A measurement of the W boson mass at CMS

Lorenzo Bianchini
Università e INFN Pisa

Università di Pisa

Istituto Nazionale di Fisica Nucleare

European Research Council
Established by the European Commission

Overview

- **First CMS measurement** of m_W (CERN seminar)
  - CMS-PAS-SMP-23-002
- Long-term involvement of **CMS Pisa group** in m_W
  - Main contribution to this work
- **Highly intricate analysis** (“The devil is in the details”)
  - Today I won’t be exhaustive in all details ☺

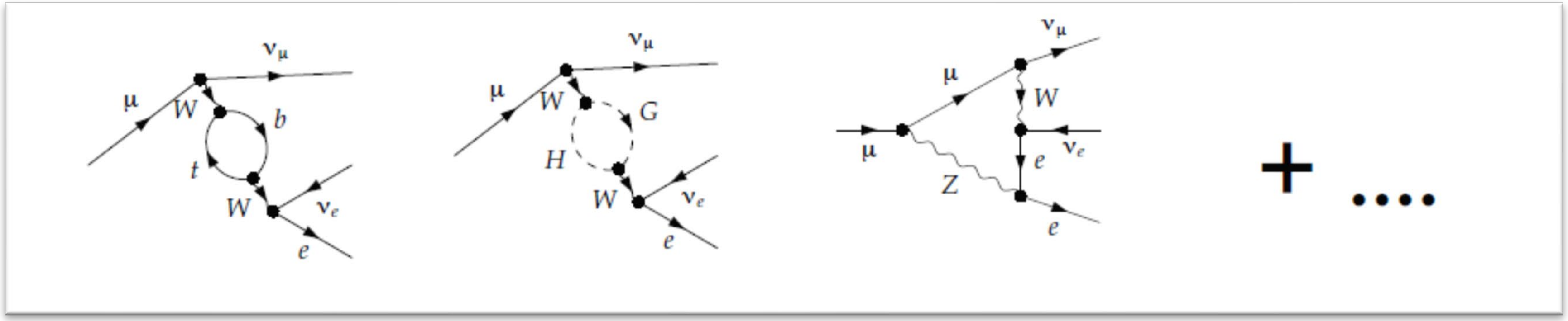
The SM prediction for m_W

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

See e.g. JHEP 05 (2015) 154

The SM prediction for m_W

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



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

See e.g. JHEP 05 (2015) 154

The SM prediction for m_W

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

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

SM @ 2 loops ⇒

$m_W = \mathbf{80353 \pm 6\ MeV}$ (75 ppm)

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

The SM prediction for m_W

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

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

SM @ 2 loops ⇒

~~$m_W = \mathbf{80353 \pm 6\ MeV}$ (75 ppm)~~

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

BSM

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

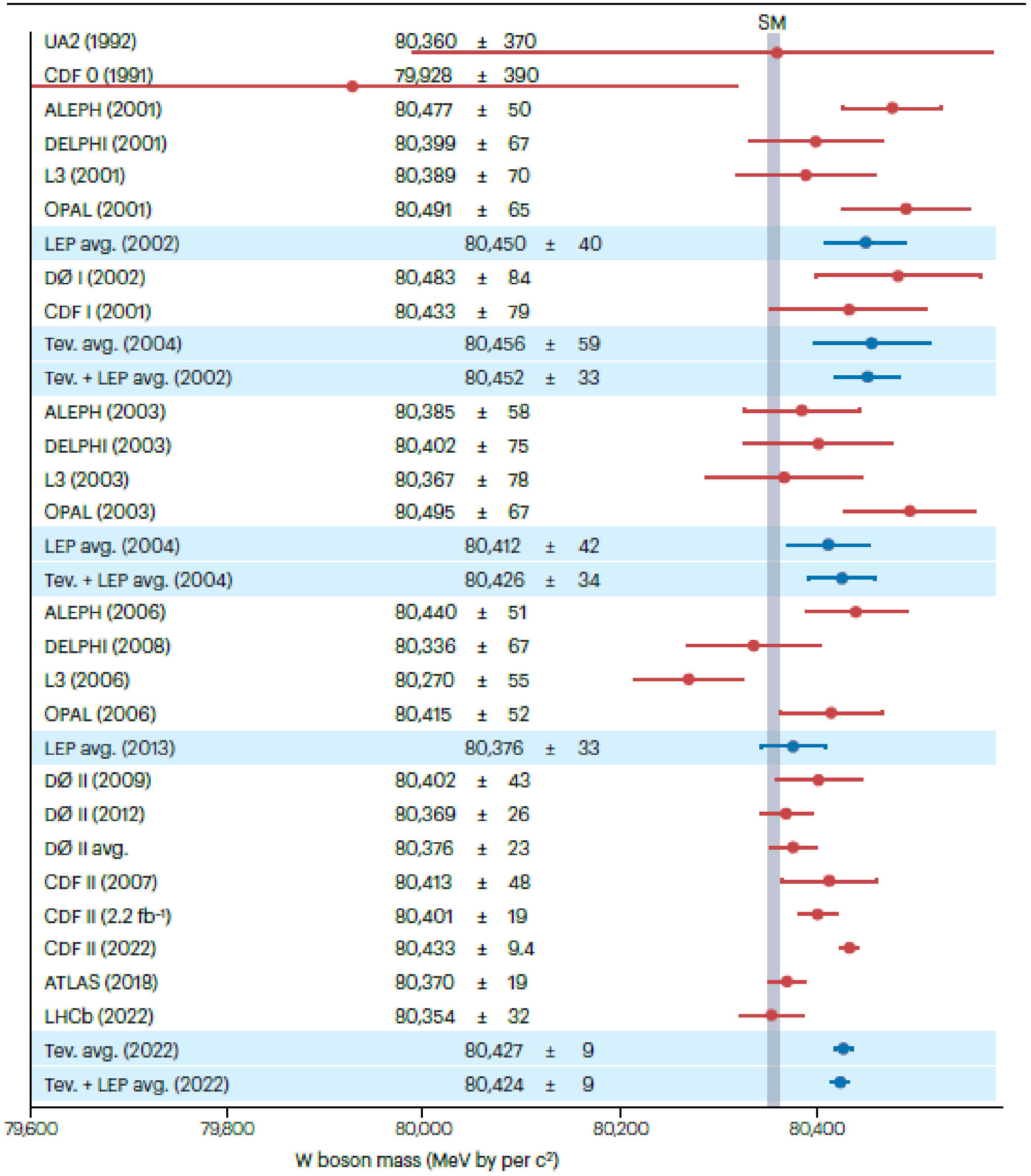
Extra $SU(2)$ doublets ?

Extra $U(1)'$?

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

1992

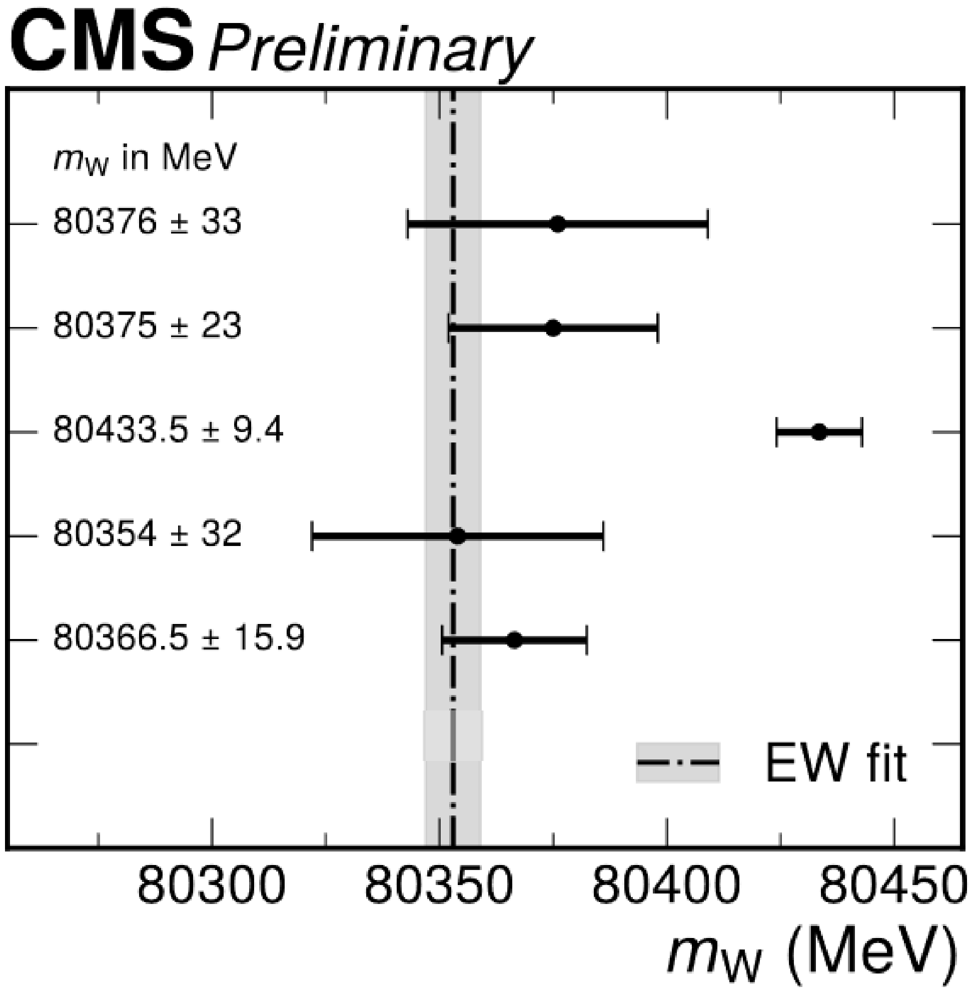
2022



+2 new results in 2024

Two weeks ago

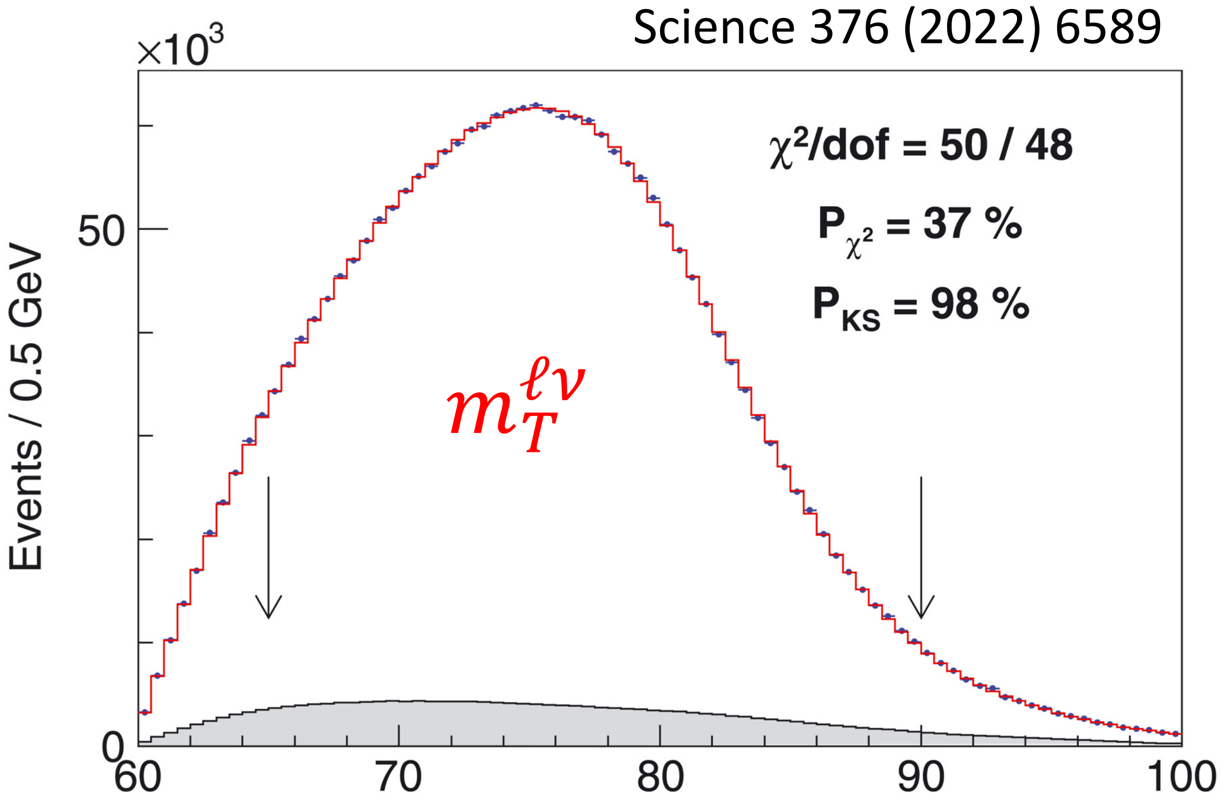
LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arxiv:2403.15085, subm. to EPJC
CMS
???



- CDF in strong disagreement with SM
- PDG-average (w/o CDF): $\mathbf{80369.2 \pm 13.3}$ **MeV**

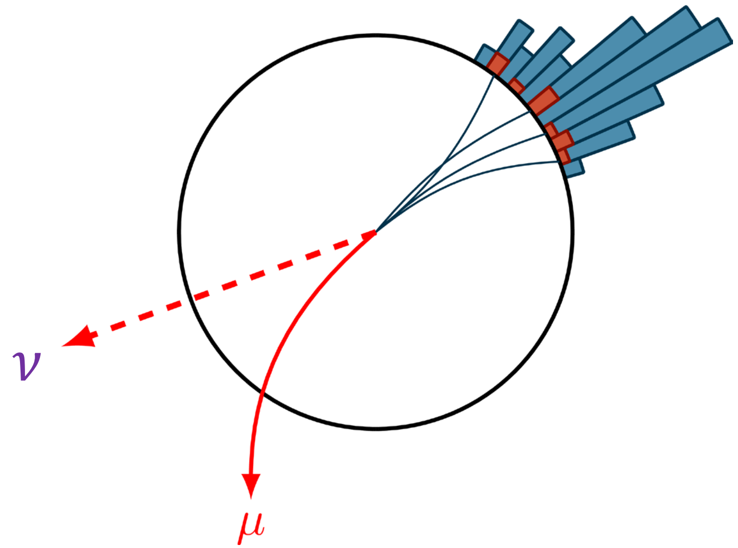
➔ **This calls for a new measurement**

Hadron colliders



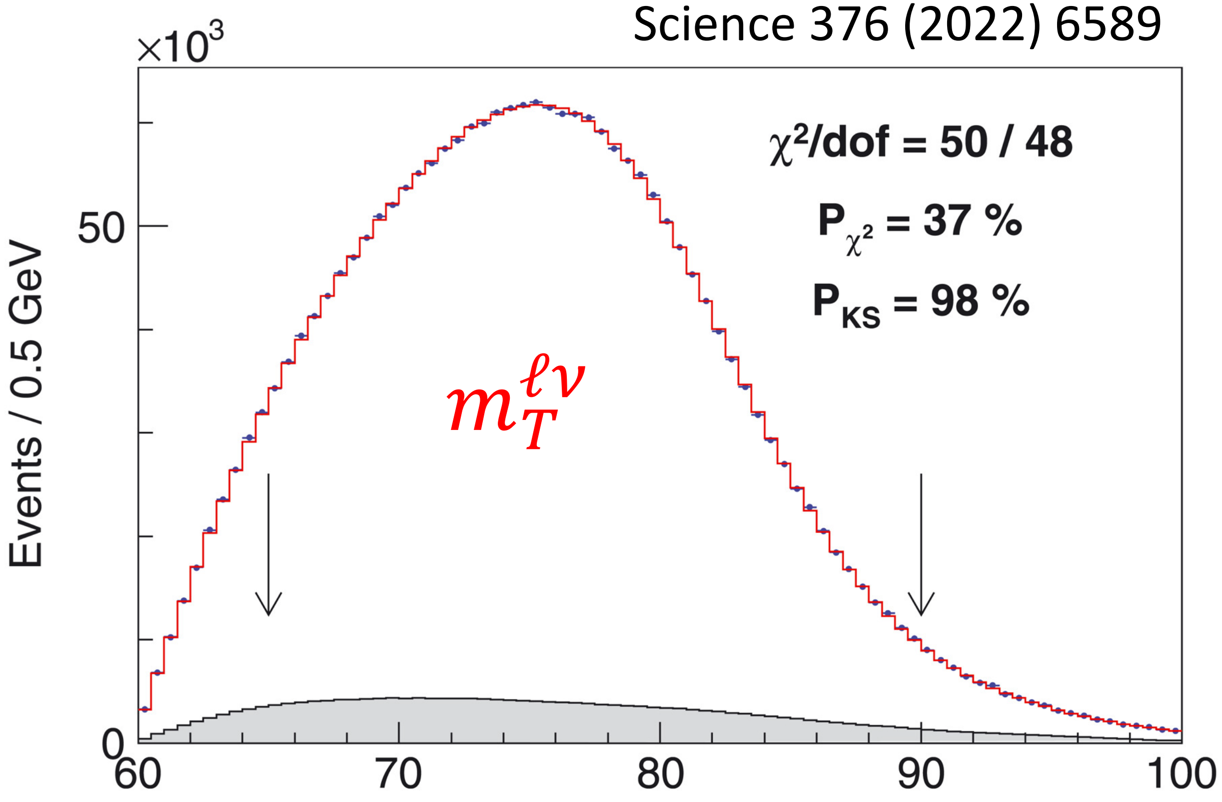
$W \rightarrow q\bar{q}$ unfeasible

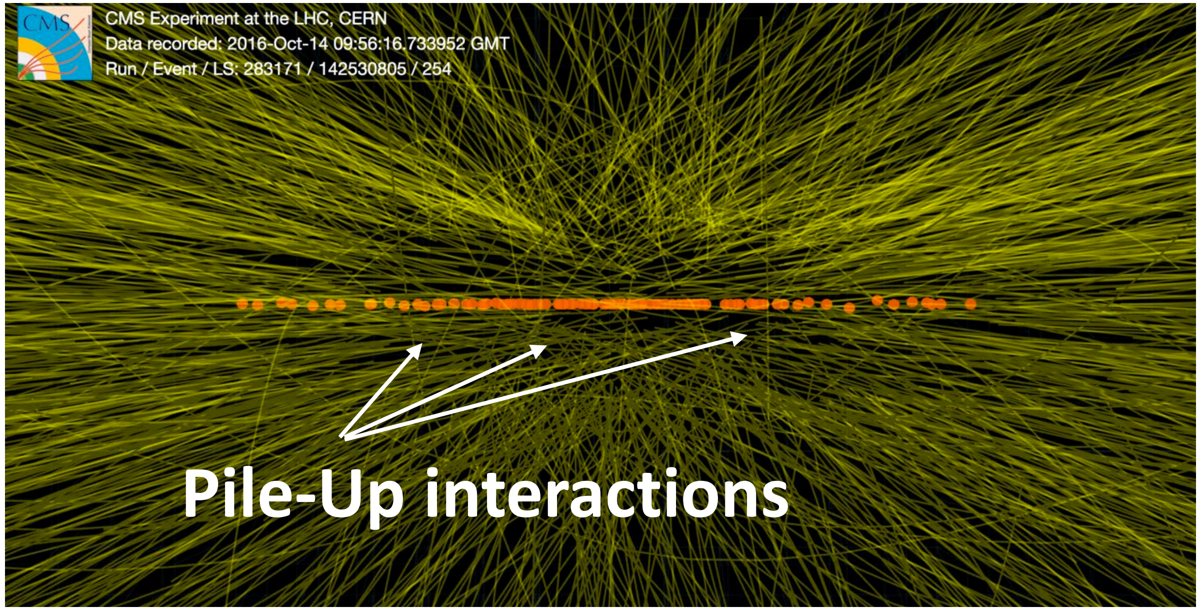
➔ focus on $W \rightarrow \ell\nu$ decay



Hadron colliders

Science 376 (2022) 6589

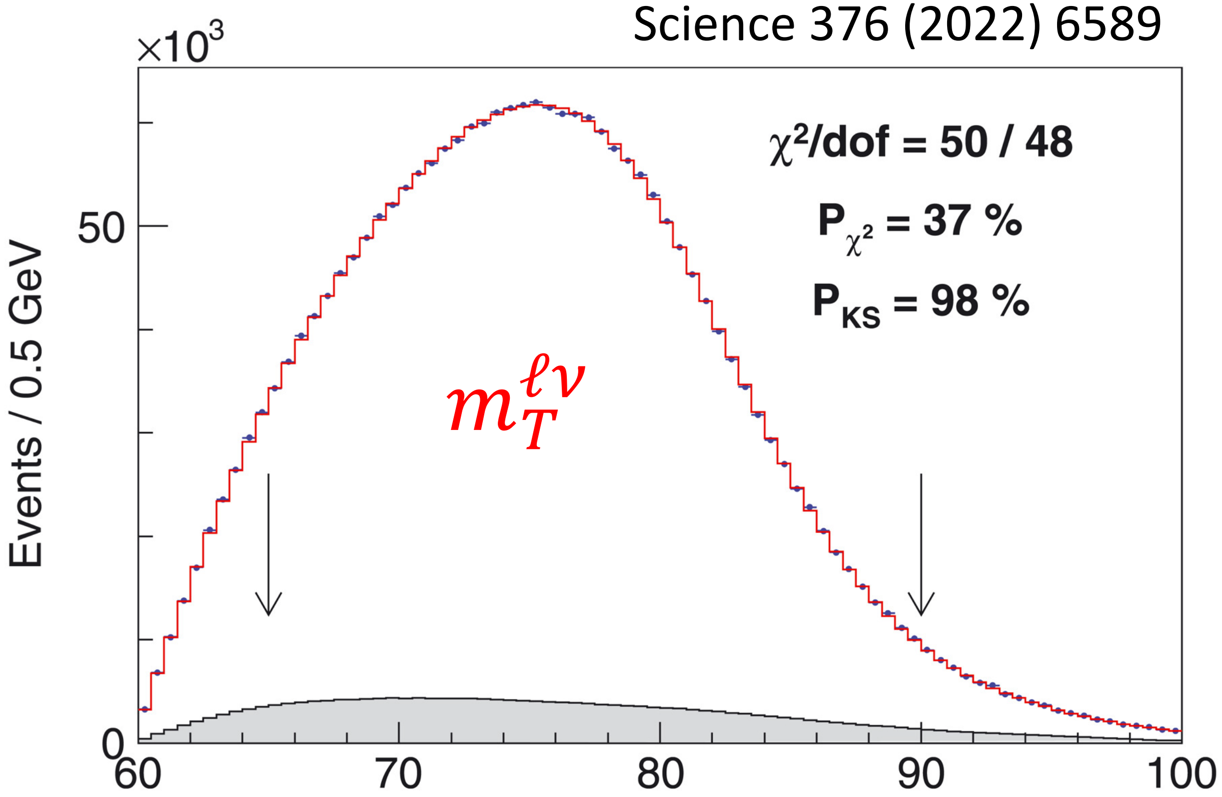




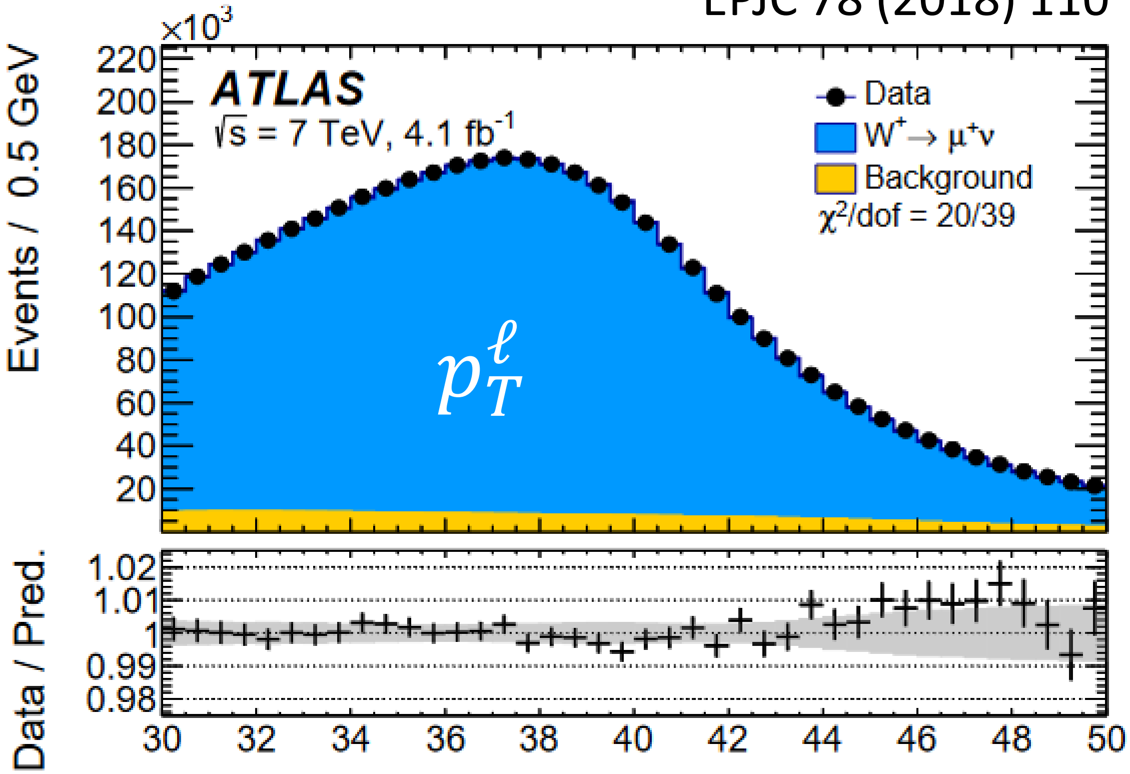
➔ Benefits of $m_T^{\ell\nu}$ vastly reduced at the LHC

