華中師範大學
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# Experimental status of $m_W$ measurements at LHC and Tevatron


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07/13/2023

# Outlines

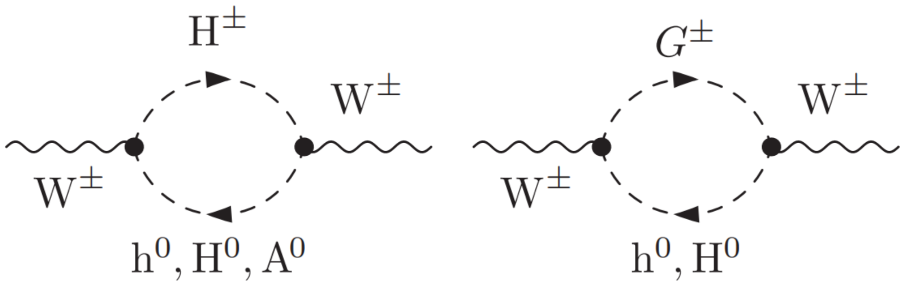
- Introduction
- $W$ mass measurement ($m_W$) from LHC and Tevatron
  - CDF $m_W$ measurement — PRL 108 (2012) 151803, Science 376 (2022) 170
  - DZero $m_W$ measurement — PRL 108 (2012) 151804
  - ATLAS $m_W$ measurement — EPJC 78 (2018) 110, Erratum ibid. C 78 (2018) 898, ATLAS-CONF-2023-004
  - LHCb $m_W$ measurement — JHEP 01 (2022) 036
  - CMS $m_W$ status — CMS-PAS-SMP-14-007
- Summary

# Introduction

- $m_W$ is related to other fundamental parameters in SM EW sector

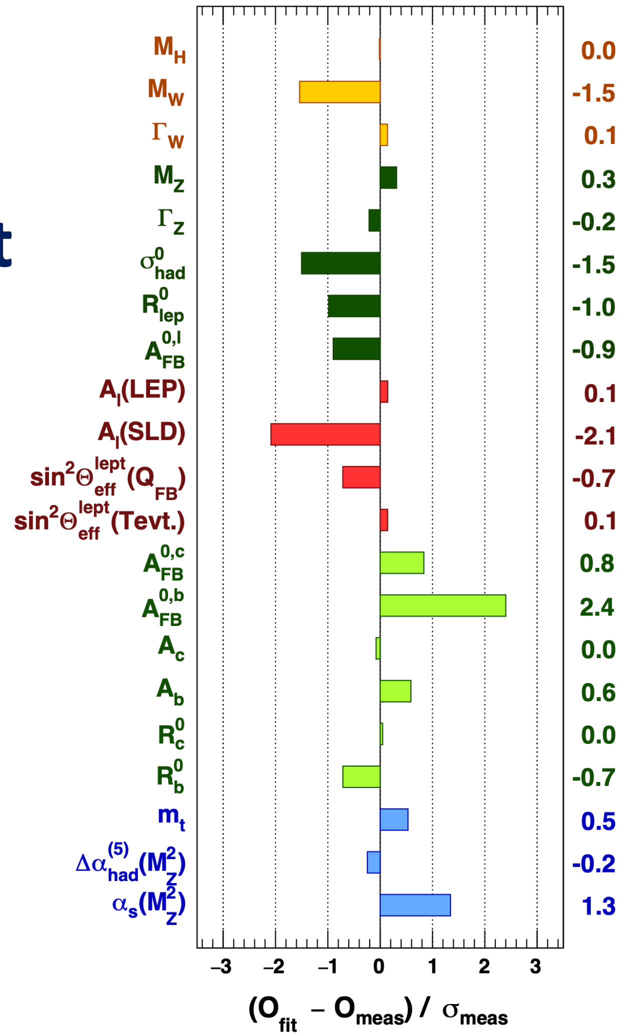
$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta)$$


- Radiative corrections (Δ) dominated by top quark and Higgs loop, also can be affected by new physics contributions

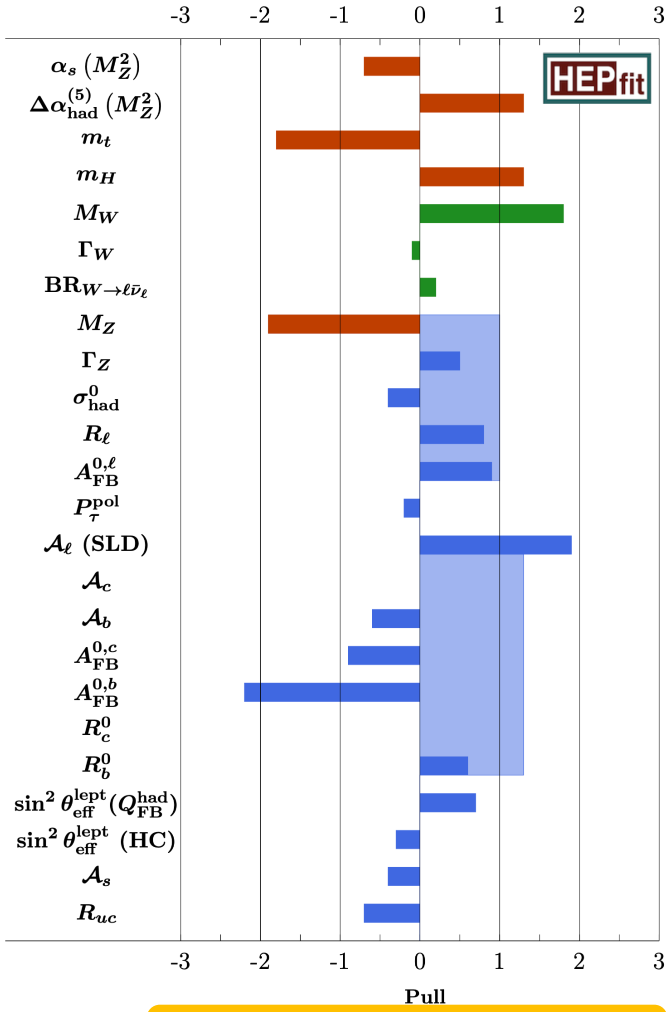


# Standard Model global fit

- Excellent agreement between individual measurement and global fit
- Tension between $A_{FB}^{b}$ and $A_{l}(SLD)$: $\sim 3.2\ \sigma$
  - Precision weak mixing angle measurement from LEP and SLD
- Other EW observables are within $2\sigma$ band



