High-precision measurement of the *W* boson mass with the CDF II detector

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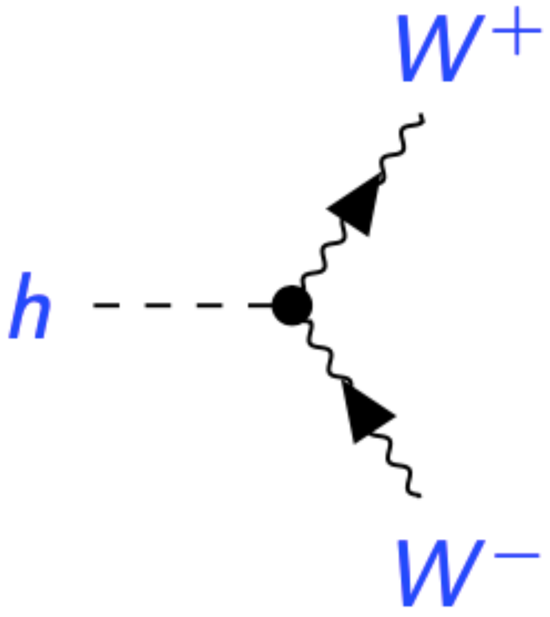
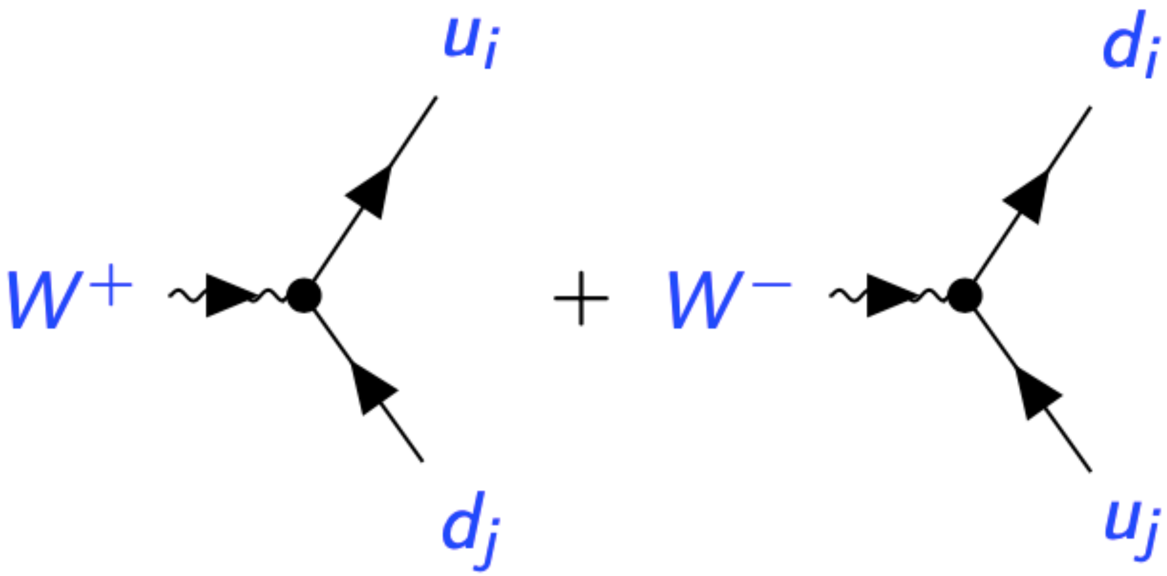
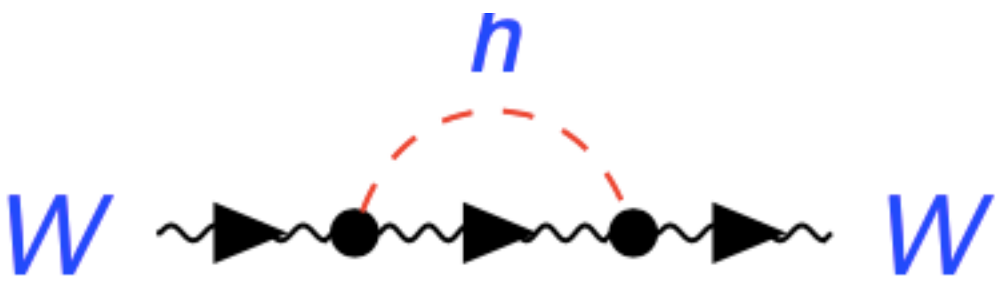
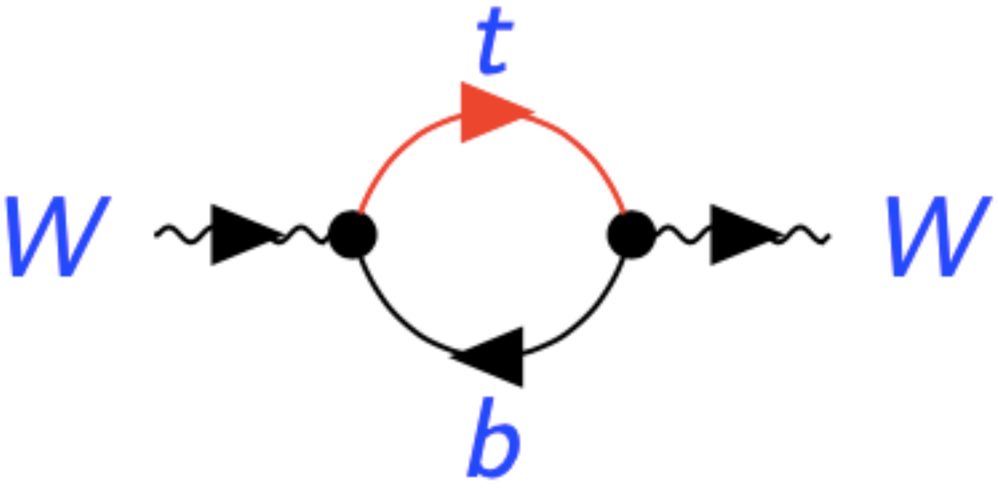
SM in the Nutshell