Hadron colliders

Science 376 (2022) 6589



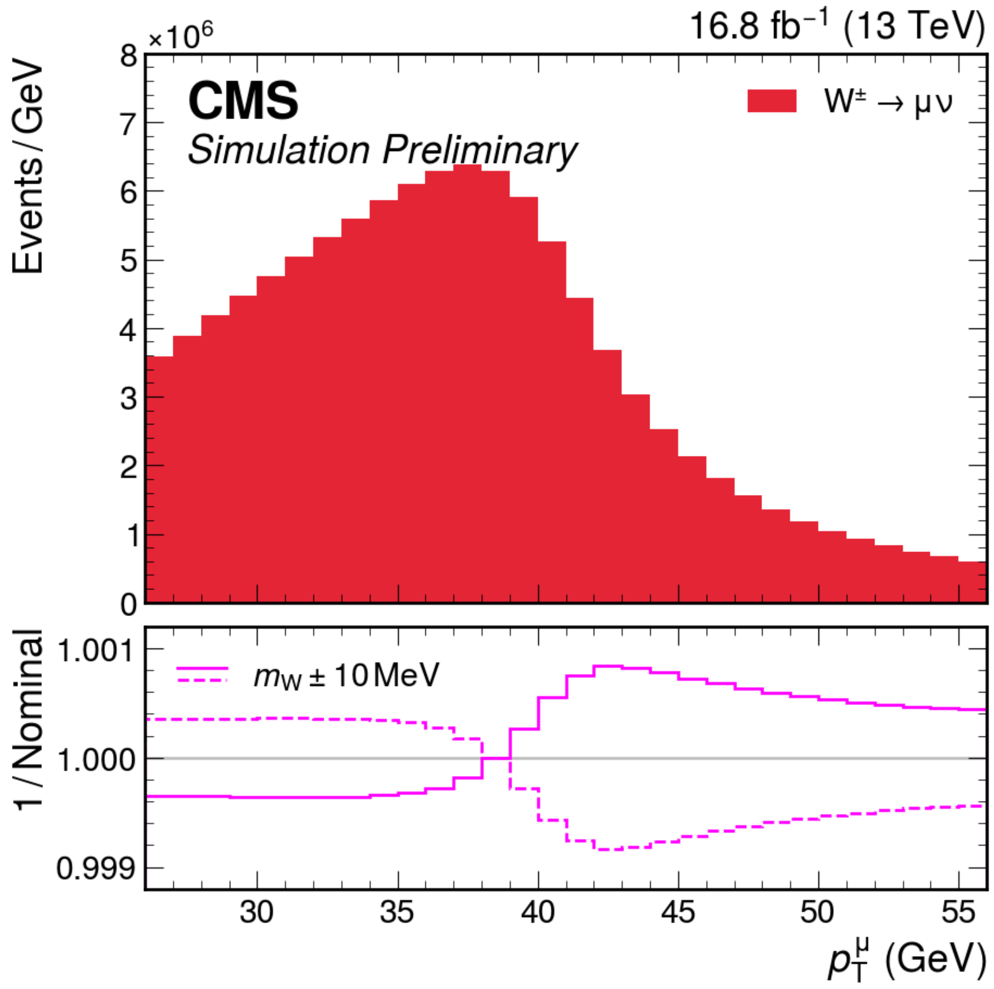
EPJC 78 (2018) 110



➔ Less sensitive to m_W

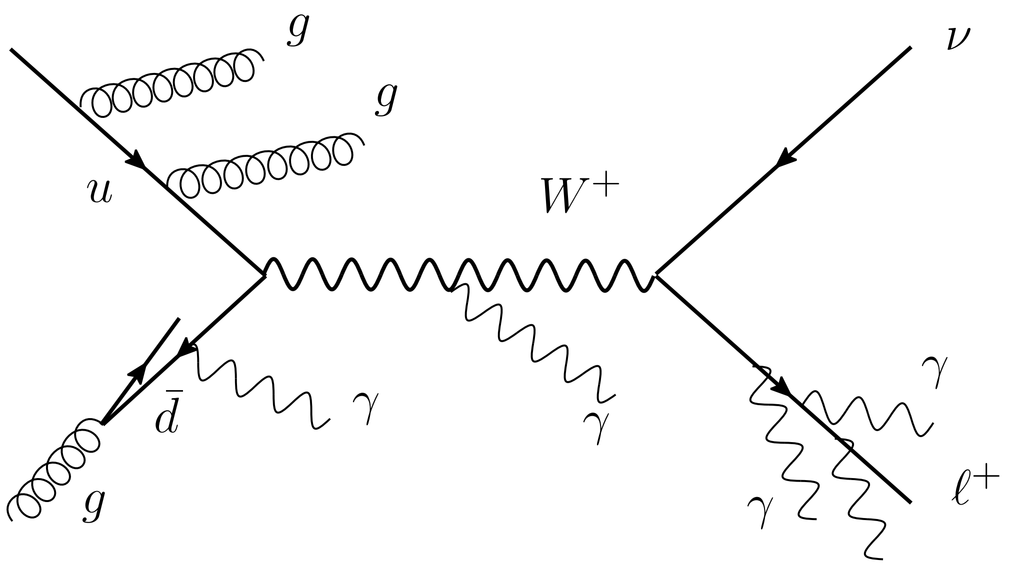
➔ Sensitive to modeling of p_T^W

Experimental accuracy on p_T^ℓ

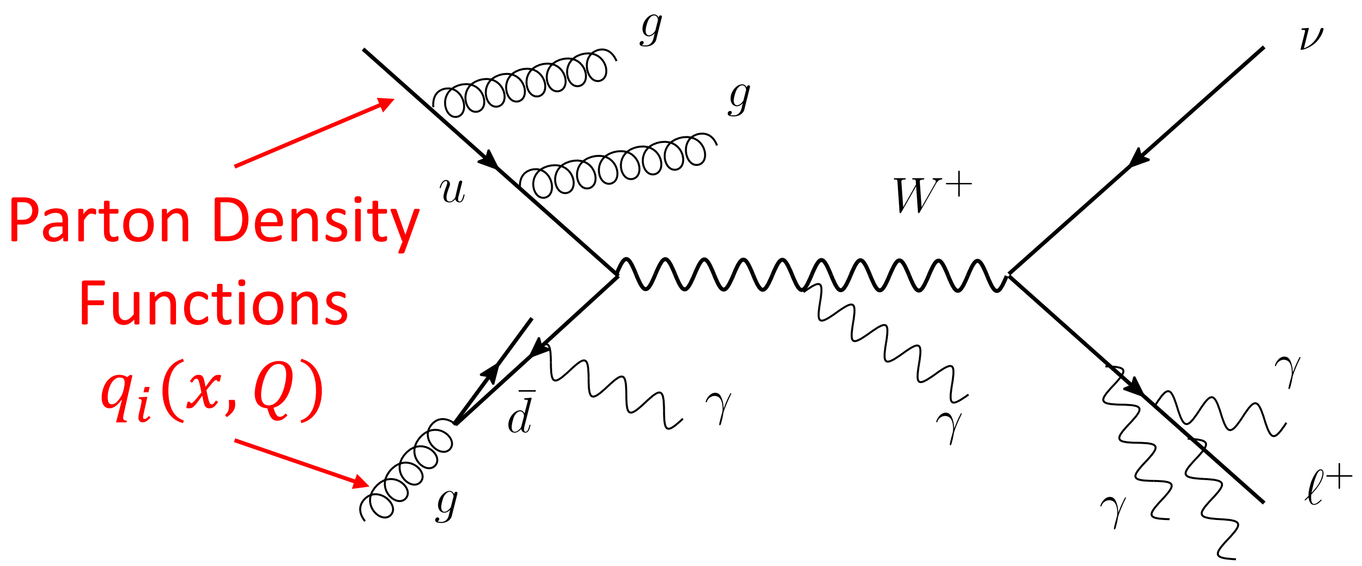


Target accuracy is 0.1%

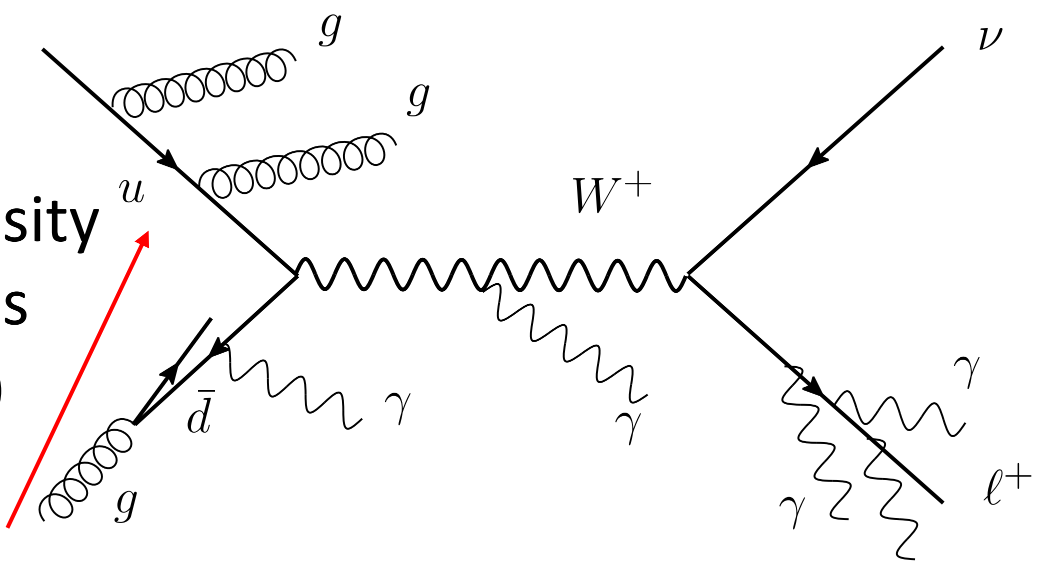
Phenomenology



Phenomenology



Phenomenology



Parton Density Functions $q_i(x, Q)$

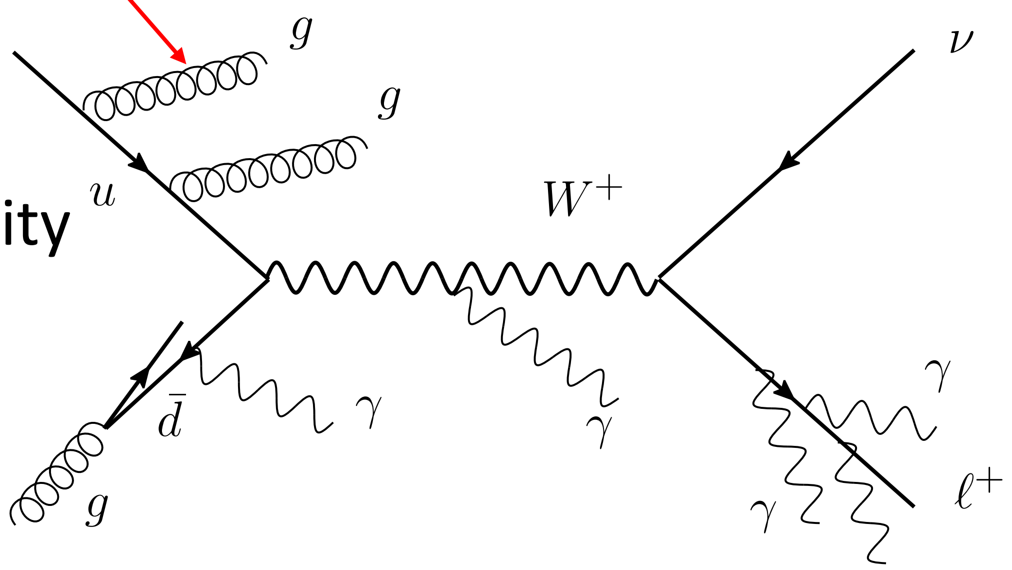
Intrinsic quark p_T

Phenomenology

Soft/collinear partonic radiation

Parton Density Functions $q_i(x, Q)$

Intrinsic quark p_T

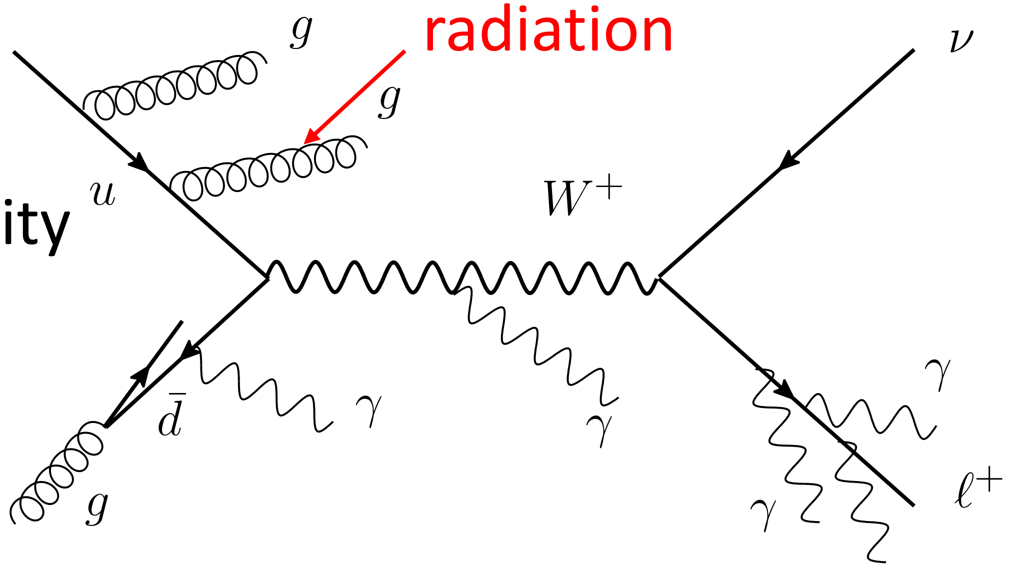


Phenomenology

Soft/collinear partonic radiation

Hard g/q radiation

Parton Density Functions $q_i(x, Q)$



Intrinsic quark p_T

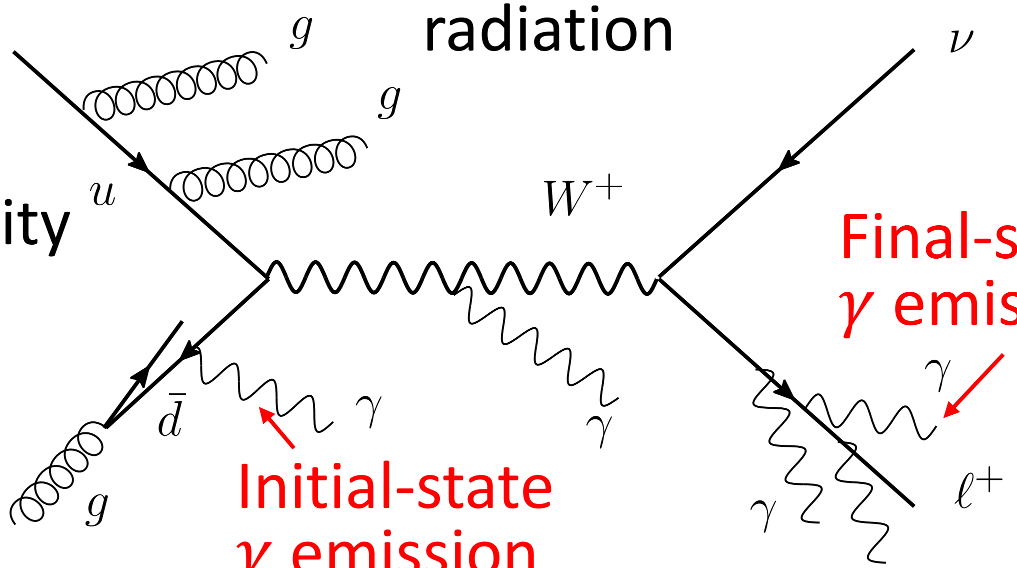
Phenomenology

Soft/collinear partonic radiation

Hard g/q radiation

Parton Density Functions $q_i(x, Q)$

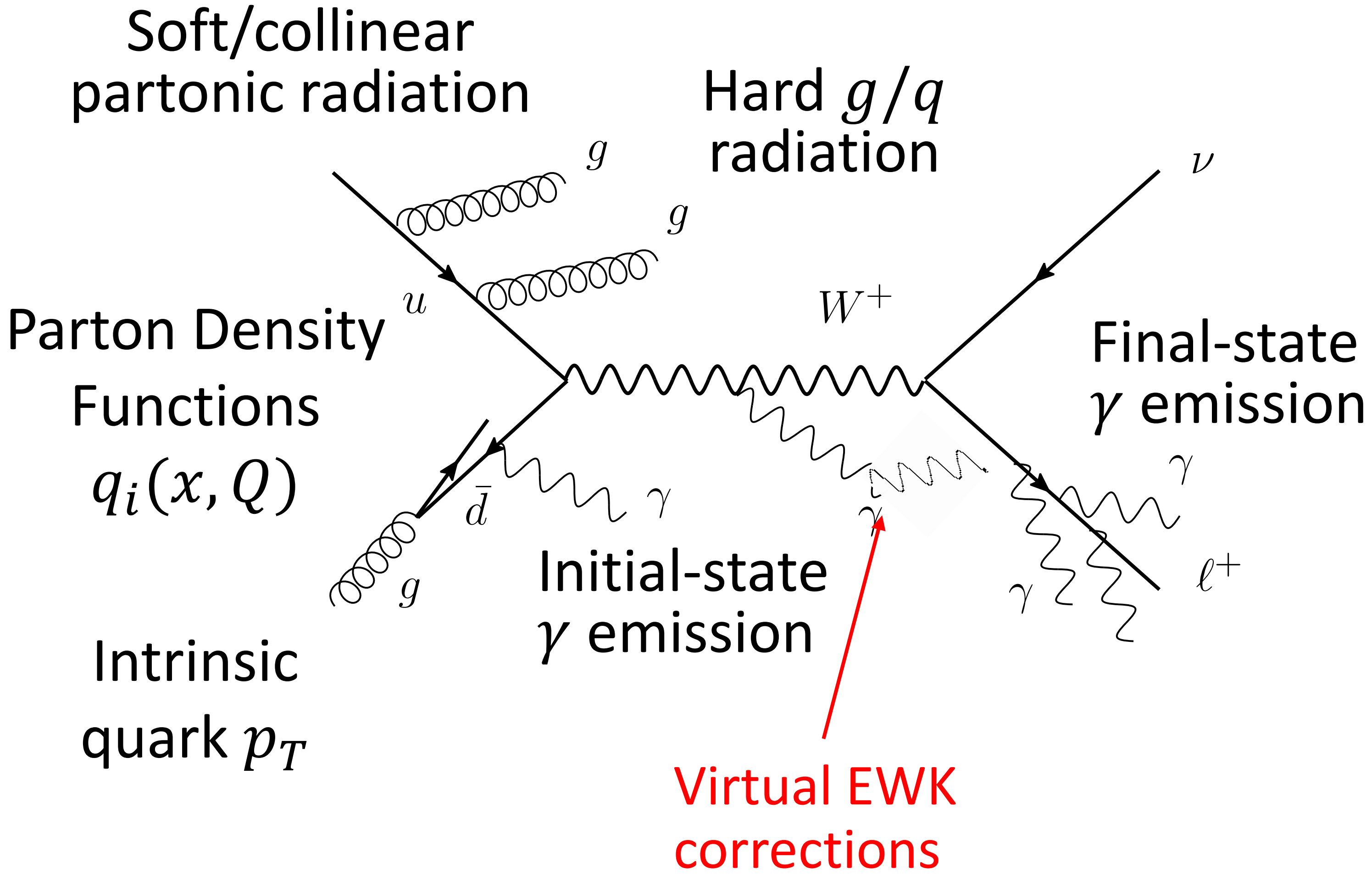
Intrinsic quark p_T



Initial-state γ emission

Final-state γ emission

Phenomenology



Phenomenology

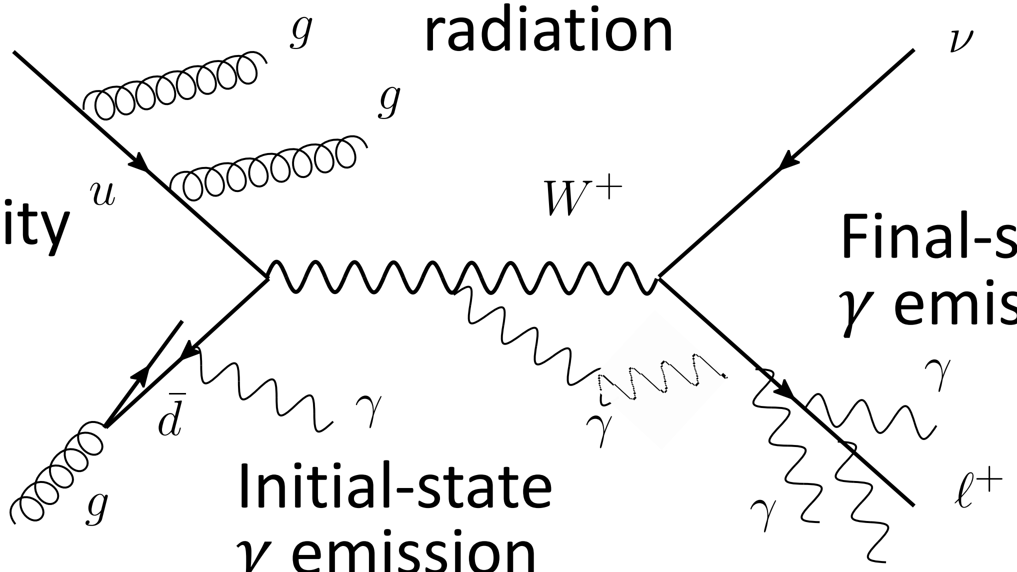
See e.g. JHEP11 (2017) 003

Soft/collinear partonic radiation

Hard g/q radiation

Parton Density Functions $q_i(x,Q)$

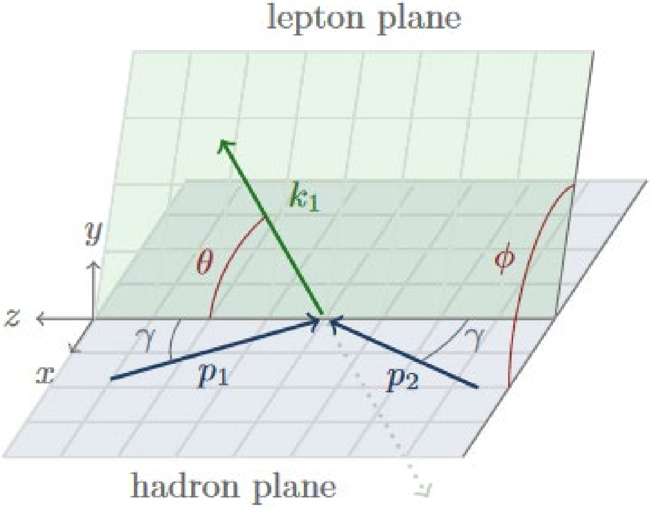
Final-state γ emission



Initial-state γ emission

Intrinsic quark p_T

Virtual EWK corrections



$$\sigma \propto H^{\mu\upsilon} L_{\mu\upsilon}$$

$$\sigma_{\mathrm{UL}} \times \{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1 \sin 2\vartheta \cos\varphi + A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta + A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\}$$

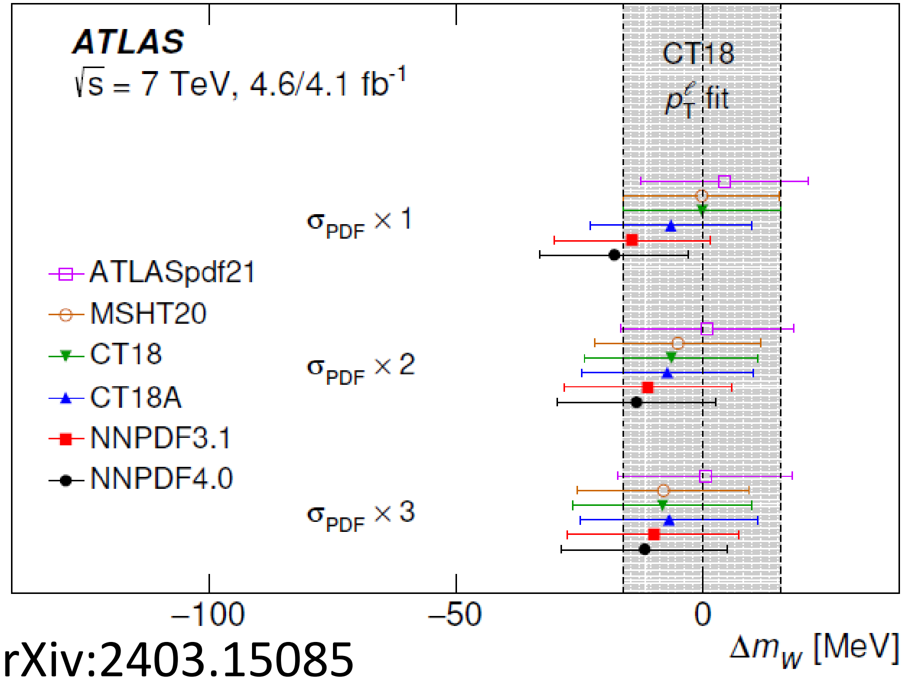
Model-dependent uncertainties

Parton Density Functions	p_T^W **spectrum**	**Angular Coefficients**	**Missing EWK corrections**
5 – 9 MeV	**2 – 30 MeV**	2 – 3 MeV	2 – 5 MeV

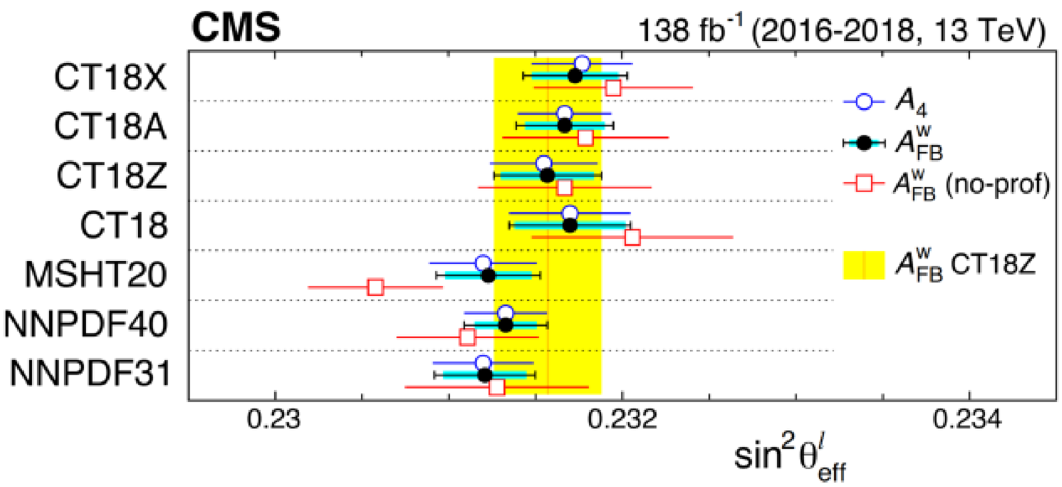
⇒ $\gtrsim {}^{1}/_{2}$ of **total uncertainty on** m_W from **modeling systematics**

PDFs

- Historically, top-ranked in modeling systematics
  - But PDFs improve with time
- Several PDF sets available:
  - **Point of concern**: spread of central values not always covered by PDF uncertainty



arXiv:2403.15085

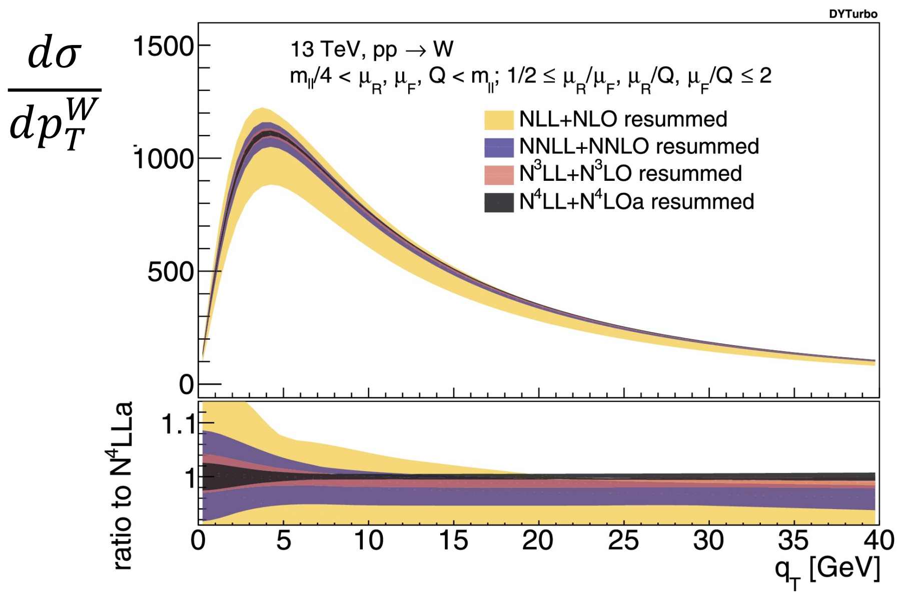


arXiv:2408.07622

p_T^W modeling

- Reminder: more relevant at the LHC
  - Recent progress in resummation not yet fully exploited

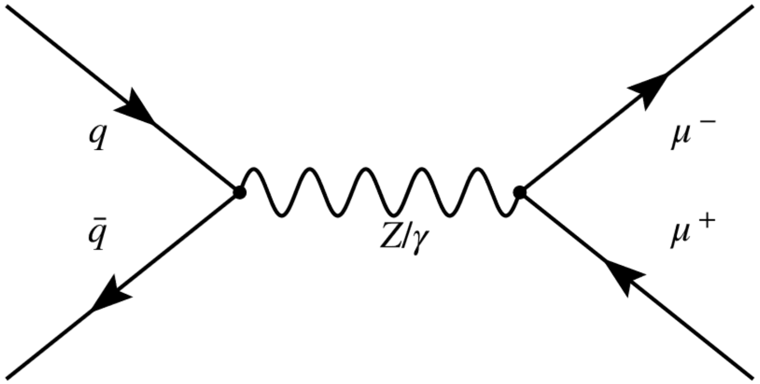
PLB 845 (2023) 138125



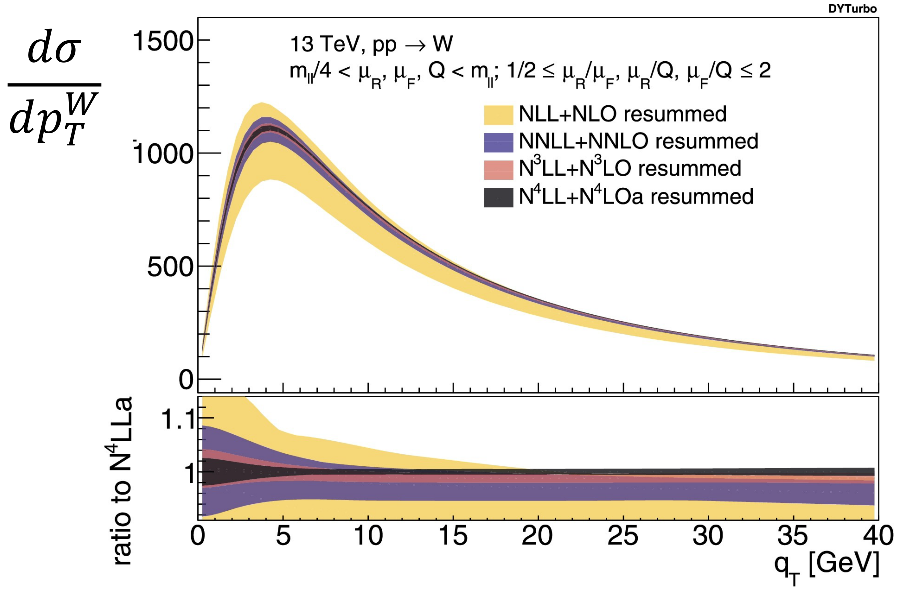
p_T^W modeling

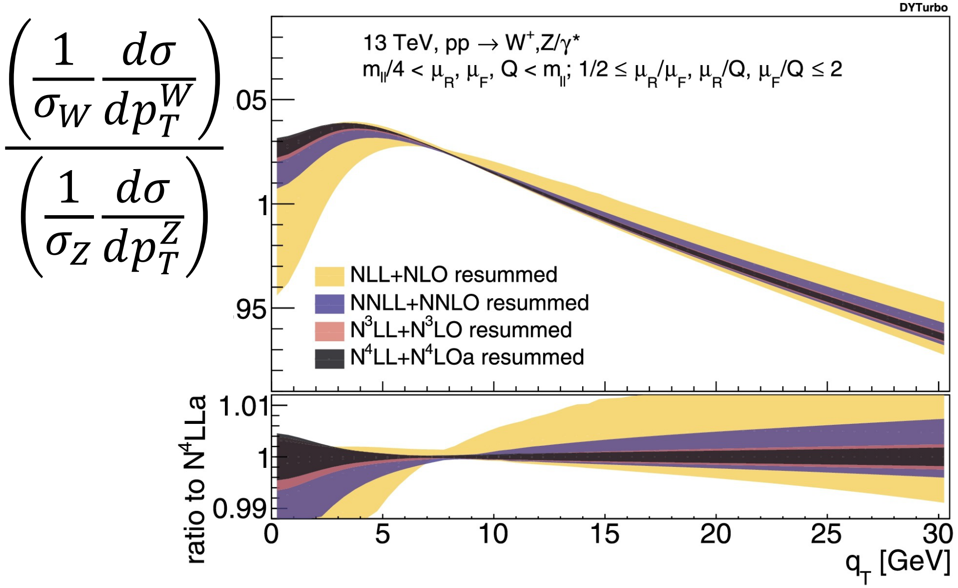
- Reminder: more relevant at the LHC
  - Recent progress in resummation not yet fully exploited

- **ALL** m_W **measurements** to date **calibrate** $\boldsymbol{p_T^W}$ with highly-precisely measured $\boldsymbol{p_T^Z}$ data



PLB 845 (2023) 138125





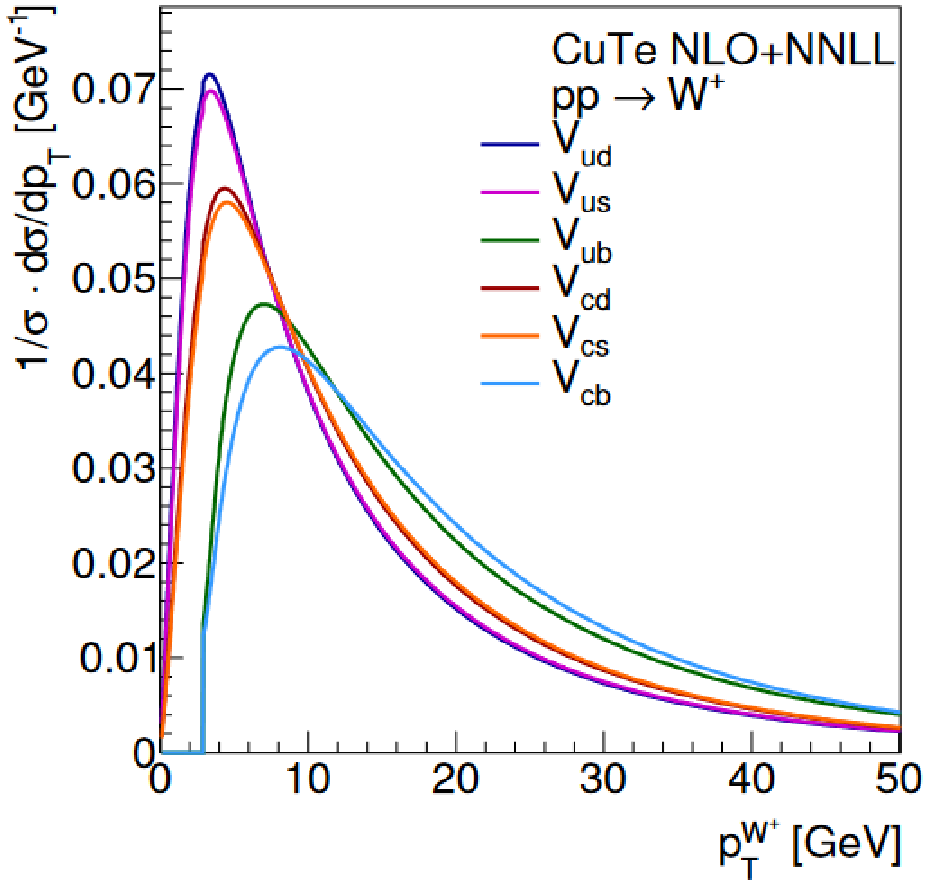
p_T^W modeling

- Reminder: more relevant at the LHC
  - Recent progress in resummation not yet fully exploited

- **ALL m_W measurements** to date **calibrate p_T^W** with highly-precisely measured p_T^Z data

- *Z*-to-*W* porting sensitive to different flavor composition of initial state
  - **model-dependent** assumptions on correlations

ATL-PHYS-PUB-2014-015



The CMS paradigm

State-of-the-art calculations		
Smaller/reliable TH uncertainties		

The CMS paradigm

State-of-the-art calculations	*Z* data ONLY as a validation sample	
Smaller/reliable TH uncertainties	No ambiguity from *Z*-to-*W* extrapolation	

The CMS paradigm

State-of-the-art calculations	*Z* data ONLY as a validation sample	In-situ constraint
Smaller/reliable TH uncertainties	No ambiguity from *Z*-to-*W* extrapolation	Full exploitation of the data → **profiling of nuisance parameters**

The CMS paradigm

State-of-the-art calculations	*Z* data ONLY as a validation sample	In-situ constraint
Smaller/reliable TH uncertainties	No ambiguity from *Z*-to-*W* extrapolation	Full exploitation of the data → **profiling of nuisance parameters**
-	Less constraining power. Poorer pre-fit agreement	Trust your correlation model!

High-statistics, high-granularity

- **CMS**: extract m_W from the **muon momentum** alone (→ **Pile-Up insensitive**)
  - Can use full LHC data samples
  - Electron channel / $m_T^{\ell\nu}$ deferred to future work (loose $m_T^{\ell\nu} > 40$ GeV for S/N)

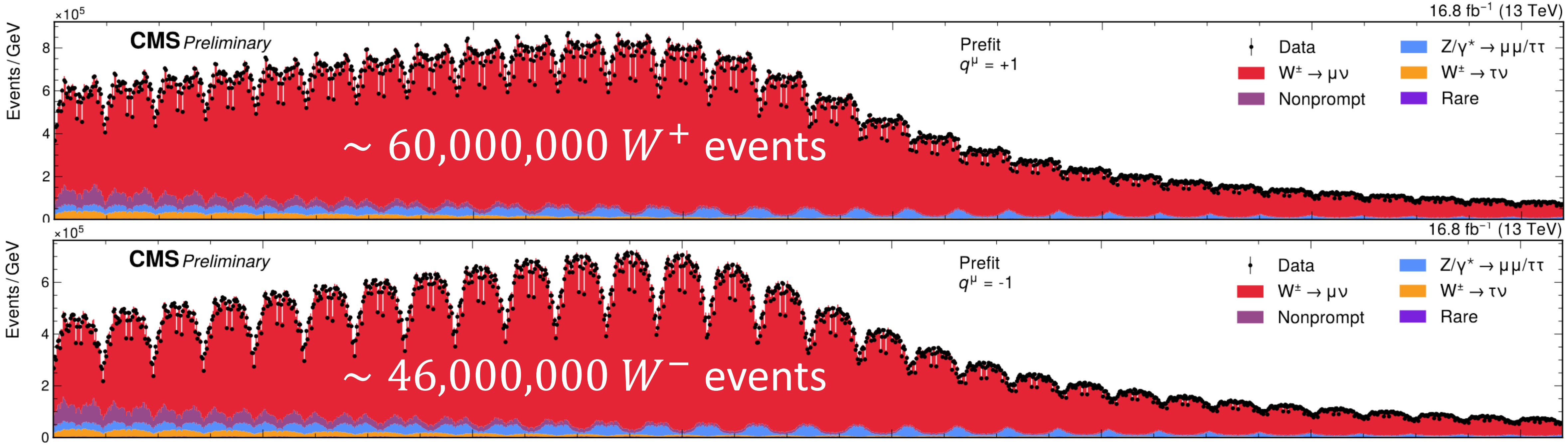
High-statistics, high-granularity

- **CMS**: extract m_W from the **muon momentum** alone (→ **Pile-Up insensitive**)
  - Can use full LHC data samples
  - Electron channel / $m_T^{\ell\nu}$ deferred to future work (loose $m_T^{\ell\nu} > 40$ GeV for S/N)
- Split events in granular 3D space: $p_T^{\ell} \times \eta^{\ell} \times$ charge

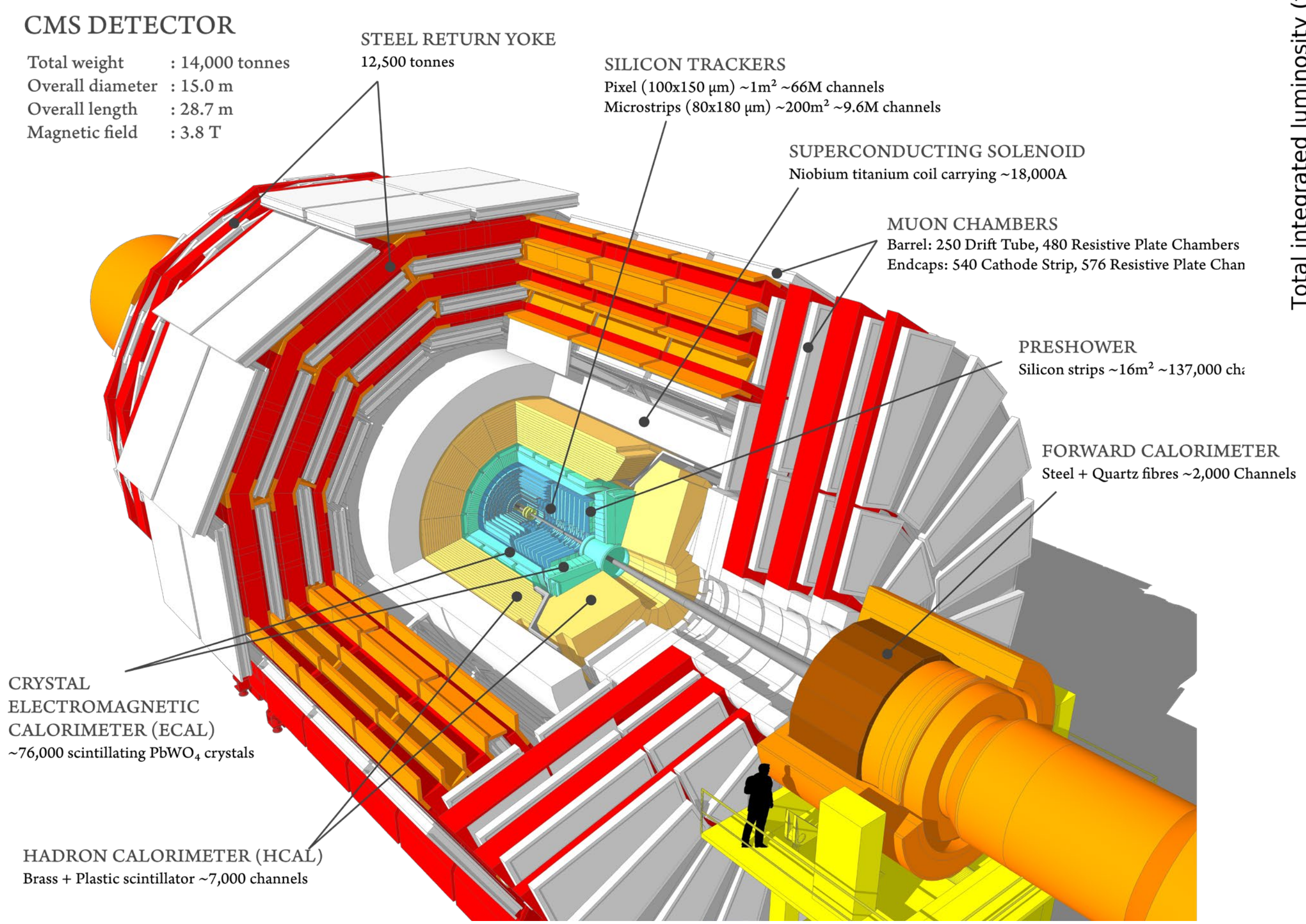
	p_T^{ℓ}	η^{ℓ} × **charge**
Sensitive to:	p_T^W, m_W	PDFs, A_i

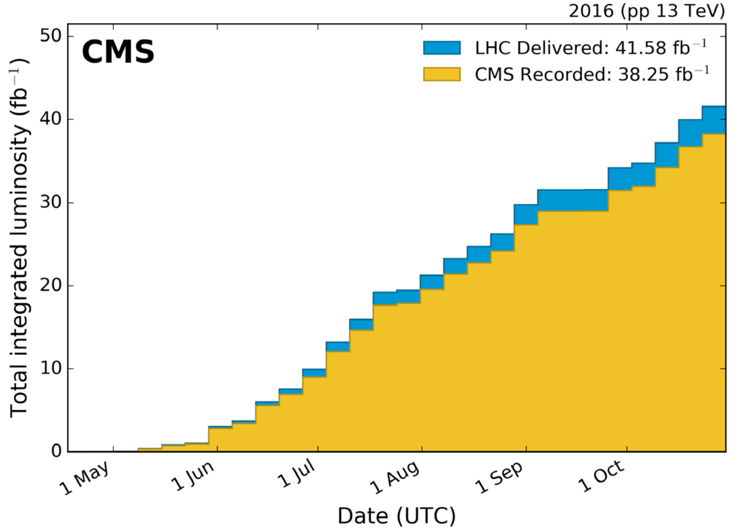
High-statistics, high-granularity

- **CMS**: extract m_W from the **muon momentum** alone (→ Pile-Up robust)
  - Can use full LHC data samples
  - Electron channel / $m_T^{\ell\nu}$ deferred to future work (loose $m_T^{\ell\nu} > 40$ GeV for S/N)
- Split events in granular 3D space: $p_T^\ell \times \eta^\ell \times$ charge → **2880 bins**



The CMS detector

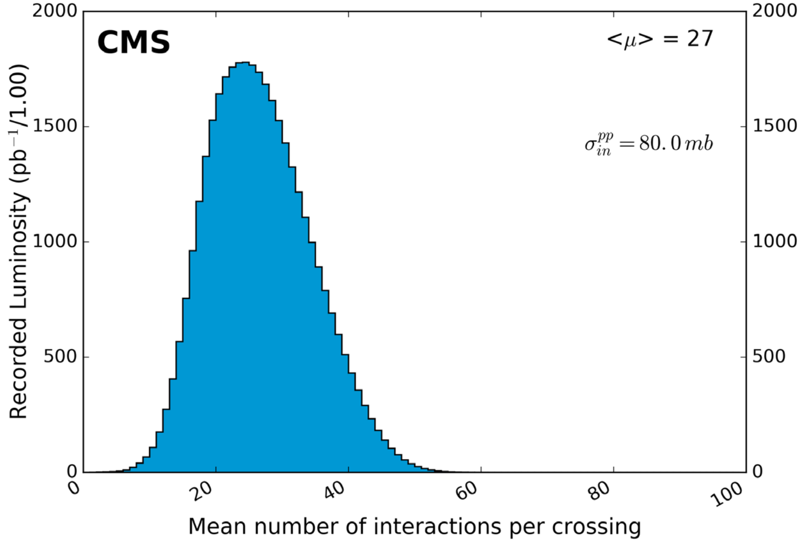




Use 2nd part of 2016 data set

➔ $L = 16.8\ \mathrm{fb}^{-1}$

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

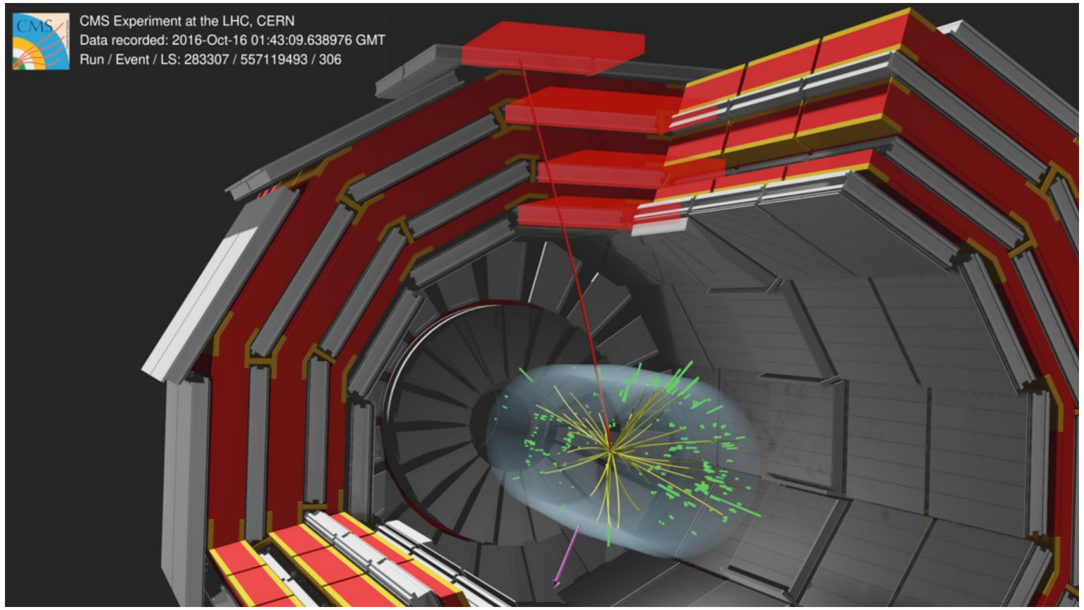


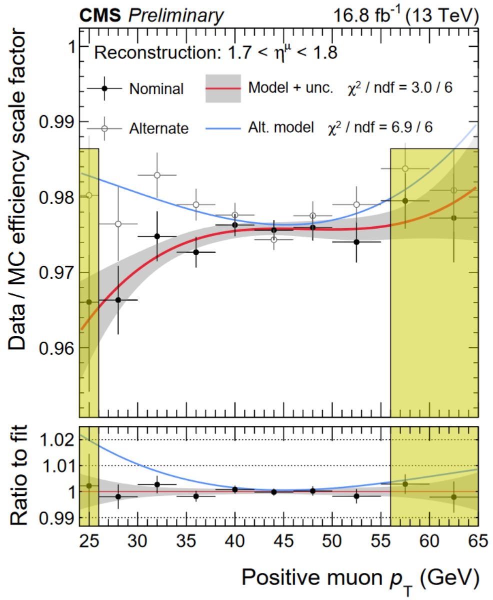
Muons in CMS

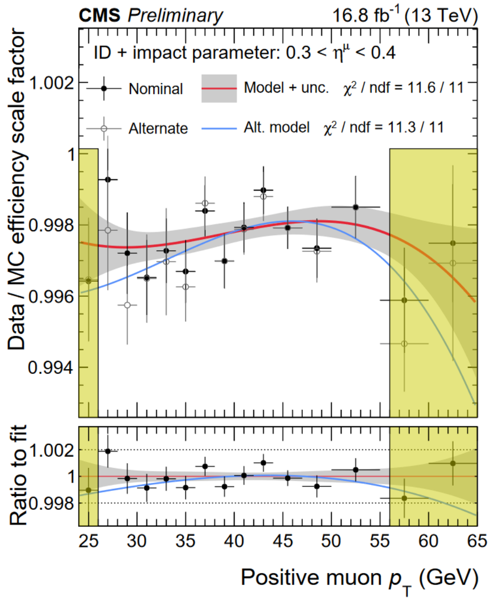
- Two-stage reconstruction
  - **Tracker** track matched with **muon** track
  - Additional **identification criteria**

- Reco/ID efficiencies measured in data using $\boldsymbol{Z \rightarrow \mu\mu}$ events
  - Careful factorization of each reconstruction/identification step

- Uncertainties propagated through $O(3{,}000)$ nuisance parameters
  - Impact on $\boldsymbol{m_W}$ → $\boldsymbol{\sim 3}$ MeV

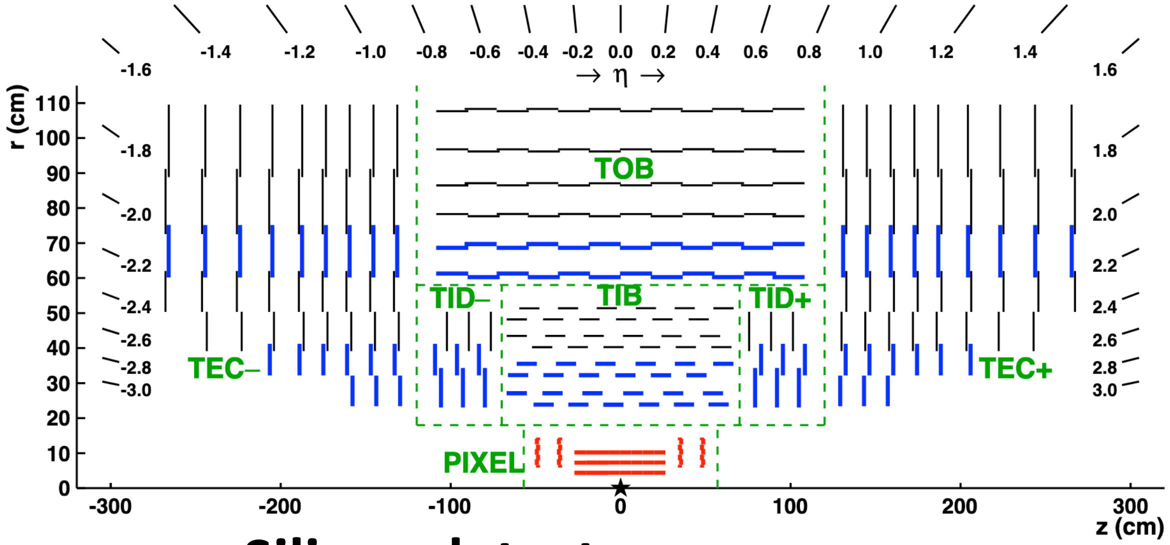






The CMS tracker

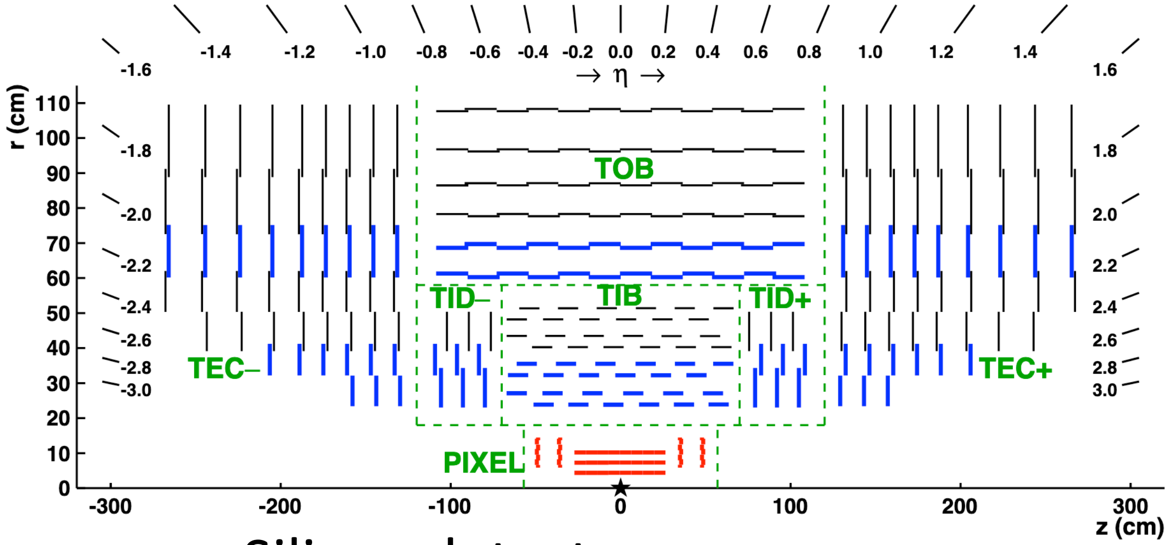
JINST 9 (2014) P10009



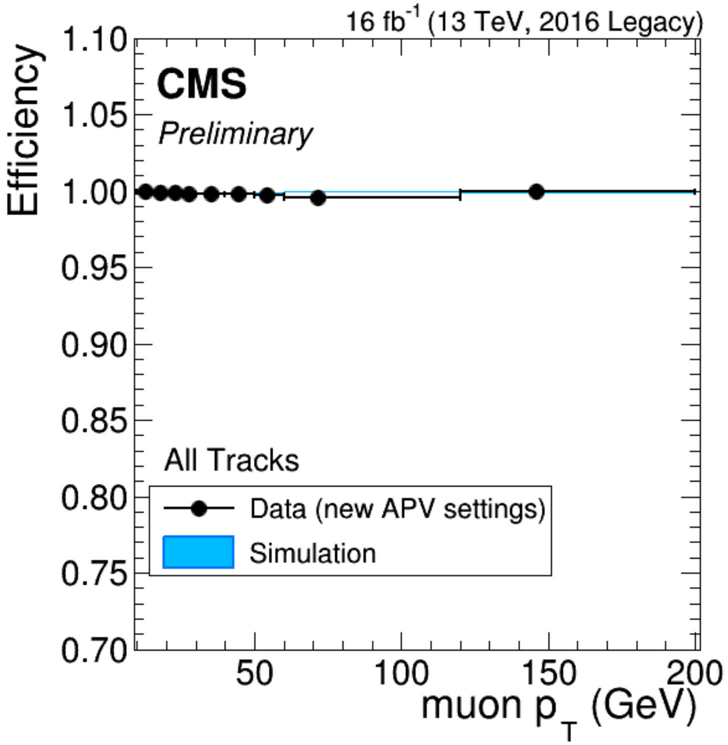
- **Silicon detector**
- Up to **~17 points** per track
  - Single-hit resolution $9 - 50\ \mu m$