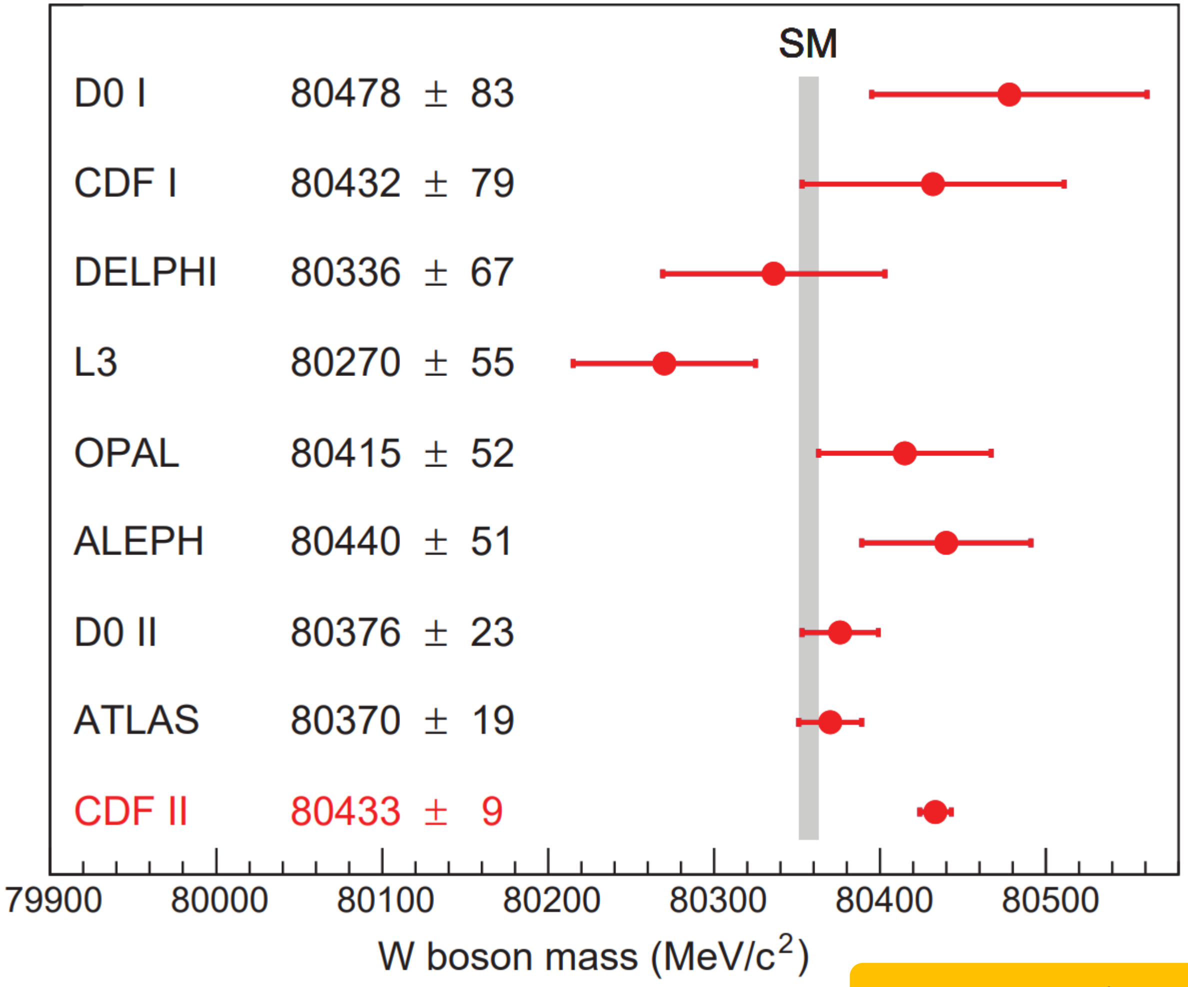

EPJC 78 (2018) 675

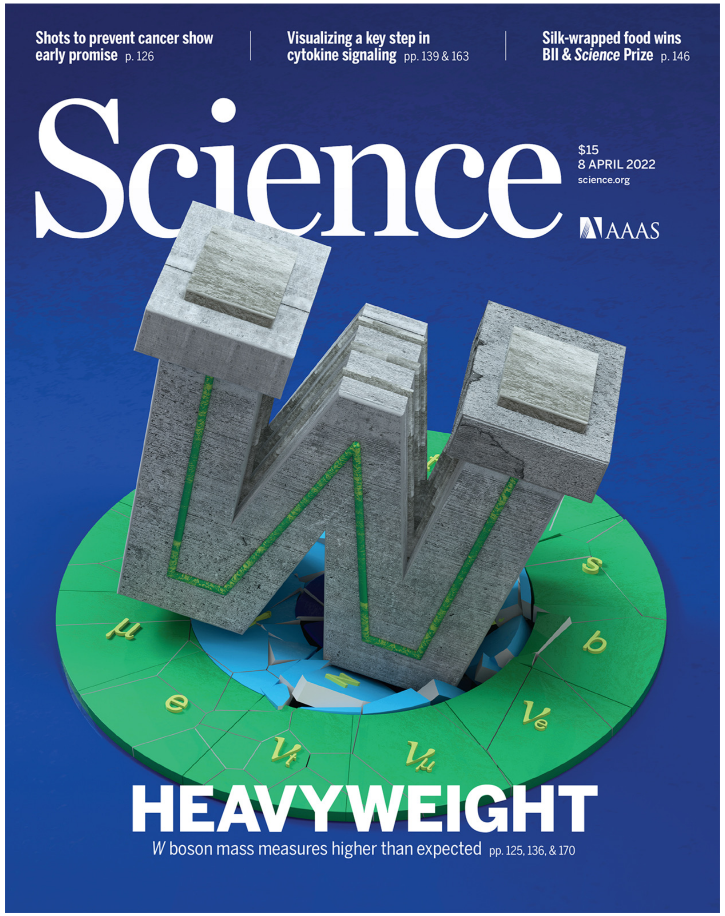



PRD 106 (2022) 3, 033003

# CDF result

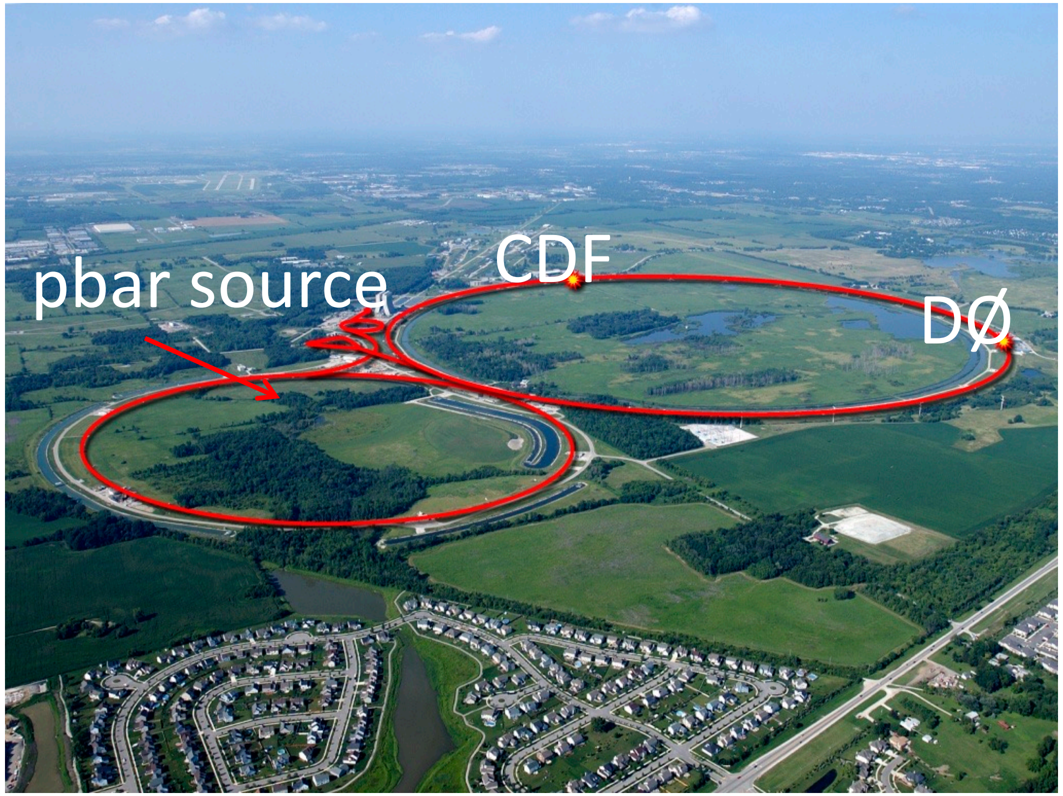
**More than 4$\sigma$ deviation**




Science 376 (2022) no.6589, 170-176

# LHC and Tevatron

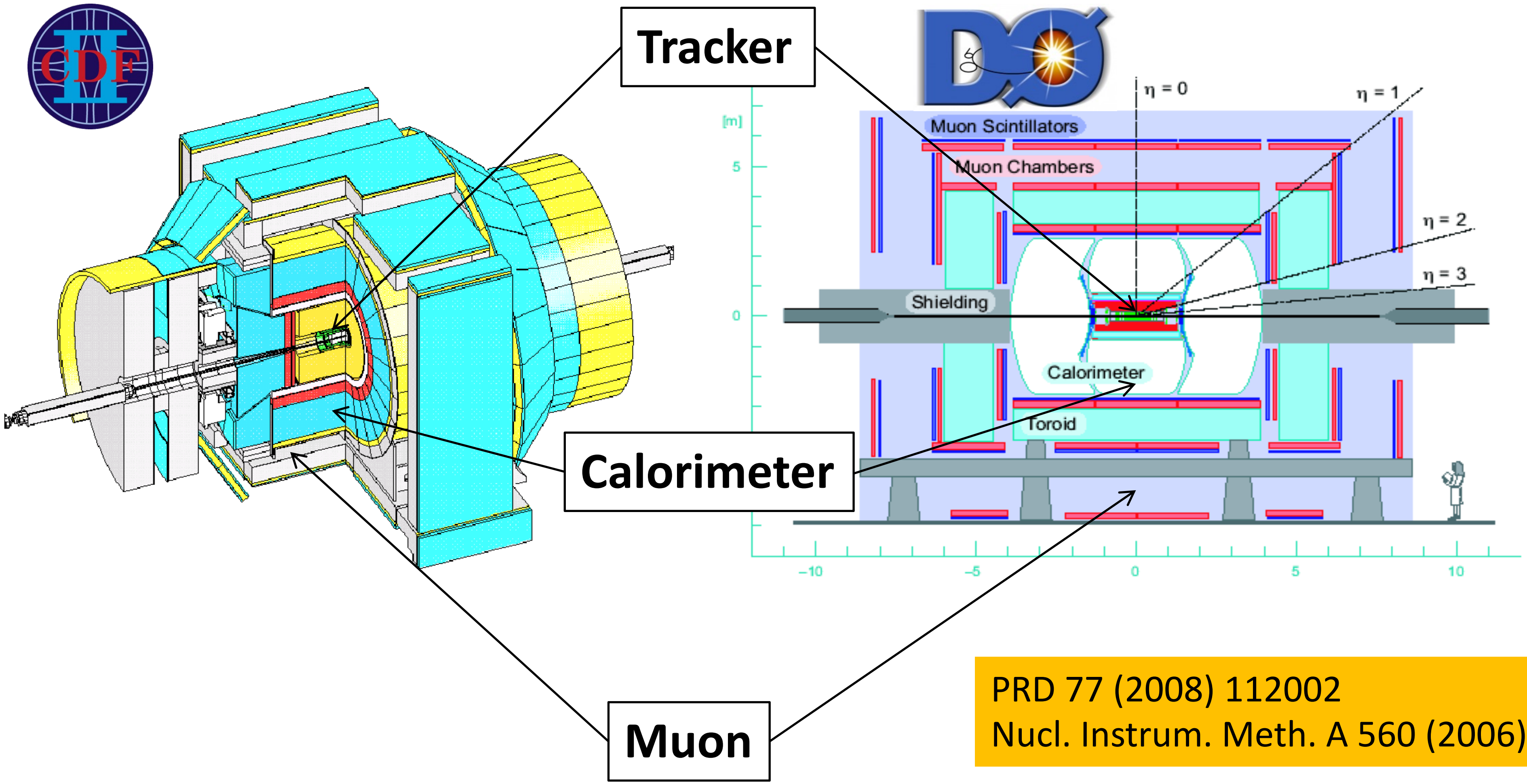

**LHC:**

- ~27 km, $pp$ collider
- 7, 8, 13, 13.6 TeV
- CERN: From 2009 to present

**Tevatron:**

- ~6.3 km, $p\bar{p}$ collider
- 1.8, 1.96 TeV
- Fermilab: From 1987 to 2011

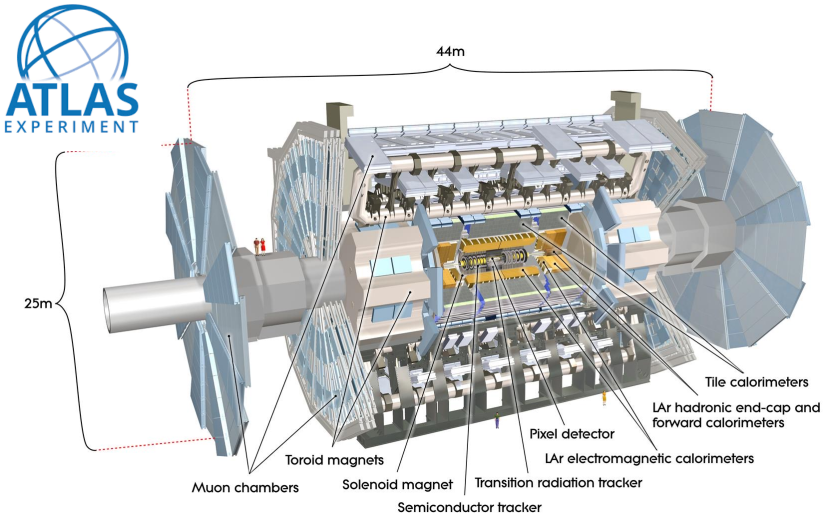
# CDF and DZero experiments

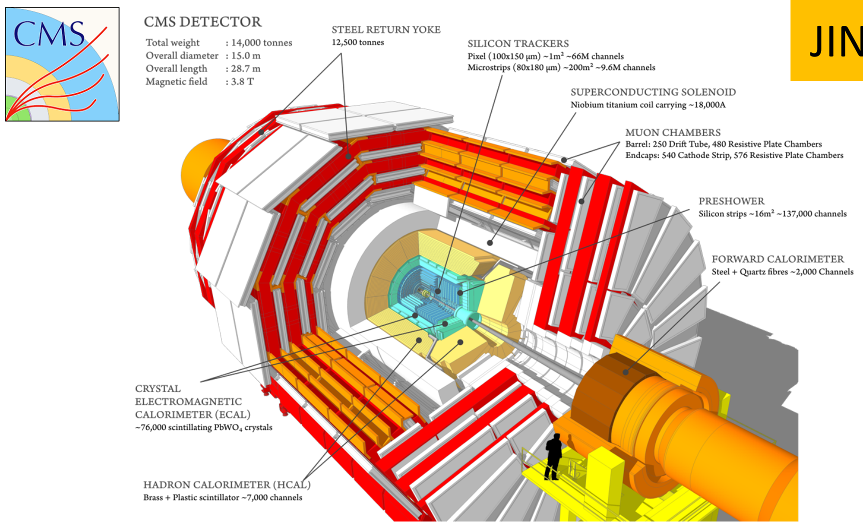


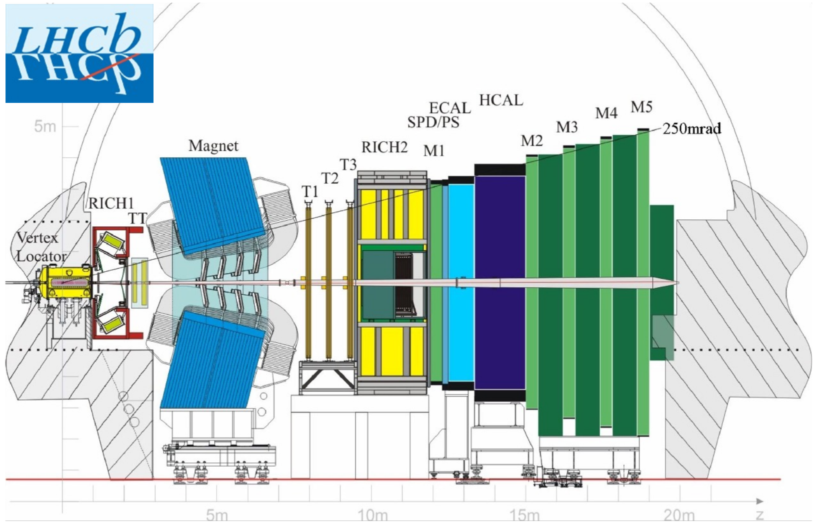

PRD 77 (2008) 112002
Nucl. Instrum. Meth. A 560 (2006) 463-537

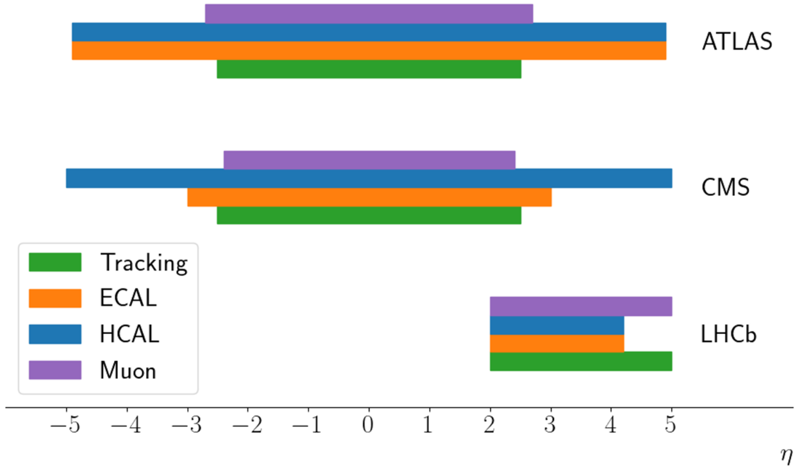
# ATLAS/CMS/LHCb expeirments

JINST 3 (2008) S08003
JINST 3 (2008) S08004
JINST 3 (2008) S08005



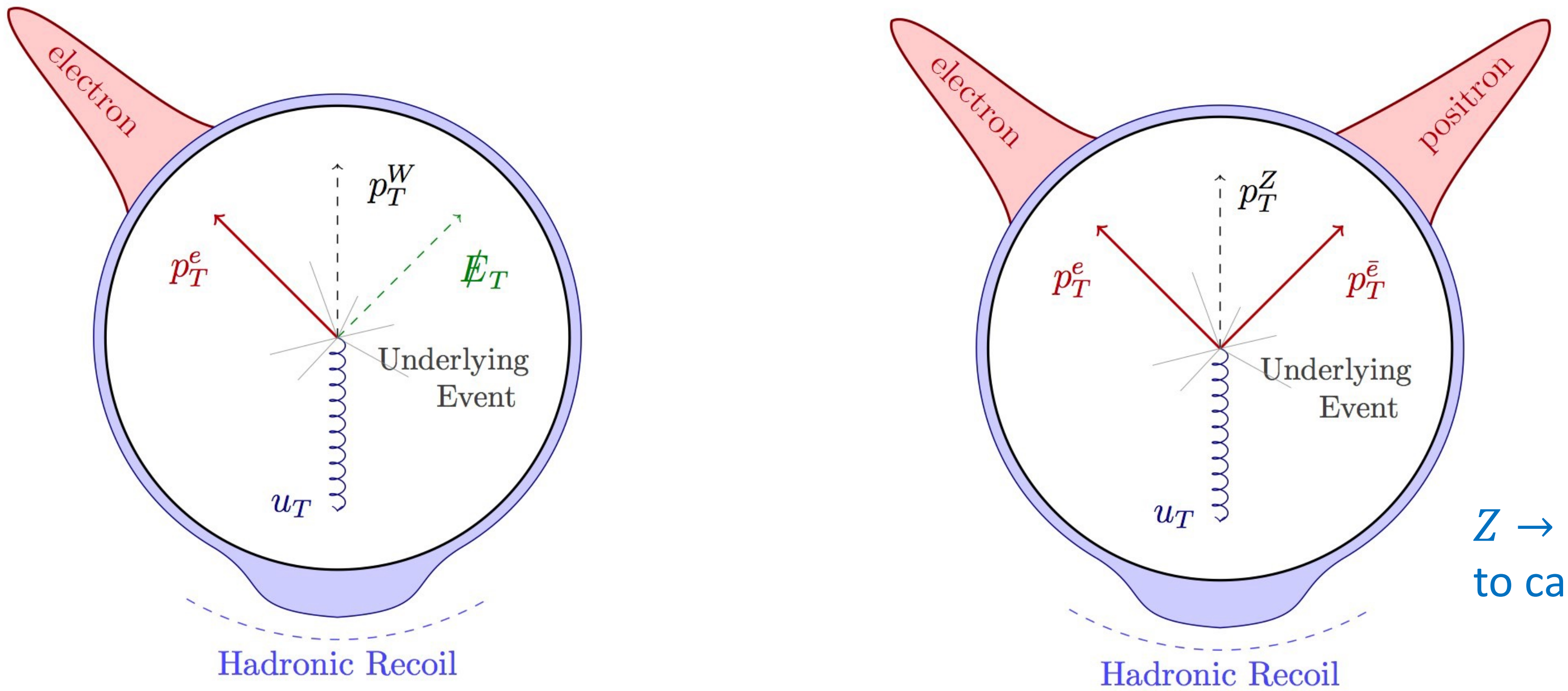



# Strategy

- **Lepton** (electron/muon) + **missing transverse energy** ($p_T^{miss}$)




