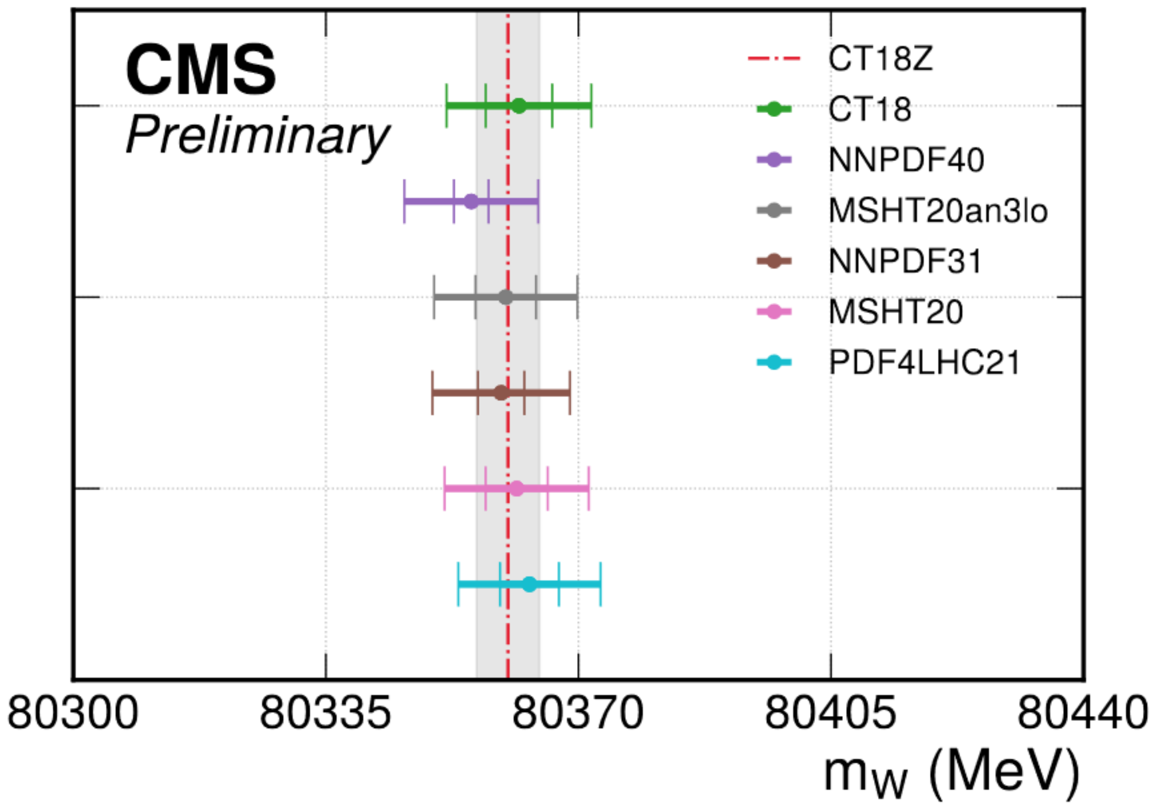


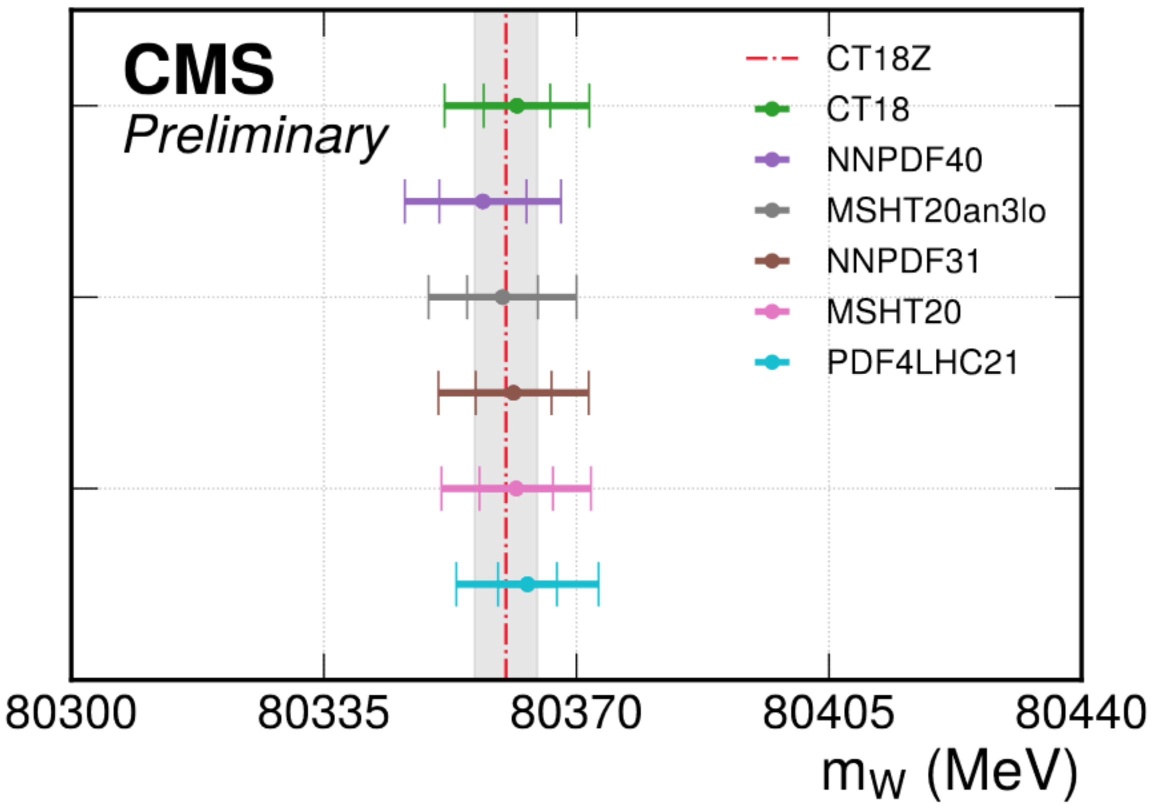
Different p_T^V uncertainty models



"Helicity fit": loose priors on $\sigma_{\mathrm{UL},0,..,4}$

PDF dependence





WITHOUT INFLATION

Spread of central values within the uncertainty of **nominal PDF set**

WITH INFLATION

Spread of central values within the uncertainty of **any PDF sets**

Comparison w/ ATLAS & CDF-II

- To enable one-to-one comparison with ATLAS, use "global" impacts

arXiv:2307.04007

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

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