The CMS tracker

JINST 9 (2014) P10009



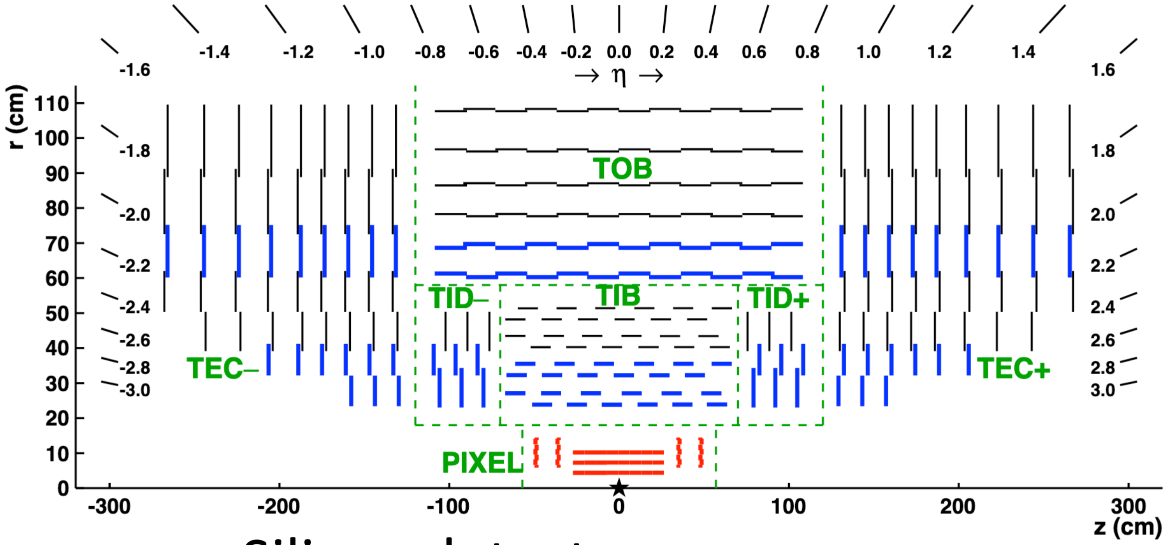
- Silicon detector
- Up to ~17 points per track
  - Single-hit resolution $9 - 50\ \mu m$
- Tracking **efficiency > 99%**

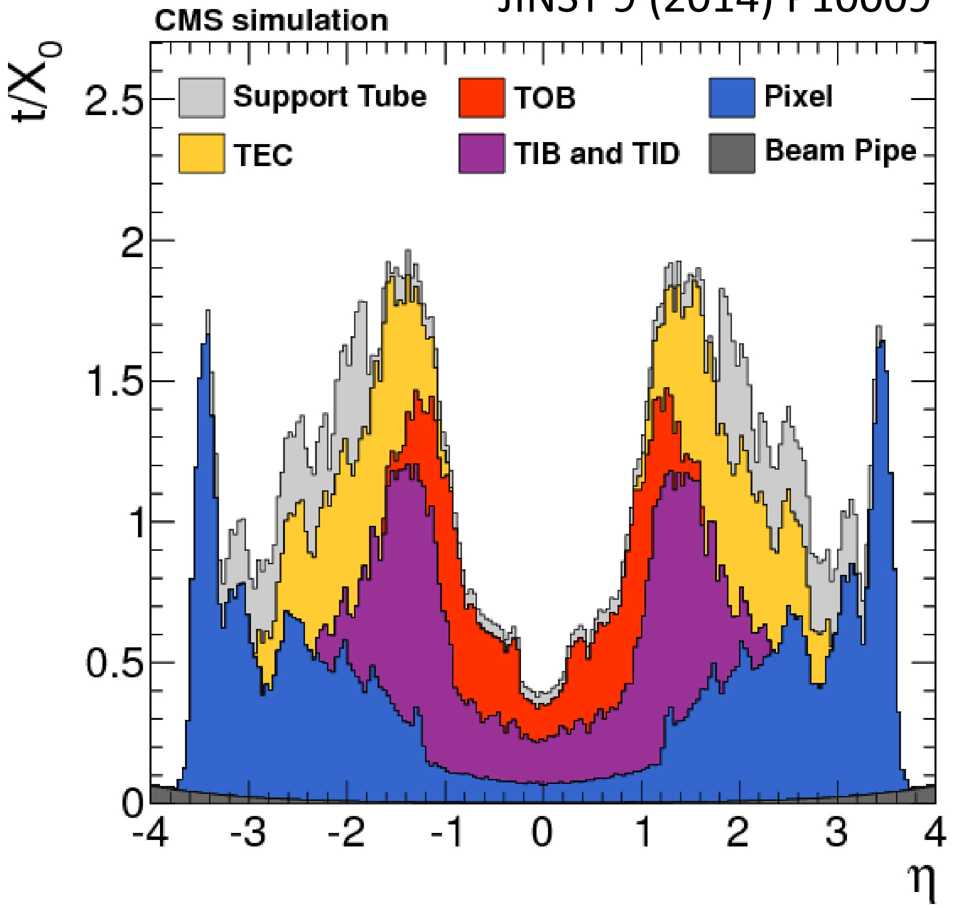


Link

The CMS tracker

JINST 9 (2014) P10009

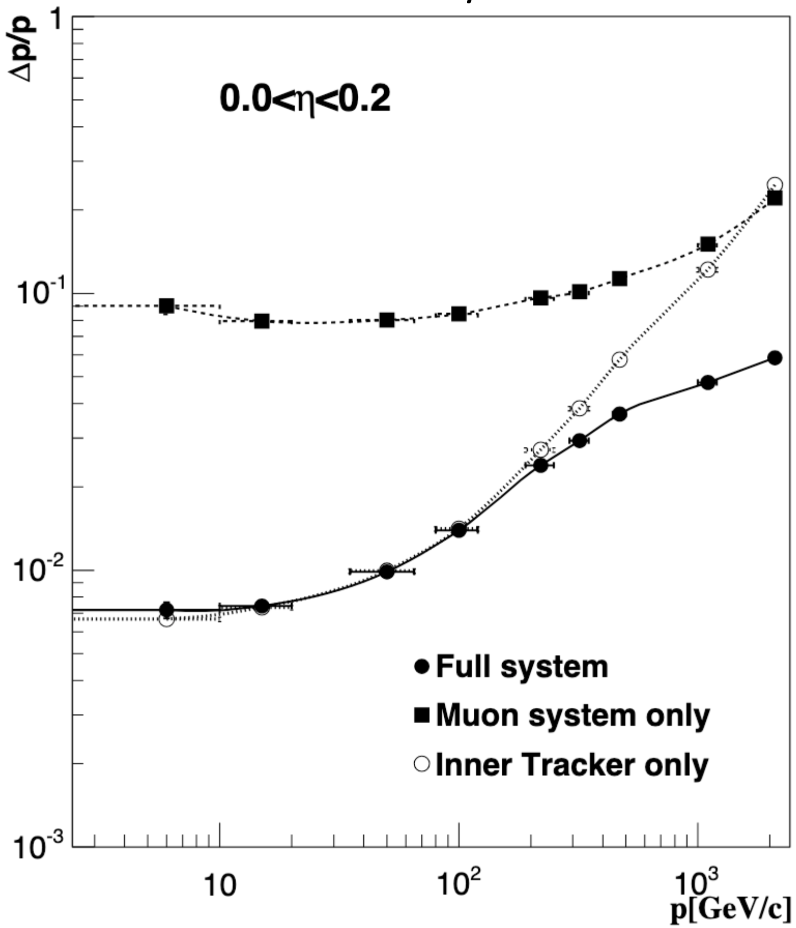




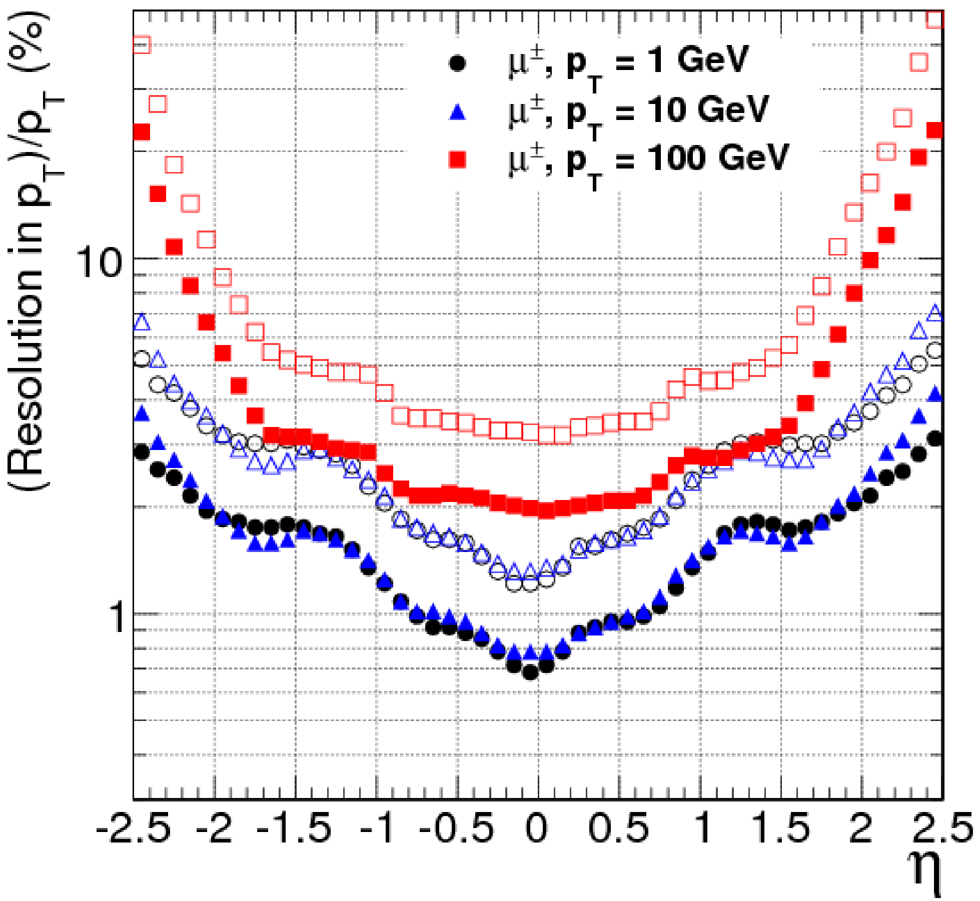
- Silicon detector
- Up to ~17 points per track
  - Single-hit resolution $9 - 50\ \mu m$
- Tracking efficiency > 99%
- **Up to 2 radiation lengths**

Momentum resolution

CERN/LHCC 2006-001



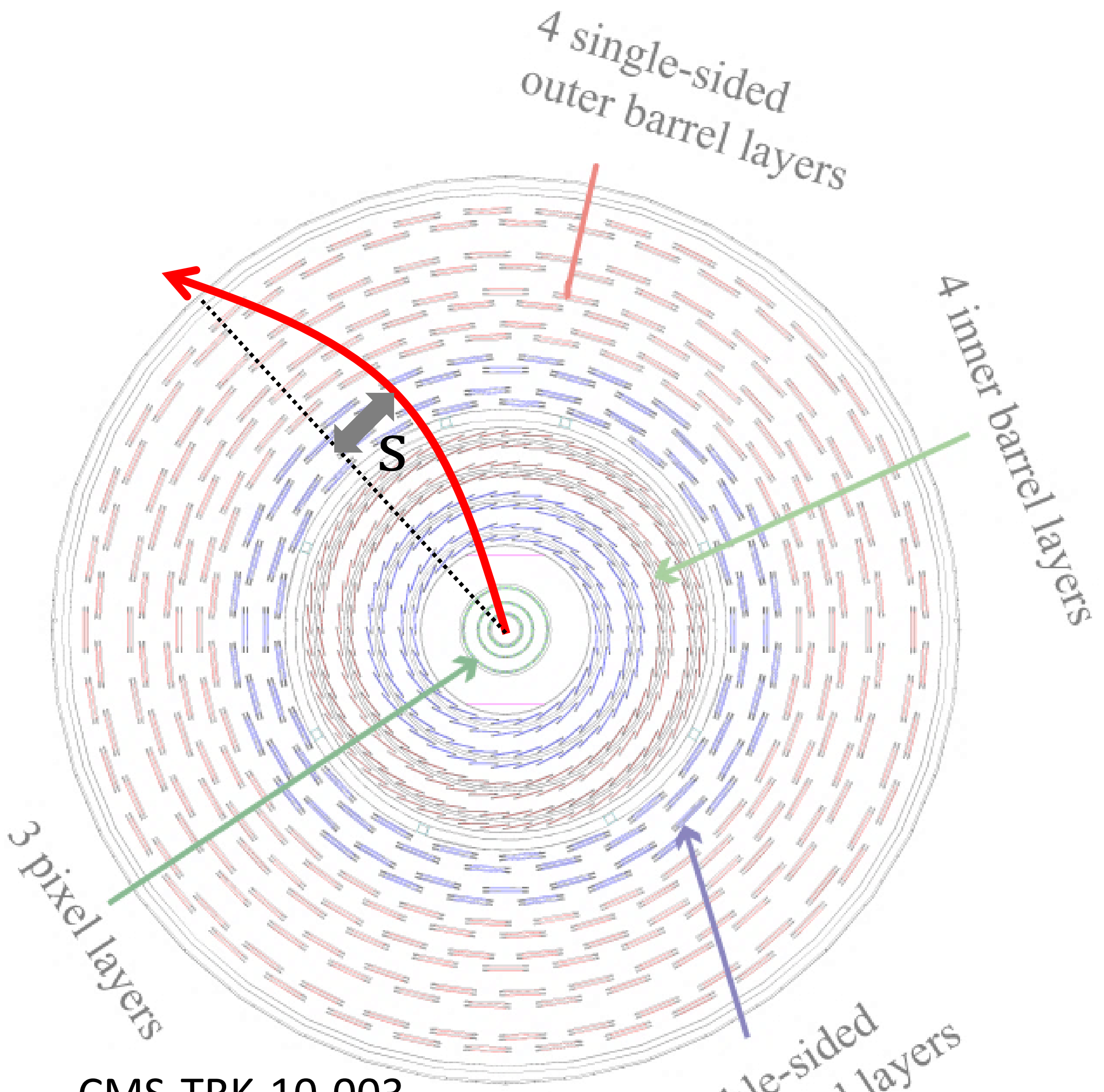
JINST 9 (2014) P10009



Momentum scale

- Target is $\frac{\delta p_T^\mu}{p_T^\mu} \lesssim 10^{-4}$ for ~40 GeV muons
  ➔ $|\delta s| \lesssim 600$ nm

- Challenges:
  - Relative **alignment** of all tracker modules NOT known to this level
  - **Material** only known within ~10%
  - A priori knowledge of ***B*-field** $\sim 10^{-3}$



CMS-TRK-10-003
JINST 5:T03021,2010
Symmetry 14 (2022) 169

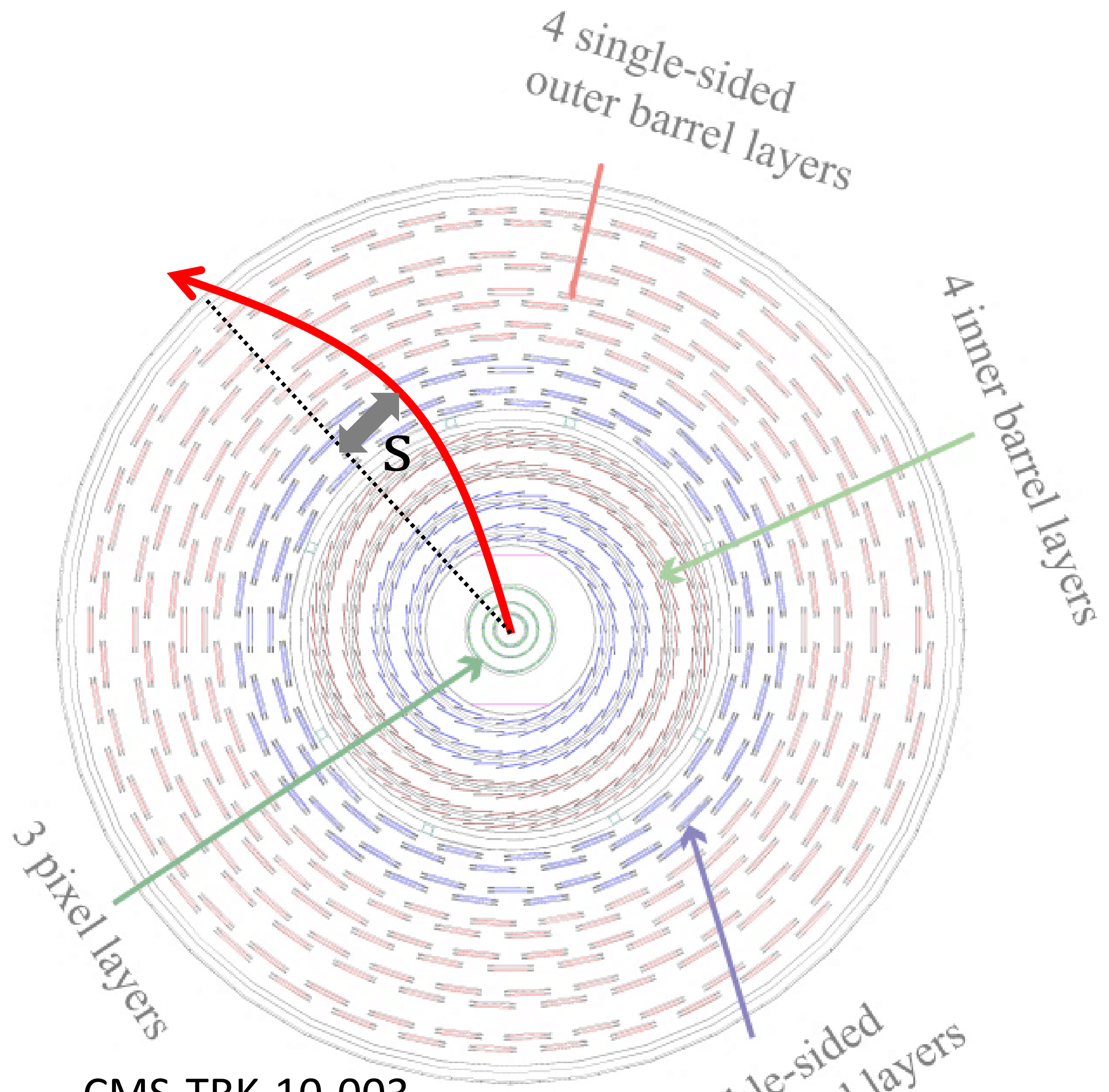
Momentum scale

- Target is $\frac{\delta p_T^\mu}{p_T^\mu} \lesssim 10^{-4}$ for $\sim$40 GeV muons

  ➔ $|\delta s| \lesssim 600$ nm

- Challenges:
  - Relative **alignment** of all tracker modules NOT known to this level
  - **Material** only known within $\sim 10\%$
  - A priori knowledge of ***B*-field** $\sim 10^{-3}$

➔ **Calibration of momentum scale in data**

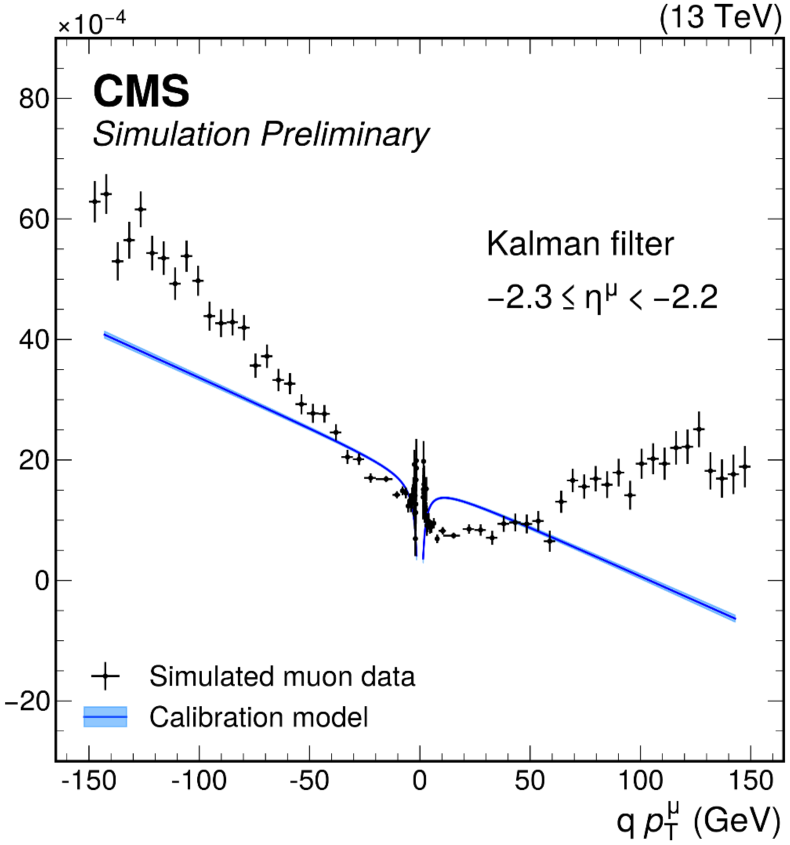


CMS-TRK-10-003
JINST 5:T03021,2010
Symmetry 14 (2022) 169

Muon momentum scale

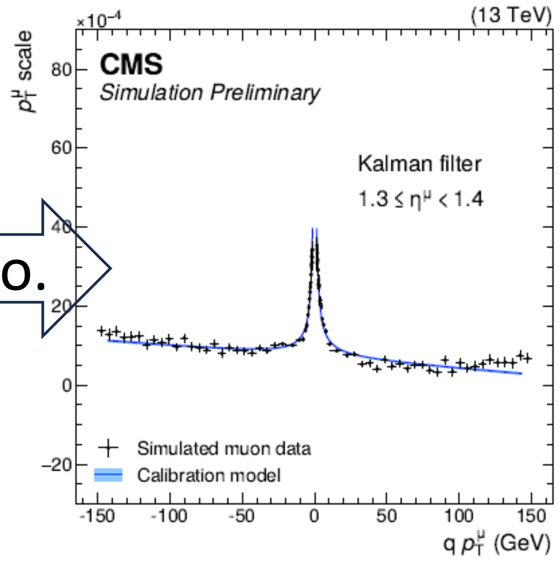
<u>Observation</u>: Even for **ideal MC**, scale was NOT unity

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

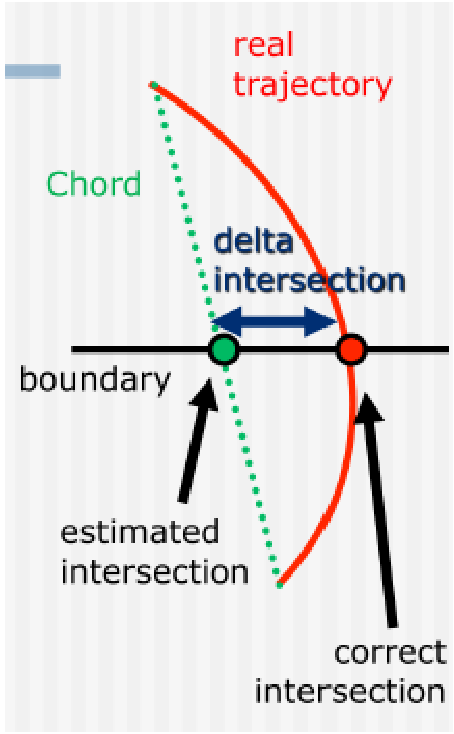


Muon momentum scale

1. **Tuning** of parameters in CMS simulation

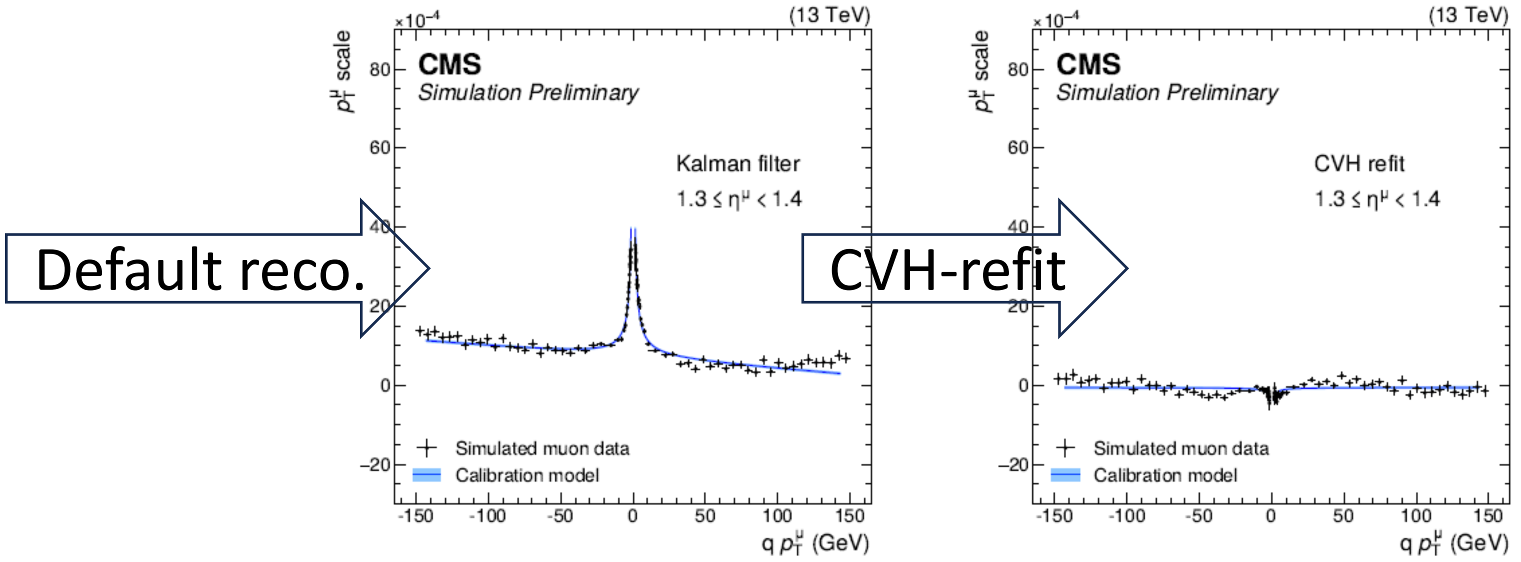


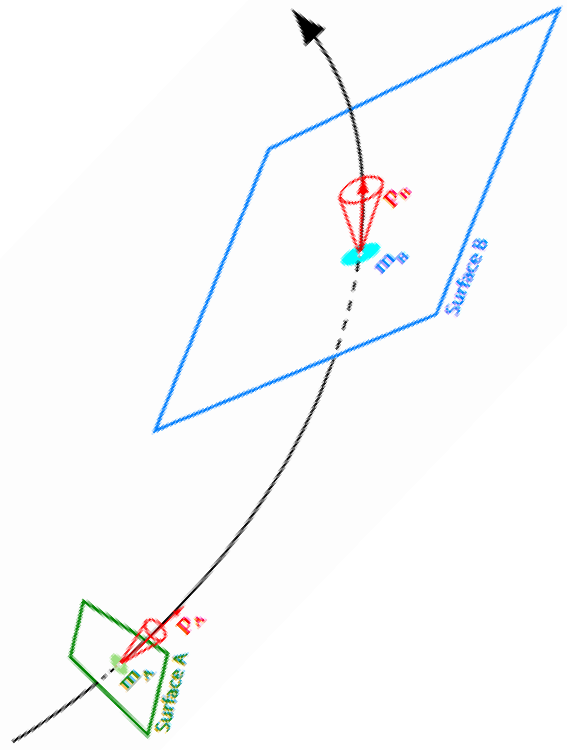
Default reco.



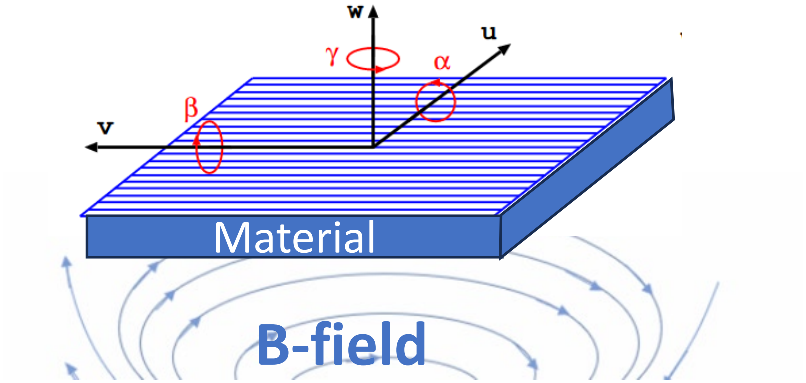
Muon momentum scale

1. **Tuning** of parameters in CMS simulation
2. **Track re-fit** with improved B-field/material treatment based on *Geant4e* (**CVH refit**)

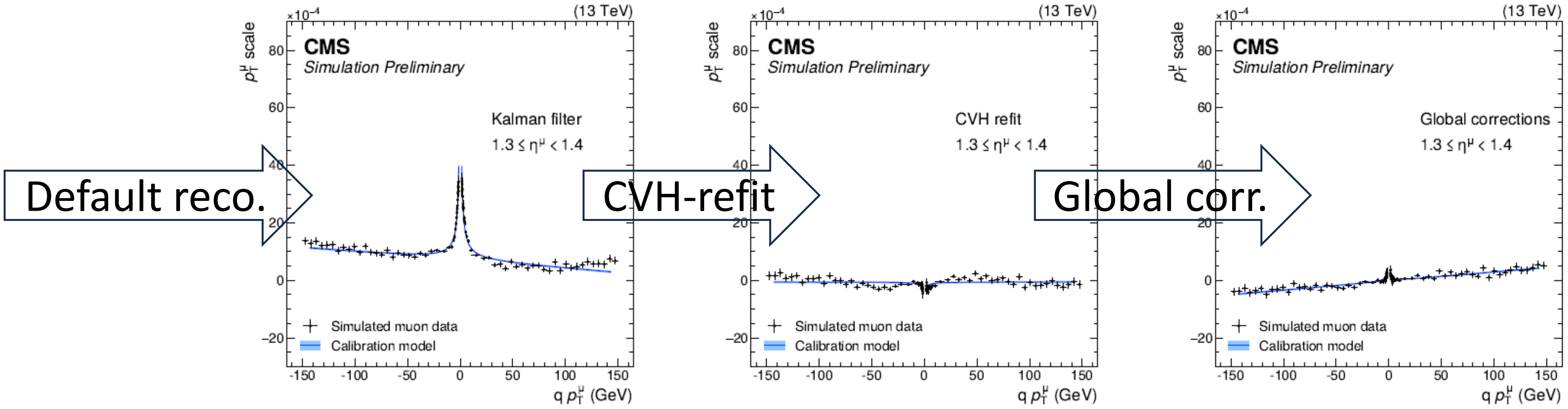




Muon momentum scale

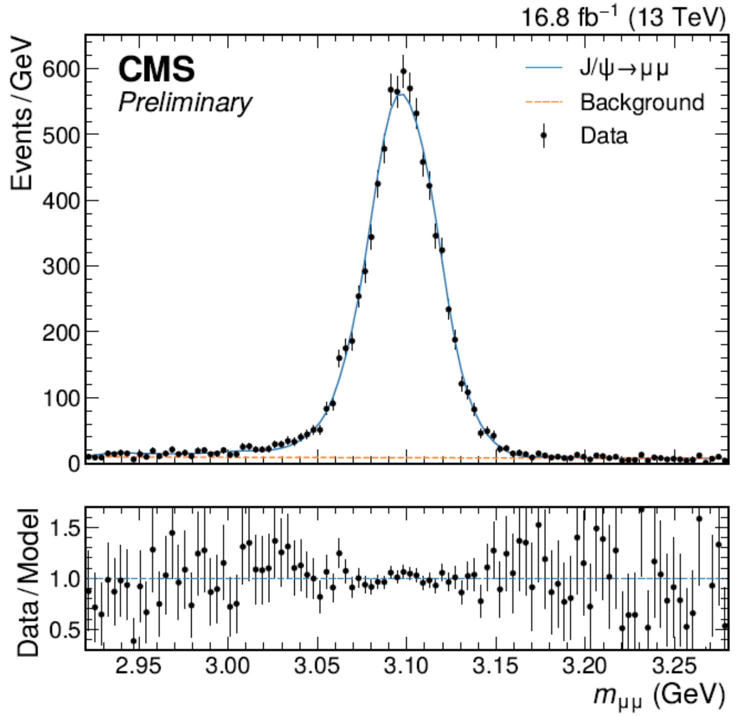


1. **Tuning** of parameters in CMS simulation
2. **Track re-fit** with improved B-field/material treatment based on *Geant4e* (**CVH refit**)
3. **Global correction** of alignment/B-field/material at the per-module level using J/Ψ events



Muon momentum scale

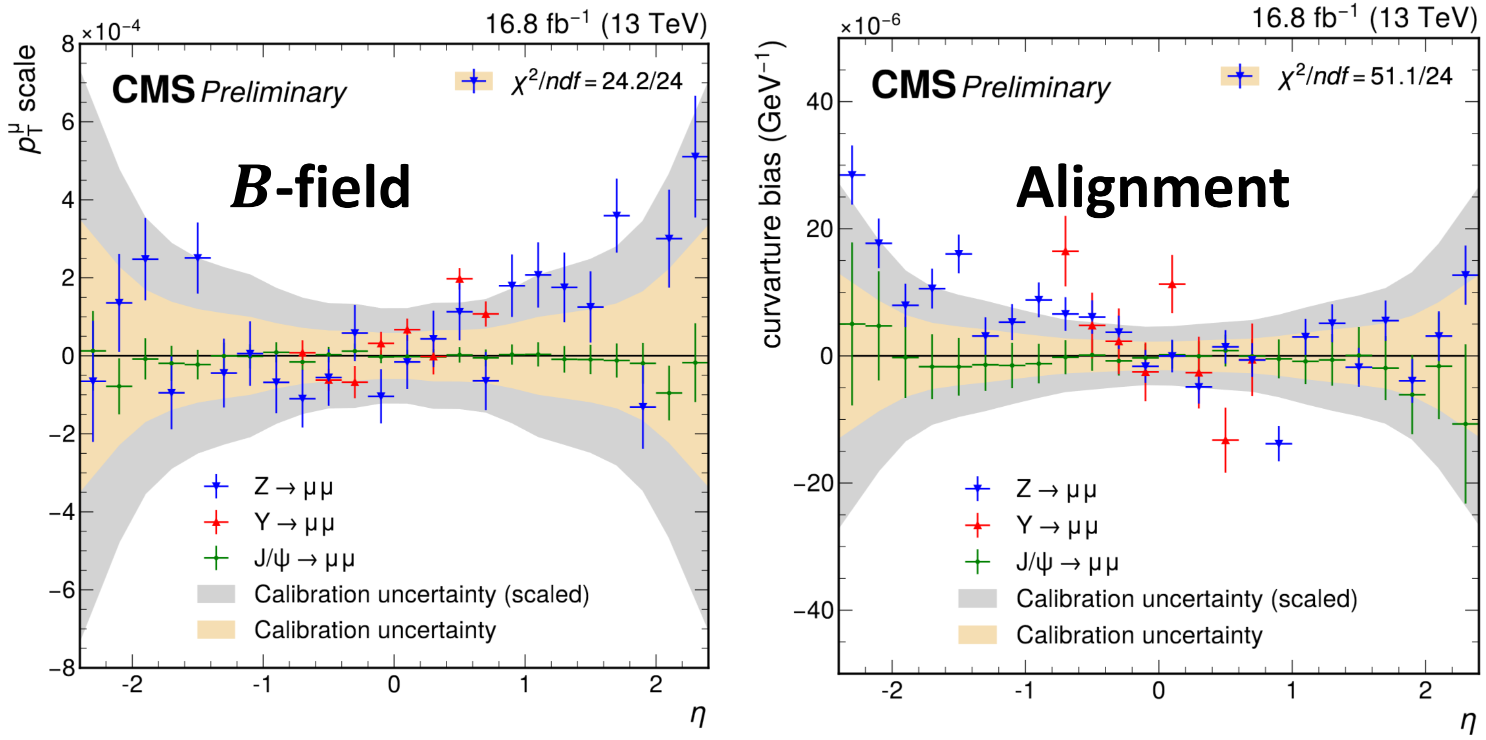
1. **Tuning** of parameters in CMS simulation
2. **Track re-fit** with improved B-field/material treatment based on *Geant4e* (**CVH refit**)
3. **Global correction** of alignment/B-field/material at the per-module level using J/Ψ events
4. **Residual scale bias** measured on J/Ψ events in a fine-grained 4D space $(p_T^+, \eta^+, p_T^-, \eta^-)$ by fitting a *parametric* model



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

Closure on Υ and Z

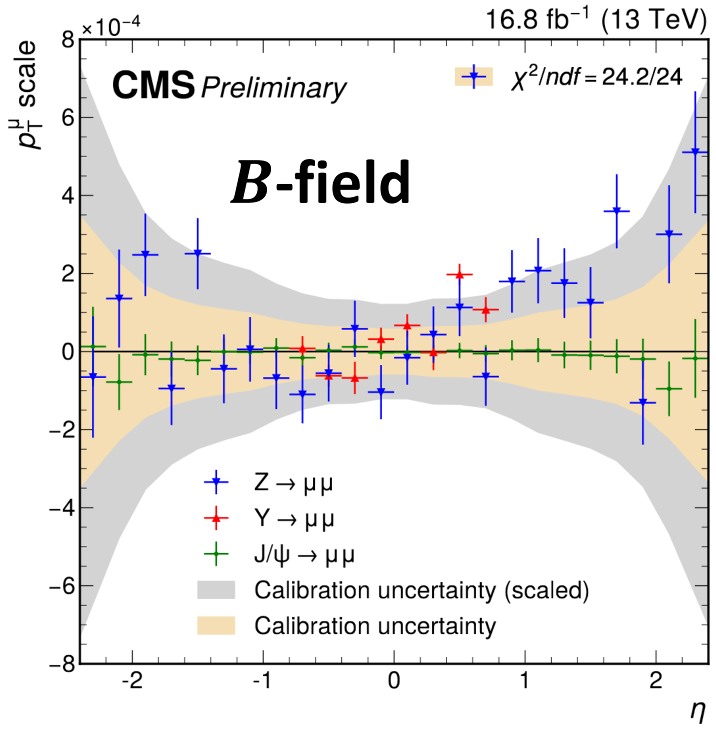
- **Parametric corrections from** J/Ψ applied to $\Upsilon, Z \to \mu\mu$ events
  - Repeat **Step 4.** ⇒ derive **residual scales** for **B-field** and **alignment**

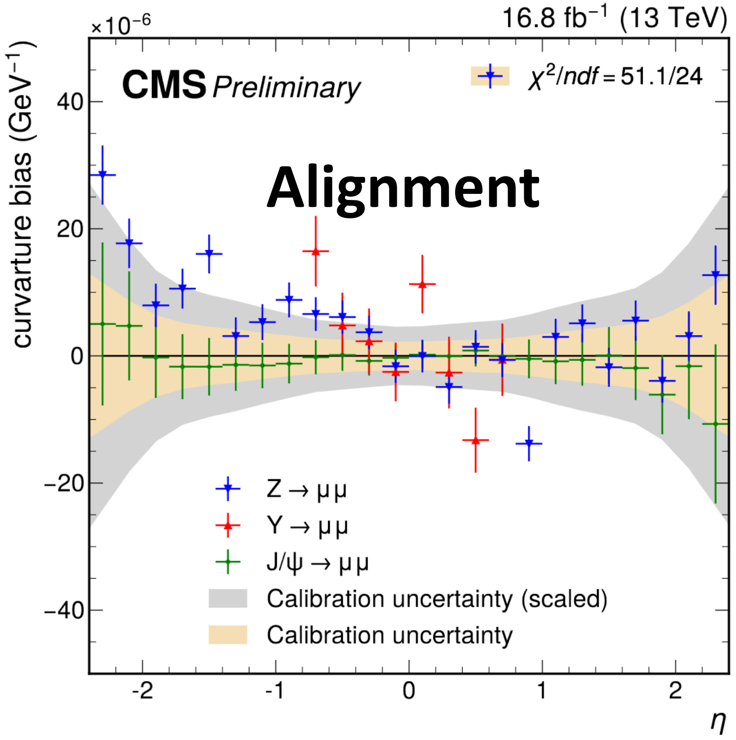


Closure on Υ and Z

- **Parametric corrections from J/Ψ** applied to $\Upsilon, Z \rightarrow \mu\mu$ events
  - Repeat **Step 4.** $\Rightarrow$ derive **residual scales** for **B-field** and **alignment**

- Compatibility with **null scale** assessed through a χ^2-test
  - Scaling of J/Ψ stat. uncert. by 2.1 was needed to cover for the largest χ^2/ndof