$Z \to \ell^+\ell^-$ events are used to calibrate signal events

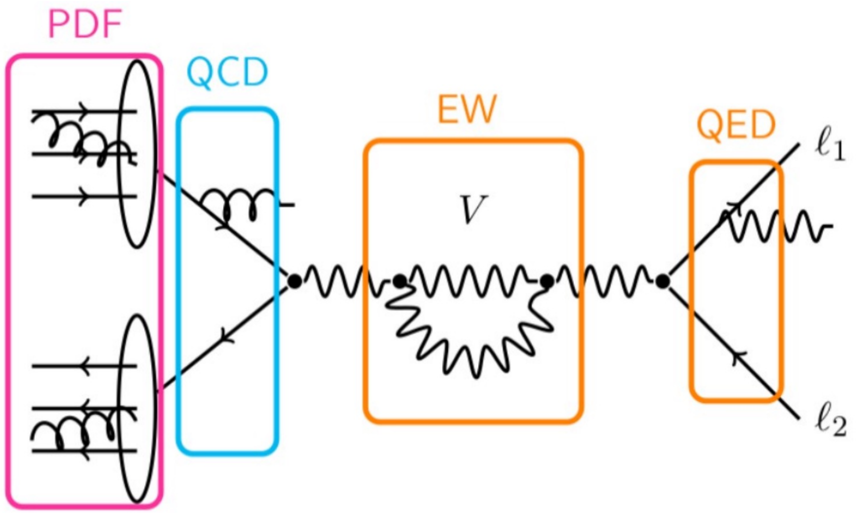
**Three observables:**

$m_T, p_T^\ell, p_T^{miss}$

$$m_T = \sqrt{2p_T^\ell p_T^{miss}(1-\cos\Delta\phi)}$$

# Generators

- ResBos, PowHEG, DYTurbo …
- Different baseline PDFs
- Different generators: a long time scale

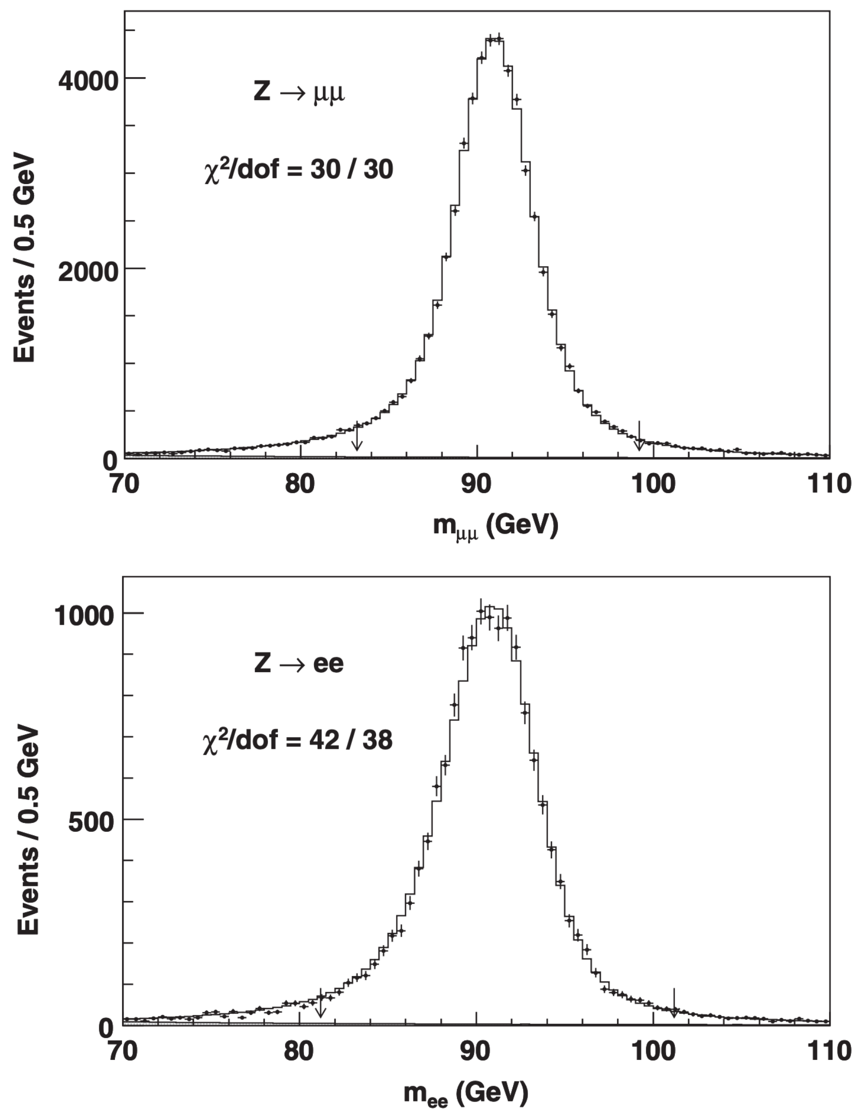



| Experiments | Generators | Order | Ai | PDFs |
|---|---|---|---|---|
| D0 | ResBos (C) | NLO+NNLL | / | CTEQ66 (NLO) |
| CDF | ResBos (CP) | NLO+NNLL | / | CTEQ6M(NLO) |
| ATLAS | PowHEG+Pythia8 | NLO+PS | NNLO | CT10(NNLO) |
| LHCb | PowHEG+Pythia8 | NLO+PS | NNLO (DYTrubo) | NNPDF3.1, CT18, MSHT 20(NLO) |

# CDF measurement (1)

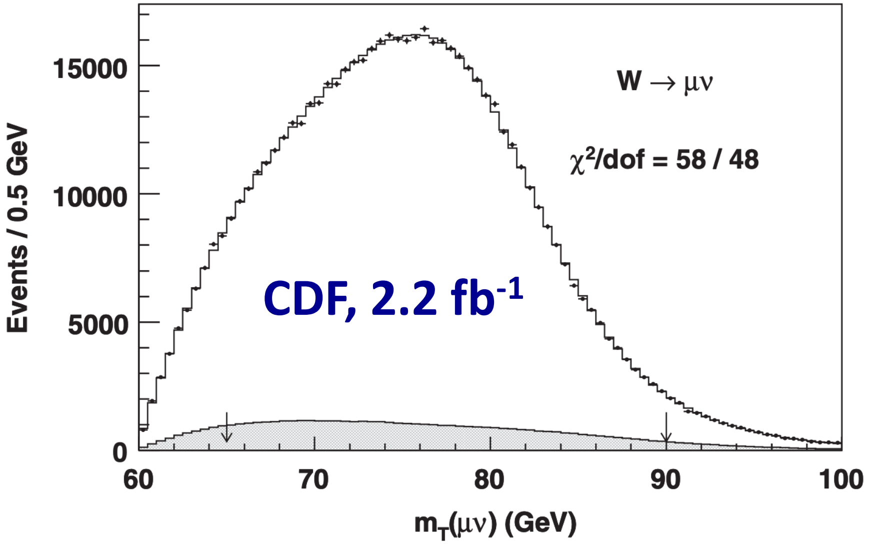
PRL 108 (2012) 151803

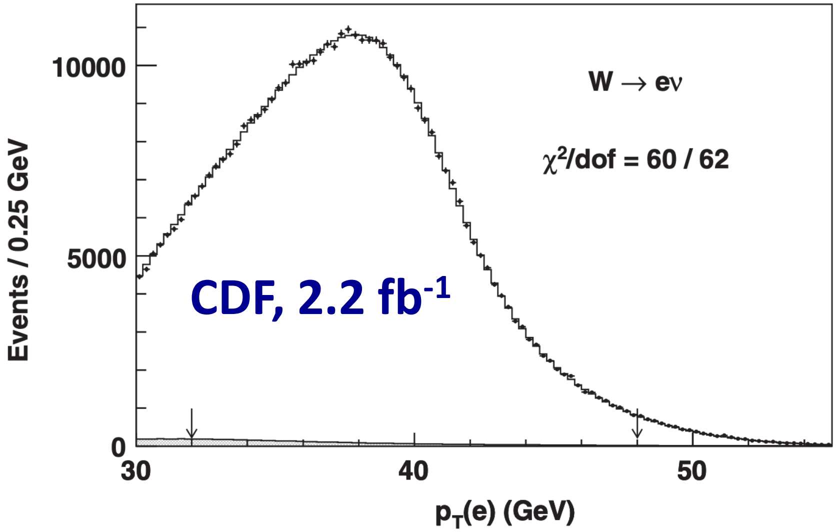
- 1.96 TeV data set (2002-2007): **2.2 $\mathbf{fb^{-1}}$**
  - Both electron and muon channels
  - $W(1.1\times10^6)$, $Z(7.6\times10^4)$
- Tracker calibration:
  - Tracker alignment using cosmic rays
  - Track momentum scale and non-linearity constrained using $J/\psi \rightarrow \mu^+\mu^-$ and $\Upsilon \rightarrow \mu^+\mu^-$ evts
  - Confirmed using $Z \rightarrow \mu^+\mu^-$ mass fit
- EM calorimeter calibration:
  - Transfer track momentum scale to EM calorimeter energy scale using fits to the $E/p$ spectrum
  - Confirmed using $Z \rightarrow e^+e^-$ mass fit



# CDF measurement (2)

PRL 108 (2012) 151803




| Distribution | $m_W$ (MeV) | Distribution | $m_W$ (MeV) |
|---|---|---|---|
| $m_T(\mu,\nu)$ | $80379 \pm 16$ (stat) | $m_T(e,\nu)$ | $80408 \pm 19$ (stat) |
| $p_T\ (\mu)$ | $80348 \pm 18$ (stat) | $p_T\ (e)$ | $80393 \pm 21$ (stat) |
| $p_T^{miss}(\mu,\nu)$ | $80406 \pm 22$ (stat) | $p_T^{miss}(e,\nu)$ | $80431 \pm 25$ (stat) |
| **CDF Combination (2.2 fb$^{-1}$)** | **$80387 \pm 19$ (syst + stat) MeV** | | |

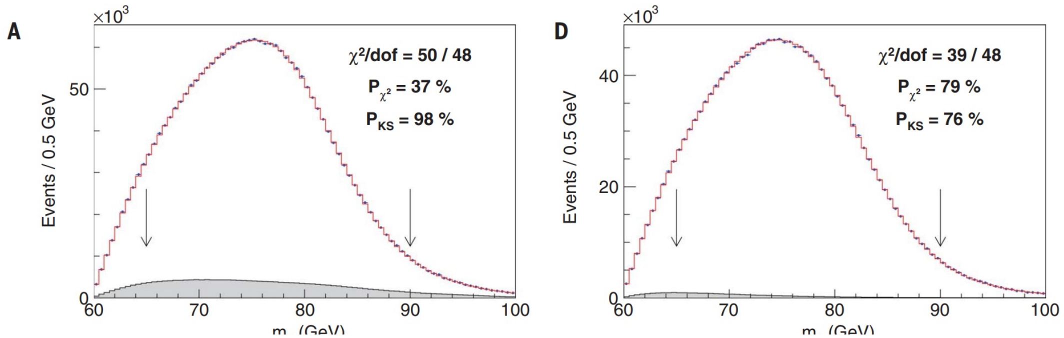
# CDF measurement (3)