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

arXiv:2403.15085

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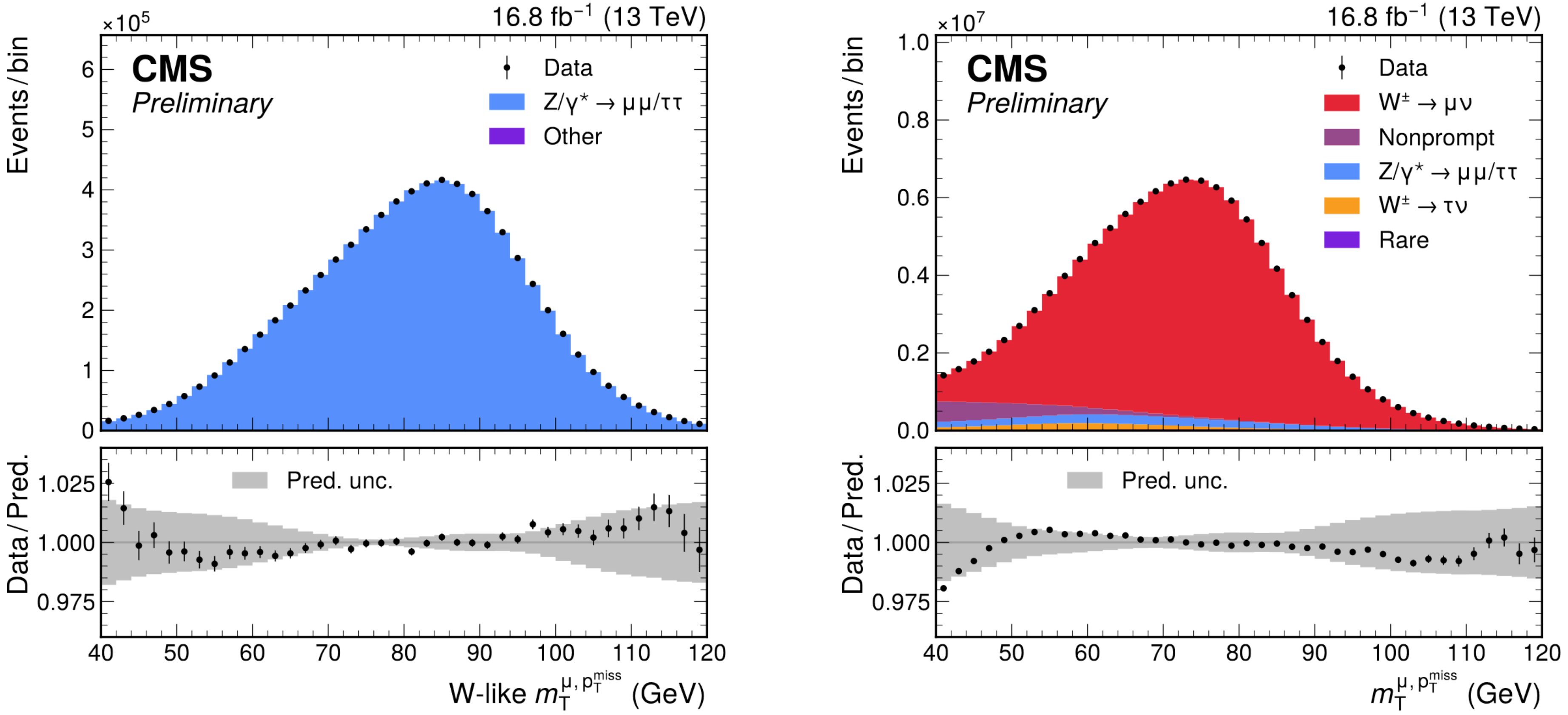
Science 376 (2022) 6589

Recoil



16.8 fb^{-1} (13 TeV)
×10^5
CMS
Preliminary
Data
$Z/\gamma^* \to \mu\mu/\tau\tau$
Other
Events/bin
Data/Pred.
Pred. unc.
W-like $m_T^{\mu, p_T^{miss}}$ (GeV)
16.8 fb^{-1} (13 TeV)
×10^7
CMS
Preliminary
Data
$W^\pm \to \mu\nu$
Nonprompt
$Z/\gamma^* \to \mu\mu/\tau\tau$
$W^\pm \to \tau\nu$
Rare
Events/bin
Data/Pred.
Pred. unc.
$m_T^{\mu, p_T^{miss}}$ (GeV)