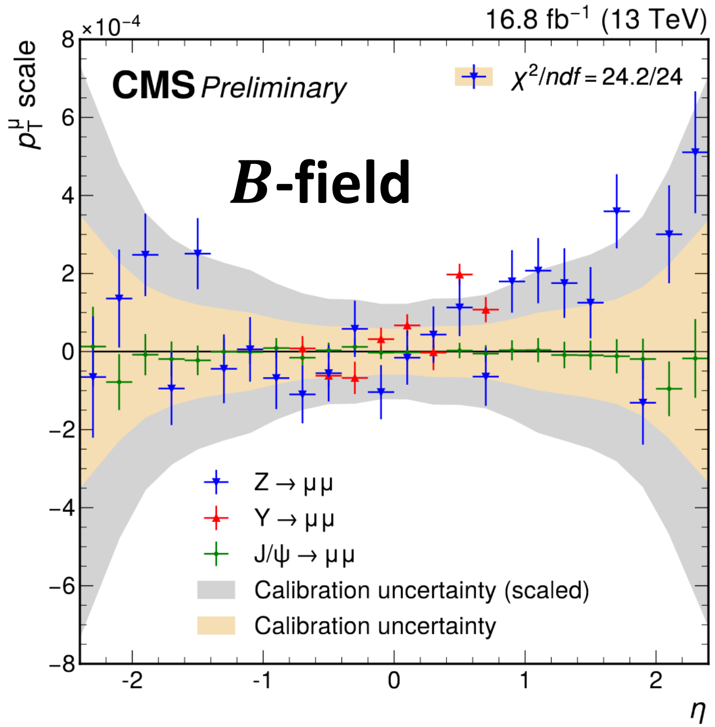
Closure on Υ and Z

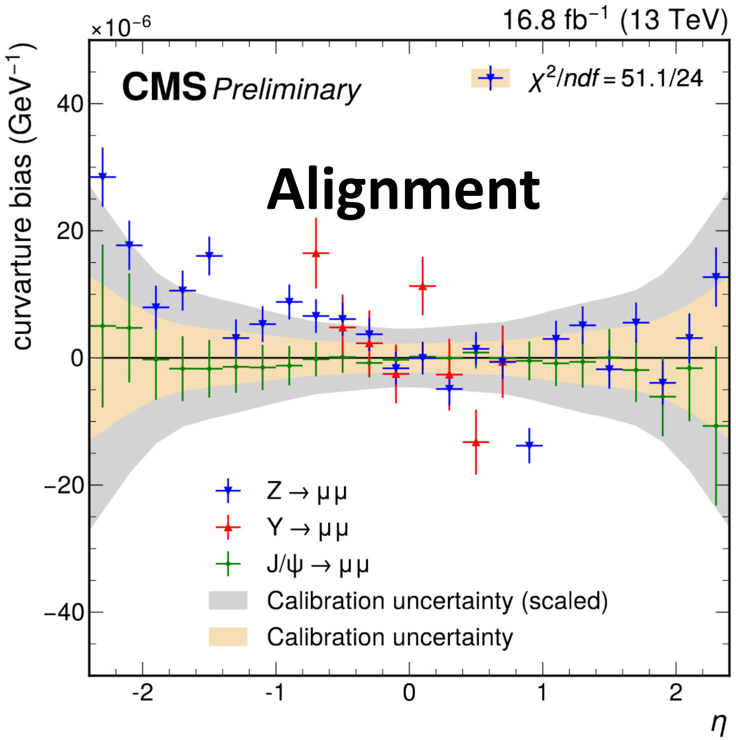
- **Parametric corrections from** J/Ψ applied to $\Upsilon, Z \to \mu\mu$ events
  - Repeat **Step 4.** ⇒ derive **residual scales** for **B-field** and **alignment**

- Compatibility with **null scale** assessed through a χ^2-test
  - Scaling of J/Ψ stat. uncert. by 2.1 was needed to cover for the largest χ^2/ndof

Corollary:

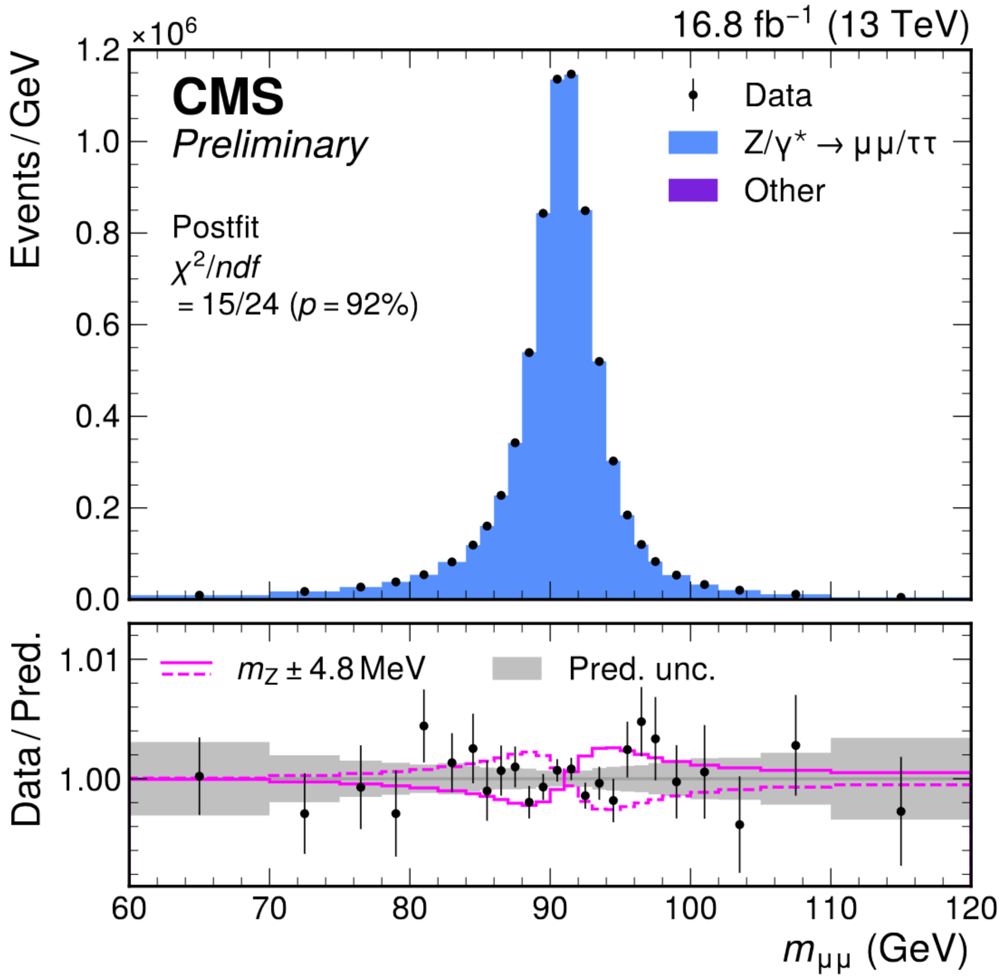
Scale uncertainty not better than uncertainty from closure.





Impact on m_W → 4.8 MeV

Closure test



- Validation of scale calibration by fitting the $(m^{\mu\mu}, \eta^{\mu-\mathrm{fwd}})$ distribution

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

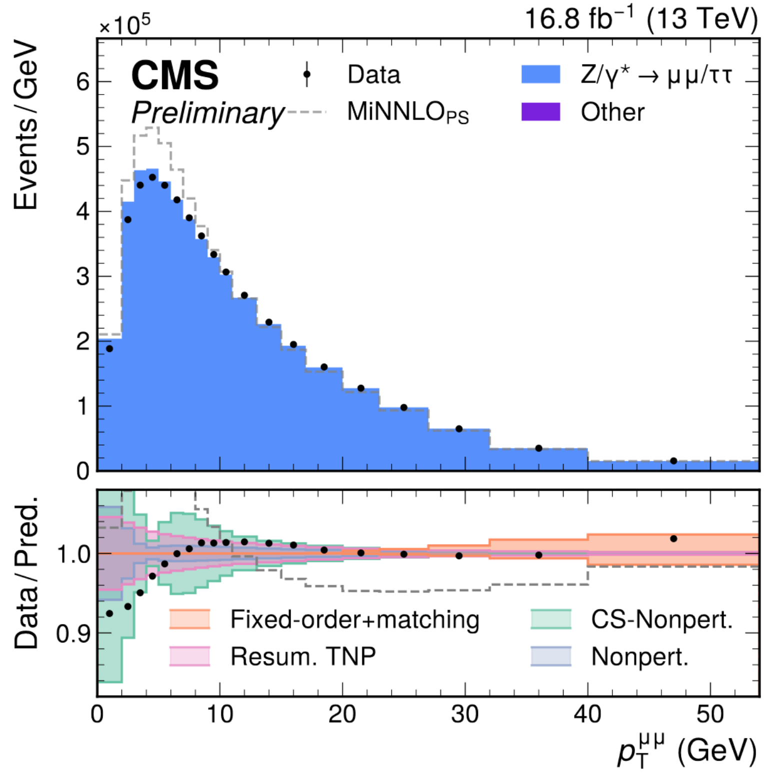
- **Not an independent measurement of m_Z**

W and Z modeling

- State-of-the art calculations for **production and decay of W, Z**
  - *MiNNLO$_{PS}$* + *Pythia8* + *Photos* (→NNLO)
  - Reweighting of σ_{UL} to all-order resummed calculations from the *SCETLib* matched to *DYTurbo* (→N^{3}LL+NNLO)

- (p_T^Z, y^Z) **kept unblinded at all times** to help gauging the goodness of our model

- Residual $\lesssim 10\%$ disagreement at low p_T^Z **without tuning** not unexpected



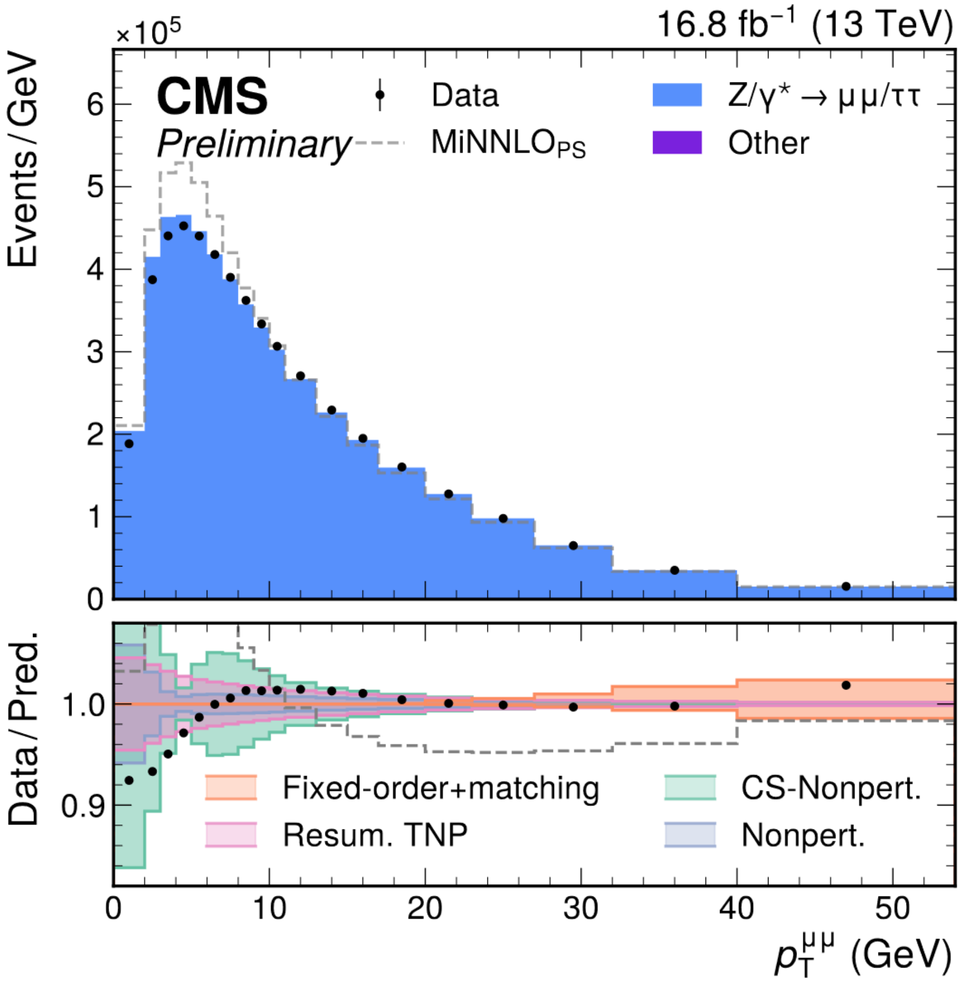
W and Z modeling

JHEP07(2022)129

- **Non-perturbative**
  - Inspired by non pert. TMD PDFs + heuristic model for intrinsic partonic momentum
- **Resummation TNP**
  - Unknown coefficients of truncated expansion

$$f^{\text{predicted}}(\alpha) = f_0 + f_1\,\alpha + f_2\,\alpha^2 + f_3(\theta_3)\,\alpha^3$$

- **Fixed-order + matching**
  - Relevant at high p_T^V

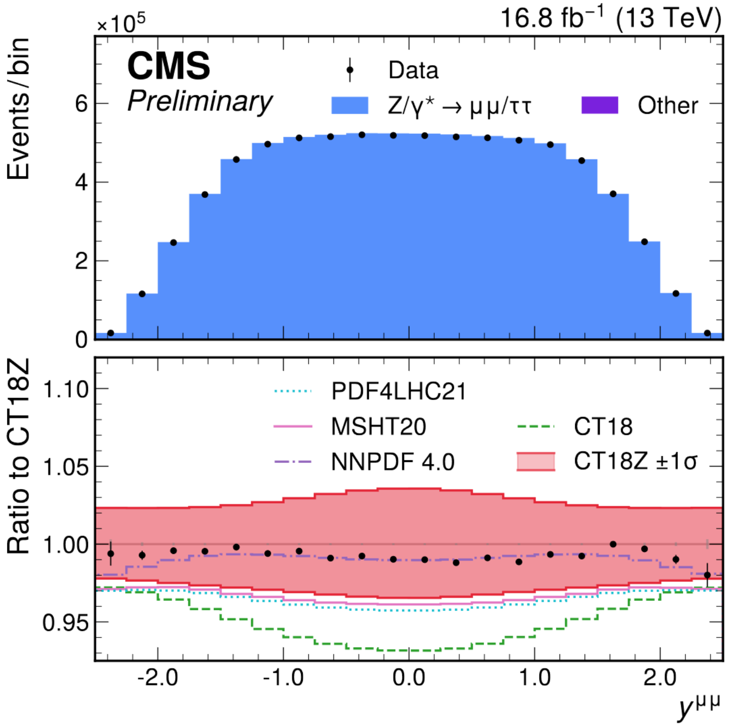


Impact on m_W → ~2 MeV

PDFs

- $n = 7$ modern sets of PDFs have been considered
- For each set, we determine **inflation factors** needed to cover the other $n-1$
  - i.e. $|m_W^{\text{alt.}} - m_W^{\text{nom.}}| \leq \sigma_{\text{PDF}}$
- We choose **CT18Z** as our nominal PDF
  - gives a good pre-fit agreement on y^Z
  - covers other sets **within its original unc.**

Impact on m_W → $\sim$4.4 MeV



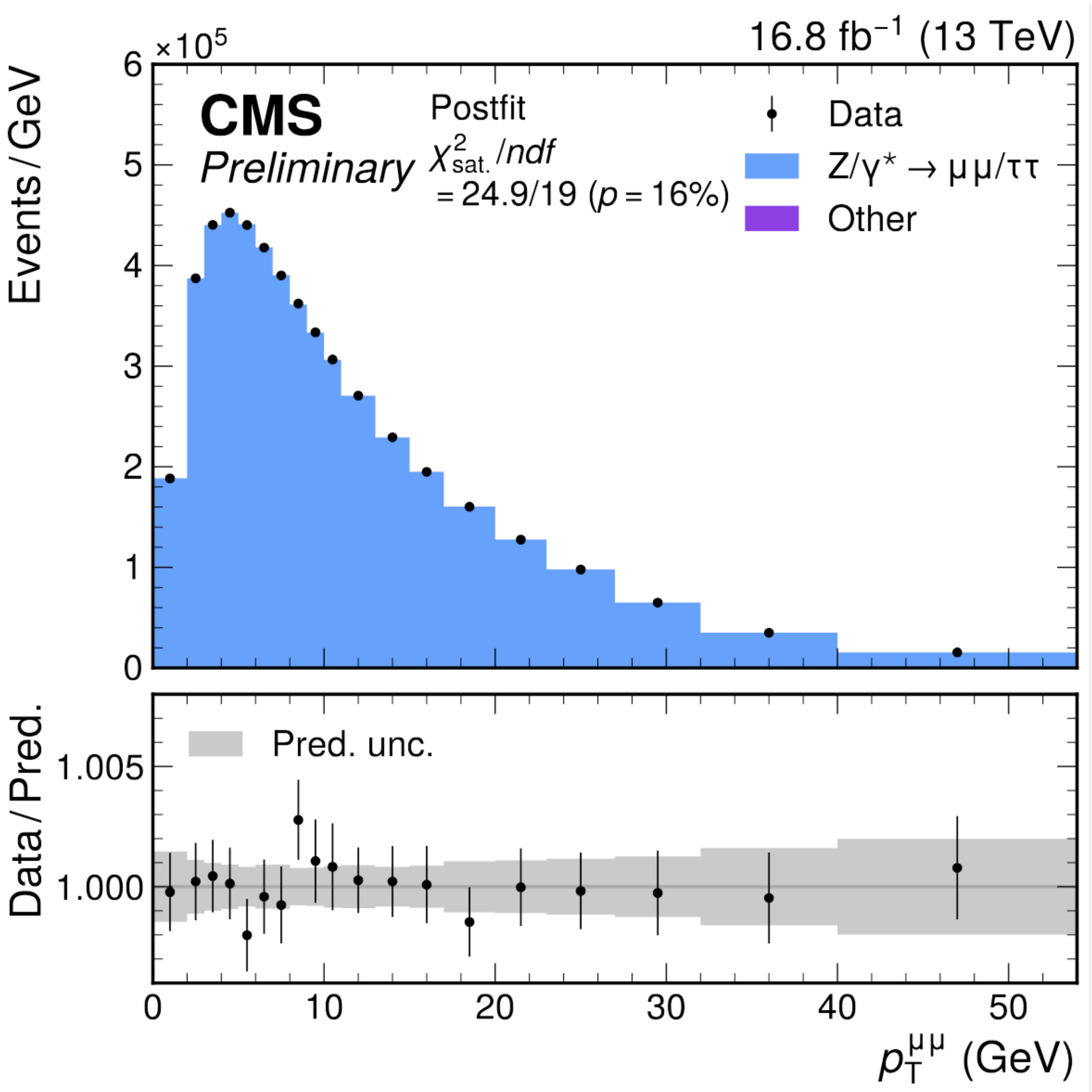
PDF set	Scale factor	Impact in m_W (MeV) Original σ_{PDF}	Scaled σ_{PDF}
CT18Z	–	4.4	
CT18	–	4.6	
PDF4LHC21	–	4.1	
MSHT20	1.5	4.3	5.1
MSHT20aN3LO	1.5	4.2	4.9
NNPDF3.1	3.0	3.2	5.3
NNPDF4.0	5.0	2.4	6.0

Model validation

- Theory model validated by fitting (p_T^Z, y^Z) spectrum
  - Agreement at the permille level

- This gives us **confidence** (p_T^W, y^W) **will be equally well described** from the likelihood fit to ***W*** **data ONLY**

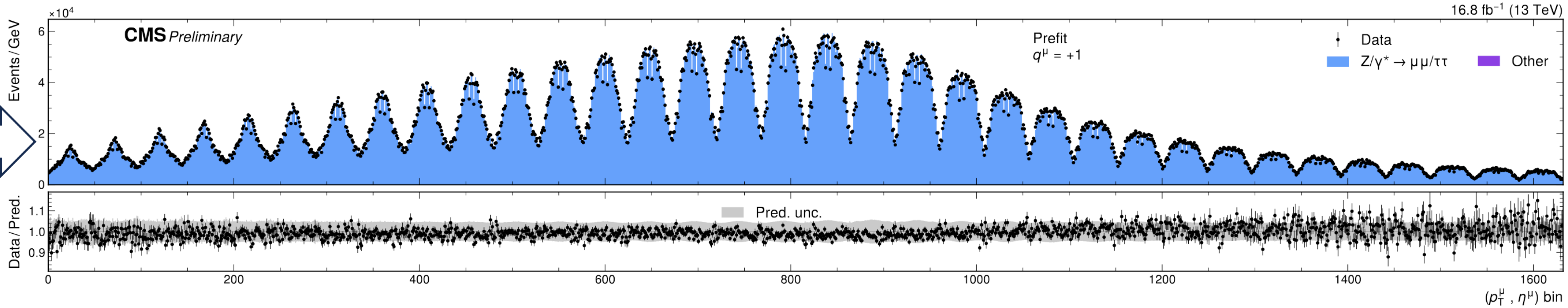
- We want to **prove it in a more** W**-like** configuration



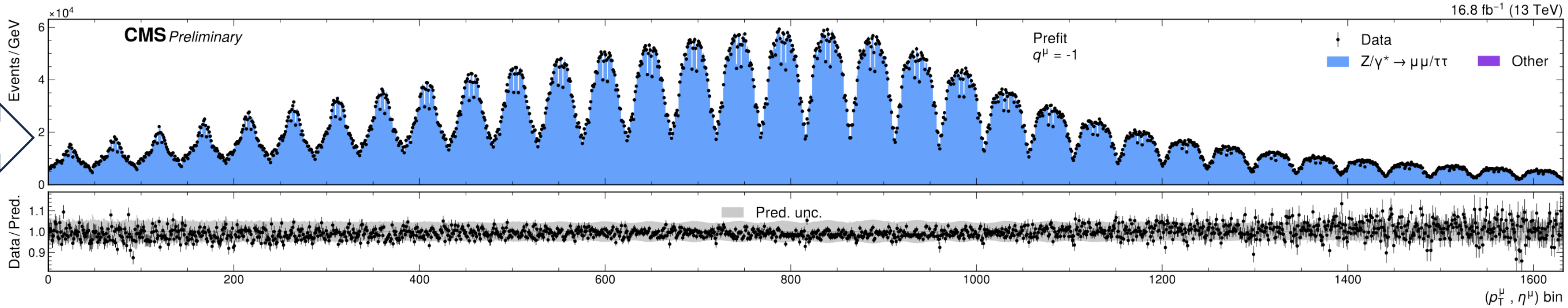
Validation: W-like

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

μ^+ in **even**-numbered events

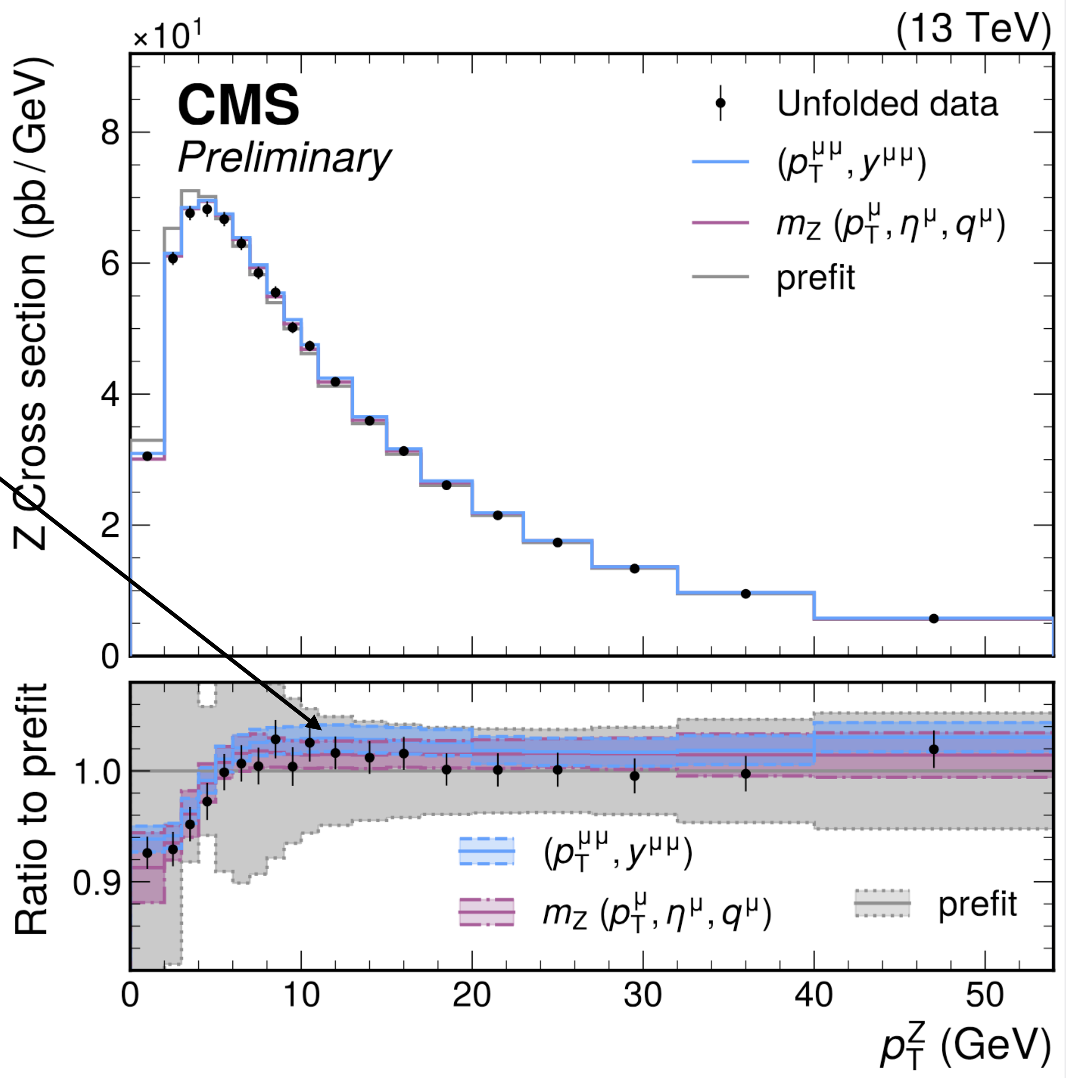


μ^- in **odd**-numbered events



W-like: p_T^Z modeling

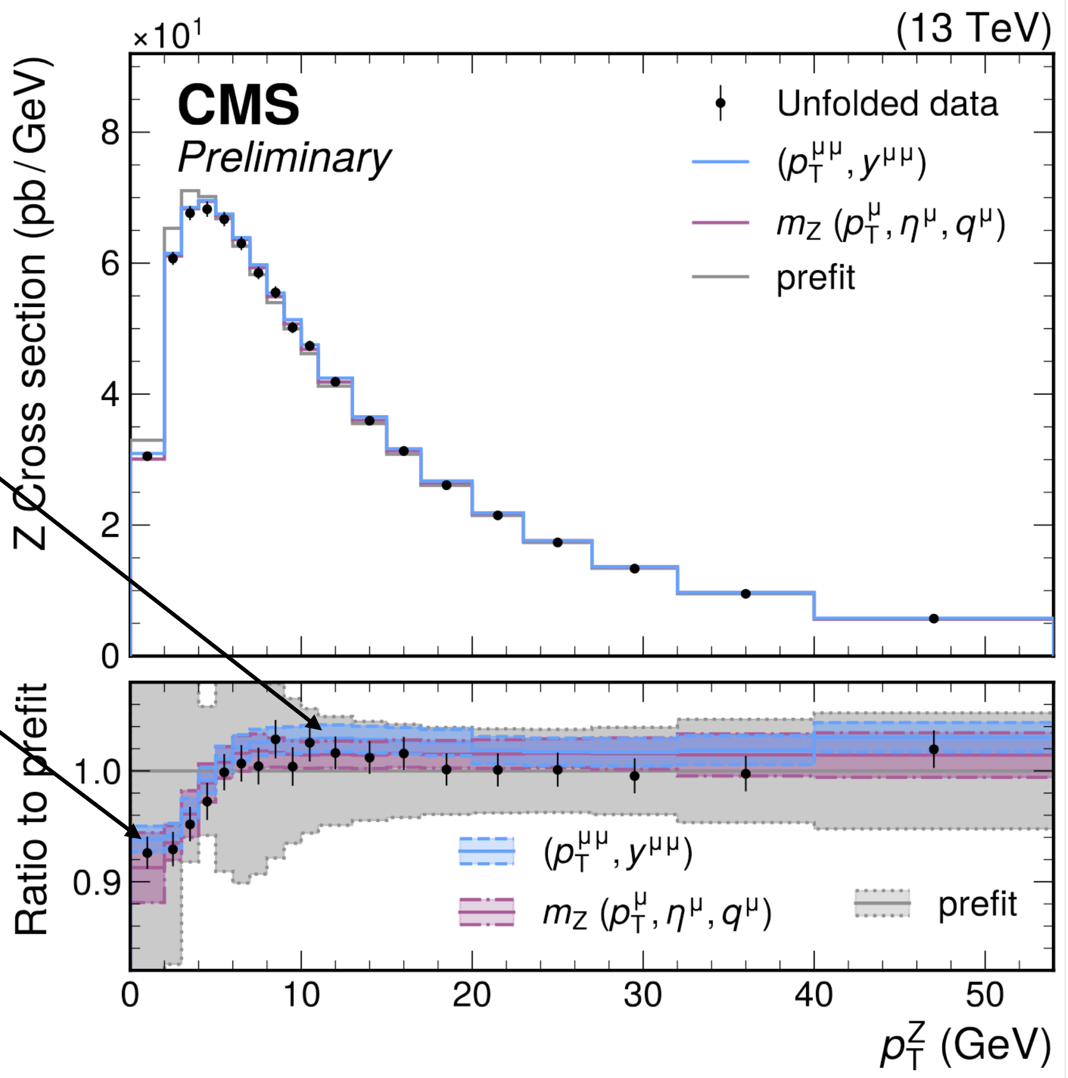
Unfolded
$(\boldsymbol{p_T^Z}, \boldsymbol{y^Z})$



W-like: p_T^Z modeling

Unfolded (p_T^Z, y^Z)

p_T^Z from model fit to (p_T^Z, y^Z)

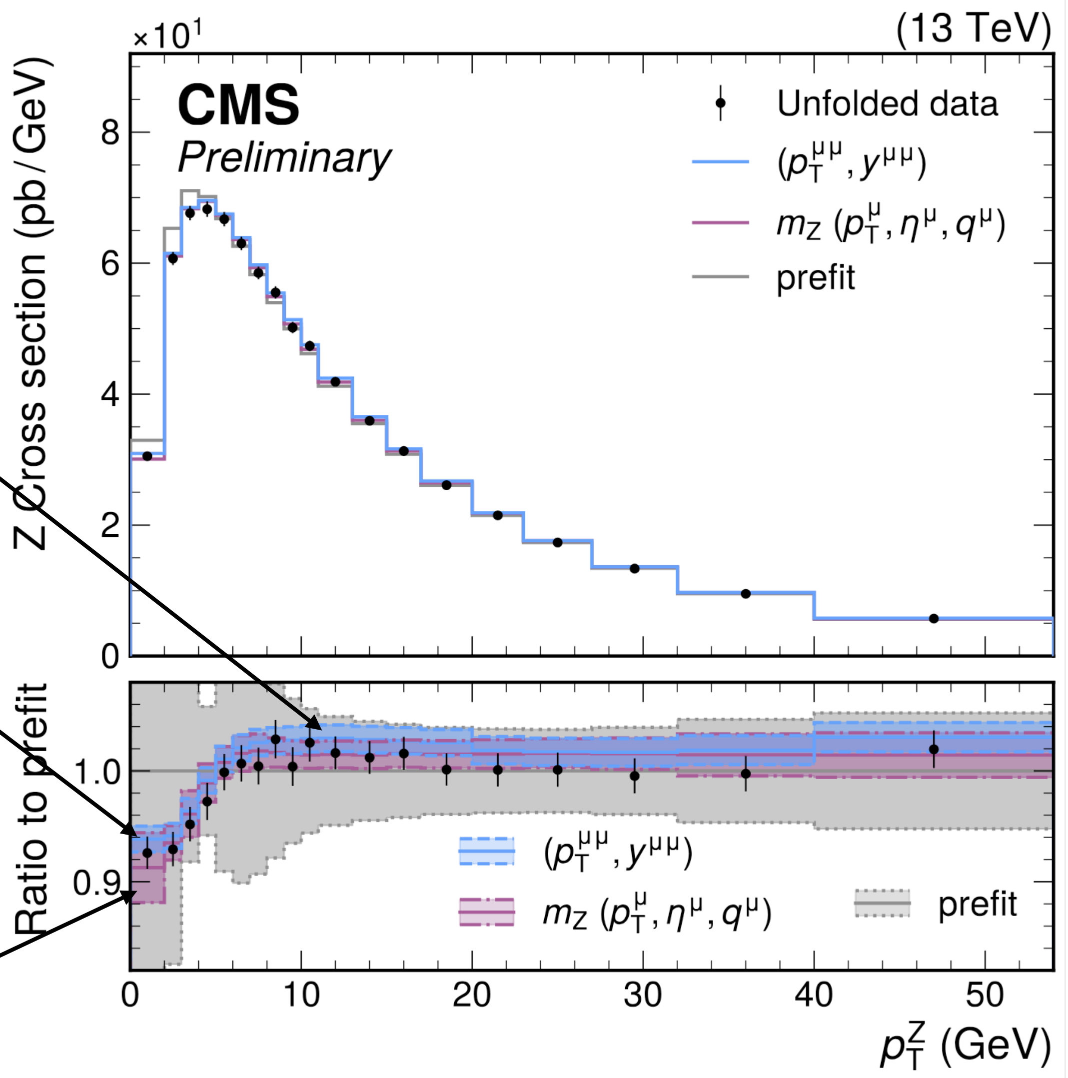


W-like: p_T^Z modeling

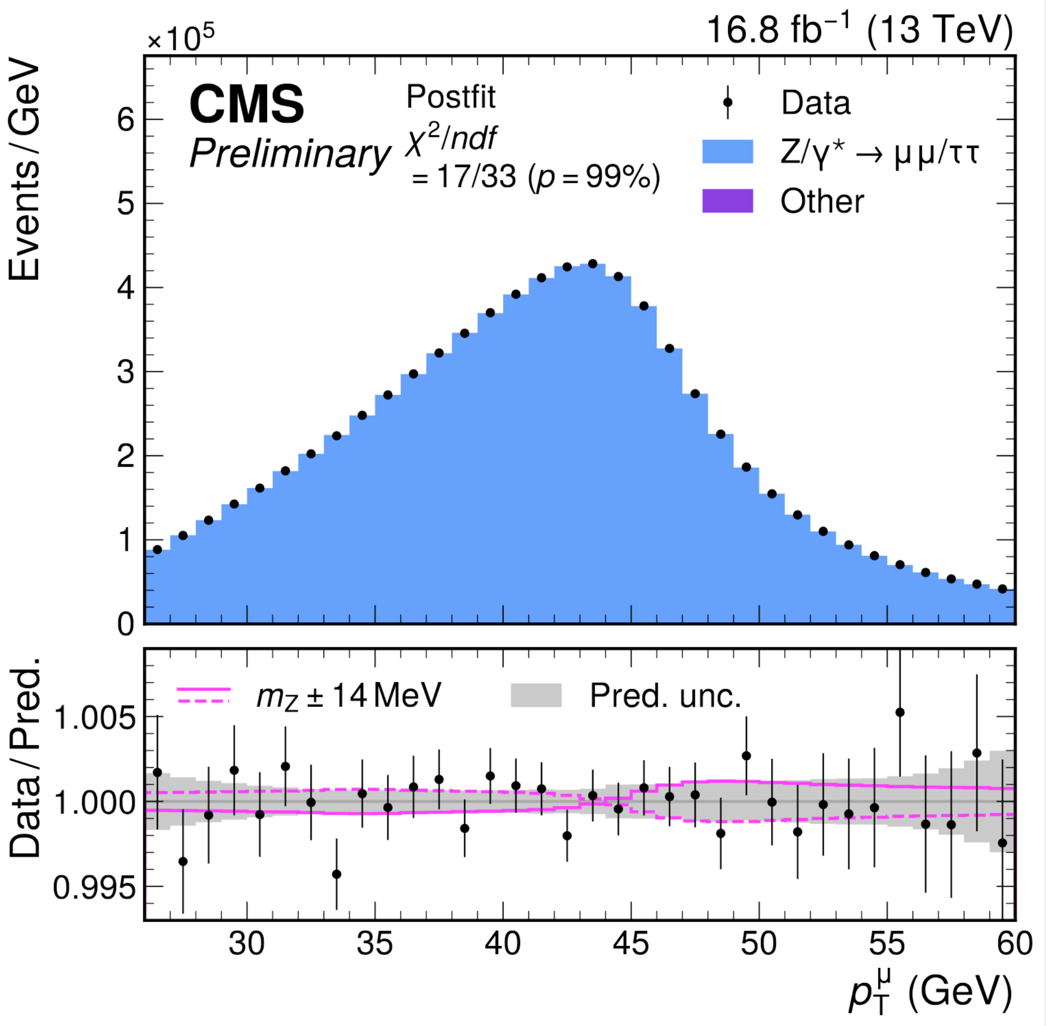
Unfolded (p_T^Z, y^Z)

p_T^Z from model fit to (p_T^Z, y^Z)

p_T^Z from model fit to (q, p_T^μ, η^μ)

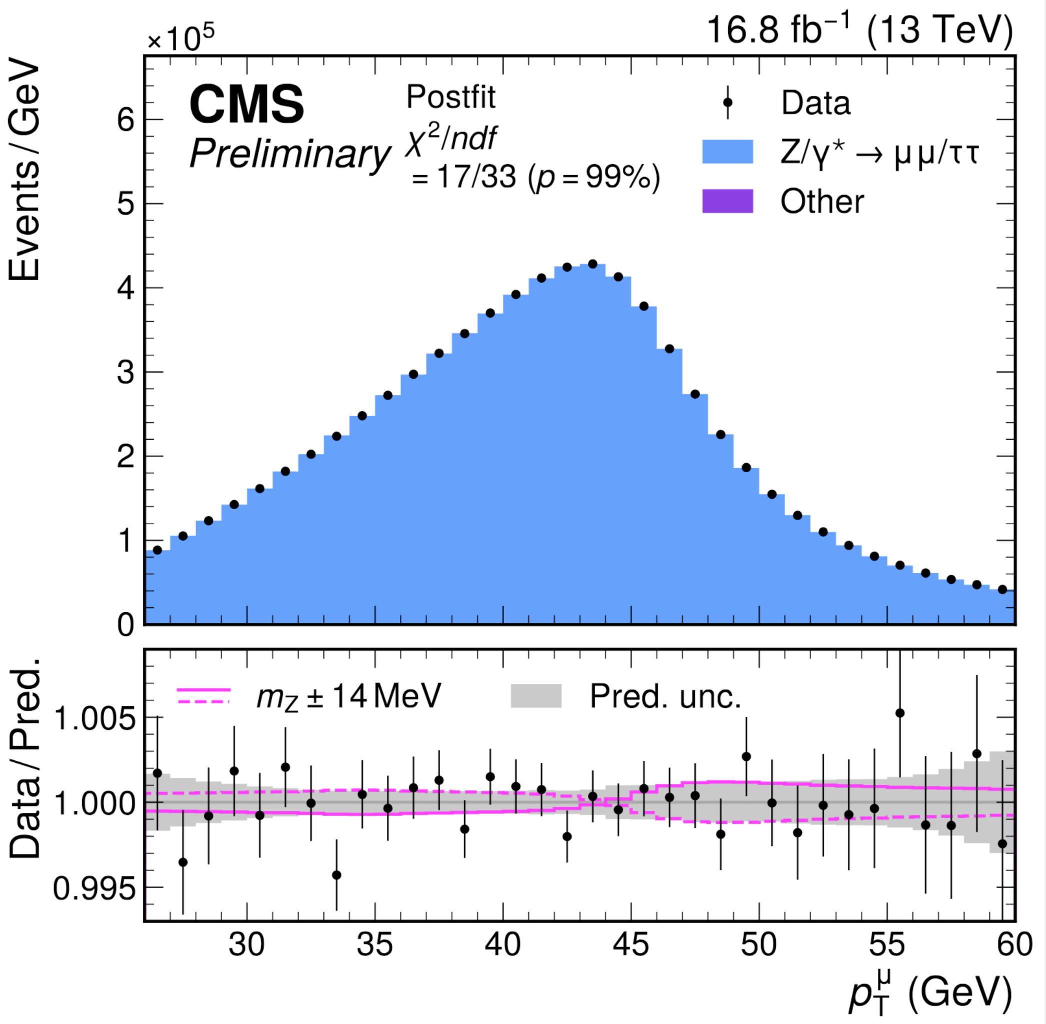


W-like: results

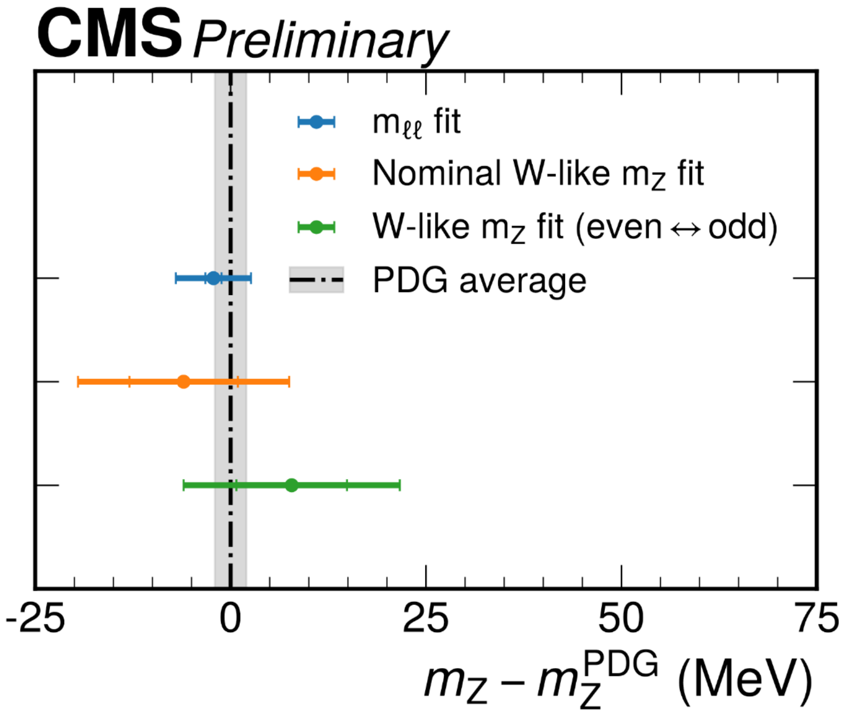


- Total uncertainty on m_Z is **13.5 MeV**
  - Muon scale (5.6), angular coeff. (4.9), muon reco (3.8)
  - m_Z kept blind until all checks completed