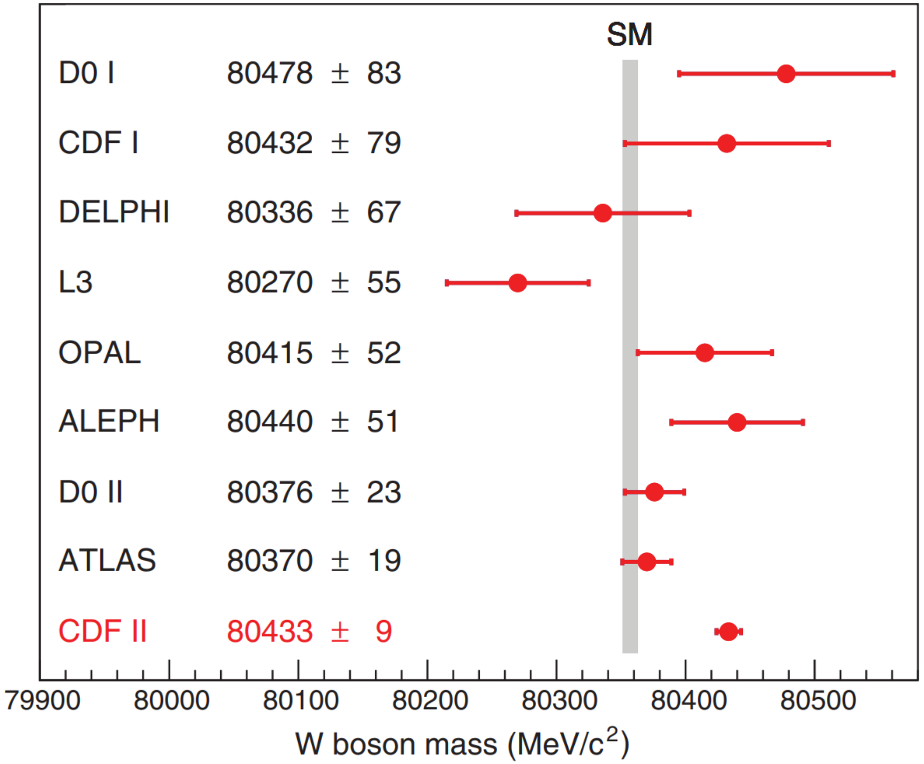
Science 376 (2022) 170

- **Full data-sets (2002-2011): 8.8 $\mathrm{fb}^{-1}$**
  - $W(4.2\times10^6), Z(3.0\times10^5)$
- **Improvements:**

$$80433.5 \pm 6.4(\text{stat}) + 6.9(\text{syst}) = 80433.5 \pm 9.4 \text{ MeV}$$

| Method or technique | impact | section of paper |
|---|---|---|
| Detailed treatment of parton distribution functions | +3.5 MeV | IV A |
| Resolved beam-constraining bias in CDF reconstruction | +10 MeV | VI C |
| Improved COT alignment and drift model [65] | uniformity | VI |
| Improved modeling of calorimeter tower resolution | uniformity | III |
| Temporal uniformity calibration of CEM towers | uniformity | VII A |
| Lepton removal procedure corrected for luminosity | uniformity | VIII A |
| Higher-order calculation of QED radiation in $J/\psi$ and $\Upsilon$ decays | accuracy | VI A & B |
| Modeling kurtosis of hadronic recoil energy resolution | accuracy | VIII B 2 |
| Improved modeling of hadronic recoil angular resolution | accuracy | VIII B 3 |
| Modeling dijet contribution to recoil resolution | accuracy | VIII B 4 |
| Explicit luminosity matching of pileup | accuracy | VIII B 5 |
| Modeling kurtosis of pileup resolution | accuracy | VIII B 5 |
| Theory model of $p_T^W/p_T^Z$ spectrum ratio | accuracy | IV B |
| Constraint from $p_T^W$ data spectrum | robustness | VIII B 6 |
| Cross-check of $p_T^Z$ tuning | robustness | IV B |



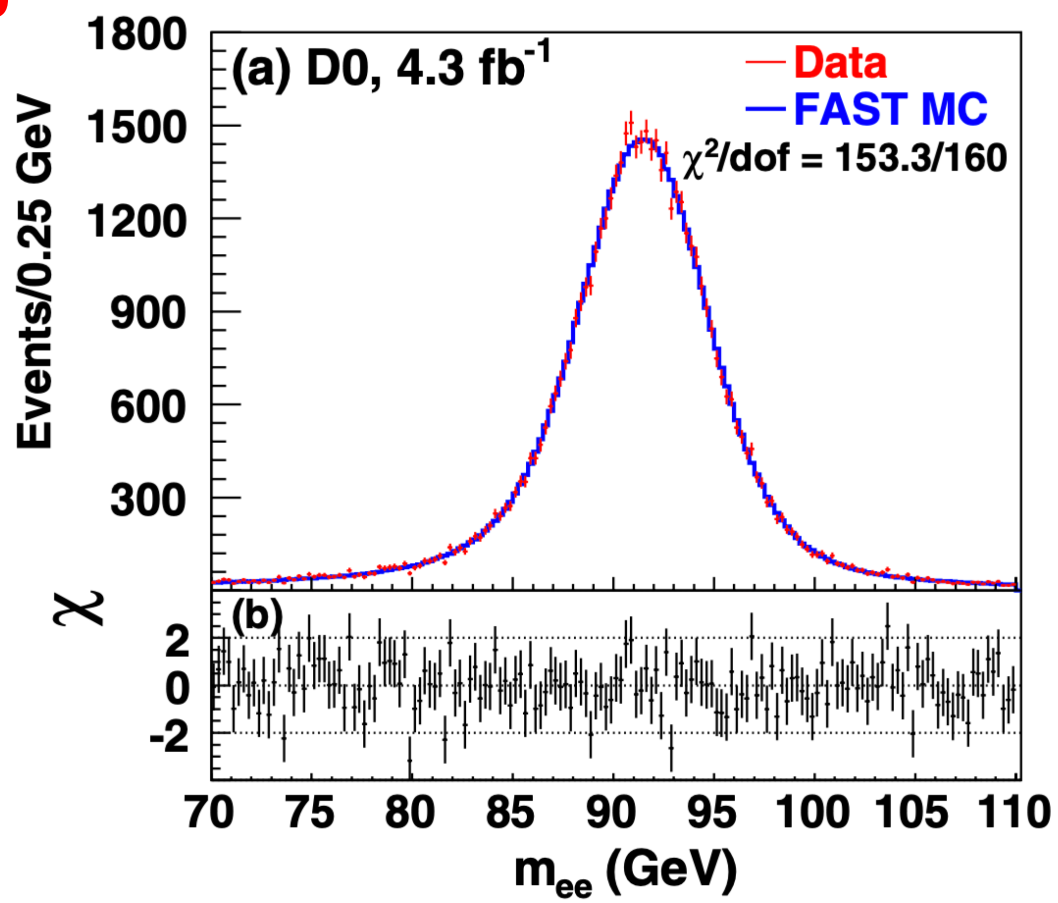



# Dzero measurement (1)

PRL 108 (2012) 151804

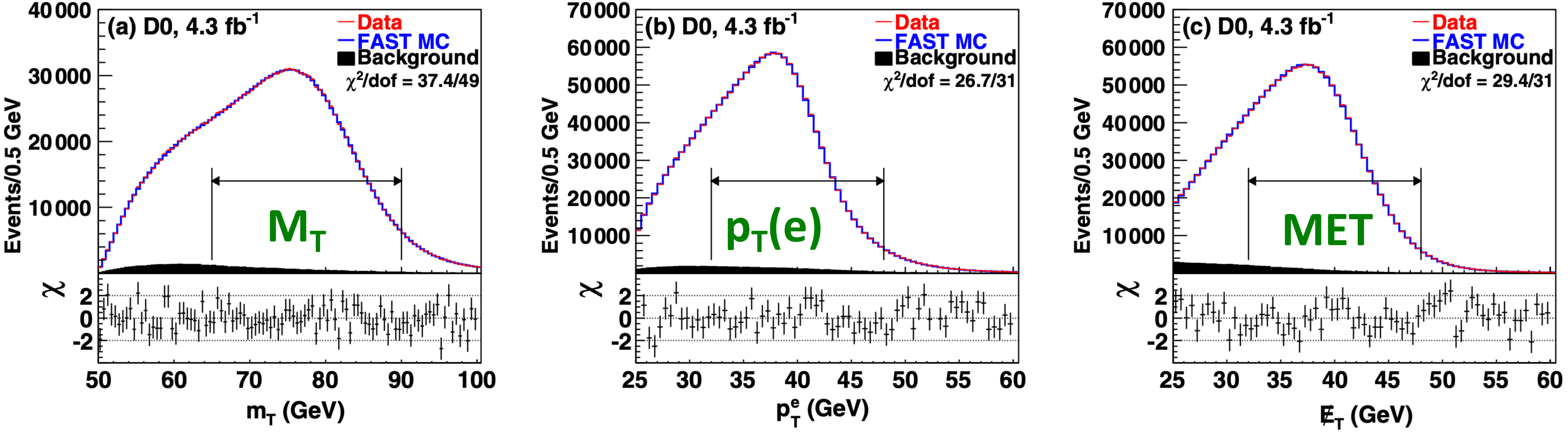
- 1.96 TeV data-set (2006-2009): $4.3\ \mathrm{fb}^{-1}$
  - Electron channel only
  - $W(1.7\times10^{6})$, $Z(5.5\times10^{4})$

- Lepton energy calibration using $Z \rightarrow e^{+}e^{-}$ events
  - Calorimeter calibration
  - Simulation of effect of inst. Luminosity
  - Correction for dead material
  - Modeling of underlying energy flow
  - Electron energy scale calibration



# Dzero measurement (2)

PRL 108 (2012) 151804




**Fitted $m_W$:**

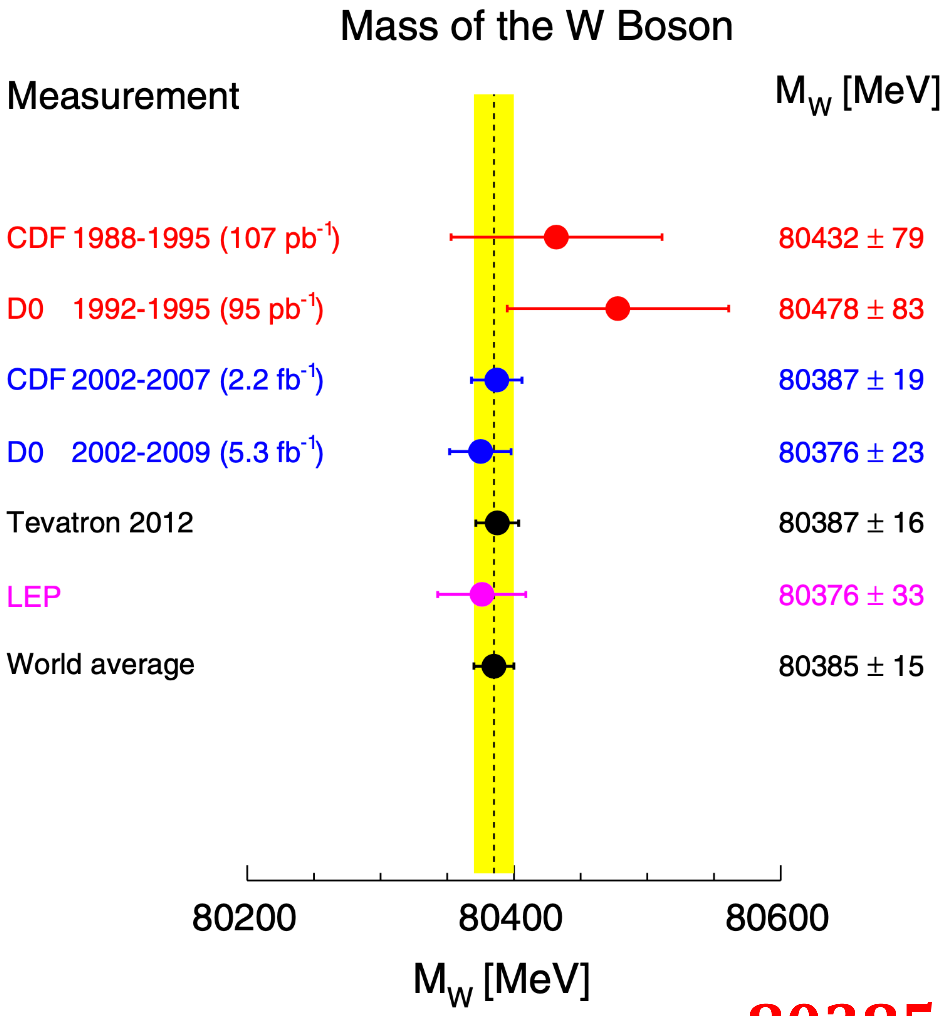
**$80367 \pm 13$ (stat) $\pm 22$(syst) MeV**