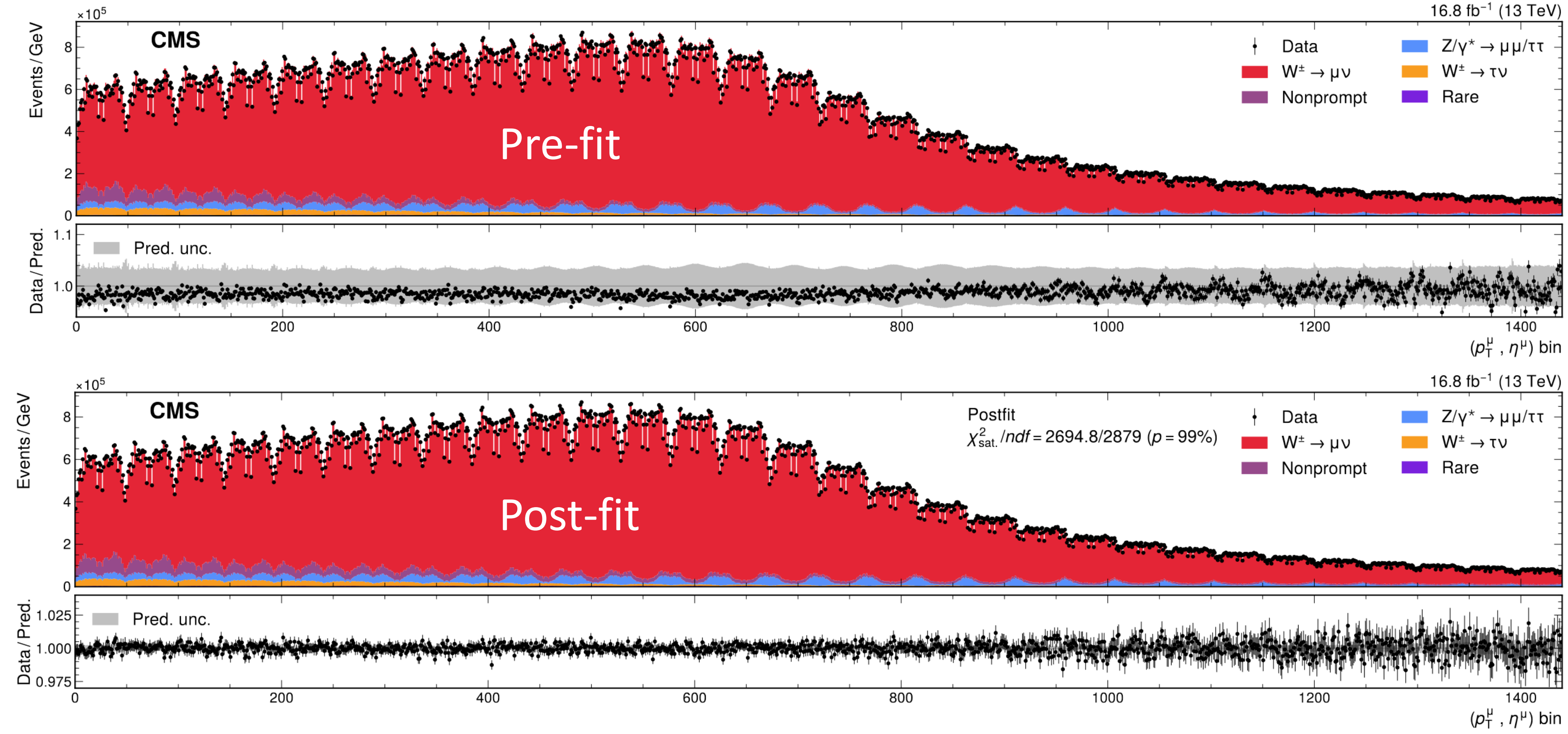
W-like: results



- Total uncertainty on m_Z is **13.5 MeV**
  - Muon scale (5.6), angular coeff. (4.9), muon reco (3.8)
  - m_Z kept blind until all checks completed

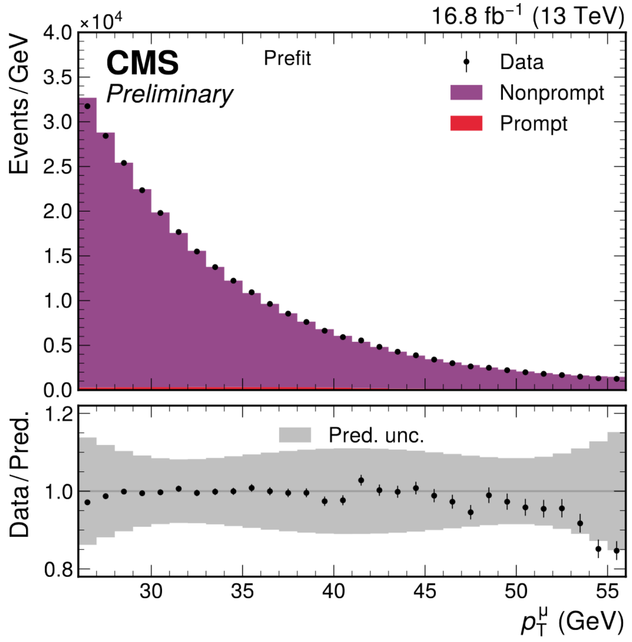


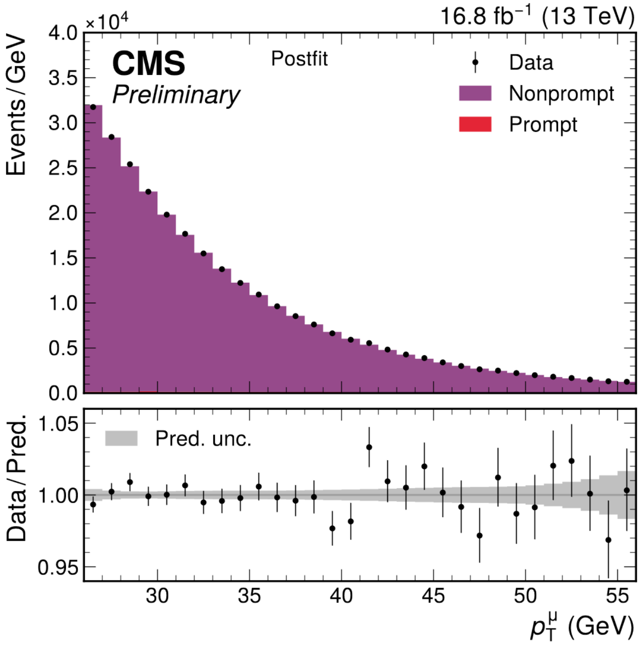
Moving to the W



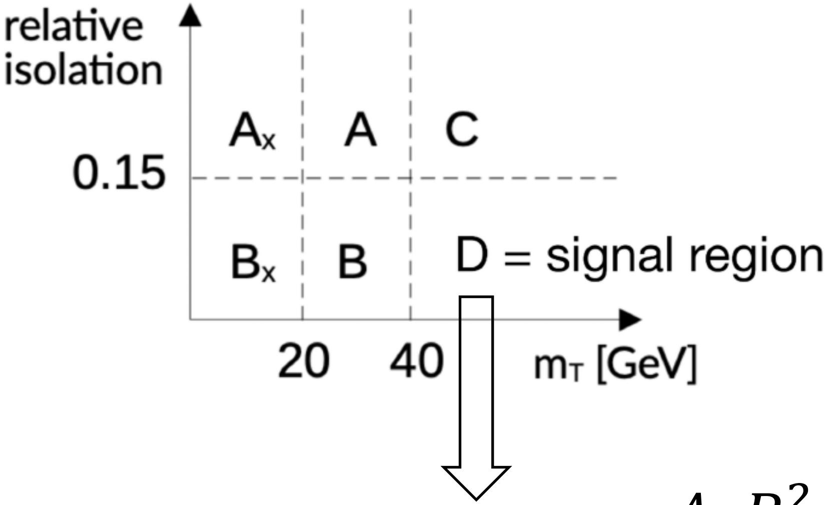
Non-prompt background

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





In each (η, p_T) bin:



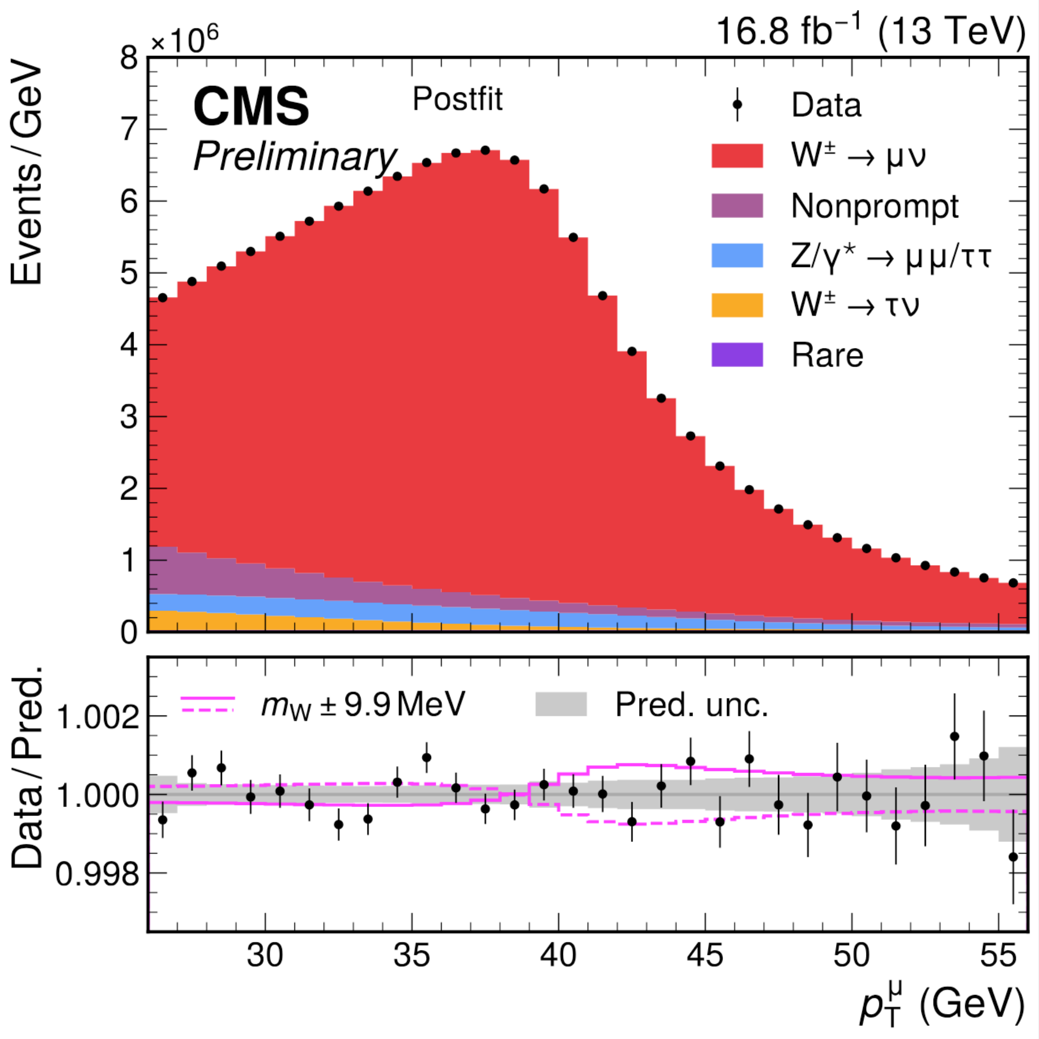
$$D = C \cdot \frac{A_x B^2}{A_x A^2}$$

- Functional dependence of each region on p_T is enforced:

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

Impact on m_W → ~3 MeV

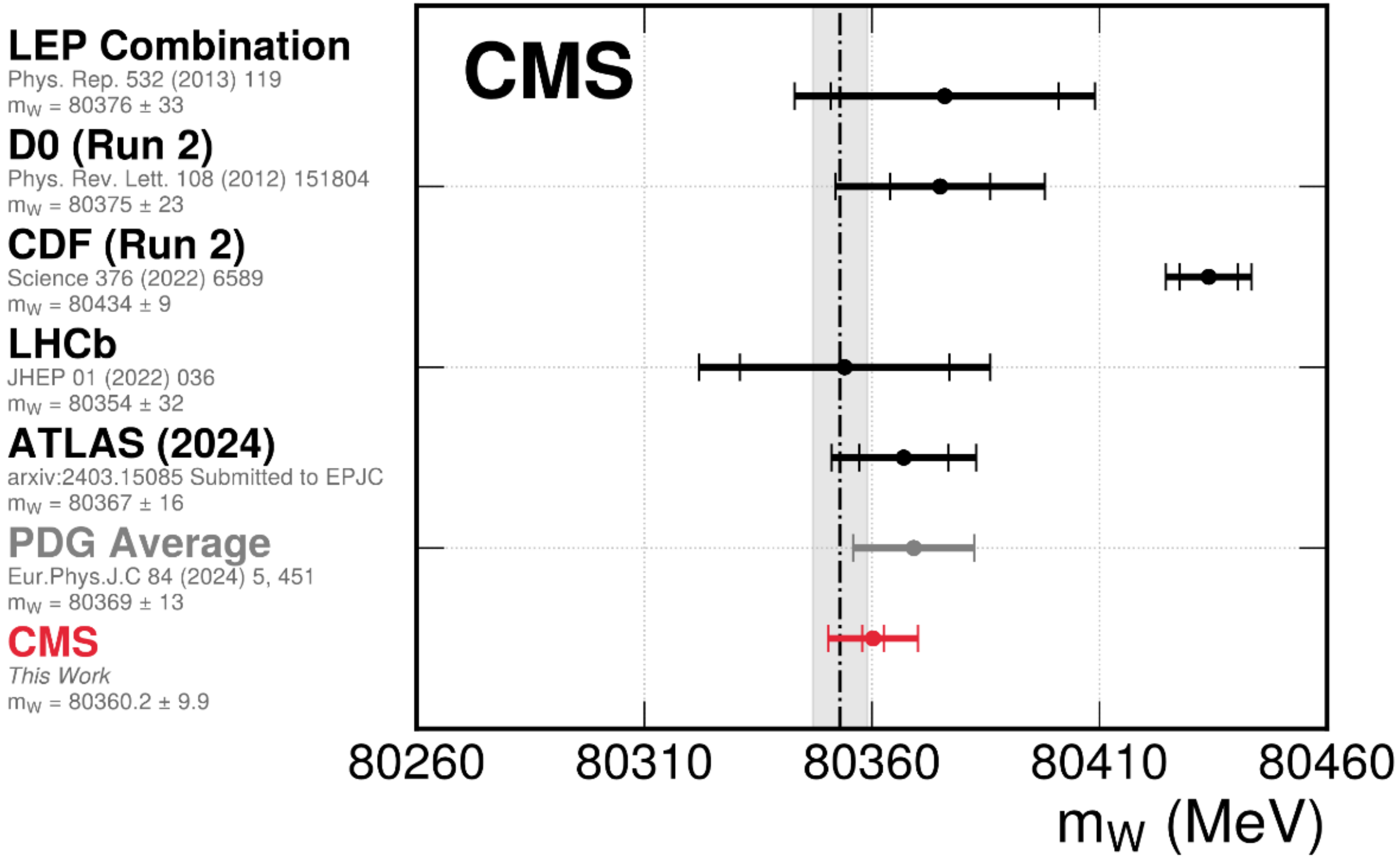
Unblinding the W fit



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

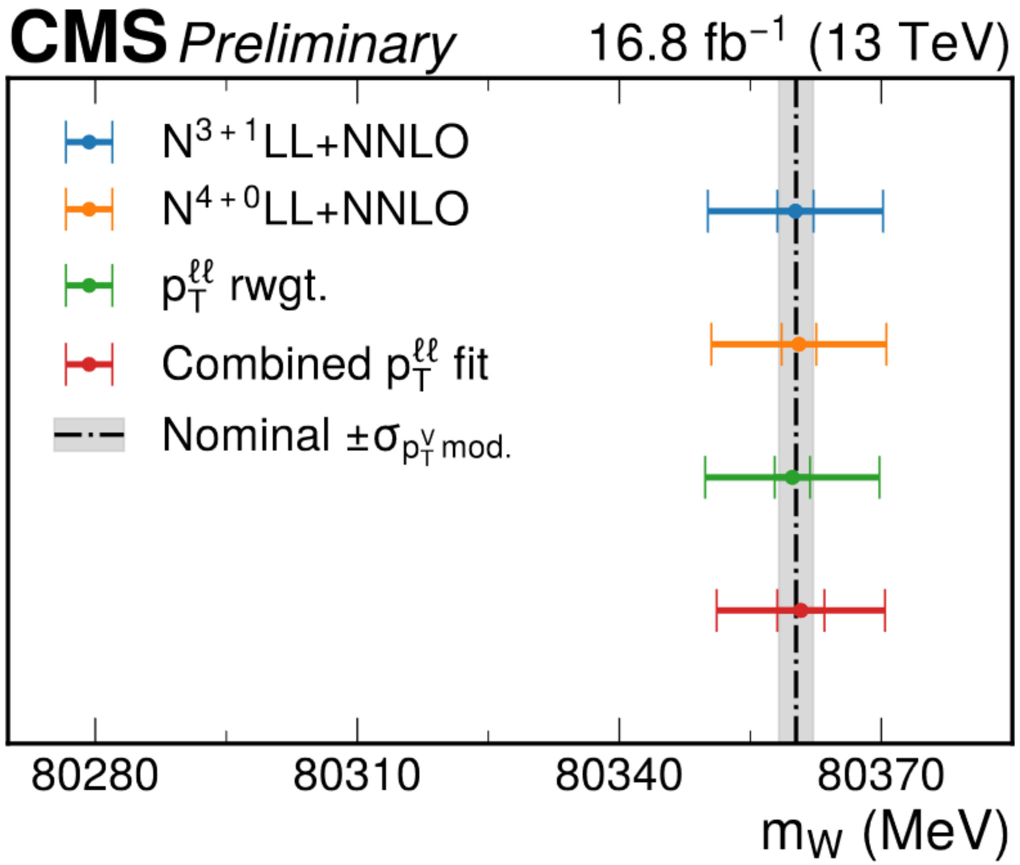
Source of uncertainty	Impact Nominal in m_Z	Impact Nominal in m_W
Muon momentum scale	5.6	4.8
Muon reco. efficiency	3.8	3.0
W and Z angular coeffs.	4.9	3.3
Higher-order EW	2.2	2.0
p_T^V modeling	1.7	2.0
PDF	2.4	4.4
Nonprompt background	–	3.2
Integrated luminosity	0.3	0.1
MC sample size	2.5	1.5
Data sample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

Results

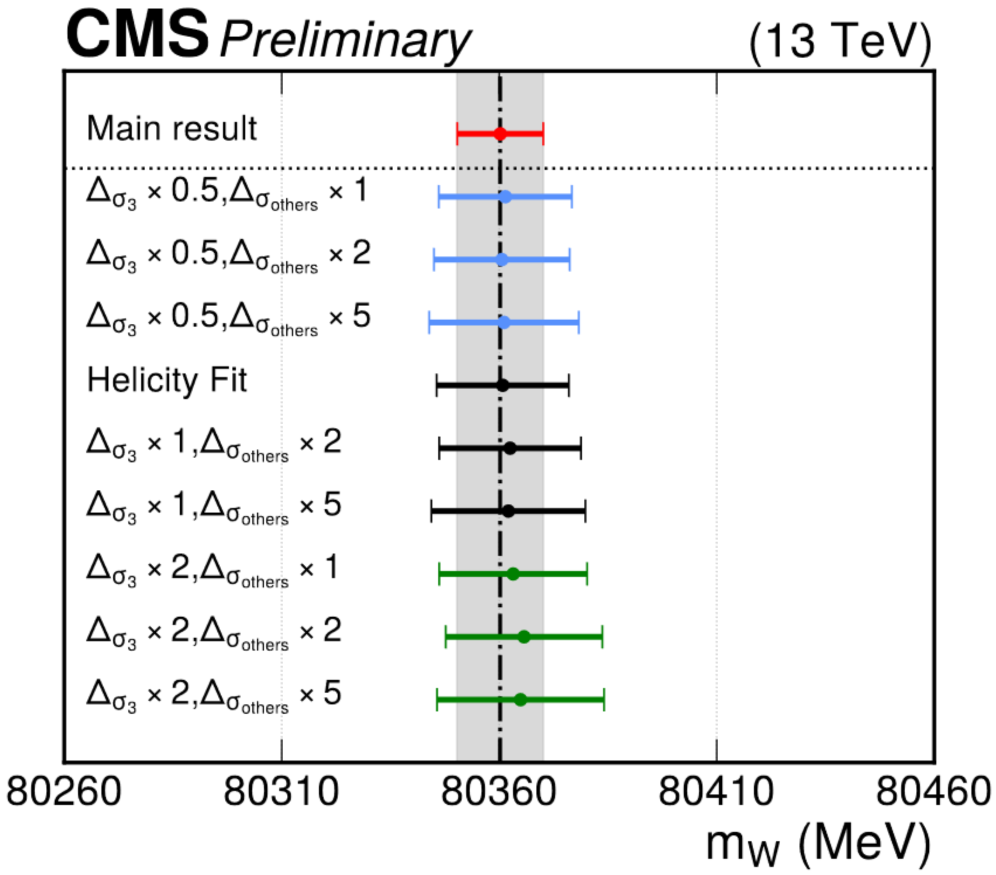


$$m_W = 80360.2 \pm 9.9 \text{ MeV}$$

Test of model dependence

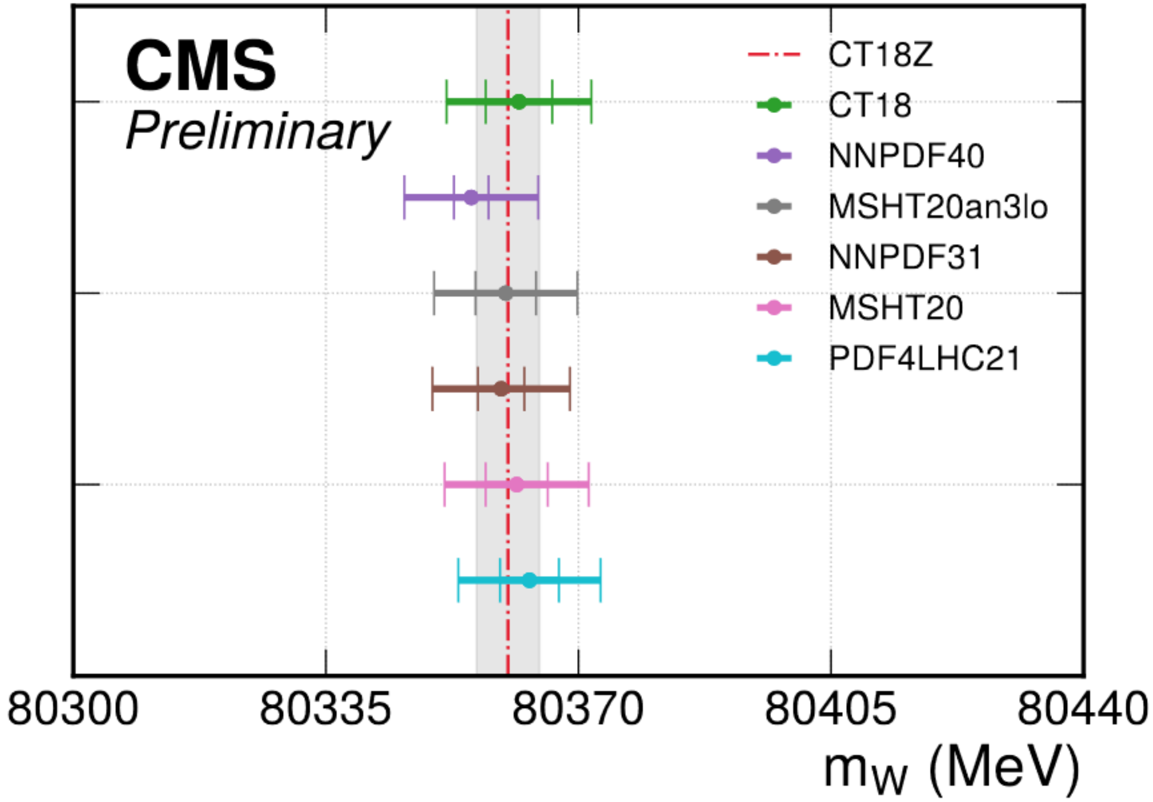


Different p_T^V uncertainty models



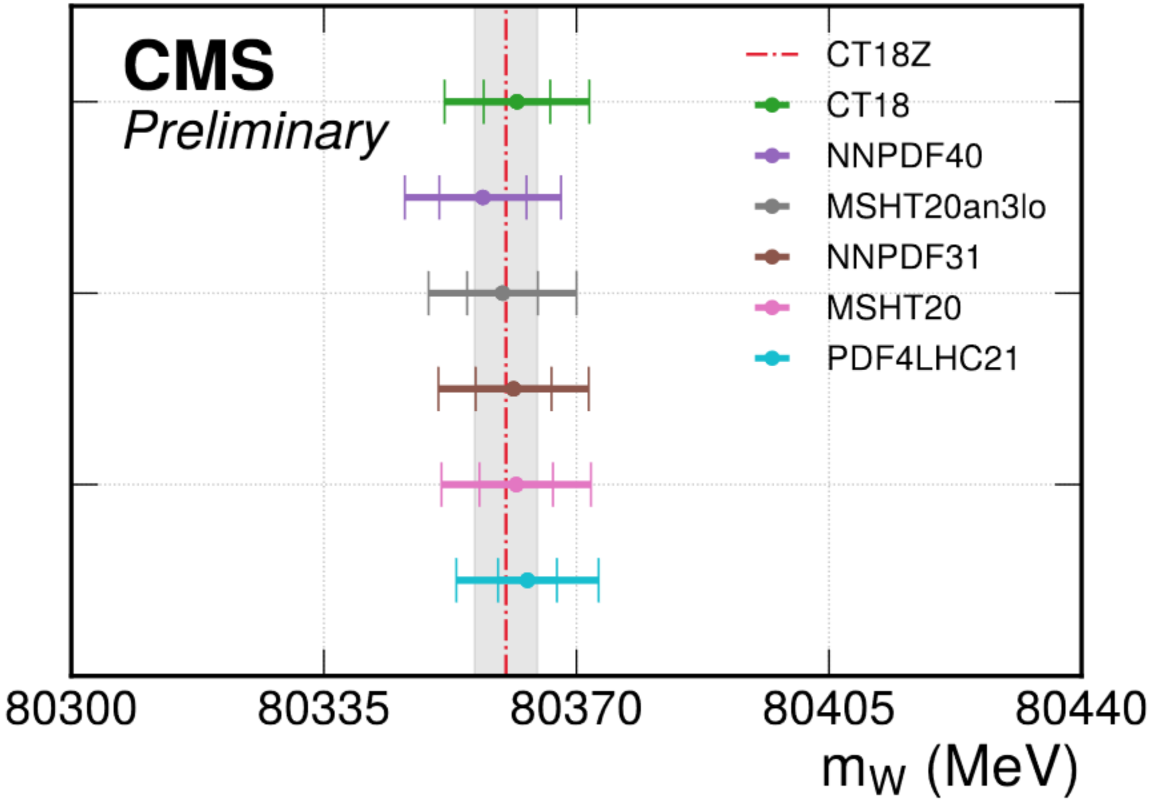
"Helicity fit": loose priors on $\sigma_{\mathrm{UL},0,..,4}$

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

arXiv:2403.15085

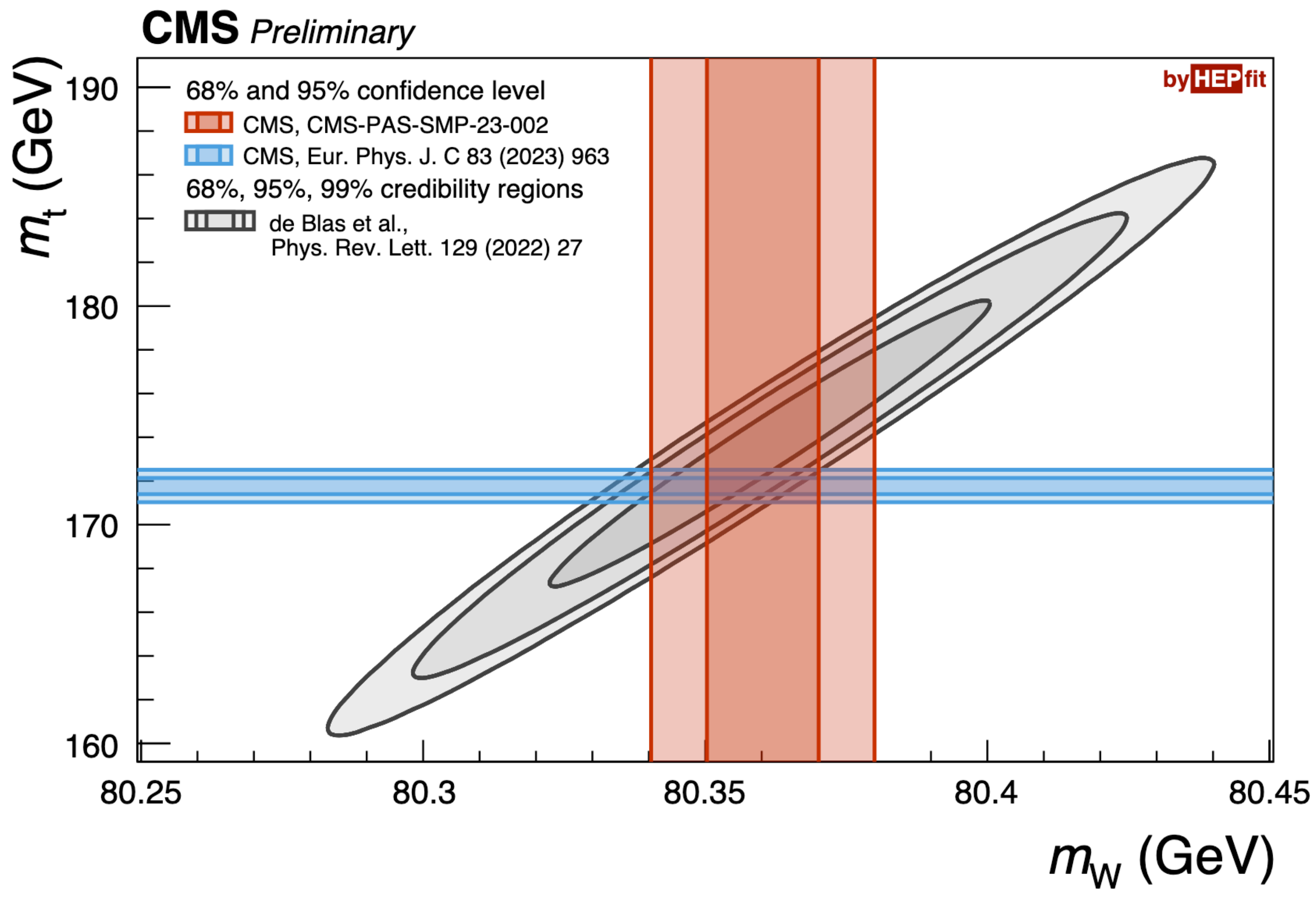
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5

For "global" impacts see arXiv:2307.04007

Source of uncertainty	Impact (MeV)			
	Nominal		Global	
	in m_Z	in m_W	in m_Z	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

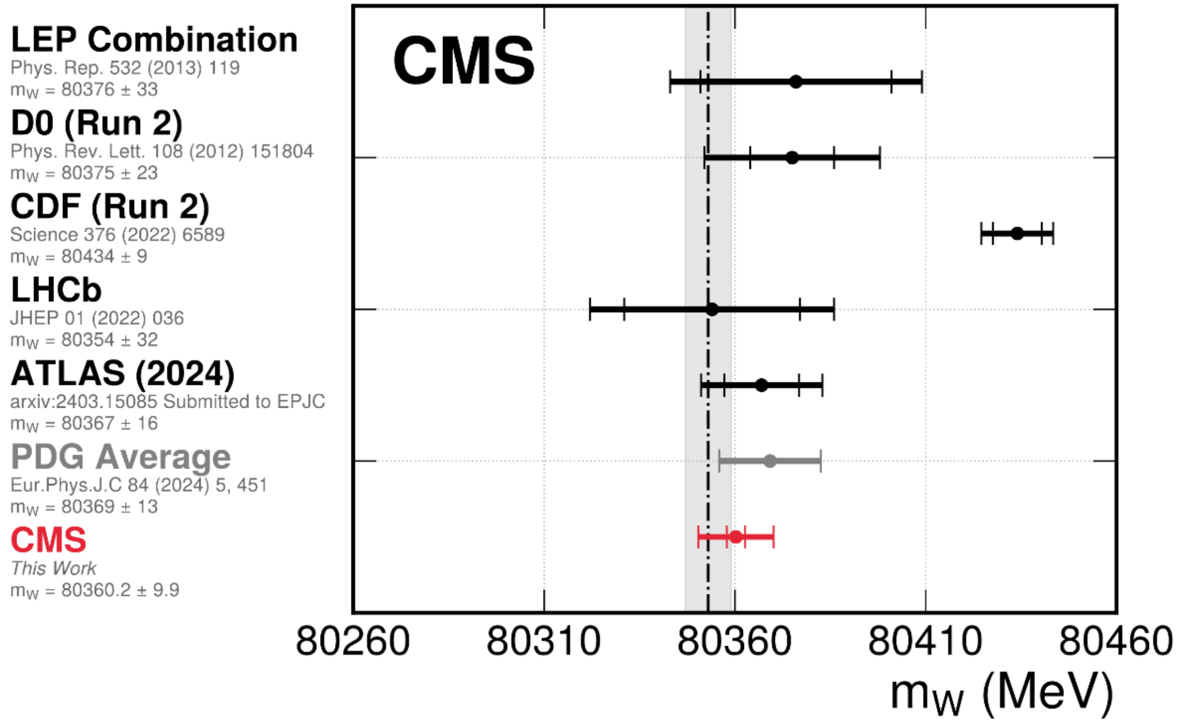
CMS-PAS-SMP-23-002

The EWK fit and direct CMS (m_{t}, m_W)

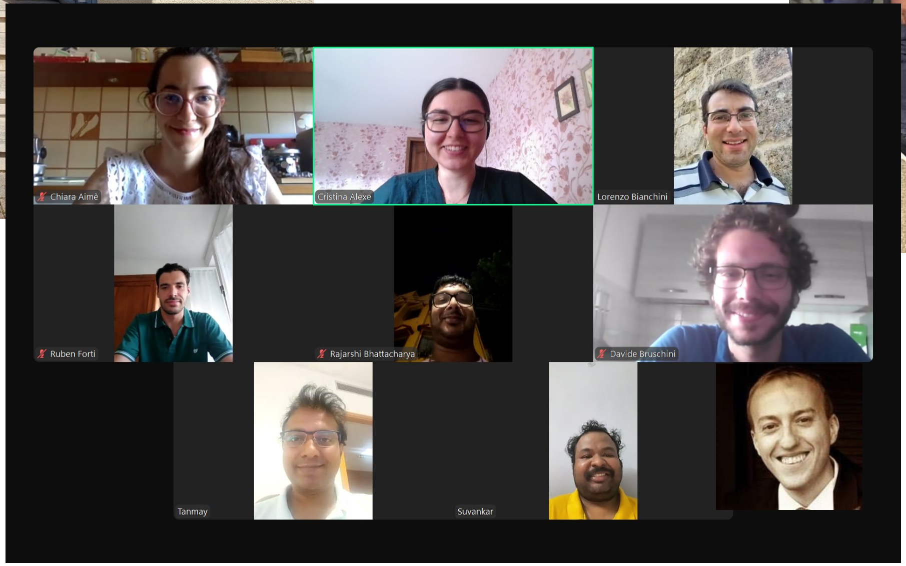


Conclusions

- **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 (excluding CDF)
- The **first in a line** of new precision EWK measurements by CMS



Thanks to all CMS and Pisa collaborators

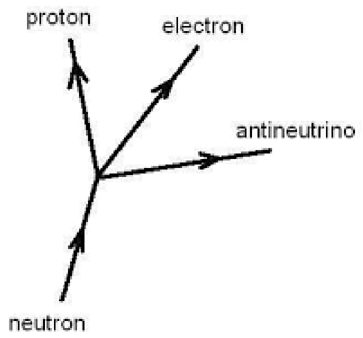


ASYMOW project

Grazie per l’attenzione!

Backup

Towards the W boson



- E. Fermi (1934): a theory of β-decay
- R. Glashow (1961): a model of partial symmetries (γ, W^+, W^-, Z^0)
- S. Weinberg (1967): a model of leptons

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

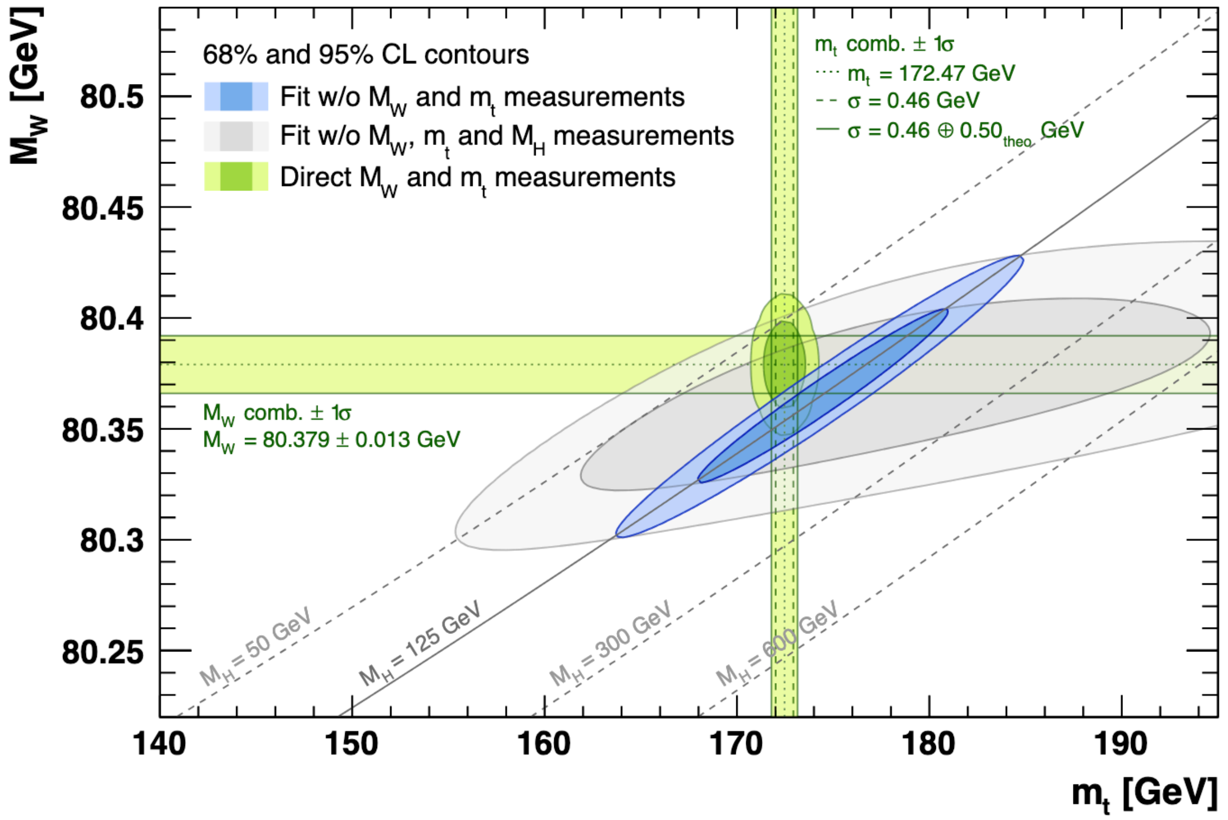
$$\begin{cases} m_W^2 = \dfrac{\pi\, \alpha_{EM}}{\sqrt{2} G_F \sin^2\theta_W} \gtrsim (40\ \mathrm{GeV})^2 \\ m_Z^2 = \dfrac{\pi\, \alpha_{EM}}{\sqrt{2} G_F \sin^2\theta_W \cos^2\theta_W} \gtrsim (80\ \mathrm{GeV})^2 \end{cases}$$

- 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.* (1976-1983): ***W*, *Z* discovery** ⇒ $m_W = \mathbf{80.2} \pm 1.5$ GeV, $m_Z = \mathbf{91.5} \pm 1.8$ GeV

The EWK fit in the post-Higgs era

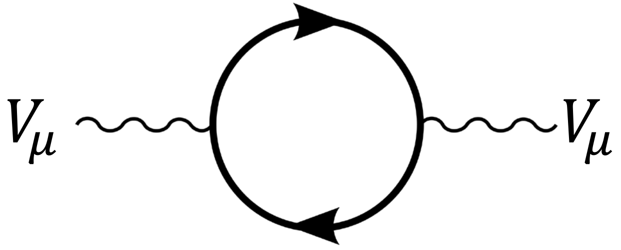
- M.H.O. → 4 MeV
- m_{top} → 4 MeV
- M_Z → 2.6 MeV
- α_s → 2.6 MeV
- $\Delta\alpha^{(5)}_{had}$ → 2.4 MeV

Eur. Phys. J. C78, 675 (2018)



M_W as a probe of NP

- Pivotal role in determination of **oblique parameters *S,T,U***
  - bounds on universal new physics

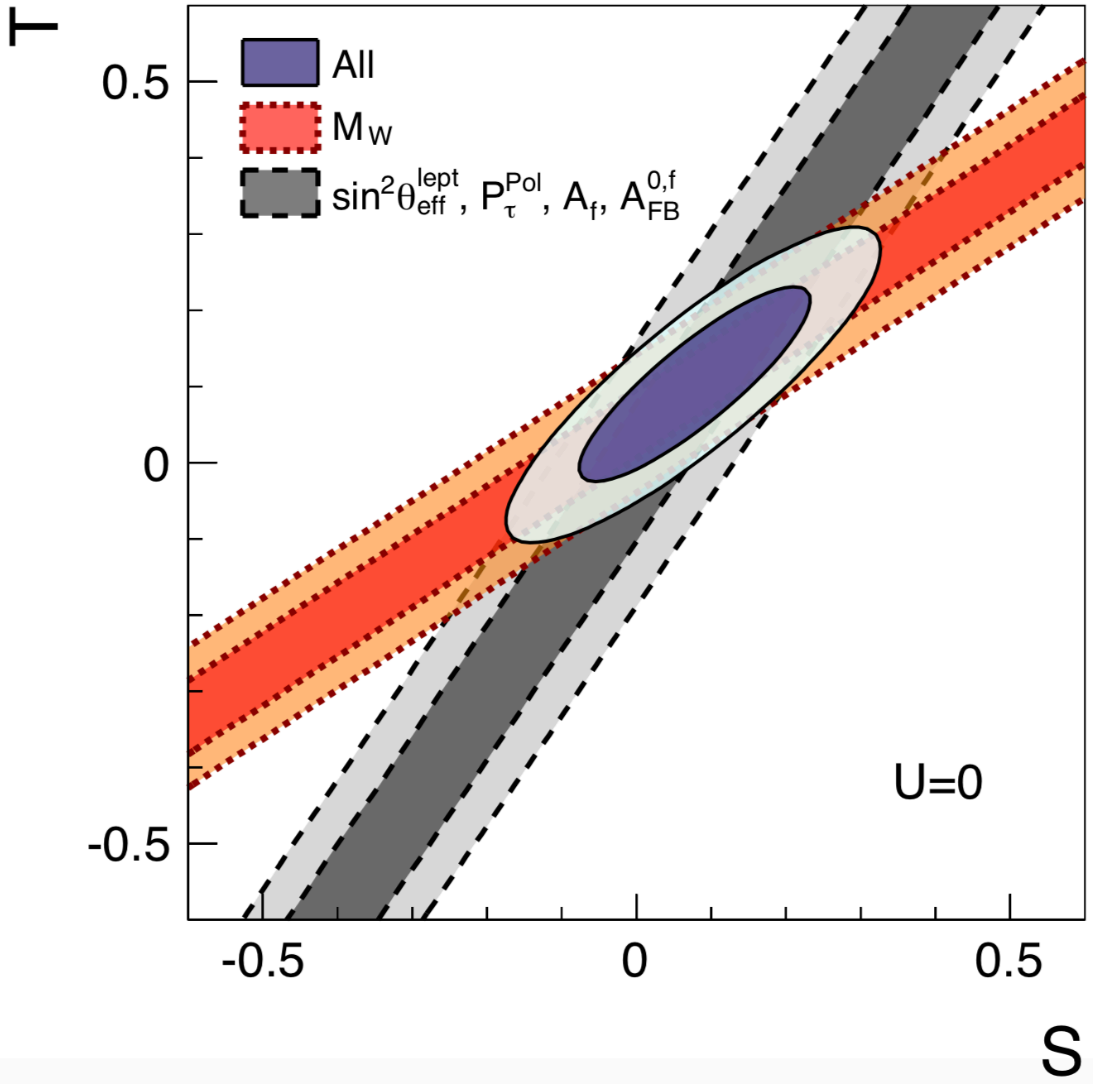


$$M_Z^2 = M_{Z0}^2 \frac{1 - \widehat{\alpha}(M_Z)T}{1 - G_F M_{Z0}^2 S/2\sqrt{2}\pi} ,$$

$$M_W^2 = M_{W0}^2 \frac{1}{1 - G_F M_{W0}^2 (S+U)/2\sqrt{2}\pi} ,$$

Before CDF-II

JHEP12(2016)135



Workflow

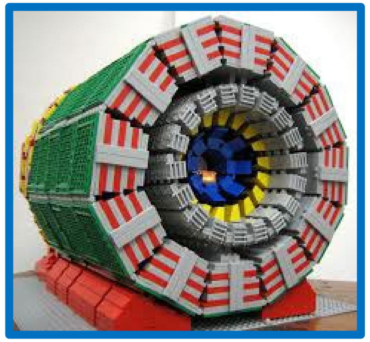
$m_{W,1}$ $m_{W,2}$ $m_{W,3}$

$$w_{\mathrm{MC}} \times \left(\frac{\varepsilon^A_{\mathrm{Data}}}{\varepsilon^A_{\mathrm{MC}}}\right) \times \left(\frac{\varepsilon^B_{\mathrm{Data}}}{\varepsilon^B_{\mathrm{MC}}}\right) \times \left(\frac{\varepsilon^C_{\mathrm{Data}}}{\varepsilon^C_{\mathrm{MC}}}\right) \times \cdots$$

$$p_{\mathrm{MC}} \to (1+\alpha)p_{\mathrm{MC}}$$

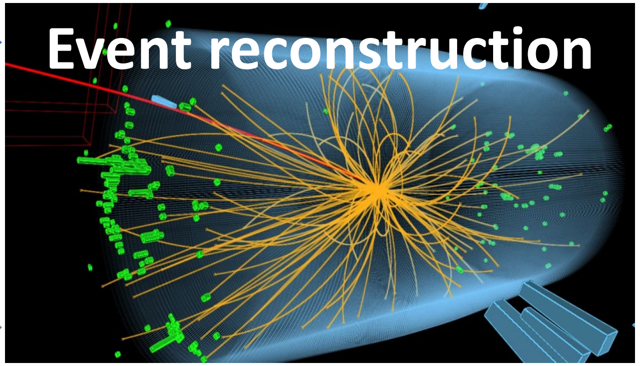
Monte Carlo
$pp \to \mu^{\pm} + X$

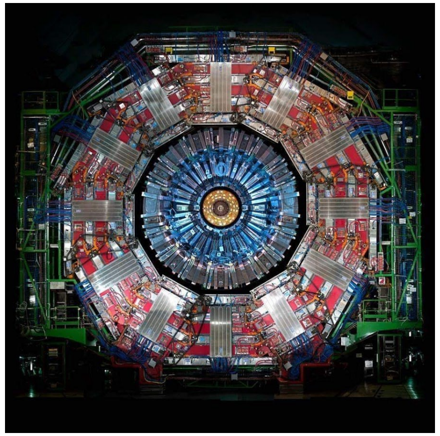
$\otimes$



MC

DATA

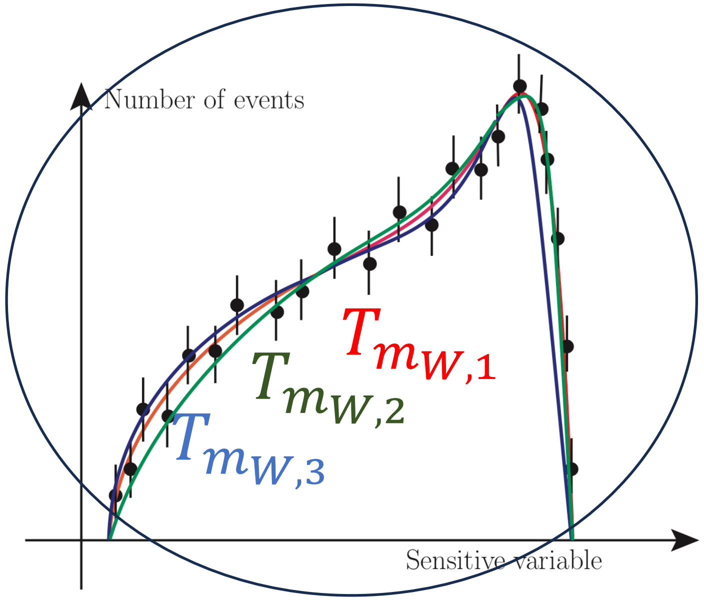




Detector

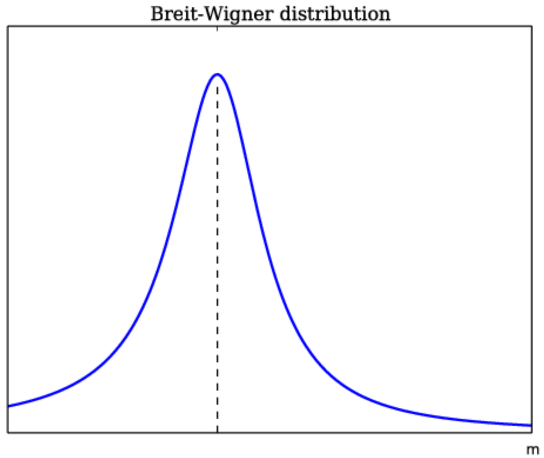
```
if( A && B && C ... ){
/* ... */
}
else{
/* ... */
}
```

Data analysis

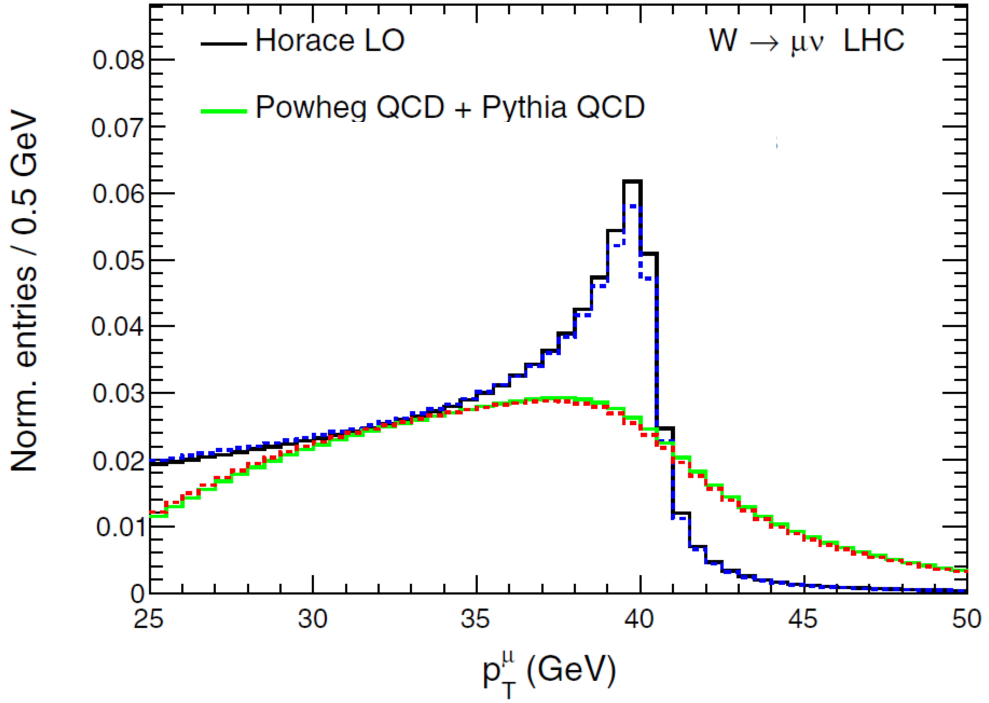


Measuring m_W at hadron colliders

- $W \to q\bar{q}$ unfeasible ➔ focus on $W \to \ell\nu$ decay
  - But: **ν's cannot be reconstructed**



m_W



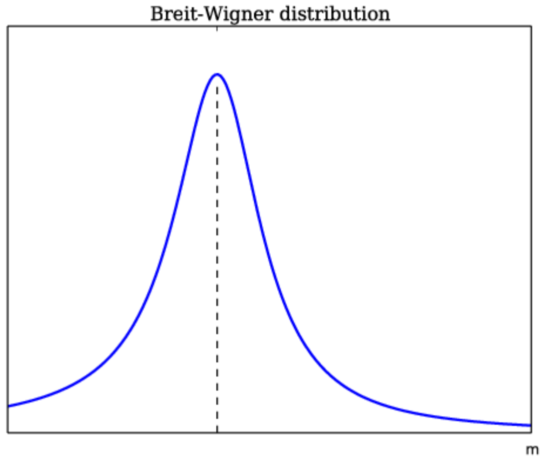
Lepton p_T^ℓ

- **GOOD**: enhancement at Jacobian peak
- **BAD**: very sensitive to W **dynamics**

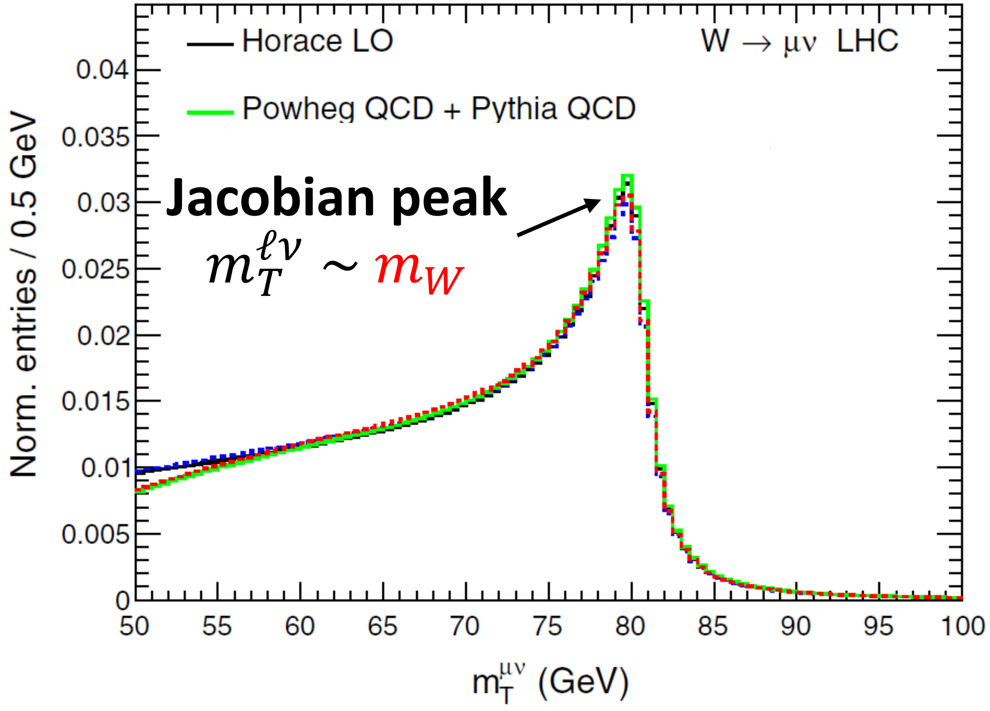
$$p_T^\ell \xrightarrow{\mathbf{p}_T^W} p_T^\ell\left(1 + \mathcal{O}\left(\frac{p_T^W}{m_W}\right)\right)$$

Measuring m_W at hadron colliders

- $W \to q\bar{q}$ unfeasible ➔ focus on $W \to \ell\nu$ decay
  - But: **ν's cannot be reconstructed**



m_W



"Transverse mass" $m_T^{\ell\nu}$

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

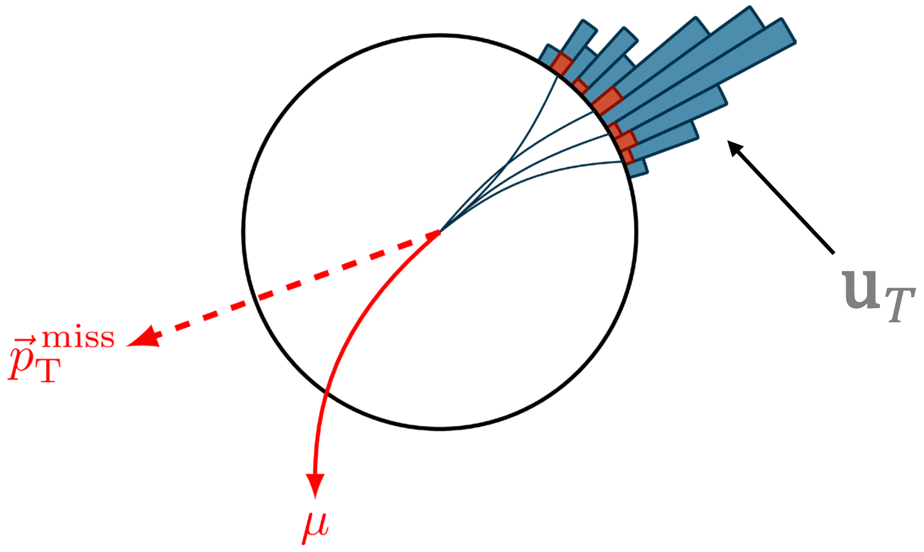
- **GOOD**: less sensitive to W dynamics

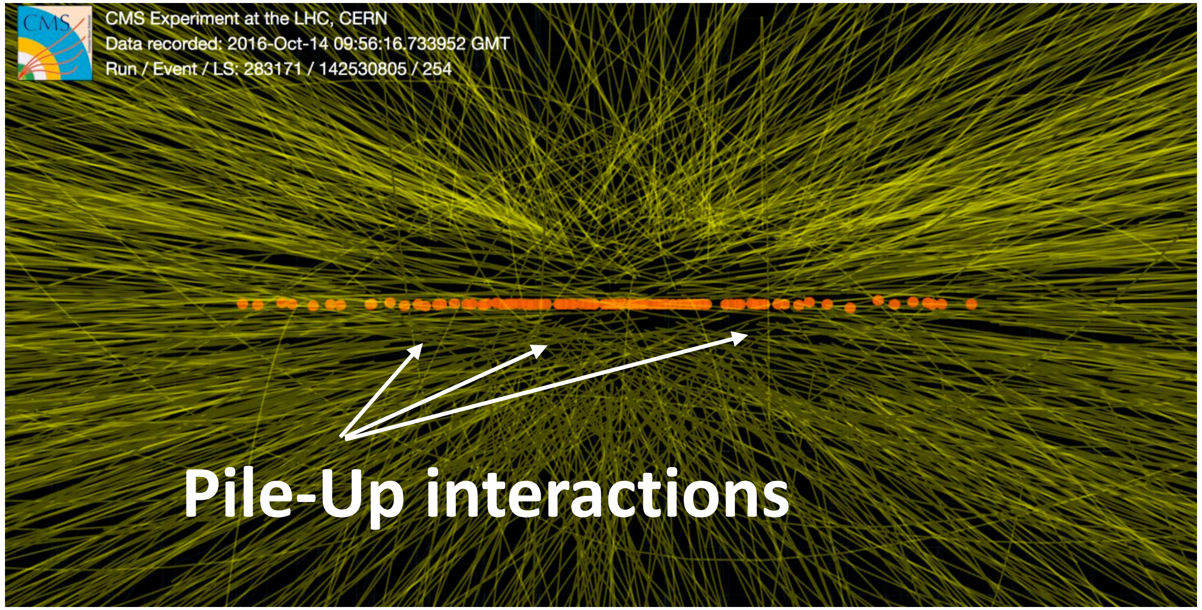
$$m_T^{\ell\nu} \overset{\mathbf{p}_T^W}{\Longrightarrow} m_T^{\ell\nu}\left(1 + \mathcal{O}\left(\frac{p_T^W}{m_W}\right)^2\right)$$

- **BAD**: requires knowledge of p_T^W

Measuring m_W at hadron colliders

- $\mathbf{p}_T^W \sim$ **hadronic recoil** $(\mathbf{u}_T)$
- $\mathbf{u}_T$ resolution degraded by Pile-Up

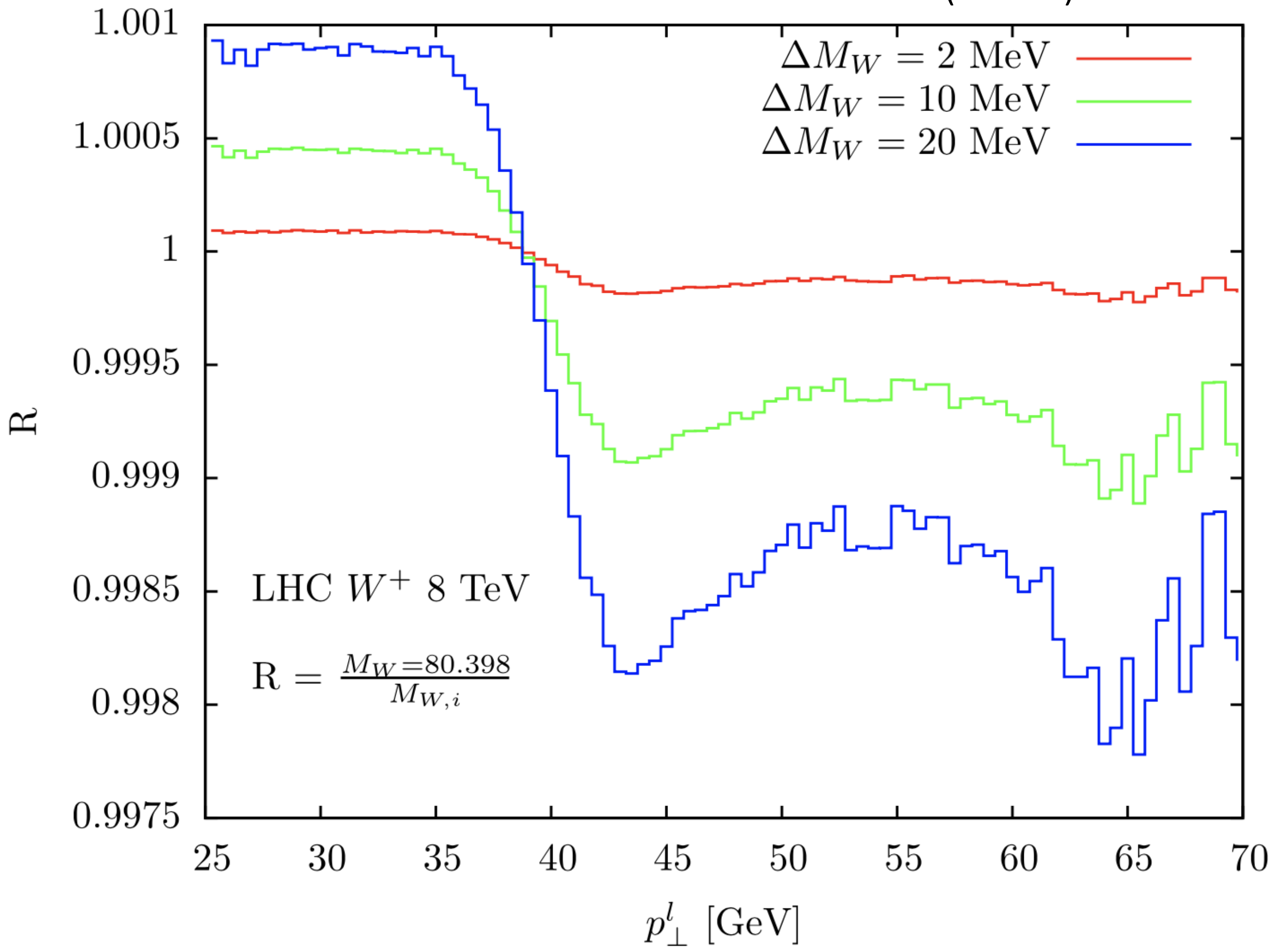




Experimental accuracy: p_T^l

Impact of a 10 MeV shift of M_W on the p_T^l spectrum → **0.1%**

PRD 91 (2015) 113005



- This is unlike other mass measurement which can rely on neat mass peaks
  - The full *W* production x decay chain must be modeled at the **1% level**

Profiling

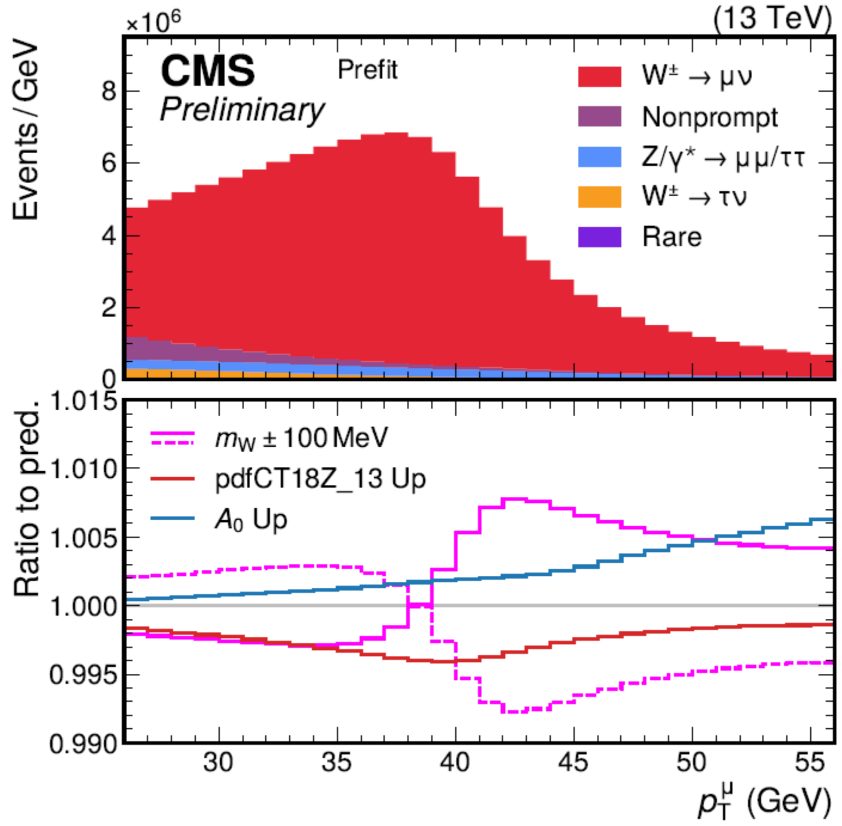
- Model uncertainties as Nuisance Parameters

$$-2\ln \mathscr{L}_{\mathrm{NP}}(\vec{\theta},\vec{\alpha}) = \sum_{i,j}\left(m_i - t_i(\vec{\theta}) - \sum_r \Gamma_{ir}(\alpha_r - a_r)\right) V_{ij}^{-1}\left(m_j - t_j(\vec{\theta}) - \sum_s \Gamma_{js}(\alpha_s - a_s)\right) + \sum_r (\alpha_r - a_r)^2.$$

  - Already considered in LHCb and ATLAS re-analysis

- Clear advantage when model uncertainties can be constrained by the data

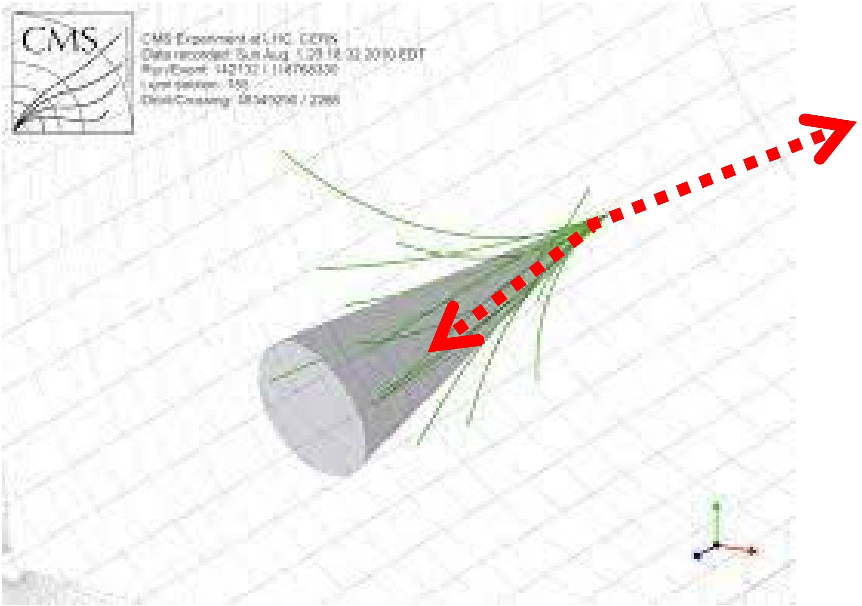
CMS-PAS-SMP-23-002

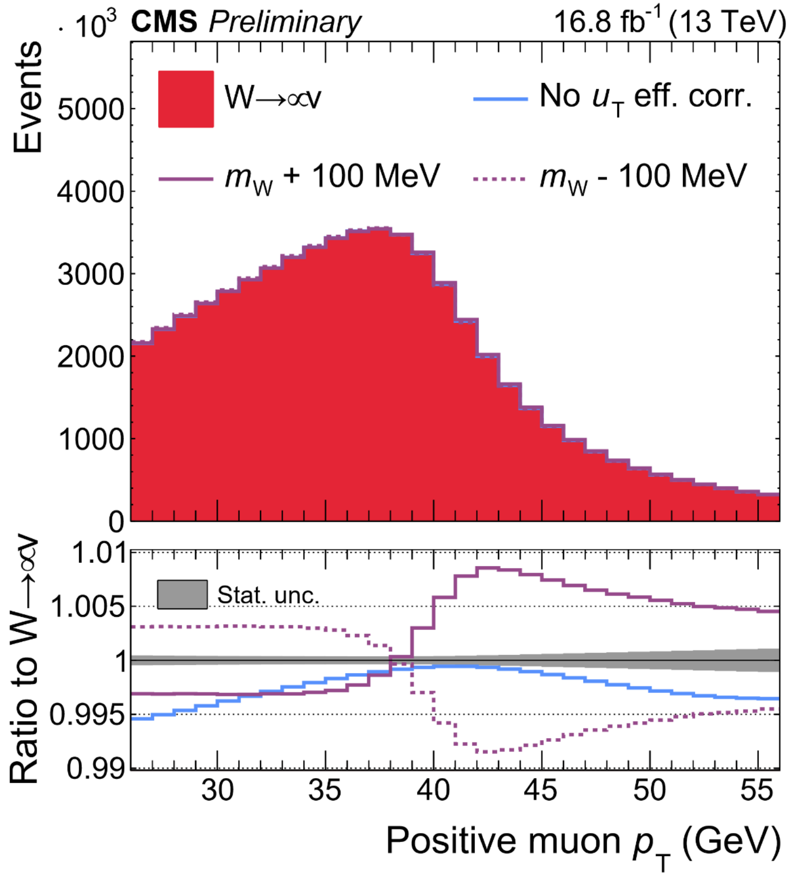


CMS-PAS-SMP-23-002

Muon isolation

- Special treatment of isolation efficiency needed to remove potential bias
  - Related to interplay with hadronic recoil





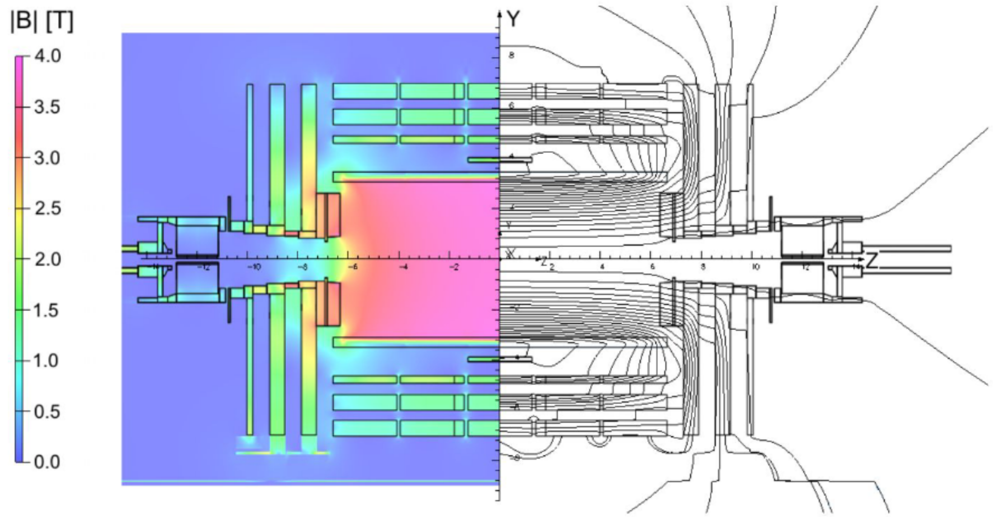
Isolation efficiencies in 3D: $p_T^\mu \times \eta^\mu \times (\hat{\boldsymbol{p}}_T^\mu \cdot \boldsymbol{u}_T)$

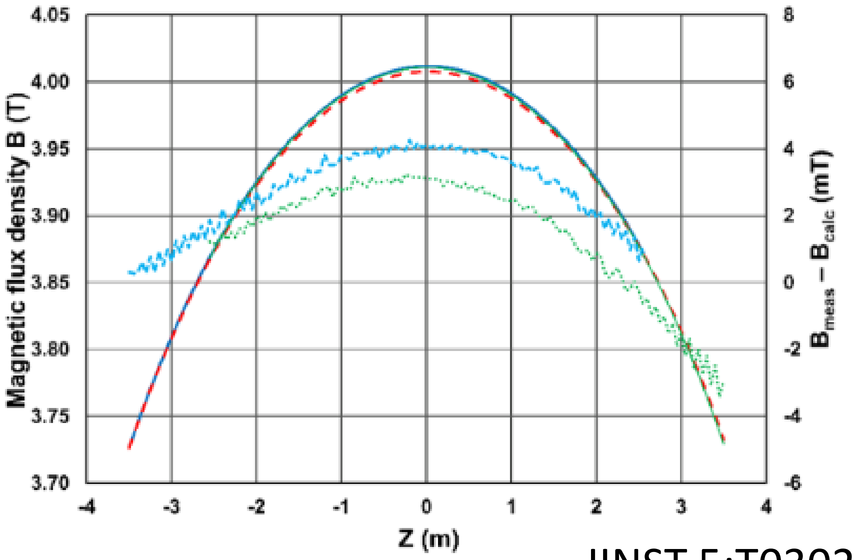
➔ ~ 7 MeV bias, if neglected

Track momentum

- B-field measured in 2006 at the **surface of the cavern** and with **empty coil**
  - Hall probes calibrated to $\mathbf{3 \times 10^{-4}}$
  - $\frac{\Delta B}{B} = -8 \times 10^{-4}$ between surface and *in situ* NMR survey
- Track fit uses a TOSCA map for B-field
  - Differences up to $\mathbf{2}$ mT compared to *in situ* survey (with some z –dependence)

B-field known a priori within $< 10^{-3}$





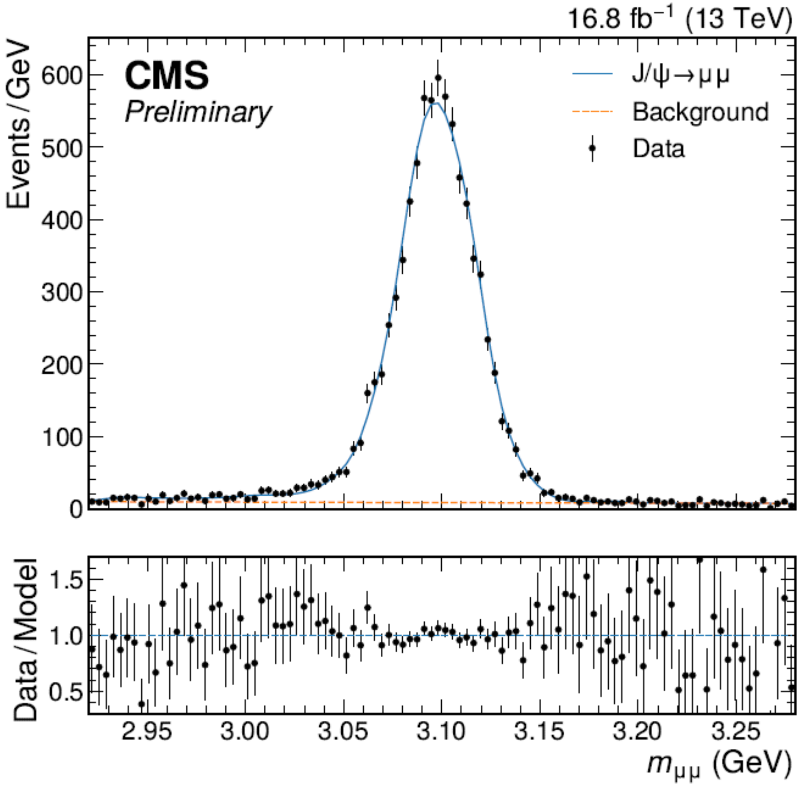
(b)

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

Muon momentum scale

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

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

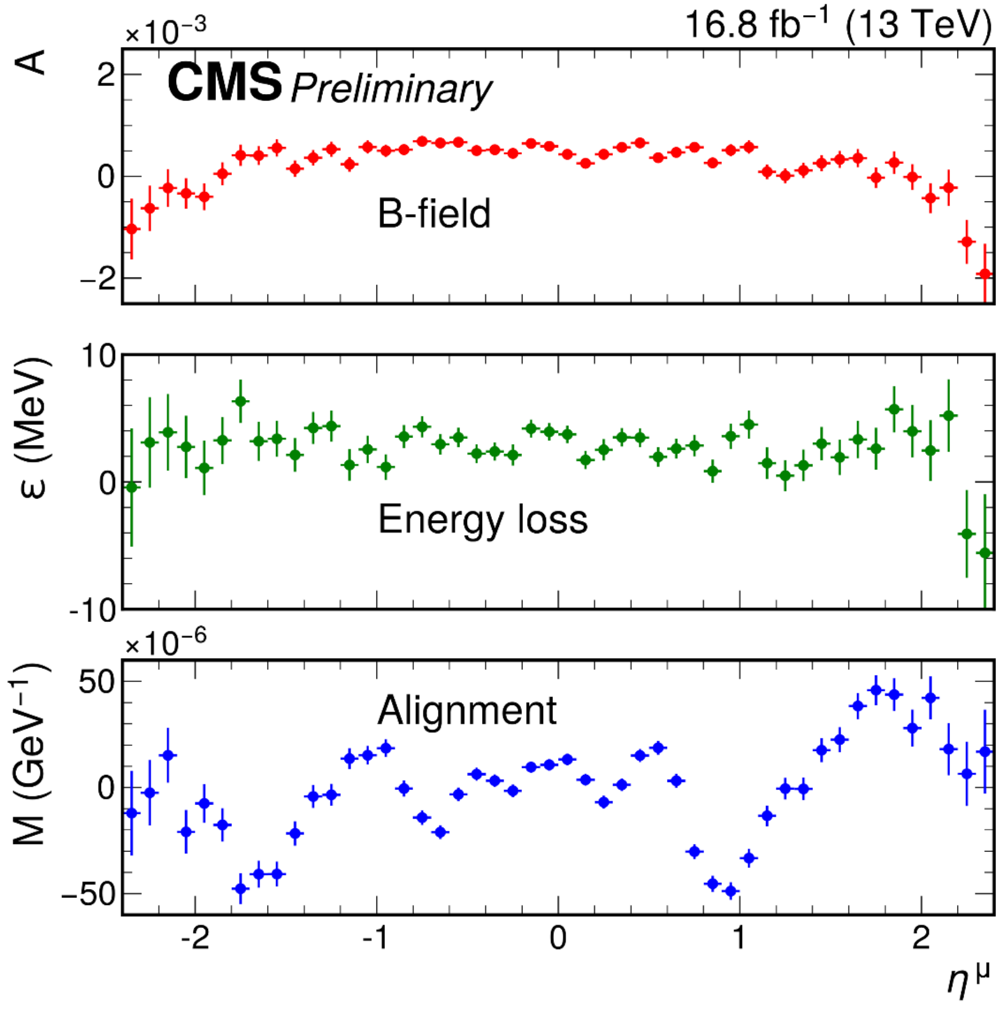


- Fit a **scale shift $\boldsymbol{\Sigma}$** in each 4D bin
- Finally, do a χ^2 fit of $(A_\eta, \varepsilon_\eta, M_\eta)$ from all bins