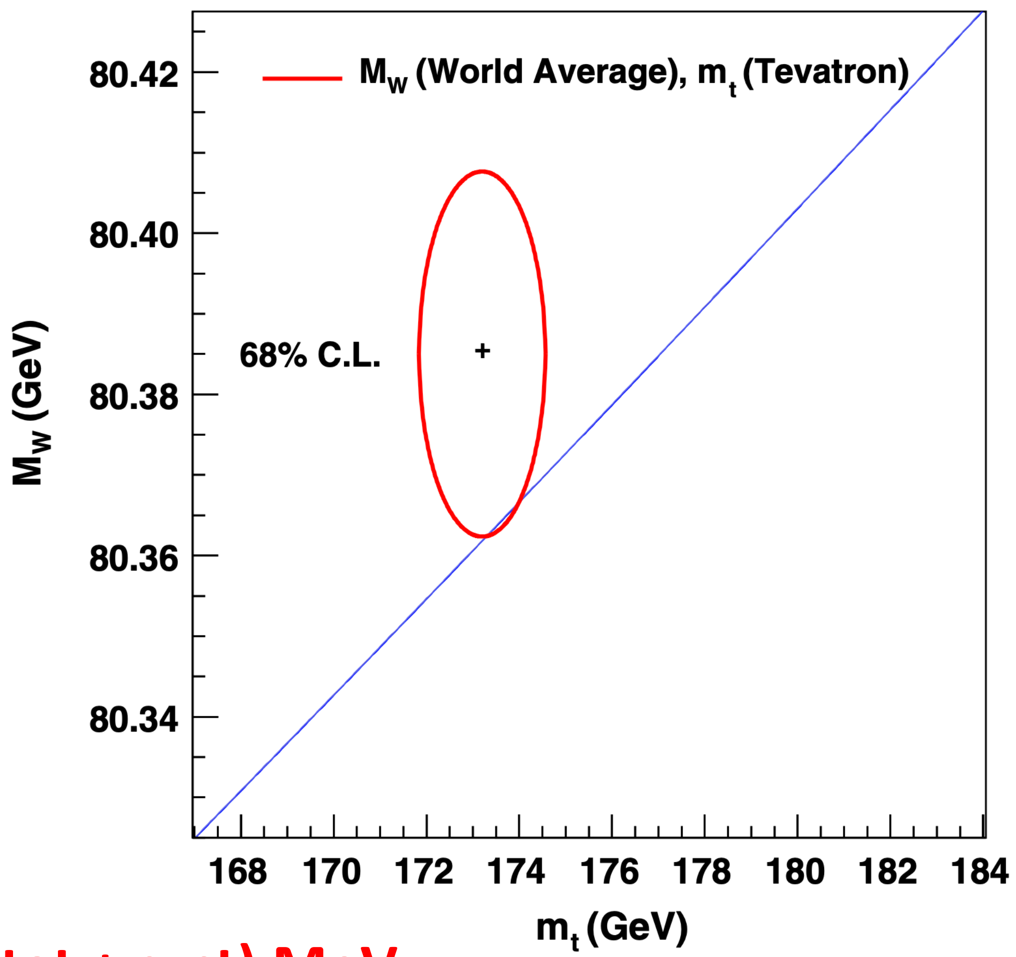
1.1 fb$^{-1}$ with MET
4.3 fb$^{-1}$ without MET

**Combined (5.3 fb$^{-1}$): $80357 \pm 23$ (stat + syst) MeV**

# Tevatron Combination (2013)

PRD 88 (2013) 052018

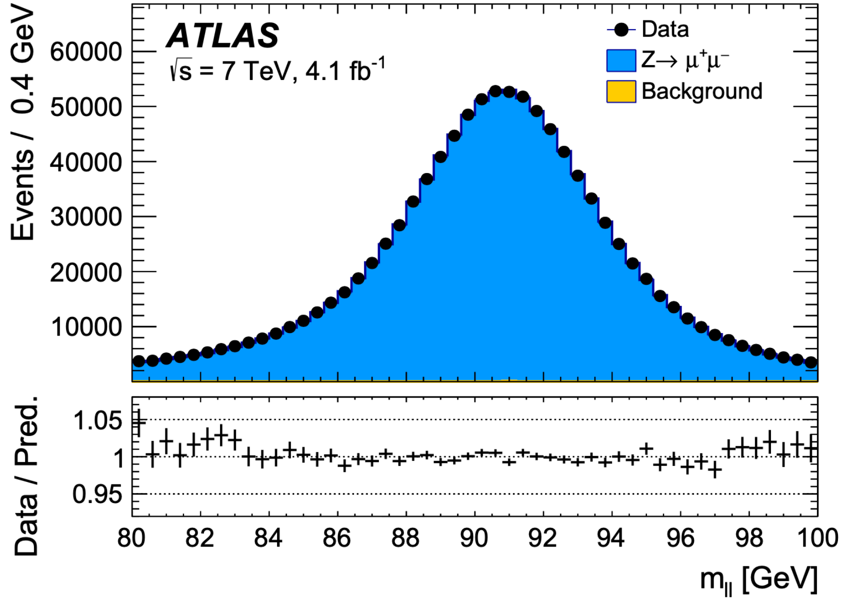


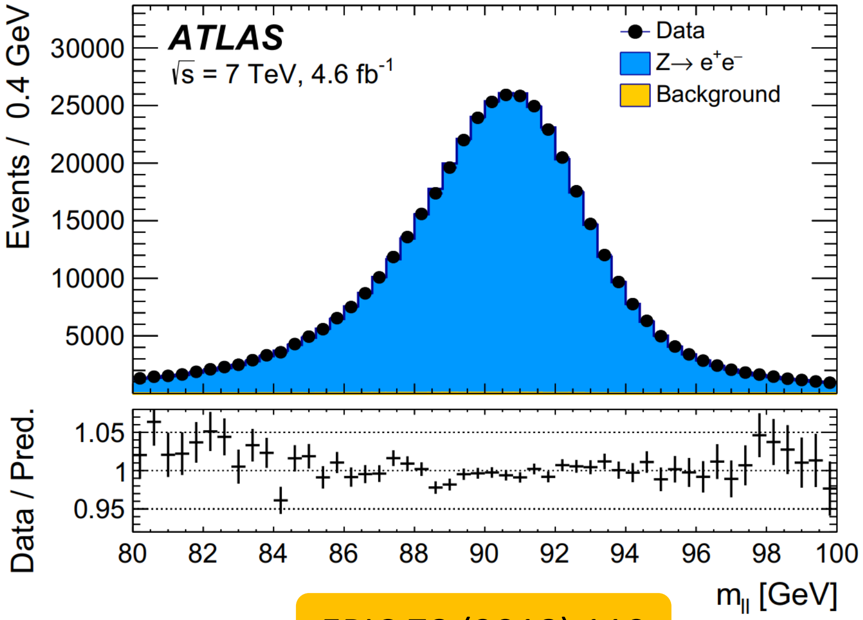



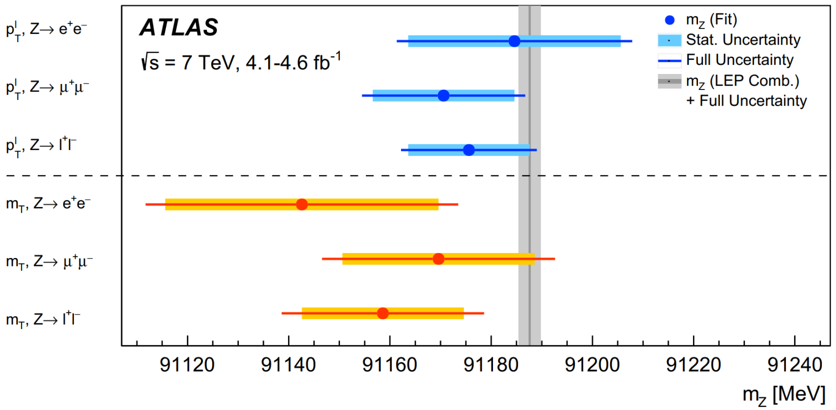

**$80385 \pm 15$ (stat + syst) MeV**

# ATLAS measurement

- 7 TeV data-set (2011), $4.6\ \mathrm{fb}^{-1}$
  - both electron and muon channels
  - $W(1.4\times10^{7})$, $Z(1.8\times10^{6})$
- Use $Z \to \ell^+\ell^-$ events to calibrate lepton momentum and recoil response
- Validation with $Z \to \ell^+\ell^-$ :
  - Treat one of the charged lepton as neutrino
  - $p_T^{miss}$ and $m_T$ to check recoil calibration




EPJC 78 (2018) 110

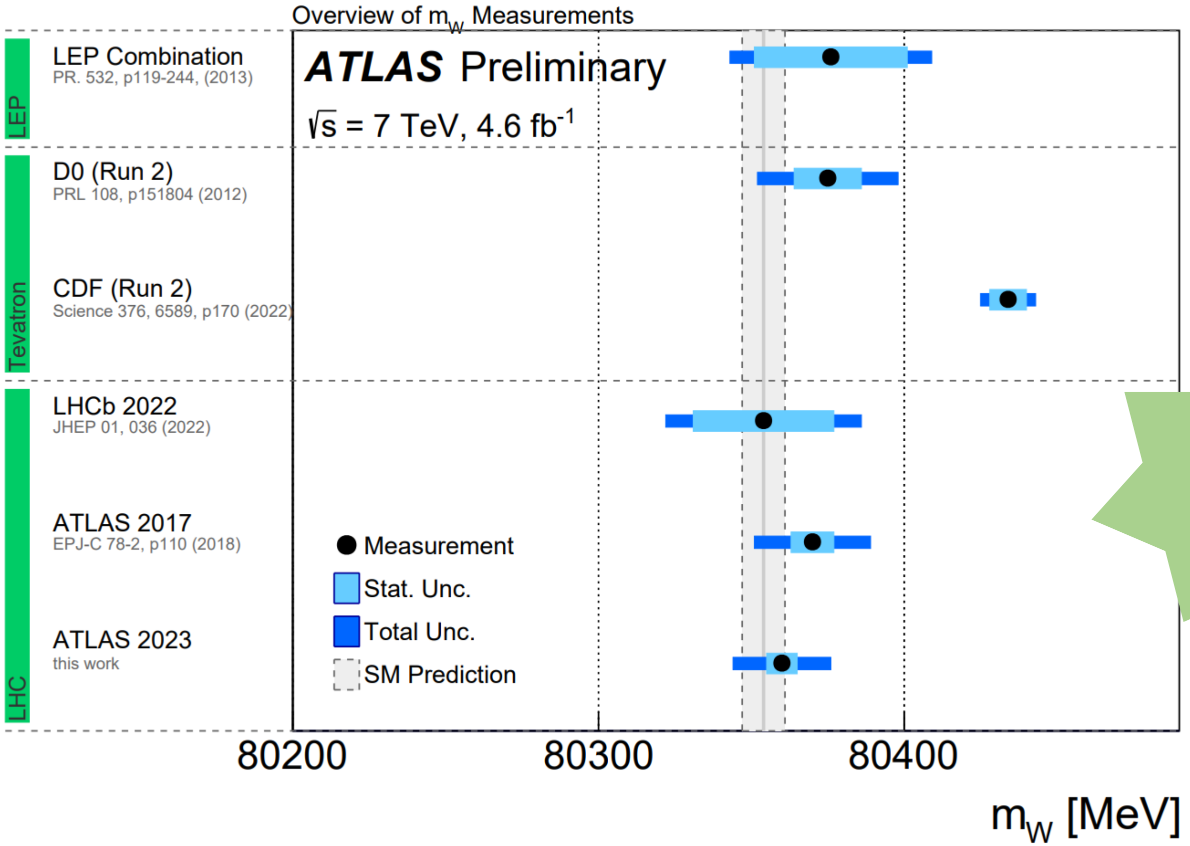
# ATLAS measurement: updated

ATLAS-CONF-2023-004

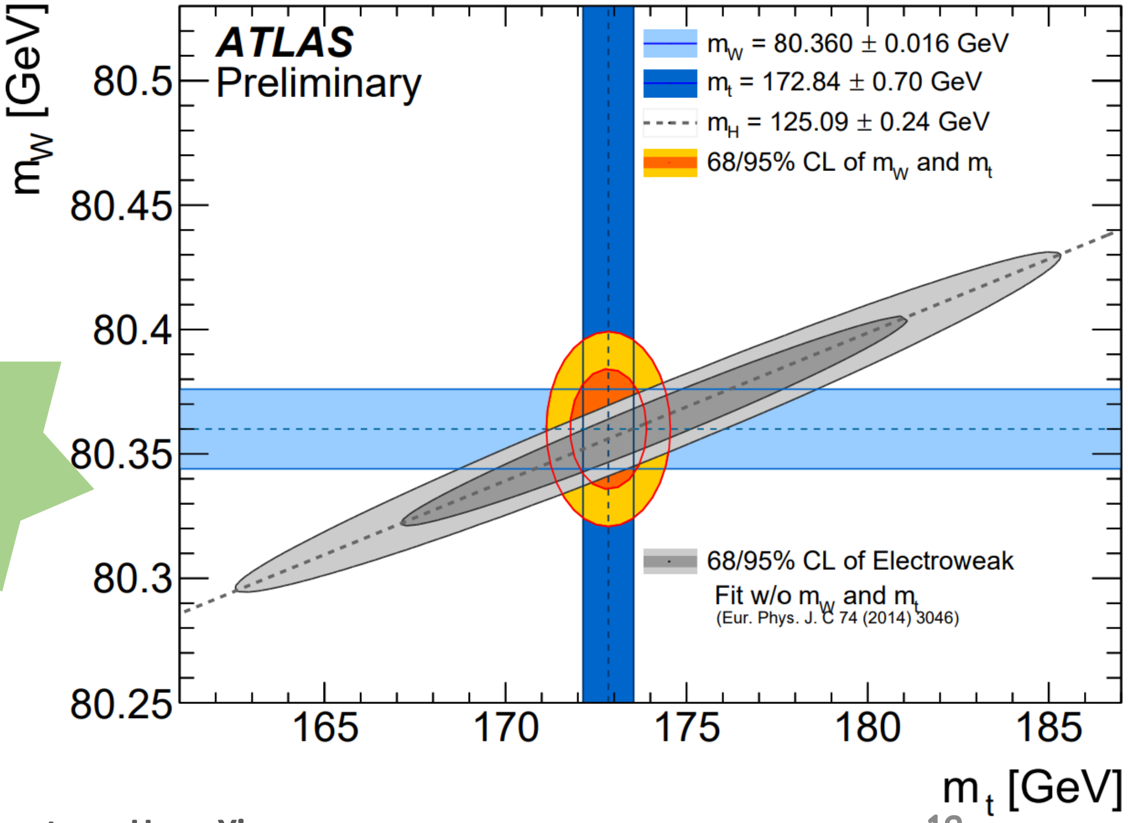
**Improvements:**

- Rigorous checks of modeling
  - $p_T(W)$ measurement: ATLAS-CONF-2023-028
- Modeling checks result in updates of PDFs and the evaluation of EW correction