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

Parametrized scale corrections

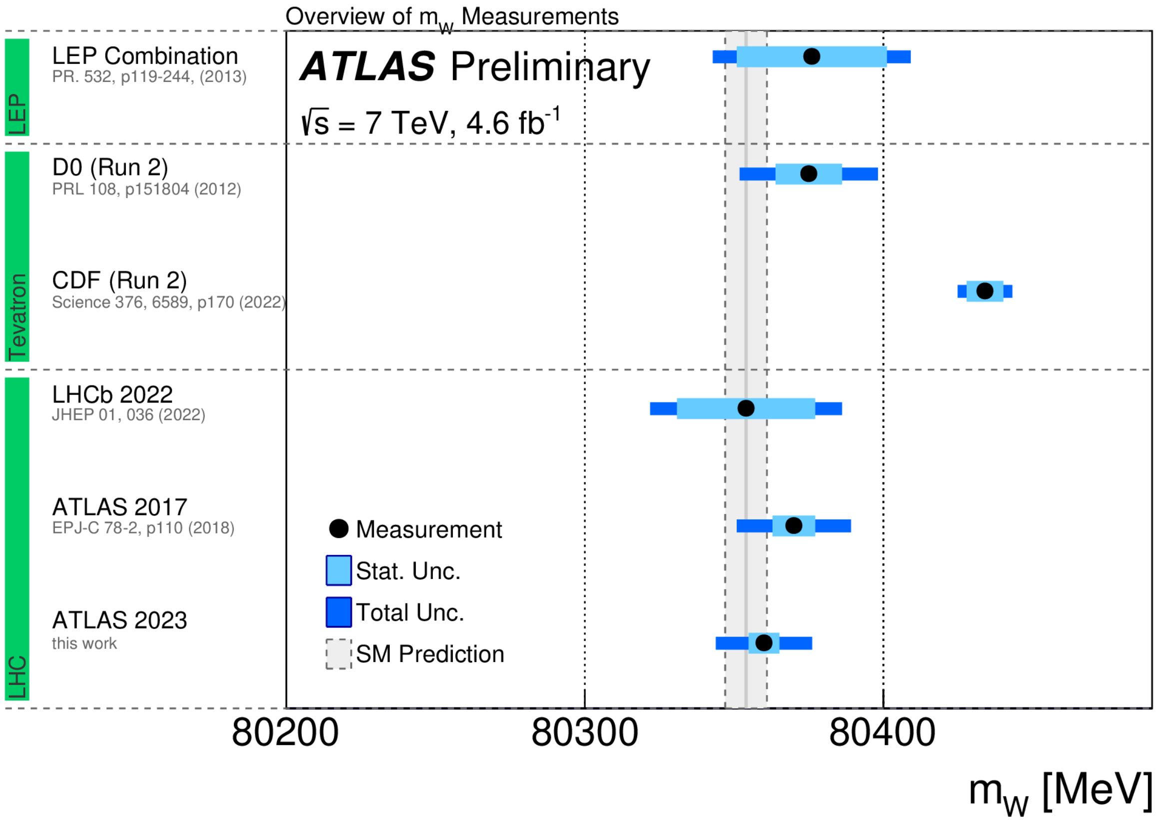
- Scale correction in the range $(5 \div 10) \times 10^{-4}$
- Model suited for extrapolating scale correction/uncertainty at any value of p_T



Impact on m_W

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

SUmmary



Overview of m_W Measurements
ATLAS Preliminary
$\sqrt{s}$ = 7 TeV, 4.6 fb^{-1}
LEP
LEP Combination
PR. 532, p119-244, (2013)
Tevatron
D0 (Run 2)
PRL 108, p151804 (2012)
CDF (Run 2)
Science 376, 6589, p170 (2022)
LHC
LHCb 2022
JHEP 01, 036 (2022)
ATLAS 2017
EPJ-C 78-2, p110 (2018)
ATLAS 2023
this work
Measurement
Stat. Unc.
Total Unc.
SM Prediction
80200
80300
80400
m_W [MeV]

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

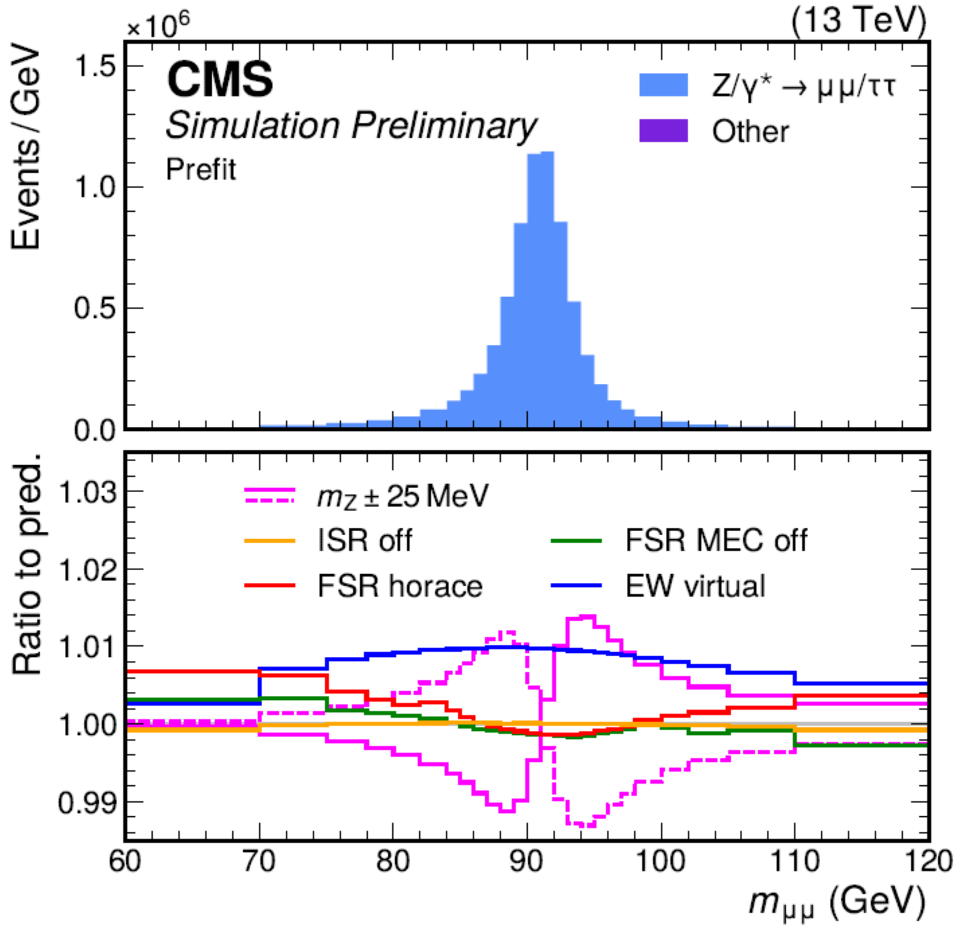
Further checks

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

EWK uncertainties

- Photos++ is used for FSR modeling at LL+MEC level + pair-production
  - uncertainty from MEC on/off and full Horace/Photos++ difference
- Uncertainty from missing virtual EW corrections using
  - ReneSANCe program (for W)
  - POWHEG-BOX-V2 (for Z)
- Photon ISR from Pythia
  - Uncertainty from QED PS on/off

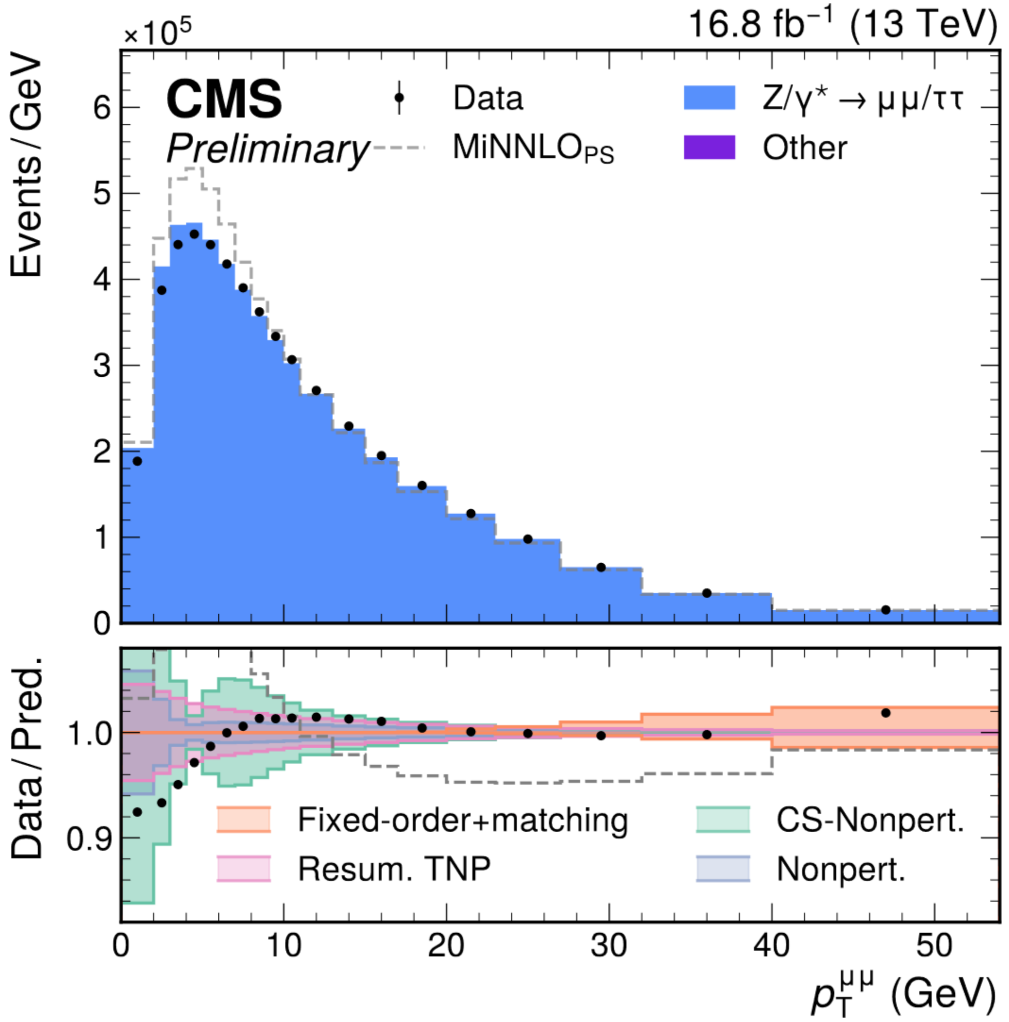


Non perturbative

- Relevant for $p_T^V \lesssim 5$ GeV
- Empirical model inspired by TMD PDFs
  - NP-model for the Collins-Soper kernel inspired/tuned on lattice data (flavor-independent)
  - Intrisic parton flavour inspired by TMD-PDFs (x-dependent)

$$\tilde{\sigma}^{\rm np}(Y) = \left[1 + \overline{\Lambda}^{(2)}(Y)\, b_T^2\right]^2 \exp(-2\Lambda^{(4)}\, b_T^4)\,,$$

JHEP07(2022)129



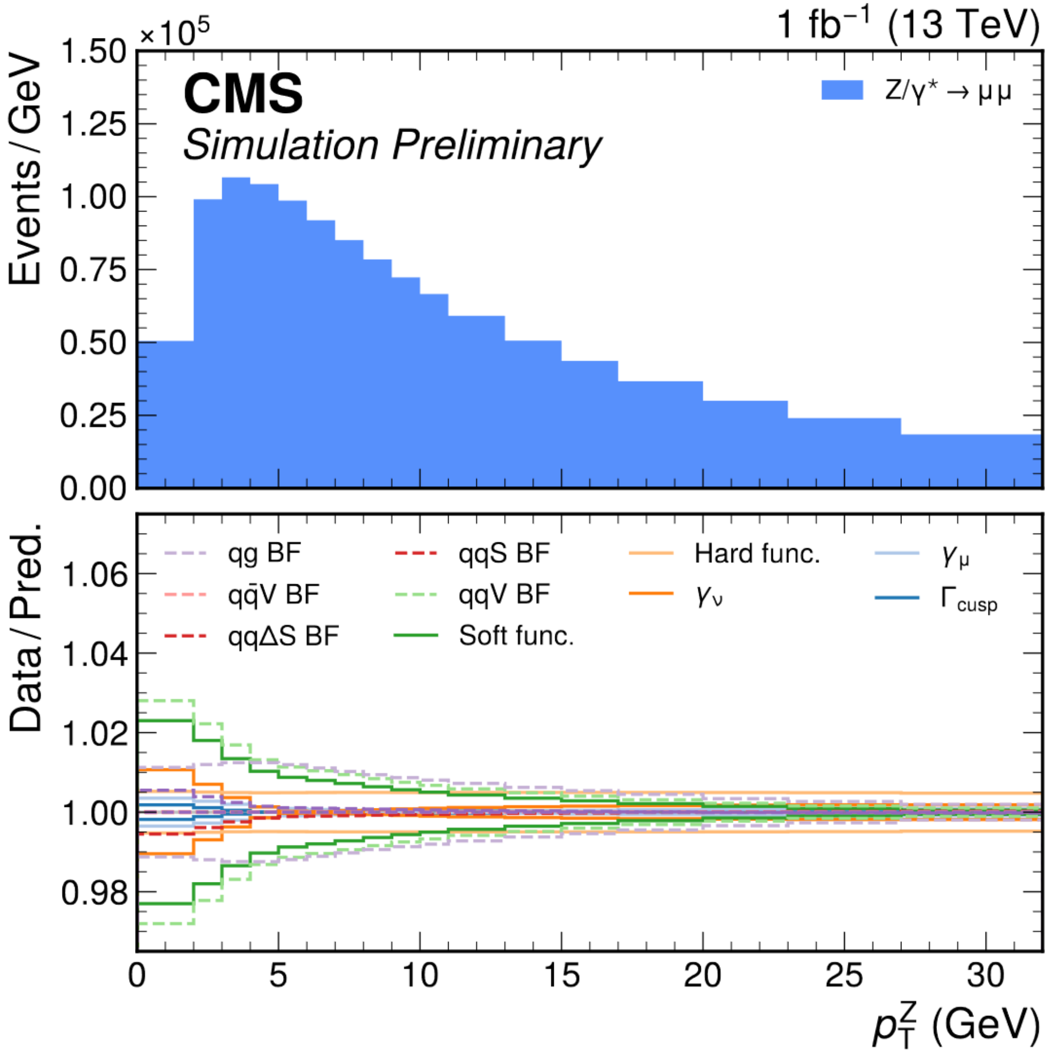
TNP

talk

- Relevant for $5 \lesssim p_T^V \lesssim 20$ GeV
- Theory Nusiance Parameteres ➔ Treat uknown numerical coefficients in series expansion as uknown nuisance parameter

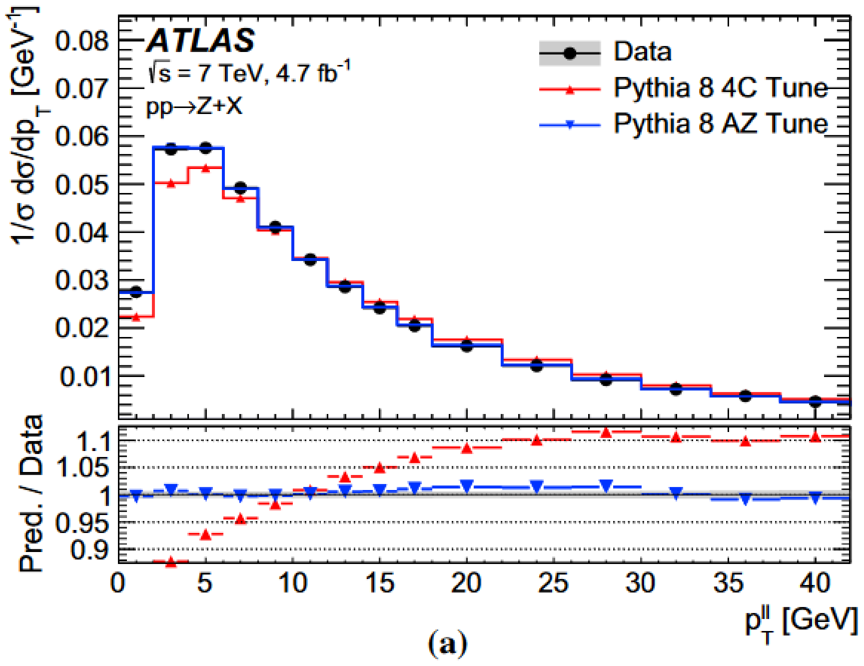
$$f^{\text{predicted}}(\alpha) = f_0 + f_1\,\alpha + f_2\,\alpha^2 + f_3(\theta_3)\,\alpha^3$$

- Better suited than scale variations
- Provide a frameweork to correlate across phase-space and NC/CC

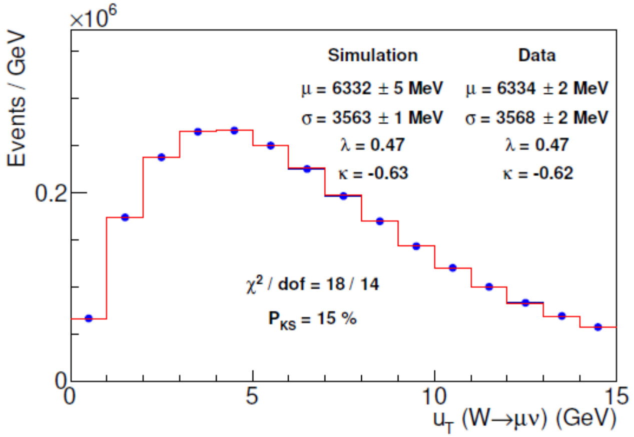


Eur. Phys. J. C (2018) 78:110

Model-dependent uncertainties



- Traditional approach (e.g. ATLAS):
  - Tuning of PS on ptZ data ➔ Systematics correlated across W/Z do not proapagte to pTW
  - Large effect (5 MeV) from muF variation fo c/b
  - Would have been 30 MeV for fully uncorrelated
  - CDF Further reduction (x4.4) of pTW/pTZ uncertainty by constraining pTW on data



- Uncertainties of flavour correlation in PS / NP models well known

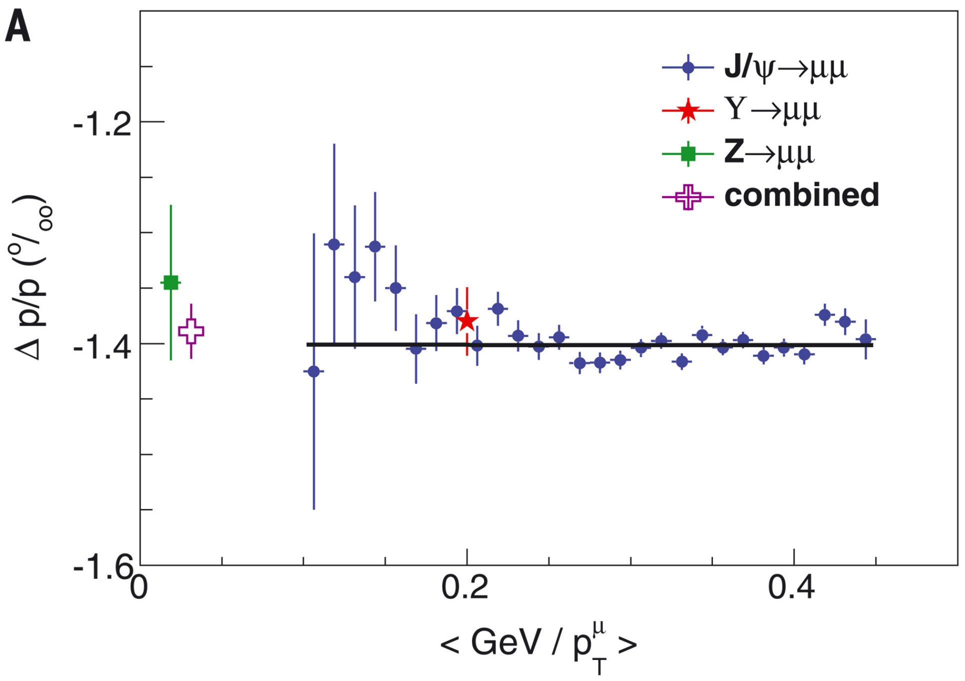
PLB 788 (2019) 542

- Usage of MC program with reduced theoretical accuracy was another point of concern
  - Can be overcome now

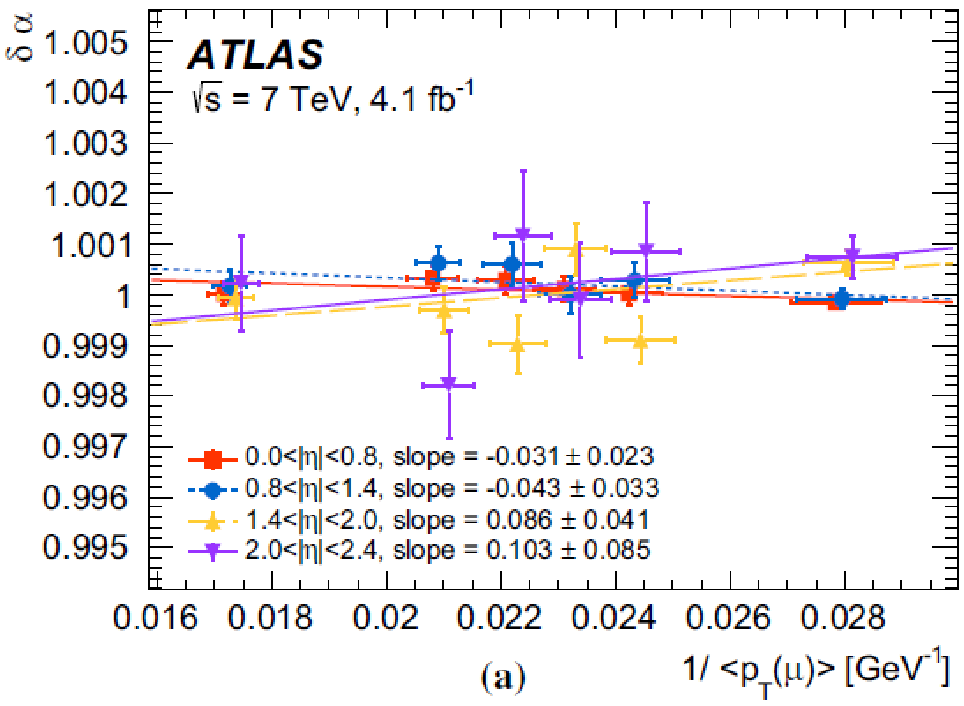
Model

- Assessment of per-muon scale is new
  - Previous experiments looked at dimuon mass scale stability vs "average"

Science 376 (2022) 6589



EPJC 78 (2018) 110



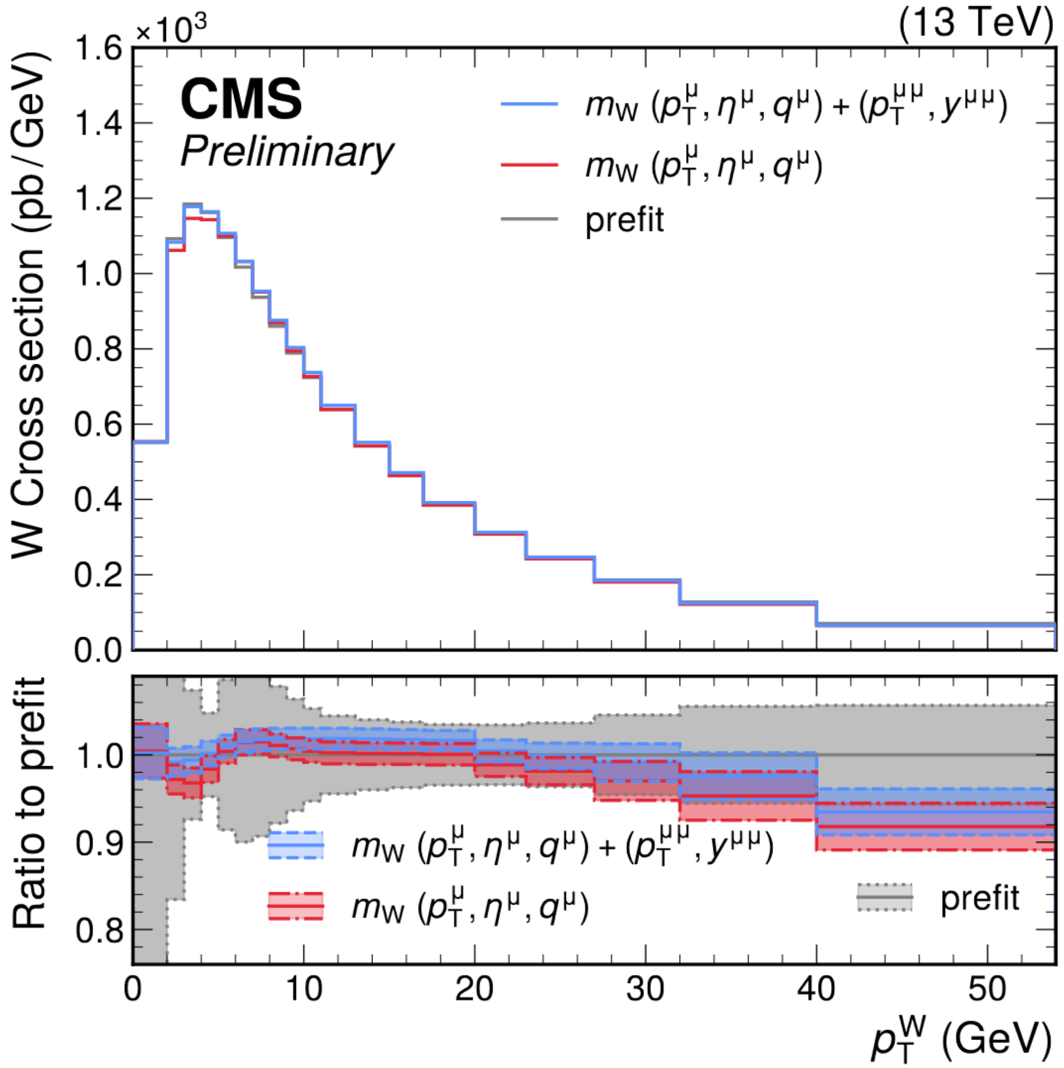
$$M_Z = 91\ 192.0 \pm 6.4_{\rm stat} \pm 4.0_{\rm syst}\ \rm MeV$$

$$[\Delta p/p]_{J/\psi+\Upsilon+Z} = (-1389 \pm 25)\ \rm ppm$$

W: p_T^W modeling

- Postfit p_T^W spectra from two alterantive fits are compared:
  - (q, p_T^μ, η^μ)
  - (q, p_T^μ, η^μ) and (p_T^Z, y^Z)

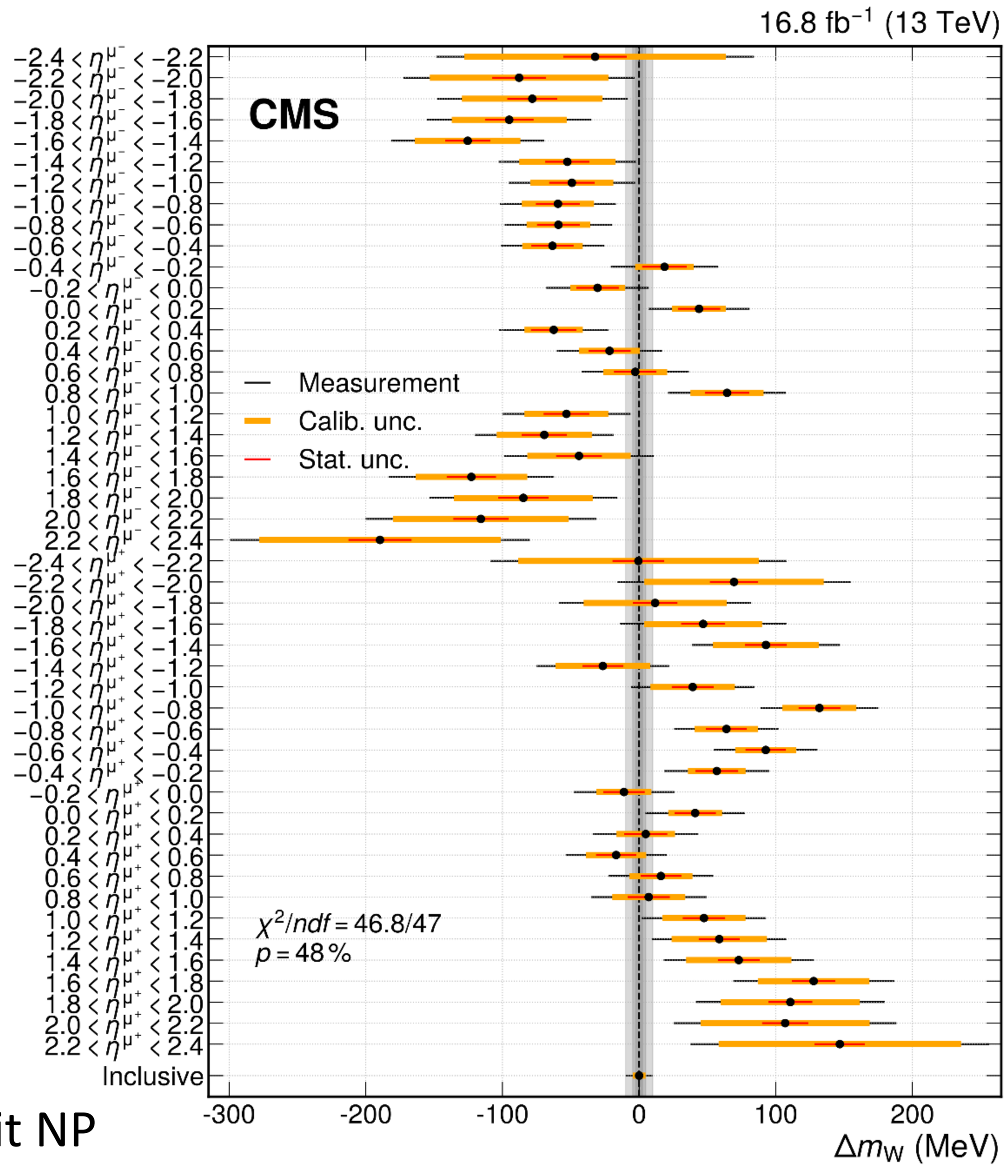
- Only a marginal gain from simultaneous fit
  - A feature of the largely uncorrelated uncertainty model



Charge asymmetry

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

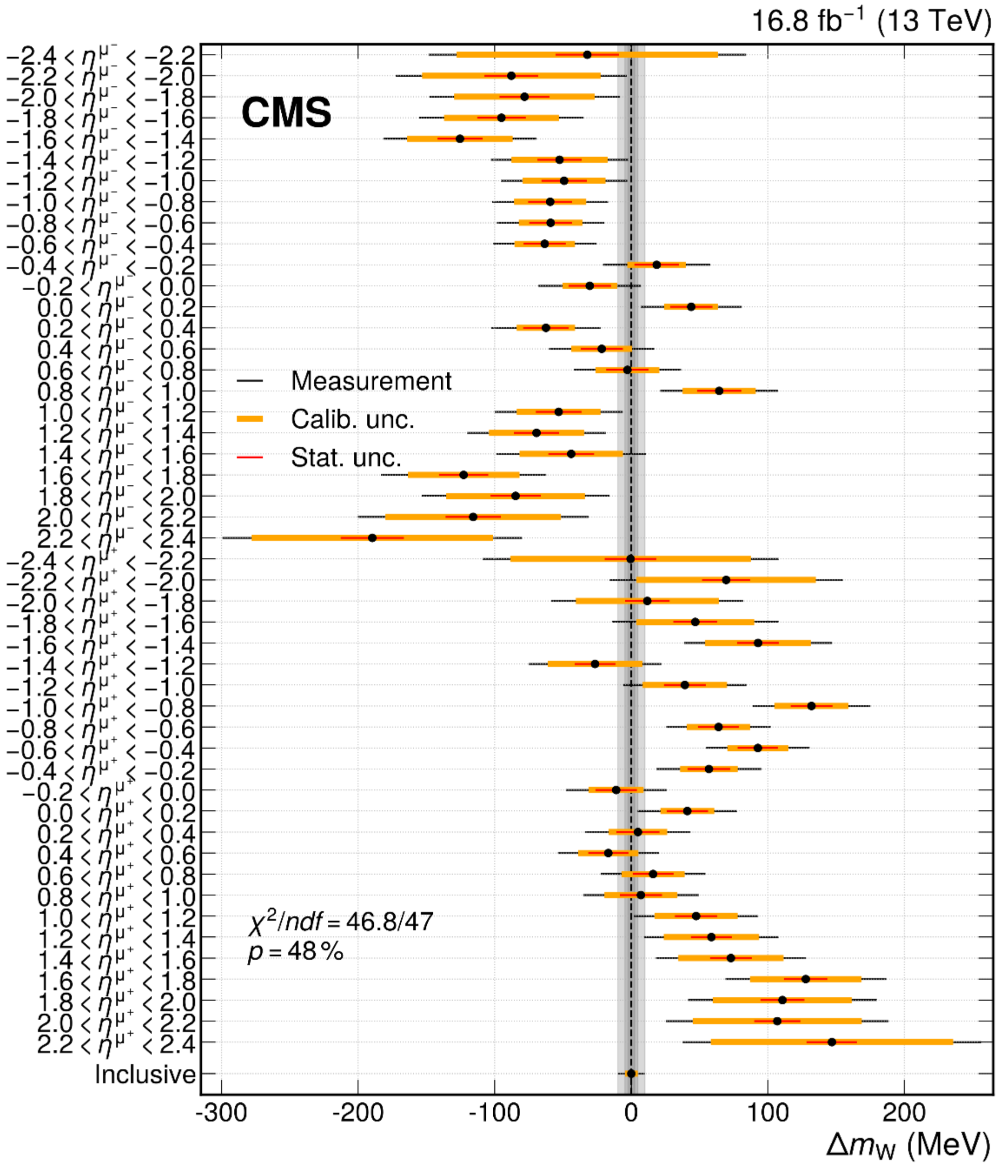
Source of uncertainty	Global impact (MeV) in $m_{Z^+} - m_{Z^-}$	in m_Z	in $m_{W^+} - m_{W^-}$	in m_W
Muon momentum scale	21.2	5.3	20.0	4.4
Muon reco. efficiency	6.5	3.0	5.8	2.3
W and Z angular coeffs.	13.9	4.5	13.7	3.0
Higher-order EW	0.2	2.2	1.5	1.9
p_T^V modeling	0.4	1.0	2.7	0.8
PDF	0.7	1.9	4.2	2.8
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

Charge asymmetry

- $m_{W^+} - m_{W^-} = \mathbf{57 \pm 30\ MeV}$
  - p-value = 6%
  - $\mathrm{Corr}(m_{W^+}, m_{W^-}) = -0.40$
  - $\mathrm{Corr}\left(m_{W^+} - m_{W^-}, \frac{m_{W^+} + m_{W^-}}{2}\right) = 0.02$
  - For comparison: $m_{Z^+} - m_{Z^-} = 31\ (6) \pm 32$ MeV



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

CMS-PAS-SMP-23-002

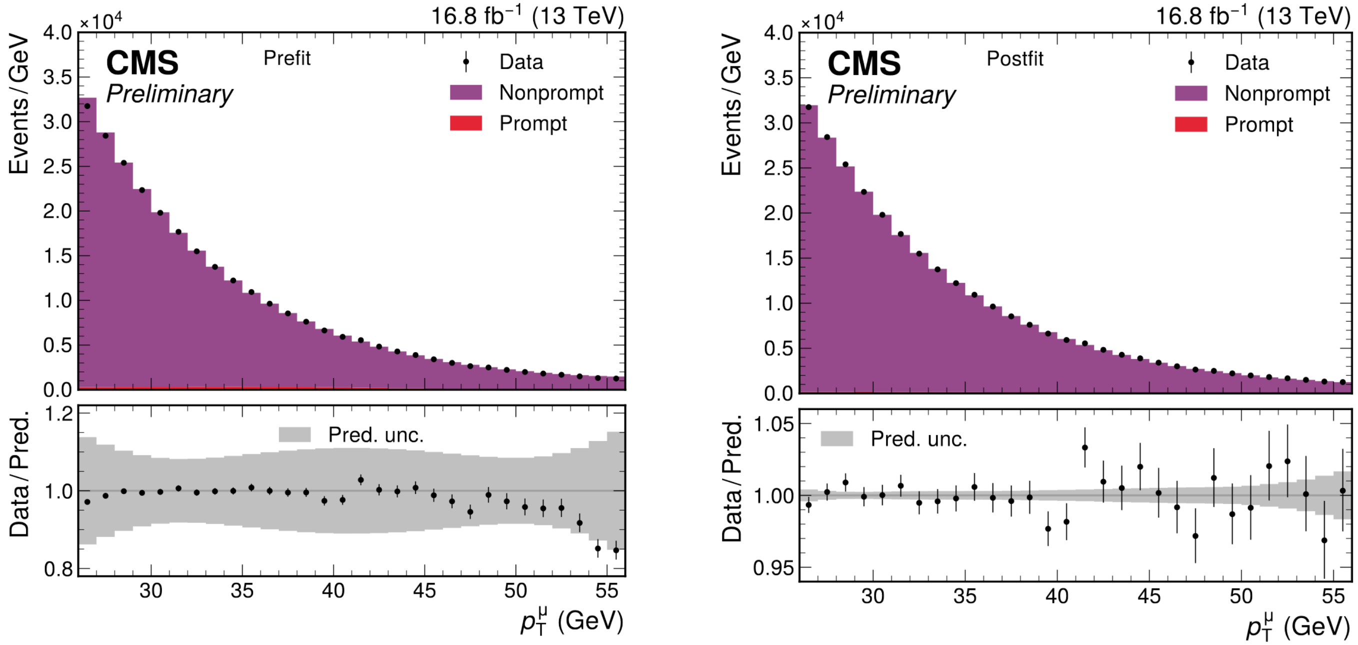
Science 376 (2022) 6589

Summary of uncertainty model

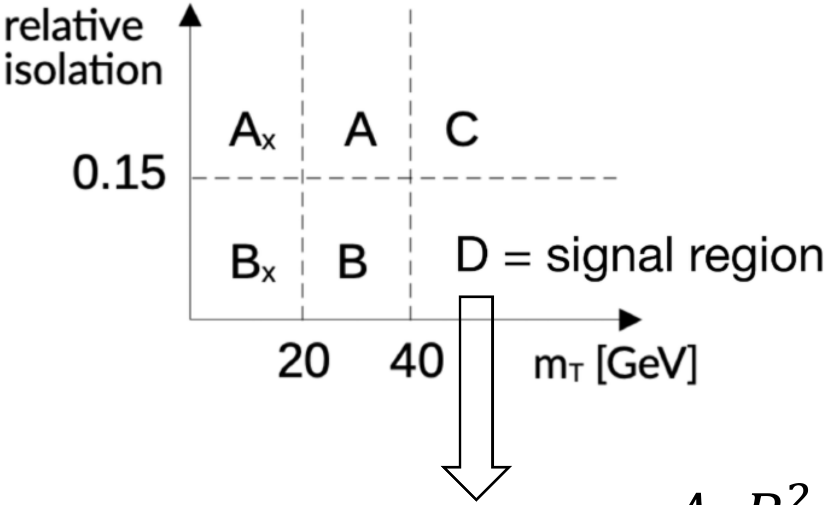
<table>
<tr><th>Systematic uncertainties</th><th>W-like m_Z</th><th>m_W</th></tr>
<tr><td>Muon efficiency</td><td>3127</td><td>3658</td></tr>
<tr><td>Muon eff. veto</td><td>–</td><td>531</td></tr>
<tr><td>Muon eff. syst.</td><td colspan="2">343</td></tr>
<tr><td>Muon eff. stat.</td><td colspan="2">2784</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>

QCD background

- Mostly muons from B/C hadrons decay (~85%)
- Data-driven estimation using an extrended ABCD method based on $relIso$: m_T
  - Validated with QCD simulation and SV-sideband



In each (η, p_T) bin:

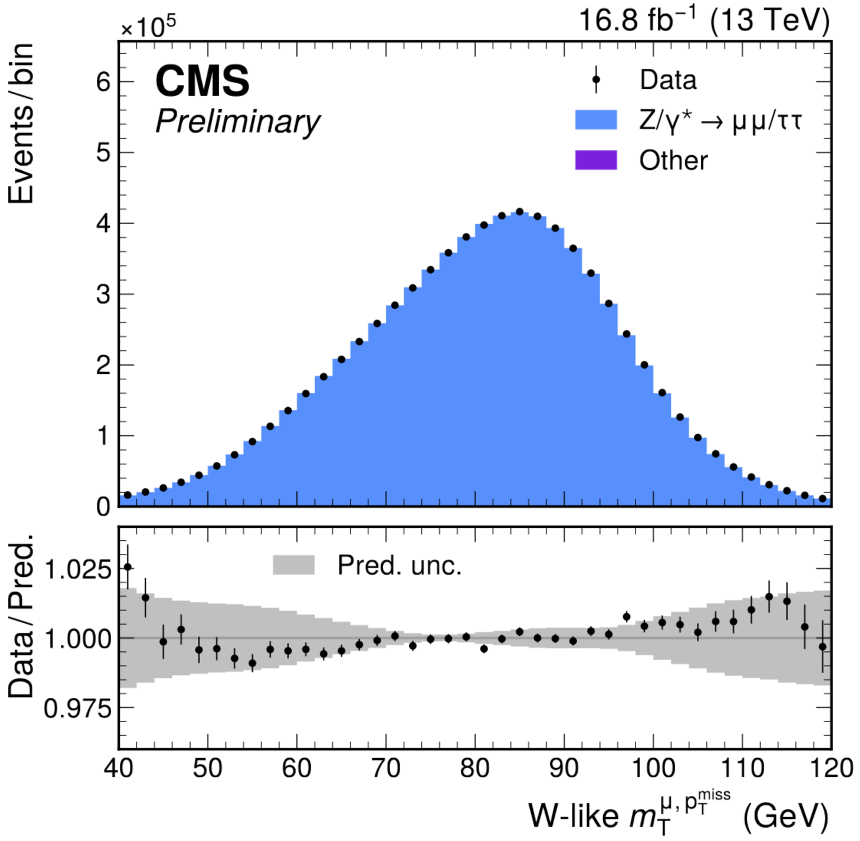


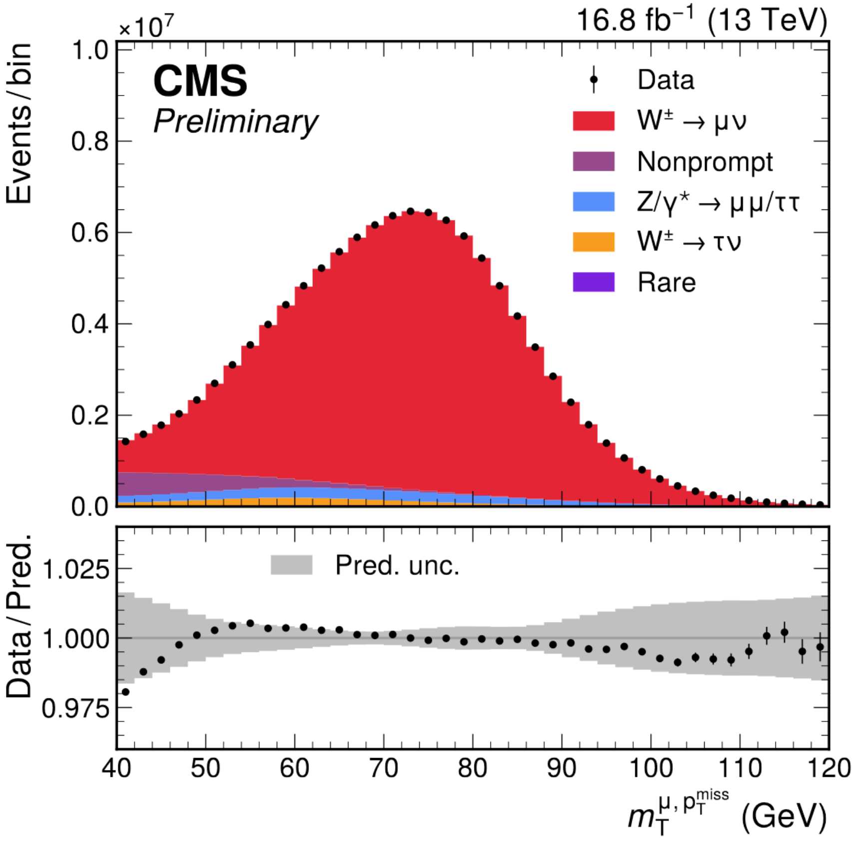
$$D = C \cdot \frac{A_x B^2}{A_x A^2}$$

- Functional dependence of each region on p_T is enforced:

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

Recoil

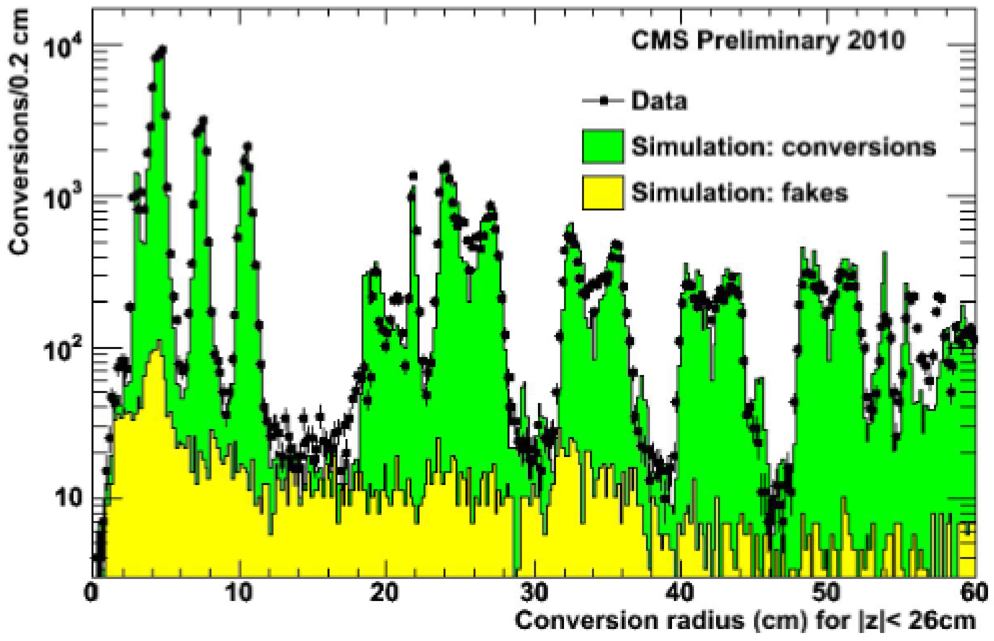

CMS
Preliminary
16.8 fb^{-1} (13 TeV)
Data
$Z/\gamma^* \to \mu\mu/\tau\tau$
Other
Events/bin
×10^5
Pred. unc.
Data/Pred.
W-like $m_T^{\mu, p_T^{miss}}$ (GeV)


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

Example: CMS

CMS-TRK-10-003

- Typical muon from W decay in CMS looses $\boldsymbol{\Delta E \approx 20-60}$ **MeV** by ionization
- Material known within 10% from detector simulation



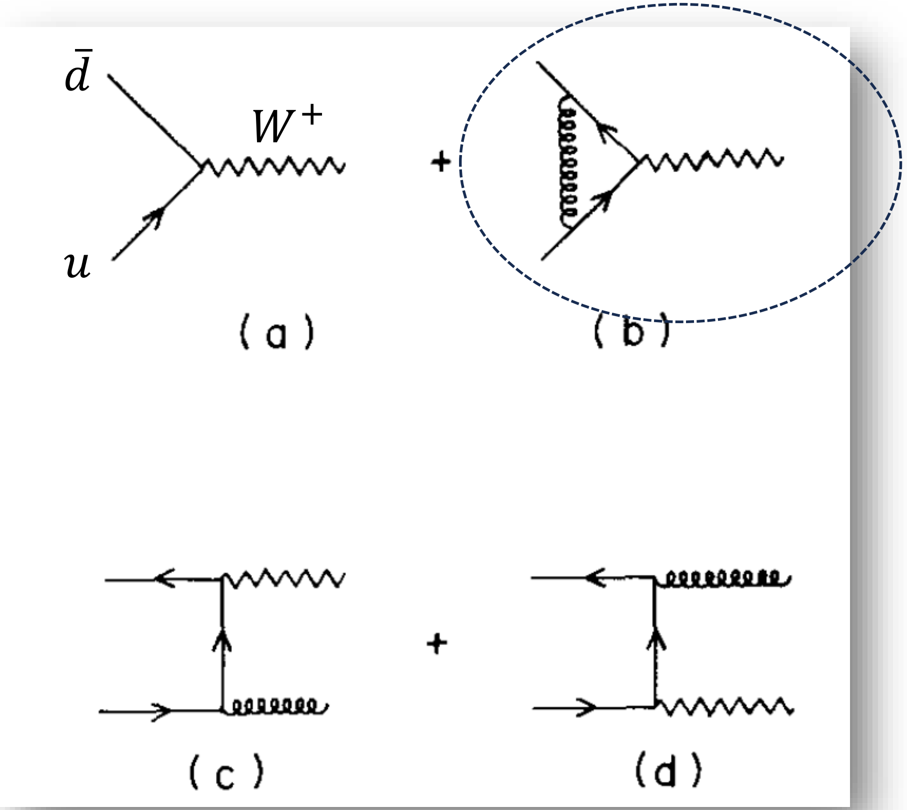
10% material mismodeling
➔ $\Delta|\mathbf{p}| = 2-6$ MeV

- Some (known) approximations in Kalman-Filter tracking
  - Speed vs accuracy compromise

The W recoil in pQCD

See e.g. G. Altarelli et al.
Nucl. Phys B 157 (1979) 461

$p_T^W = 0$



$\mathcal{O}(\alpha_s)$

$p_T^W \neq 0$

$\mathcal{O}(\alpha_s)$

Divergences cancel
exactly for inclusive observables

For less inclusive observables
*large **logarithmic** terms are left-over*

State of the art in resummation

Slides from
D. Froidevaux

Different techniques of resummation

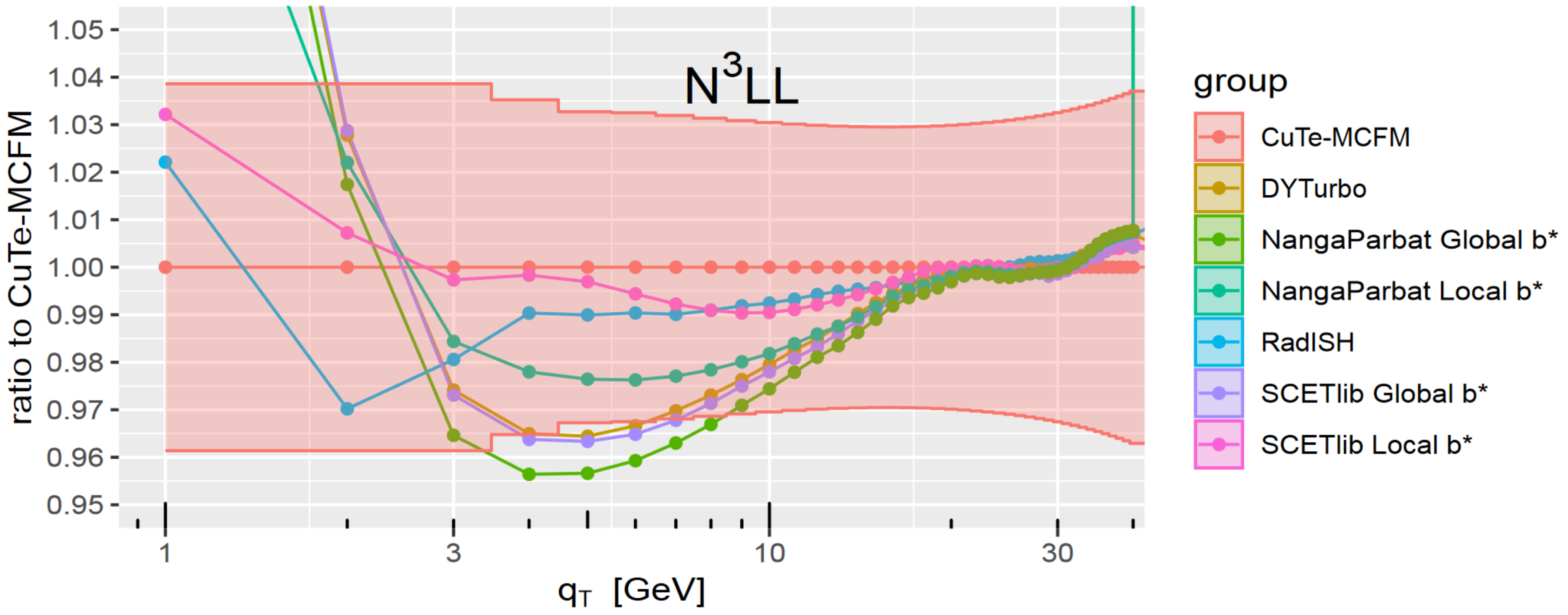
➔ *(sub-leading) differences expected a priori*

	Sudakov/ Resummation	Non-Sudakov	Matching
arTeMiDe	$\mu_f\ (\mu, \zeta_\mu)$	μ_{OPE}	No level 3
Cute-MCFM	μ, μ_h, r	μ_R, μ_F	Parameters of damping func.
DYTURBO	Q	μ_R, μ_F	Parameters of Damping func.
NangaParbat	Q, μ_b	μ_R, μ_F	Still none (damping func.)
RadISH	Q	μ_R, μ_F	Parameters of Damping func.
ResBos	C_1, C_2, C_3	μ_R, μ_F	Parameters of damping func.
Resolve	μ_S	μ_R, μ_F	No level 3
SCETlib	Δ_{resum}	Δ_{FO}	Profile scales Δ_{match}

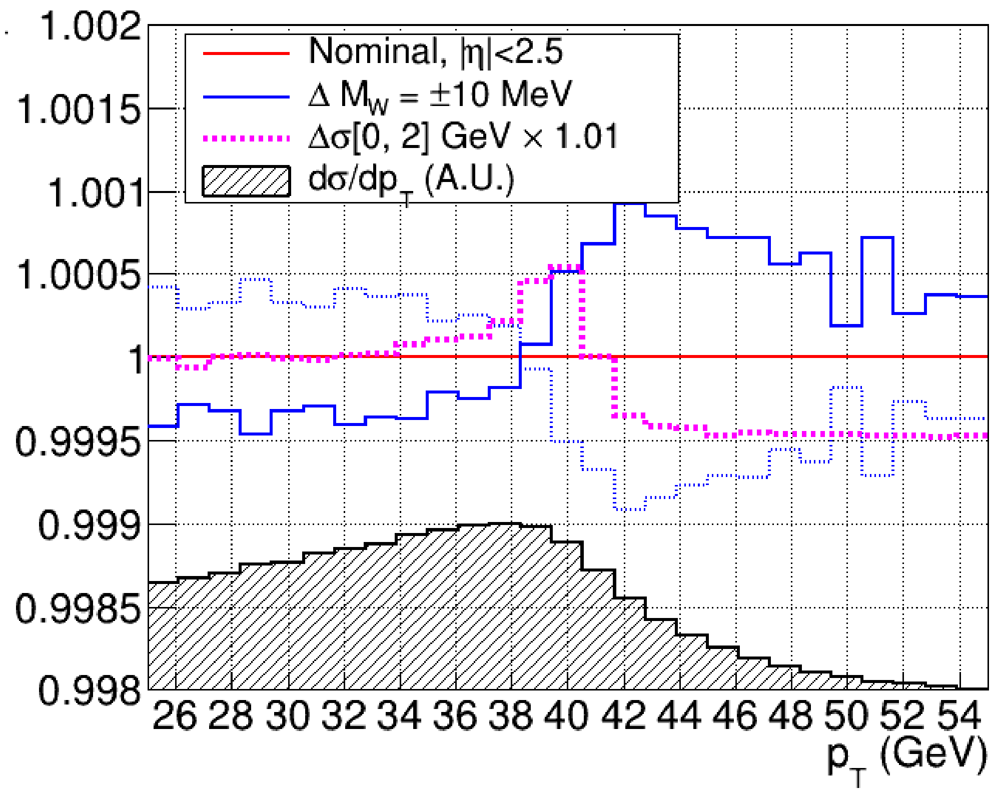
[Figure credit: V. Bertone, November '21]

State of the art

Slides from
[T. Neumann]



How well do we need to know it?



Sliding line: $\frac{d\sigma}{dp_T^W} \longrightarrow \frac{d\sigma}{dp_T^W}\left[1 + \mathbf{1\%} \cdot \delta(p_T^W - p_{T,k}^W)\right]$

Model-dependent uncertainties

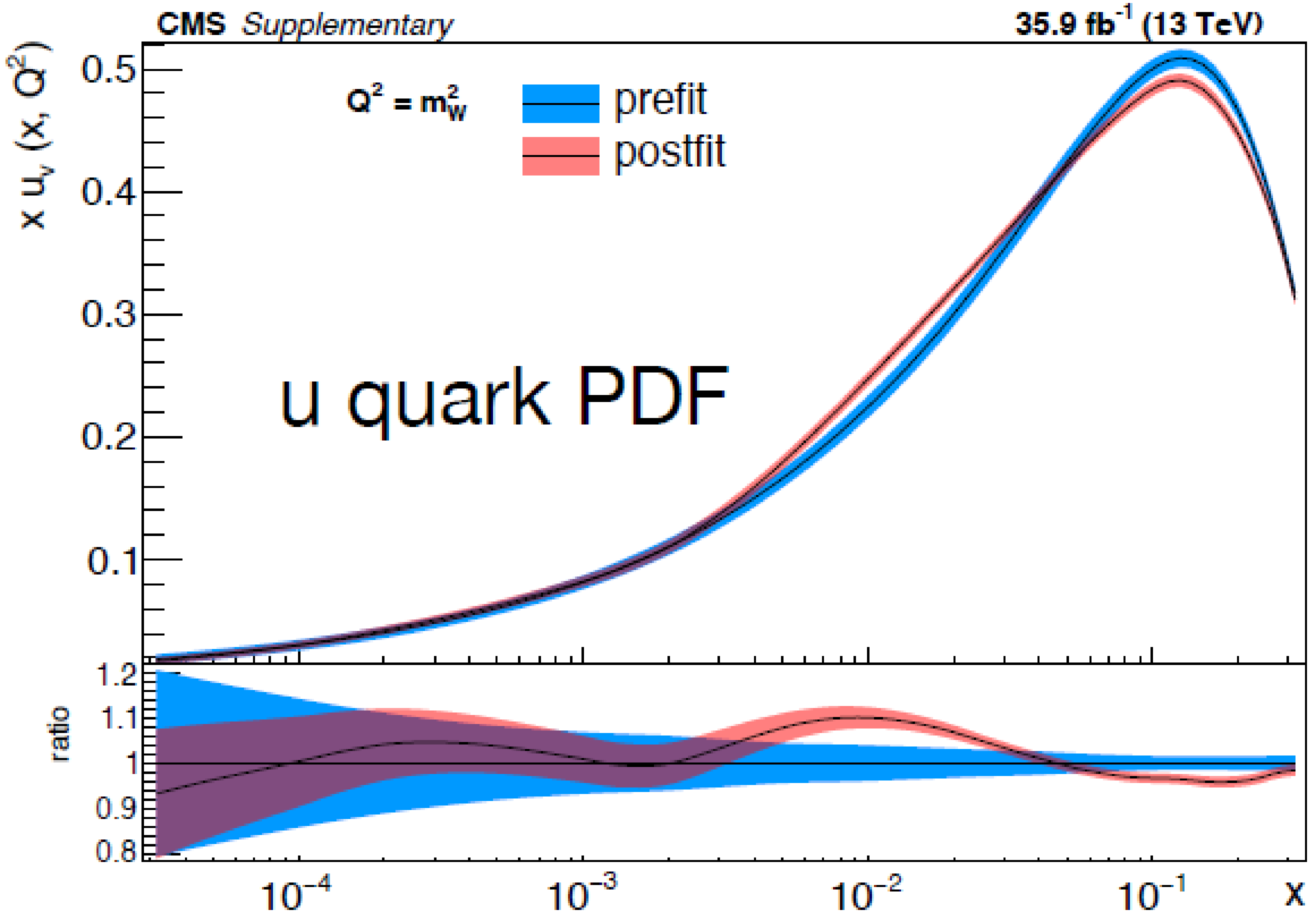
Non-perturbative aspects can be also relevant
See e.g. A. Bacchetta *et al., Phys. Lett. B* 788 (2019) 542

PDFs
Bozzi et al. Phys. Rev. D 91, 113005 (2015), Phys. Rev. D 83, 113008 (2011)
Bagnaschi e Vicini, Phys. Rev. Lett. 126 (2021) 041801

NLO+PS accuracy
Calame et al., Phys.Rev. D69 (2004) 037301

Mixed QCD-EWK
Bonciani et al., Phys. Rev. Lett. 128 (2021) 012002
Beharing et al., PRD 103, 113002 (2021)

Hist stat. & high-granularity measurements



PRD 102 (2020) 092012

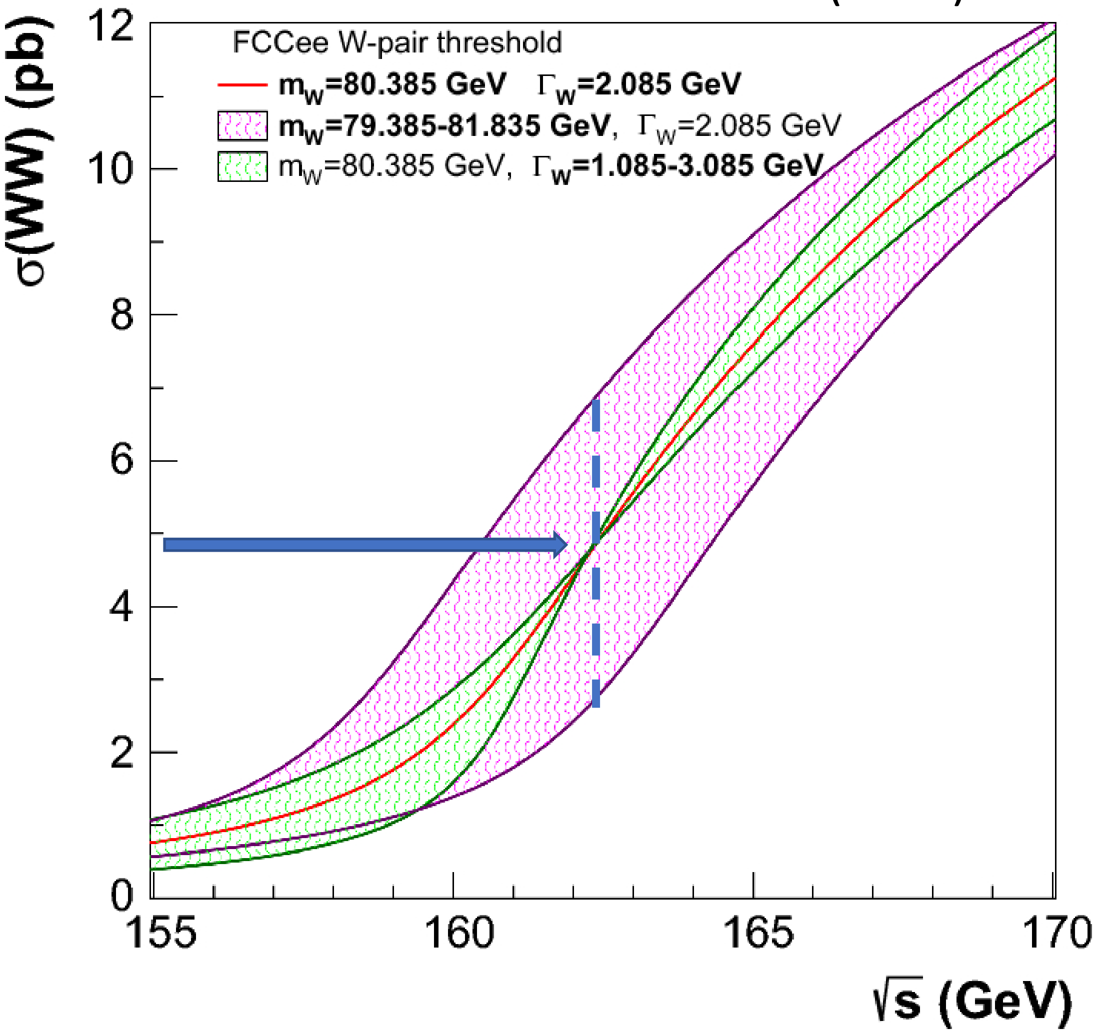
Ultimate future for M_W

- **Ultimate precision** from next-generation of lepton colliders (>2040)
  - FCC-ee + 2y at threshold → <u>0.5 MeV</u>

- Beyond any conceivable reach of hadron colliders

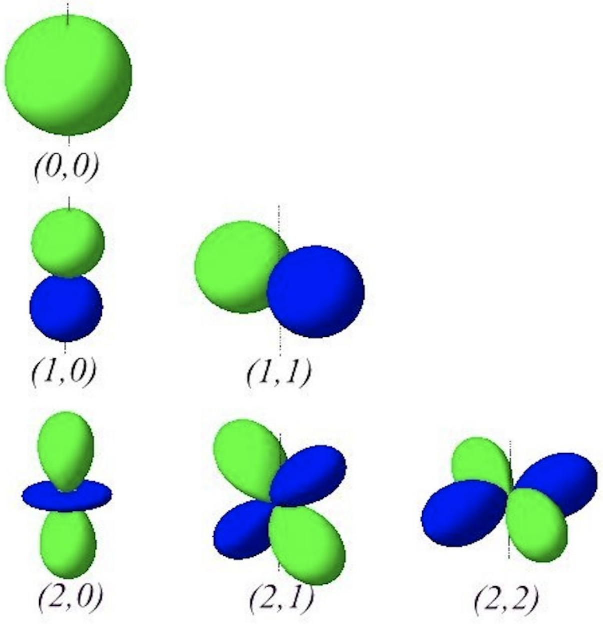
☺

EPJC 79 (2019) 474



Generalities of W and Z production

$$\frac{d\sigma}{dp_T^W\,dy\,dM\,d\cos\vartheta\,d\varphi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T^W\,dy\,dM}$$
$$\{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1\sin 2\vartheta\cos\varphi$$
$$+ A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta$$
$$+ A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\}$$

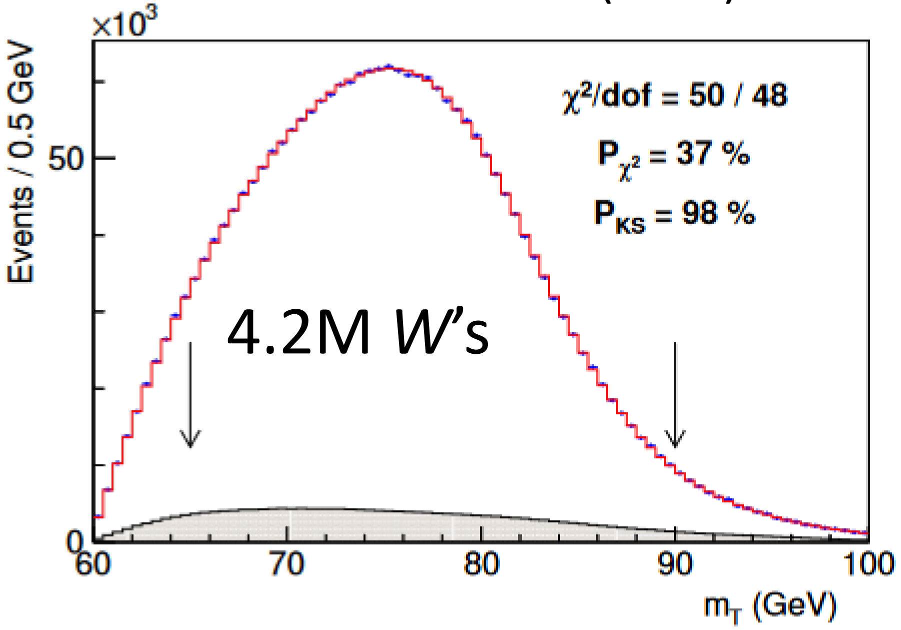


- $d\sigma^{unpol}$ and A_i can be determined in pQCD (up to NP effects)
  - PDF-dependent
  - known at NNLO_{QCD} + NLO_{EWK}
  - Resummation-improved $d\sigma^{unpol}$ and A_4 available at N^3LL+NNLO. N^4LL just arrived

arXiv:2207.07056

CDF-II

Science 376 (2022) 6589

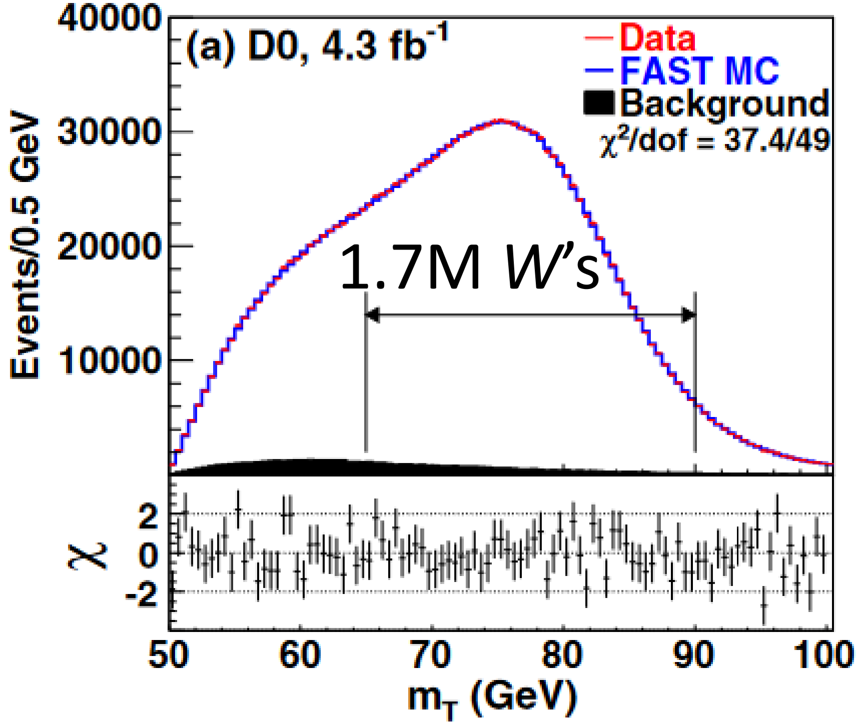


$\Delta M_W = 9$ MeV

- Physics modeling: CTEQ6M+ResBosP($*p_T^Z$)+Photos
- Detector modeling: custom MC simulation
- Calibration: data matched to J/Ψ, $\Upsilon(1s)$, Z.
- BLUE comb. of 6 channels: (p_T^l,m_T,p_T^ν) X (e,μ)
- Cross-checks: M_Z, data-taking, +/-, detector region

D0

PRD 89 (2014) 012005

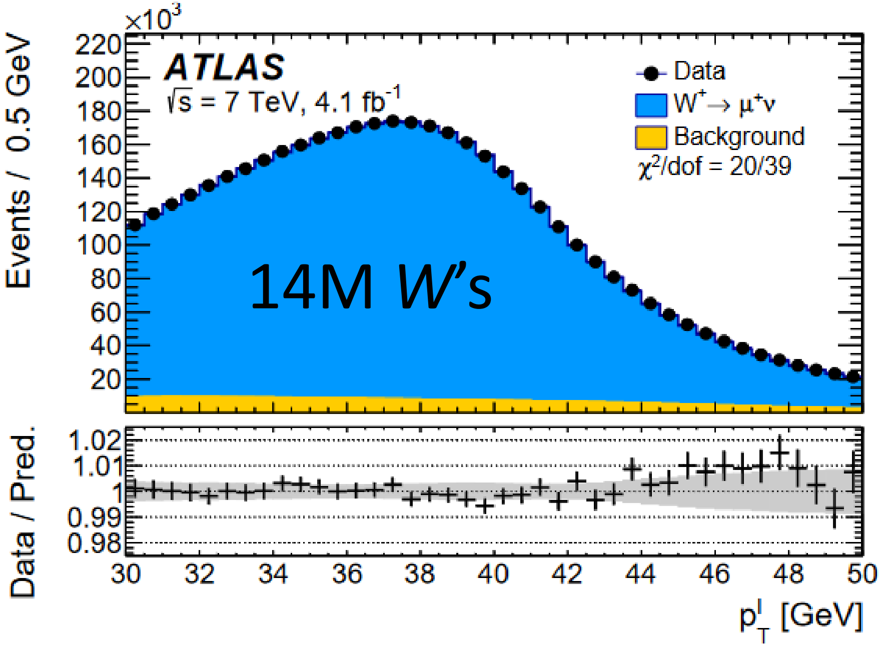


$\Delta M_W = 23$ MeV

- Physics modeling: CTEQ6.6+ResBosCP($*p_T^Z$)+Photos
- Detector modeling: custom MC simulation
- Calibration: data matched to Z
- BLUE comb. of 3 channels: (p_T^l,m_T,p_T^ν) x e
- Cross-checks: data-taking, detector region

ATLAS

EPJC 78 (2018) 110

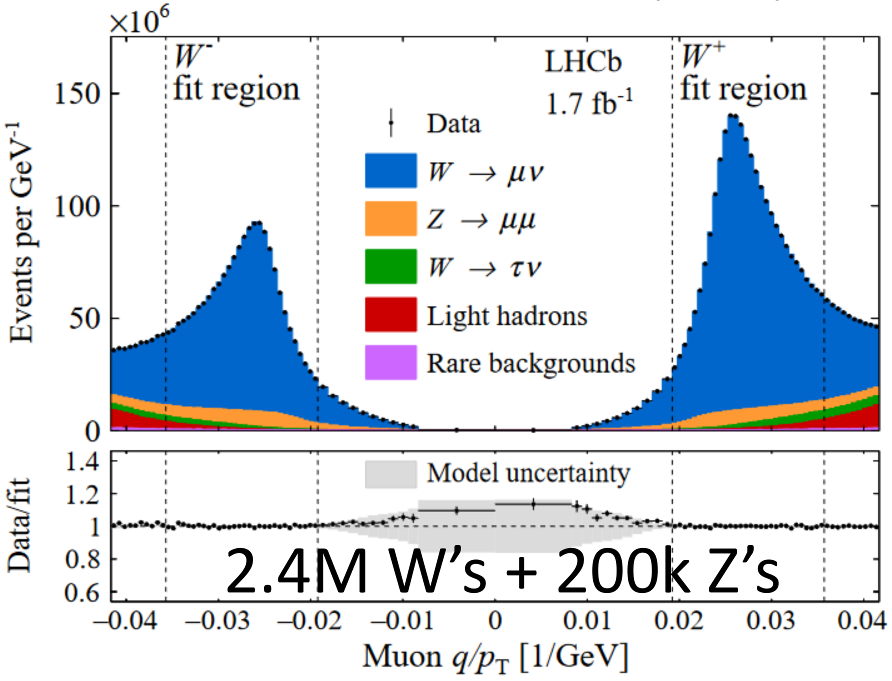


$\Delta M_W = 19$ MeV

- Physics modeling: CT10+Powheg(*DYNNLO)+Pythia(*p_T^Z)+Photos
- Detector modeling: full MC simulation
- Calibration: simulation matched to Z data
- BLUE comb. of 28 channels: $(p_T^l, m_T, p_T^\upsilon)$ X (e,μ) X η^l bin
- Cross-checks: detector region, +/-

LHCb

JHEP 01 (2022) 036



2.4M W's + 200k Z's

$\Delta M_W = 32$ MeV

- Physics modeling: NNPDF31+Powheg(*DYTurbo)+Pythia(*ϕ^*_{ll})+Photos
- Detector modeling: full MC simulation
- Calibration: simulation matched to J/Ψ, $\Upsilon(1s)$, Z
- Measurement: simultaneous fit to q/p_T^l and ϕ^*_{ll}
- Cross-checks: polarity, detector region, *W*-like M_Z

Missing systematics

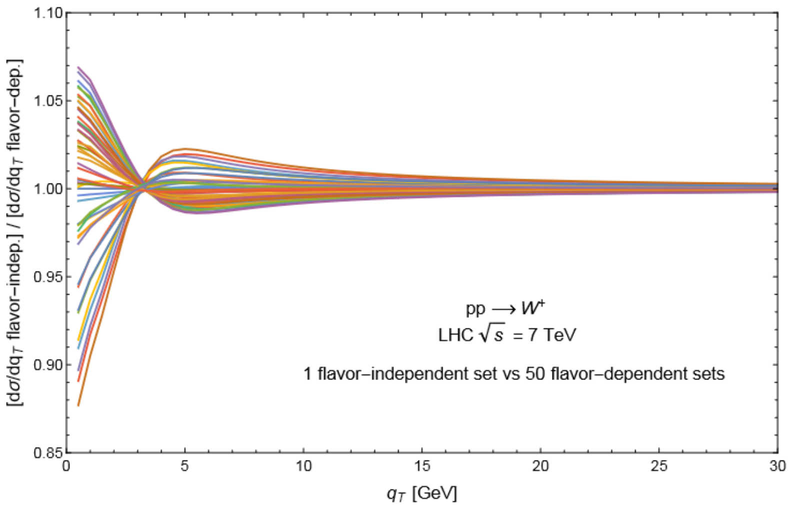
- Mixed QCD⊗EWK corrections do DY have been computed
  - Not yet included by experiments
  - Some (crude) estimates of their effect in the literature:

corrections cause bigger shifts in m_W. For example, we estimate that the cuts employed by the ATLAS collaboration in their recent extraction of the W mass [5] may lead to a shift of about $\mathcal{O}(17)$ MeV due to unaccounted mixed QCD-electroweak effects in the production process.

PRD 103, 113002 (2021)

- Impact of non-perturbative corrections to $p_T^{W/Z}$ yet to be understood
  - Assuming flavour non-universality of NP models can bring to additional O(10) MeV shifts

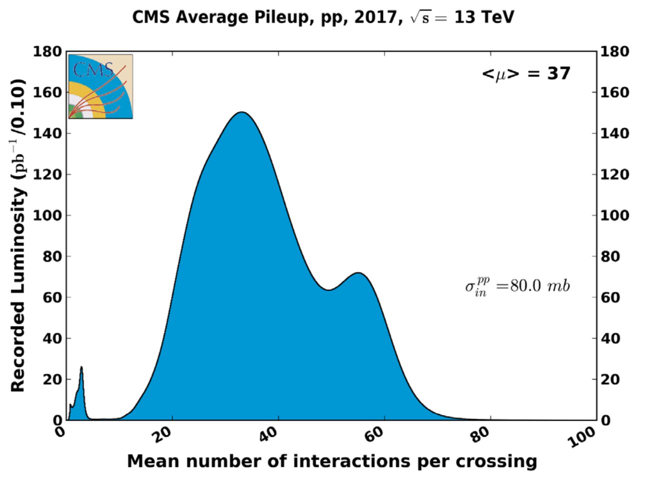
AHE. 2019 (2019) 2526897



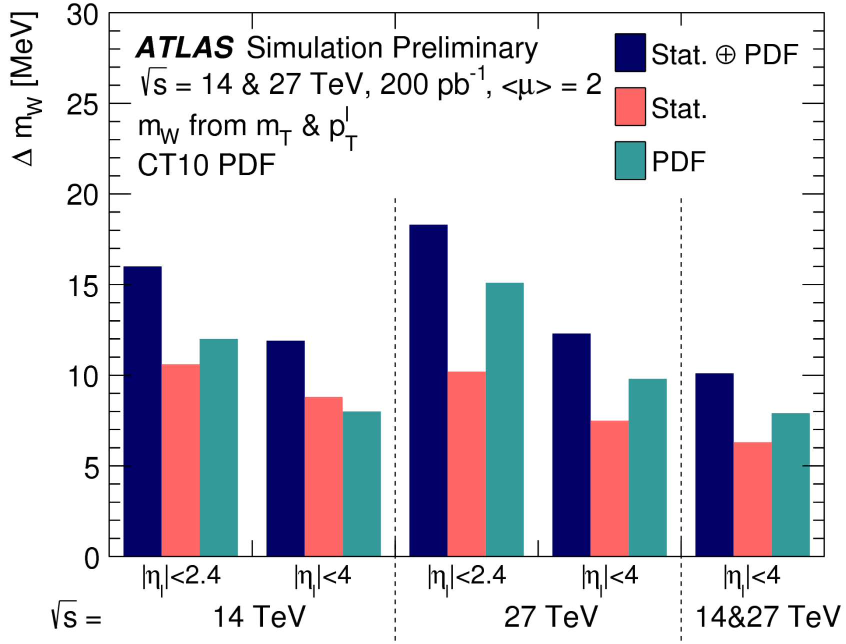
	Δm_{W^+}		Δm_{W^-}	
Set	m_T	p_T^ℓ	m_T	p_T^ℓ
1	0	-1	-2	3
2	0	-6	-2	0
3	-1	9	-2	-4
4	0	0	-2	-4
5	0	4	-1	-3
6	1	0	-1	4
7	2	-1	-1	0
8	0	2	1	7
9	0	4	-1	0

Opportunities from low-PU runs

- Dedicated low-PU runs delivered in 2017 (~200/pb).
- About 5M *W* events needed to reach 6 MeV stat-only uncertainty (as for CDF-II)
  - That is, **> 1/fb of low-PU data**, i.e. ~15/fb of lost high-PU data
- Further improvements expected from planned detector upgrades



ATL-PHYS-PUB-2018-026



D0

Source	Section	m_T	p_T^e	E_T
Experimental				
Electron energy scale	VIIC4	16	17	16
Electron energy resolution	VIIC5	2	2	3
Electron shower model	VC	4	6	7
Electron energy loss	VD	4	4	4
Recoil model	VIID3	5	6	14
Electron efficiencies	VIIB10	1	3	5
Backgrounds	VIII	2	2	2
$\sum$ (Experimental)		18	20	24
W production and decay model				
PDF	VIC	11	11	14
QED	VIB	7	7	9
Boson p_T	VIA	2	5	2
$\sum$ (Model)		13	14	17
Systematic uncertainty (experimental and model)		22	24	29
W boson statistics	IX	13	14	15
Total uncertainty		26	28	33

CDF-II

Source of systematic uncertainty	m_T fit			p_T^ℓ fit			p_T^ν fit		
	Electrons	Muons	Common	Electrons	Muons	Common	Electrons	Muons	Common
Lepton energy scale	5.8	2.1	1.8	5.8	2.1	1.8	5.8	2.1	1.8
Lepton energy resolution	0.9	0.3	-0.3	0.9	0.3	-0.3	0.9	0.3	-0.3
Recoil energy scale	1.8	1.8	1.8	3.5	3.5	3.5	0.7	0.7	0.7
Recoil energy resolution	1.8	1.8	1.8	3.6	3.6	3.6	5.2	5.2	5.2
Lepton $u_{\|\|}$ efficiency	0.5	0.5	0	1.3	1.0	0	2.6	2.1	0
Lepton removal	1.0	1.7	0	0	0	0	2.0	3.4	0
Backgrounds	2.6	3.9	0	6.6	6.4	0	6.4	6.8	0
p_T^Z model	0.7	0.7	0.7	2.3	2.3	2.3	0.9	0.9	0.9
p_T^W/p_T^Z model	0.8	0.8	0.8	2.3	2.3	2.3	0.9	0.9	0.9
Parton distributions	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9	3.9
QED radiation	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
Statistical	10.3	9.2	0	10.7	9.6	0	14.5	13.1	0
Total	13.5	11.8	5.8	16.0	14.1	7.9	18.8	17.1	7.4

LHCb

Source	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

ATLAS

Combined categories	Value [MeV]	Stat. Unc.	Muon Unc.	Elec. Unc.	Recoil Unc.	Bckg. Unc.	QCD Unc.	EW Unc.	PDF Unc.	Total Unc.	χ^2/dof of Comb.
m_T-p_T^ℓ, $W^\pm$, e-μ	80369.5	6.8	6.6	6.4	2.9	4.5	8.3	5.5	9.2	18.5	29/27