- CT18, replace CT10
- Recover 1.5% of data in electron channel
- Profile likelihood fit, instead of $\chi^2$ minimization




New results

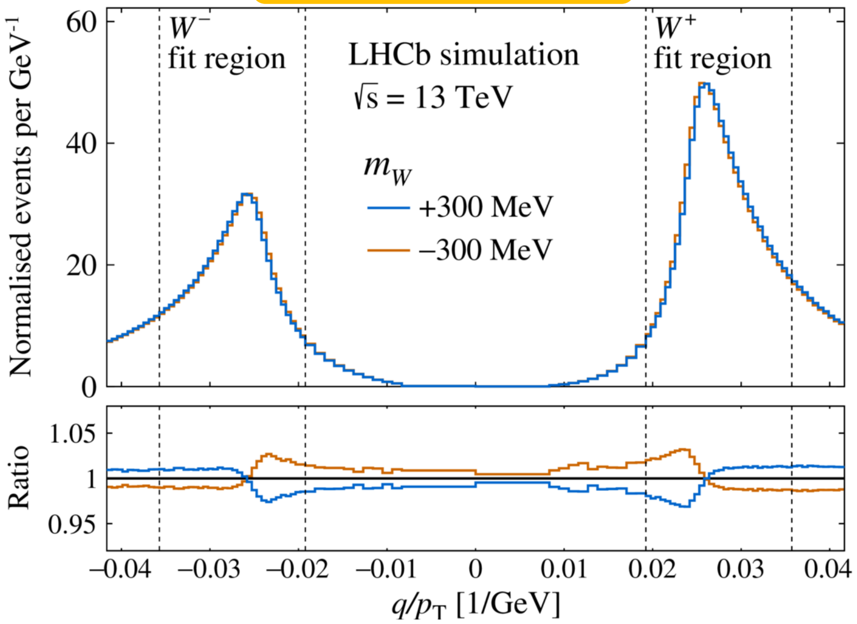


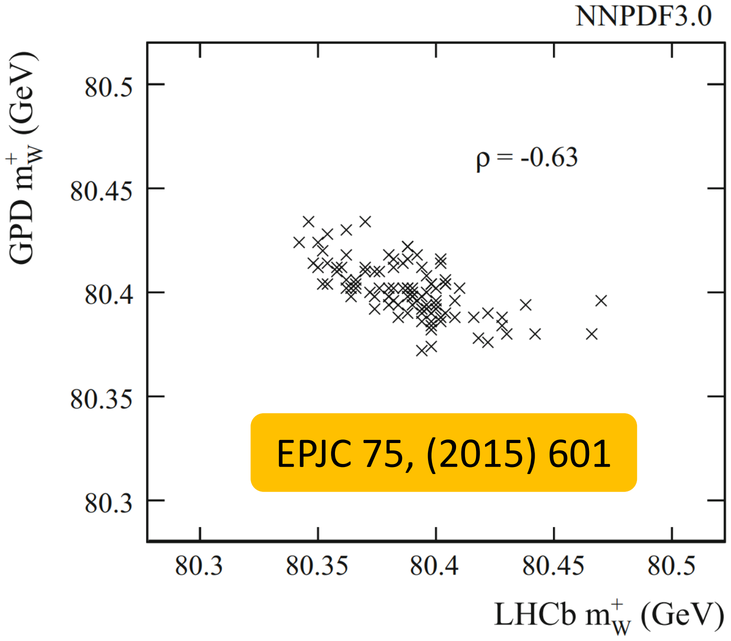
# LHCb measurement (1)

- **13 TeV data-set (2016), $\mathbf{1.6\ fb^{-1}}$**
  - Muon channel only
  - $W(1.0\times10^{6})$ , $Z(2.2\times10^{5})$
  - Muon $q/p_T$ distribution is used to measure $m_W$
    - → cannot reconstruct missing $E_t$ (not a $4\pi$ detector)
- **Complementary to ATLAS/CMS results**
  - PDFs decorrelation
  - An important measurement to reduce uncertainty from PDFs

$$\rho = \begin{pmatrix} & \mathbf{G}^+ & \mathbf{G}^- & \mathbf{L}^+ & \mathbf{L}^- \\ \mathbf{G}^+ & 1 & & & \\ \mathbf{G}^- & -0.22 & 1 & & \\ \mathbf{L}^+ & -0.63 & 0.11 & 1 & \\ \mathbf{L}^- & -0.02 & -0.30 & 0.21 & 1 \end{pmatrix}$$

JHEP 01 (2022) 036

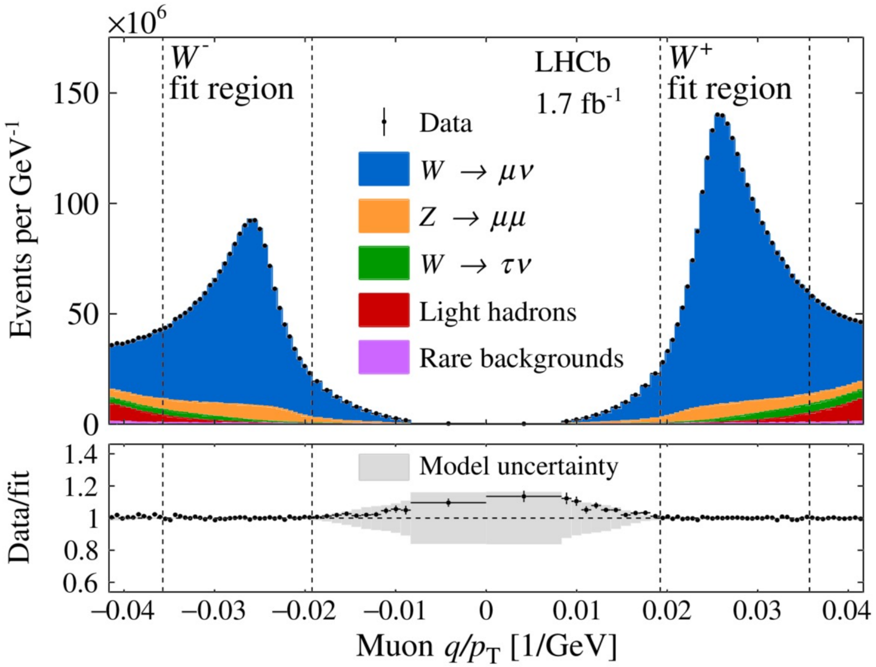


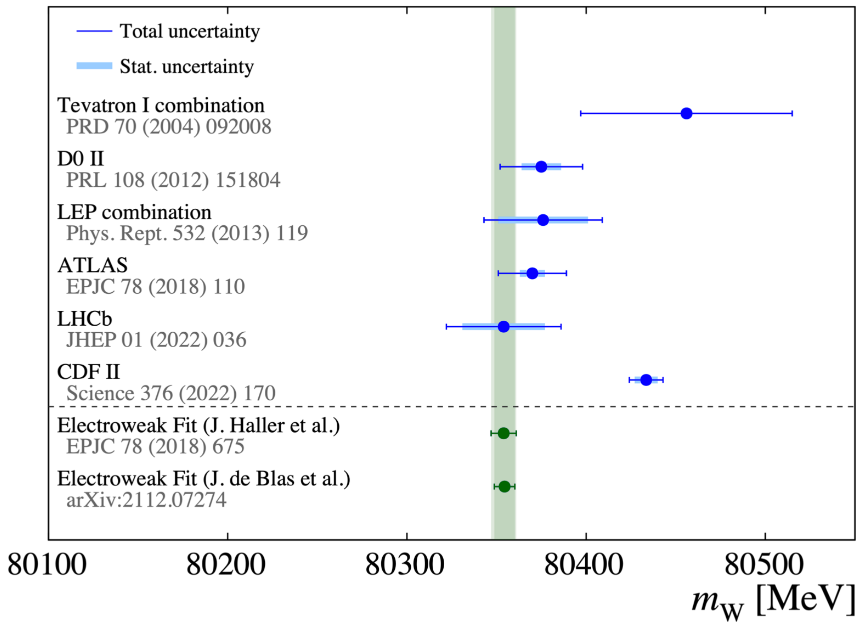



# LHCb measurement (2)

JHEP 01 (2022) 036

- The determined $m_W$ with the NNPDF31_nlo_as_0118 PDFs set
  - $\chi^2/dof = 105/102$
- Combined results obtained with NNPDF3.1, CT18, and MSHT20 PDFs sets:
  - $m_W = 80354 \pm 23(stat.) \pm 10(exp.) \pm 17(theory) \pm 9(PDF)$

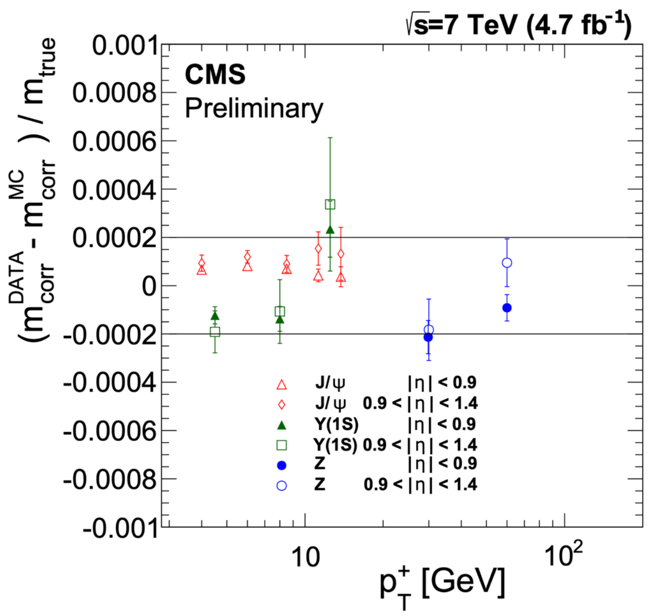


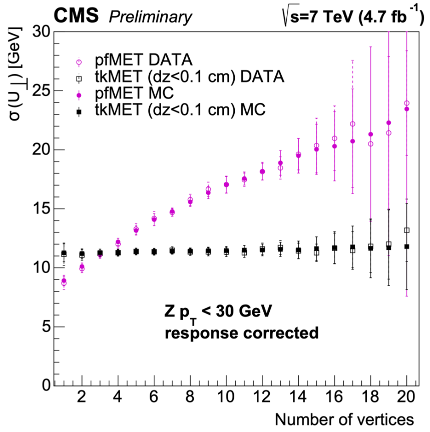
# CMS measurement

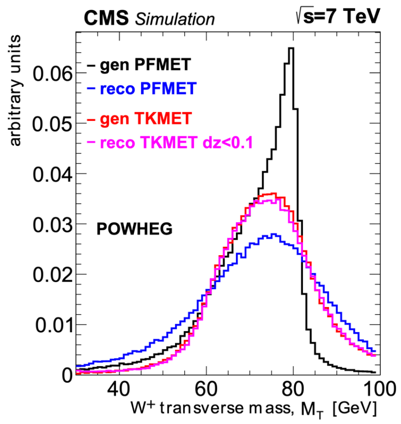
CMS-PAS-SMP-14-007

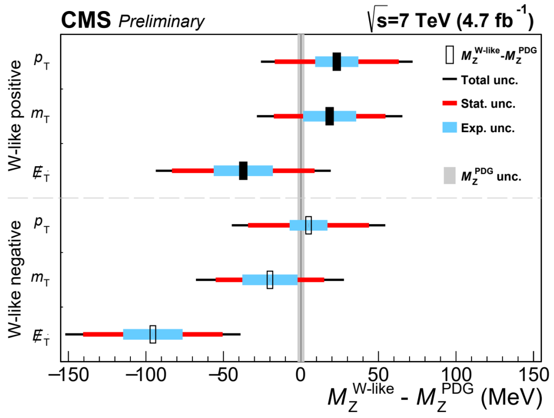
- No publication so far
- "$W$-like" measurement of the $Z$ mass
  - removing one lepton and treating as missing energy
  - 7 TeV data-set (2011), $4.7\ \mathrm{fb}^{-1}$, $<\mu>\approx 10$
  - central muon only ($|\eta| < 0.9$, instead of 2.4)




- A proof-of-principle:
  - muon $p_T$ and the recoil can be calibrated, even in the presence of large pileup

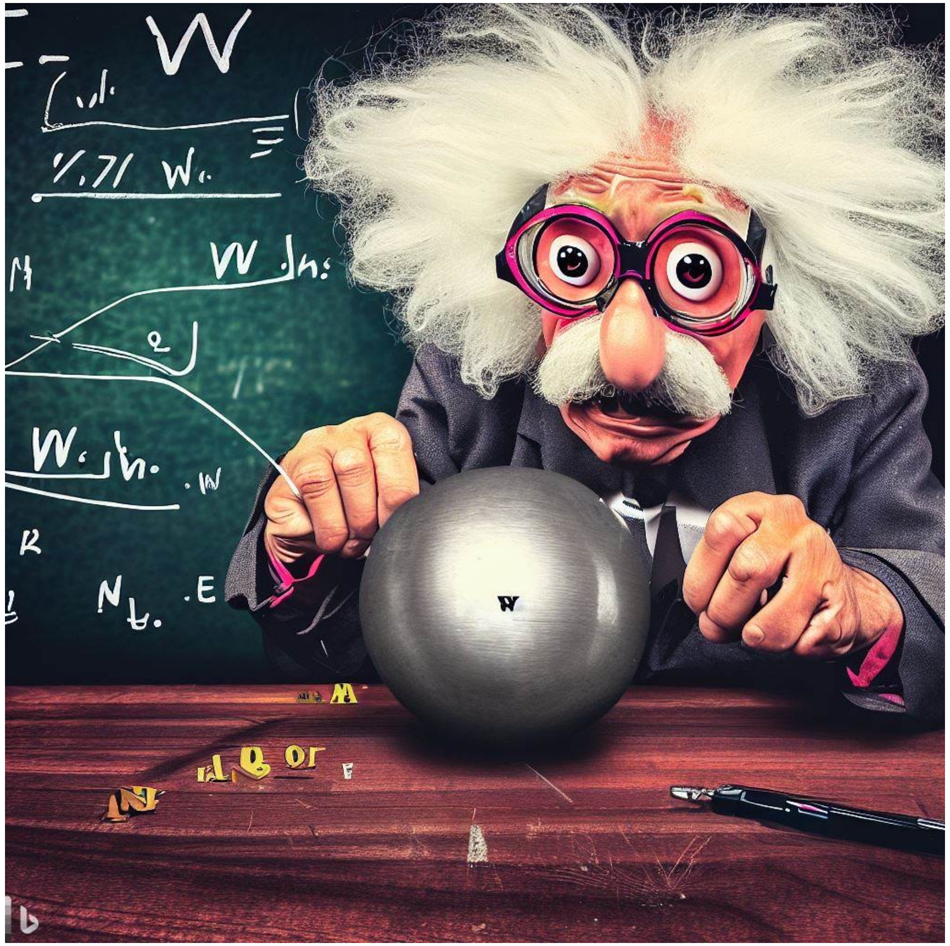


# Prospects

- **ATLAS:**
  - Reanalysis of previous publication
  - Improvement from previous measurement: 19 MeV → 16 MeV
  - Low pileup data available
- **CMS:**
  - actively working on an $m_W$ measurement
  - 200 $\text{pb}^{-1}$ low pileup data in 2017
  - Collect more in Run-3: for $m_W$ measurement
- **LHCb:**
  - Including 2017-2018 data-set
  - Target: 14 MeV(stat), 20 MeV (total)
  - Run-3: a similar detector and analysis environment



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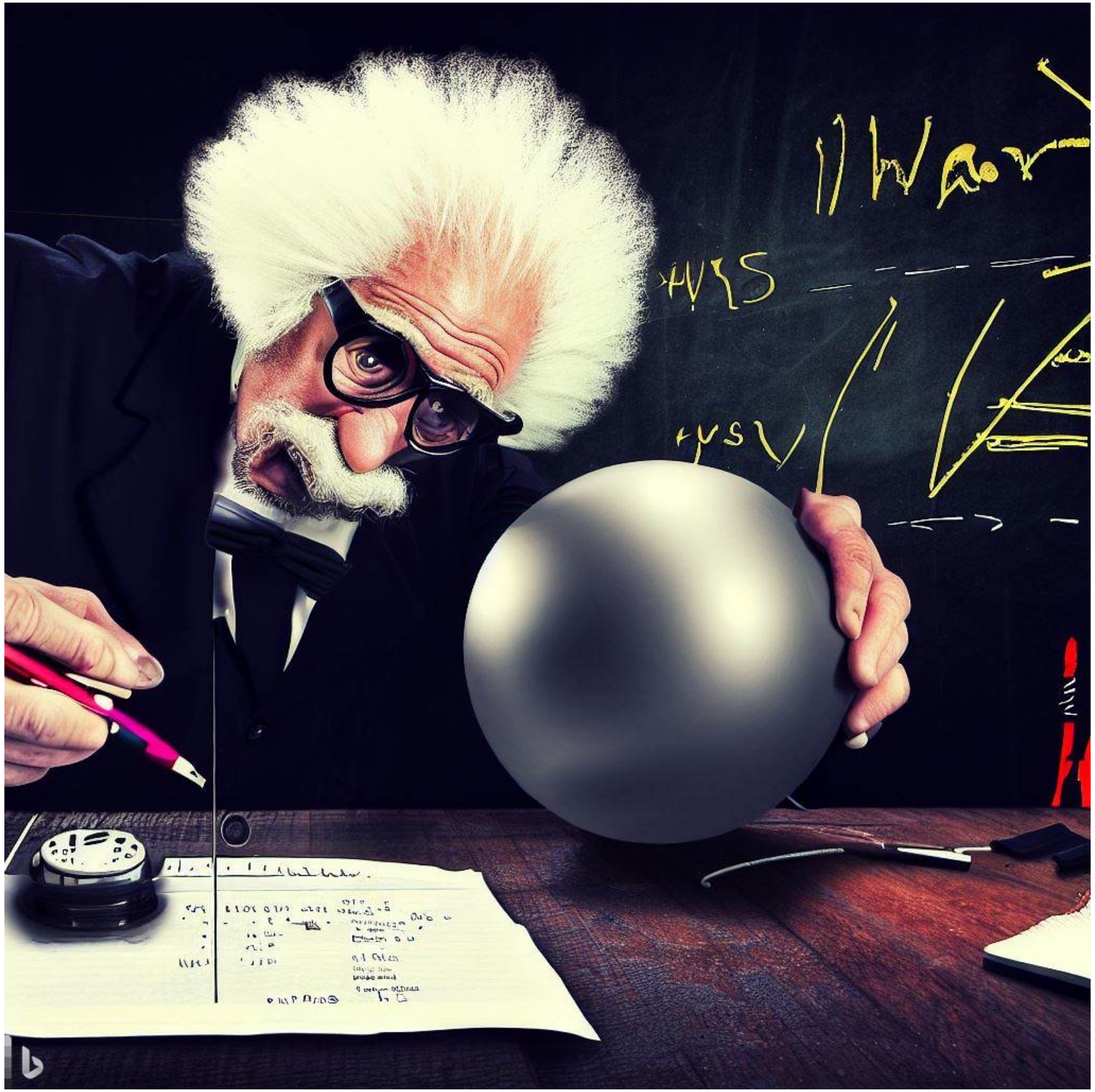
# Summary

- **Tevatron legacy measurements from CDF and DZero experiments**
  - A significant deviation between CDF result and SM expectation
  - CDF: full data-set, ~$4\sigma$ deviation
  - DZero: no plan to update with full data-set
- **LHC experiments are working on the $m_W$ measurement**
  - Many challenges at LHC: for example high pileup
  - ATLAS/LHCb published their first result on $m_W$
  - CMS is working on this analysis
- **Expect to have more updates from the LHC experiments**
  - Combination of experimental measured results is ongoing
  - Collaborations between experiments and theorists

# Backup



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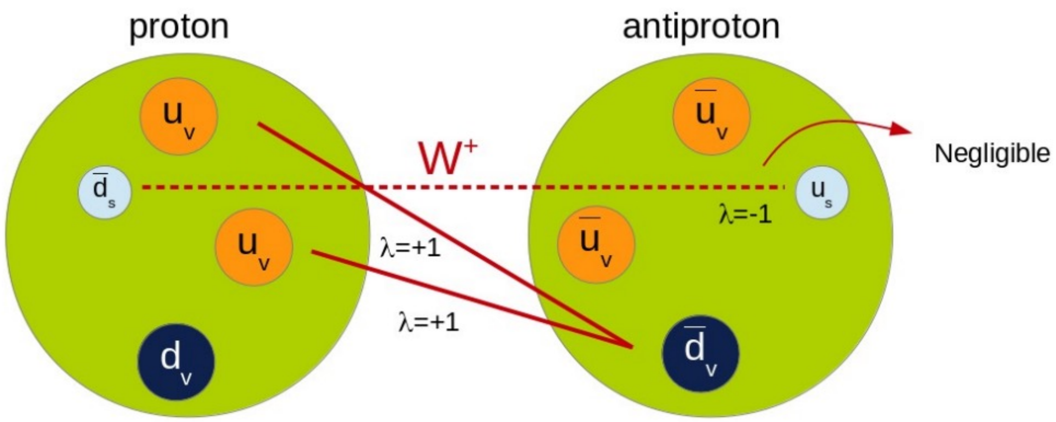
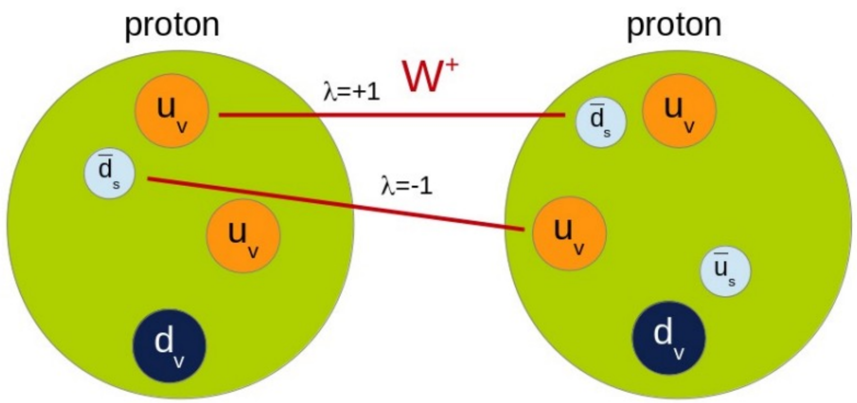
# W mass at the LHC

- A $pp$ collider has more challenges, compared to $p\bar{p}$ and $e^+e^-$ colliders




In $p\bar{p}$ collisions W bosons are mostly produced in the same helicity state




In pp collisions they are equally distributed between positive and negative helicity states

Large PDF-induced $W$-polarization uncertainty affecting the $p_T$ lepton distribution

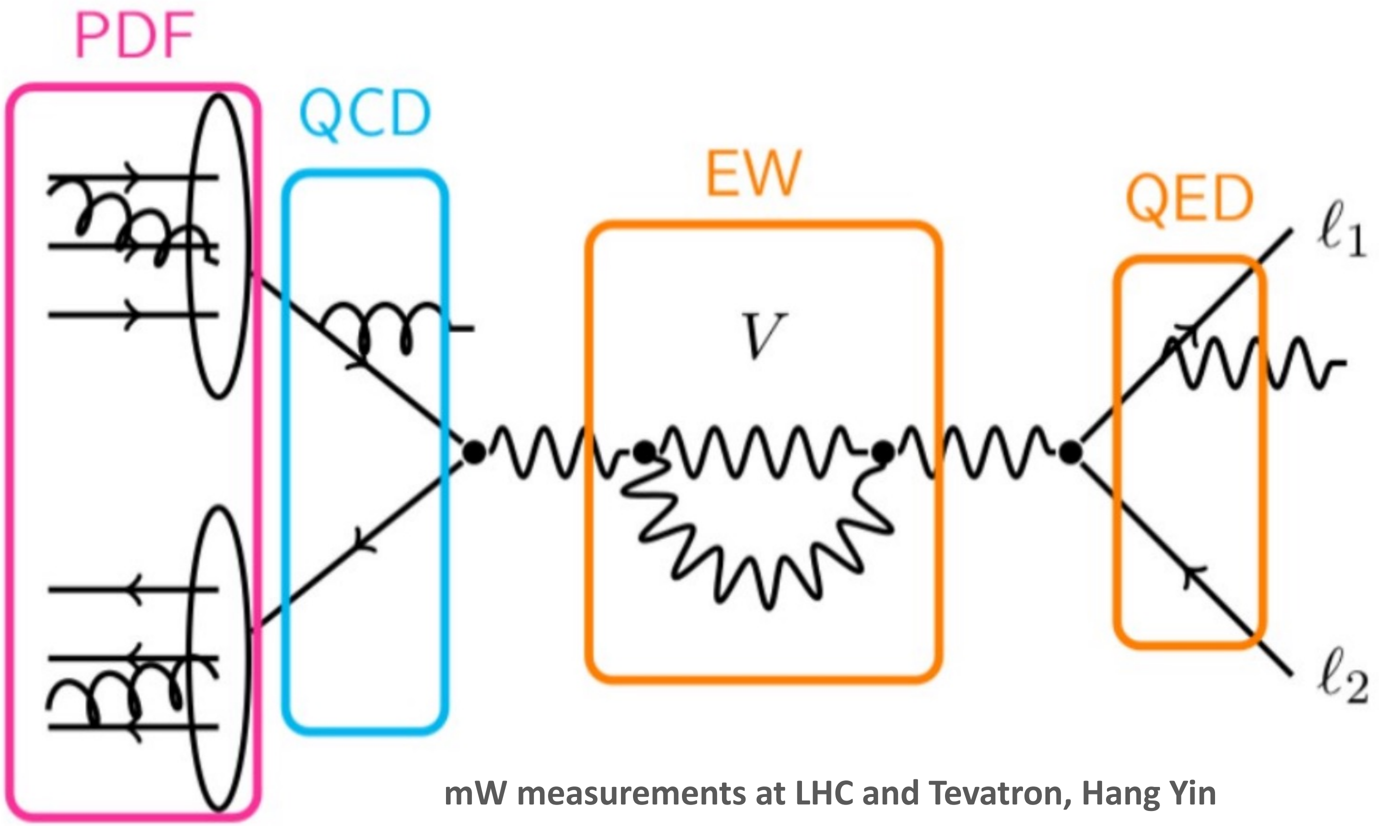
# Physics modeling

$$\frac{d\sigma}{dp_1\, dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T, y)}{dp_T\, dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta) + \sum_{i=0}^{7} A_i(p_T, y) P_i(\cos\theta, \phi)\right]$$

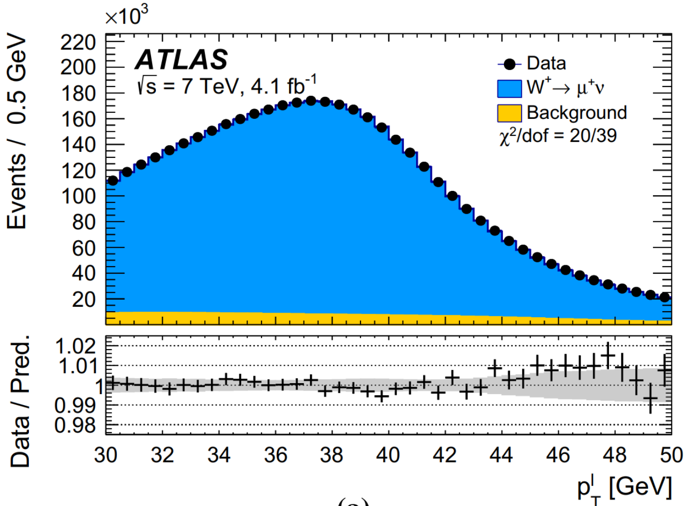
Breit-Wigner

NNLO pQCD

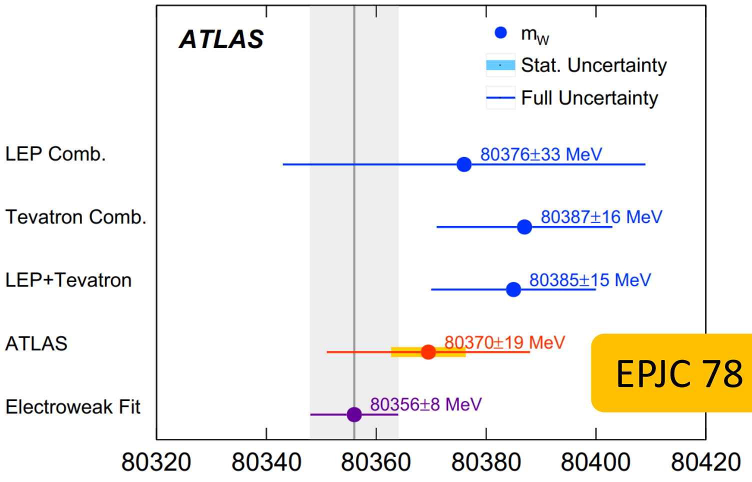
Parton Shower



# ATLAS measurement (2)



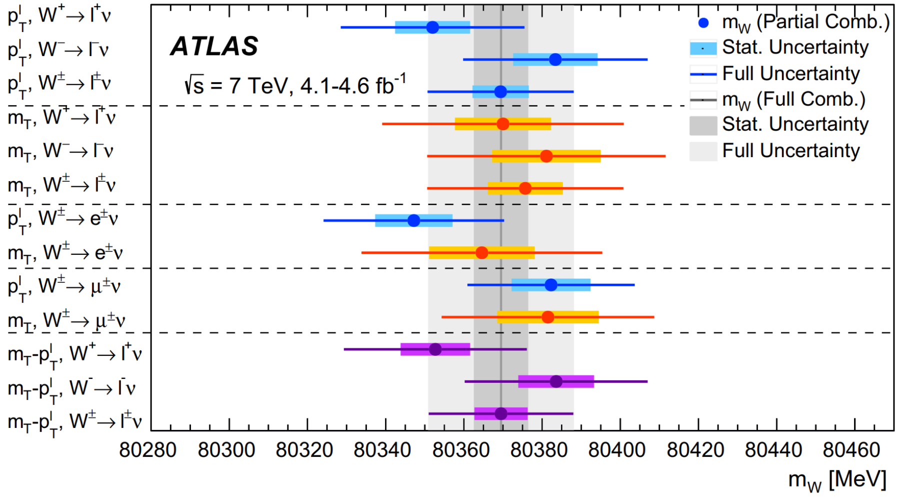

(a)

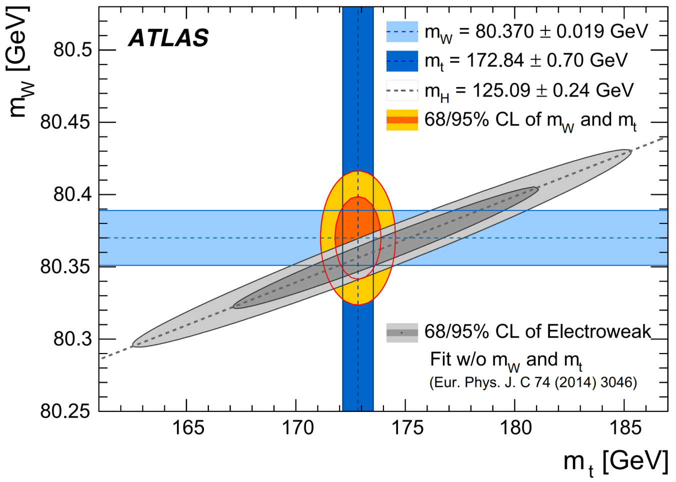



EPJC 78 (2018) 110, Erratum ibid. C 78 (2018) 898

**First measurement from LHC**

$$m_W = 80370 \pm 7(\text{stat.}) \pm 11(\text{exp.}) \pm 14(\text{mod.})\ \text{MeV}$$



# LHCb W mass measurement

- ATLAS and CMS experiments have the high pileup environment
- $W \to \mu\nu$ sample with high purity can be selected using the LHCb data, without requirement on the missing
- Anti-correlation of PDFs uncertainty: 10.5 MeV to 7.7 MeV

$$\delta_{\text{PDF}} = \begin{pmatrix} \mathbf{G}^+ & 24.8 \\ \mathbf{G}^- & 13.2 \\ \mathbf{L}^+ & 27.0 \\ \mathbf{L}^- & 49.3 \end{pmatrix}, \quad \rho = \begin{pmatrix} & \mathbf{G}^+ & \mathbf{G}^- & \mathbf{L}^+ & \mathbf{L}^- \\ \mathbf{G}^+ & 1 & & & \\ \mathbf{G}^- & -0.22 & 1 & & \\ \mathbf{L}^+ & -0.63 & 0.11 & 1 & \\ \mathbf{L}^- & -0.02 & -0.30 & 0.21 & 1 \end{pmatrix} \quad \alpha = \begin{pmatrix} \mathbf{G}+ & 0.30 \\ \mathbf{G}- & 0.45 \\ \mathbf{L}+ & 0.21 \\ \mathbf{L}- & 0.04 \end{pmatrix}$$

G: general purpose detector
L: LHCb

Correlation matrix

Weights

# Systematic uncertainties

JHEP 01 (2022) 036

| 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 |

**PDFs: average of NNPDF31, CT18 and MSHT20**

**$p_T$ model: envelope from five different models**

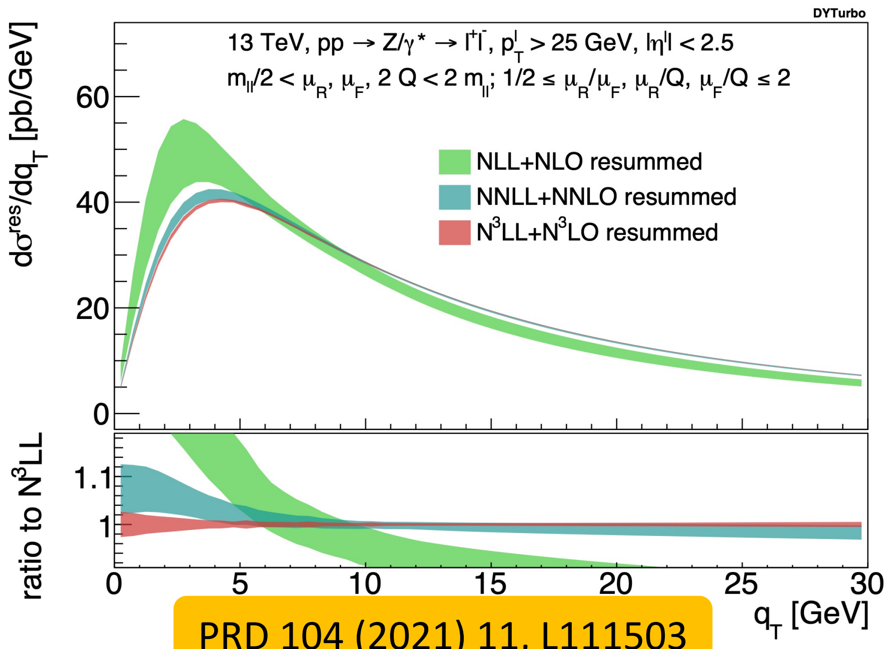
**$A_i$: scale variation**

**QED: envelope of the QED FSR from PYTHIA8, Photos, and Herweig7**

**Efficiencies: statistical uncertainties, details of method (e.g. binning, smoothing)**

# Run-2 full data-set

- The proof-of-principle measurement with the 2016 data
- A full Run-2 measurement targeting $\Delta m_W \approx 20$ MeV
  - $\Delta m_W(stat) \approx 14$ MeV
  - QCD predictions with higher perturbative accuracy are available e.g. from DYTurbo

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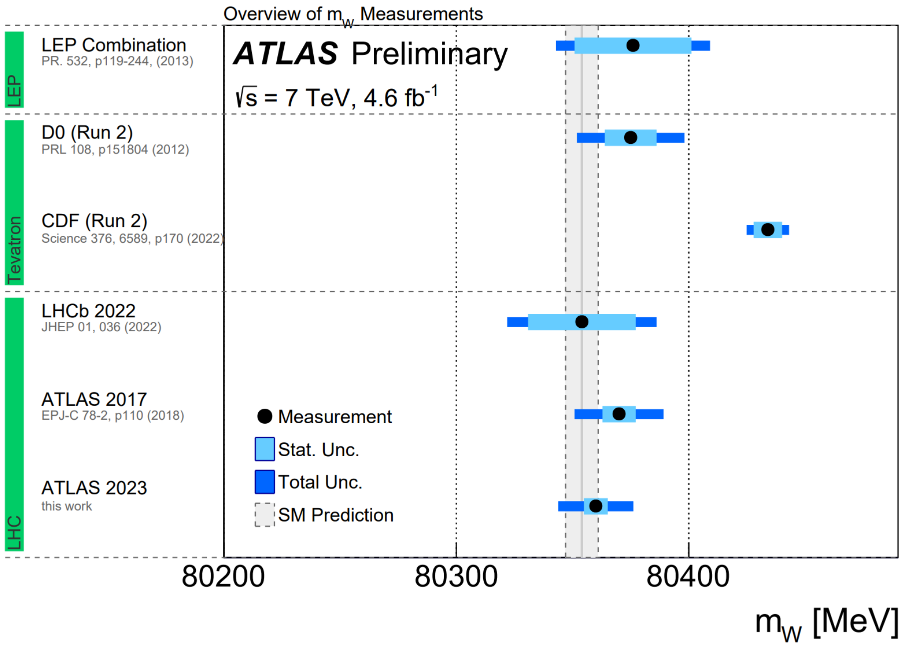
# Combinations

- **The Tevatron and LHC $m_W$ combination is ongoing**
  - Correlations dominated by PDF uncertainties
  - Some issues in the description of $W$ spin correlations in legacy ResBos codes
    - → at the level of 10 MeV




CERN-LPCC-2022-06
FERMILAB-TM-2779-V
7th July 2022

**Towards a combination of LHC and TeVatron $W$-boson mass measurements**

The LHC–TeVatron $W$-boson mass combination working group[1]

In this note methodological and modelling considerations towards a combination of the ATLAS, CDF and D0 measurements of the $W$-boson mass are discussed. As they were performed at different moments in time, each measurement employed different assumptions for the modelling of $W$-boson production and decay, as well as different fits of the parton distribution functions of the proton (PDFs). Methods are presented to accurately evaluate the effect of PDFs and other modelling variations on existing measurements, allowing to extrapolate them to any PDF set and to evaluate the corresponding uncertainties. Based on this approach, the measurements can be corrected to a common modelling reference and to the same PDFs, and subsequently combined accounting for PDF correlations in a quantitative way.

# It is a long journey …

- 1967: theory, weak force mediated by the and bosons
- 1983: boson was discovered UA1, UA2 @SppS ( GeV): GeV
- 1990: First mass with precision ( GeV) (UA2, GeV)
- 1992-1995: Tevatron Run-1 measurement (CDF & D0): Combined precision 59 MeV
- 1996-2000: LEP experiments ( ): MeV
- 2001-2012: Tevatron Run II, combined precisi
- 2012-2022: ATLAS and LHCb 19 MeV / 32 Me
- **2022: CDF 9 MeV**