$$\begin{aligned}\mathcal{L}_{SM} &= \mathcal{L}_{\text{Gauge}}(g_s, g, g') \\ &+ \mathcal{L}_{\text{Yukawa}}(y_u, y_d, y_l) \\ &+ \mathcal{L}_{\text{Higgs}}(\lambda, m_\Phi^2) \quad [-V_{\text{Higgs}}(\lambda, m_\Phi^2)]\end{aligned}$$









SM parameters and Observables

The SM has 18* parameters.

We can use different, but, related sets of parameters:

$$\begin{array}{ccccccc} g_s & g & g' & \lambda & m_\Phi & y_f & y_{ij} \\ \alpha_s & M_Z & \alpha & G_F & M_H & m_f & V_{CKM} \end{array}$$

Tree-level relations

$$\alpha_s = \frac{g_s^2(Q)}{4\pi}, \quad (4\pi)\alpha = g^2 g'^2/(g^2 + g'^2), \quad M_Z^2 = \frac{(g^2+g'^2)v^2}{4},$$

$$G_F = \frac{1}{\sqrt{2}v^2}, \qquad M_h = 2\lambda v^2 = 2|m_\Phi^2|, \qquad m_f = y_f v/\sqrt{2}$$

These relations are modified at high orders of perturbation theory.

W-boson mass prediction in the SM

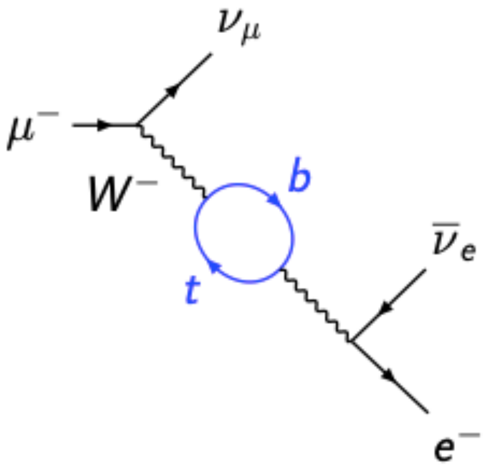
Given the relations

$$\frac{G_F}{\sqrt{2}} = \frac{1}{2v^2}, \quad (4\pi)\alpha = \frac{g^2 g'^2}{g^2 + g'^2}, \quad M_Z^2 = \frac{g_Z^2 v^2}{4}, \quad M_W^2 = \frac{g^2 v^2}{4}$$

we derive

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2(1 - M_W^2/M_Z^2)}.$$

This tree-level relation gives a prediction that is far away from the experiment



$$M_W^{tree} = 80.9387(25)\ \text{GeV}$$
$$M_W^{exp} = 80.379(12)\ \text{GeV}$$

W-boson mass prediction in the SM

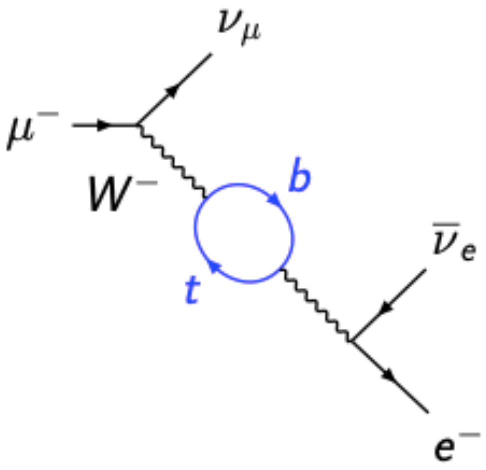
Given the relations

$$\frac{G_F}{\sqrt{2}} = \frac{1}{2v^2}, \quad (4\pi)\alpha = \frac{g^2 g'^2}{g^2 + g'^2}, \quad M_Z^2 = \frac{g_Z^2 v^2}{4}, \quad M_W^2 = \frac{g^2 v^2}{4}$$

we derive

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2(1 - M_W^2/M_Z^2)}\left[1 + \Delta r(m_h, m_t, \dots)\right]$$

This tree-level relation gives a prediction that is far away from the experiment



$$M_W^{tree} = 80.9387(25)\ \text{GeV}$$
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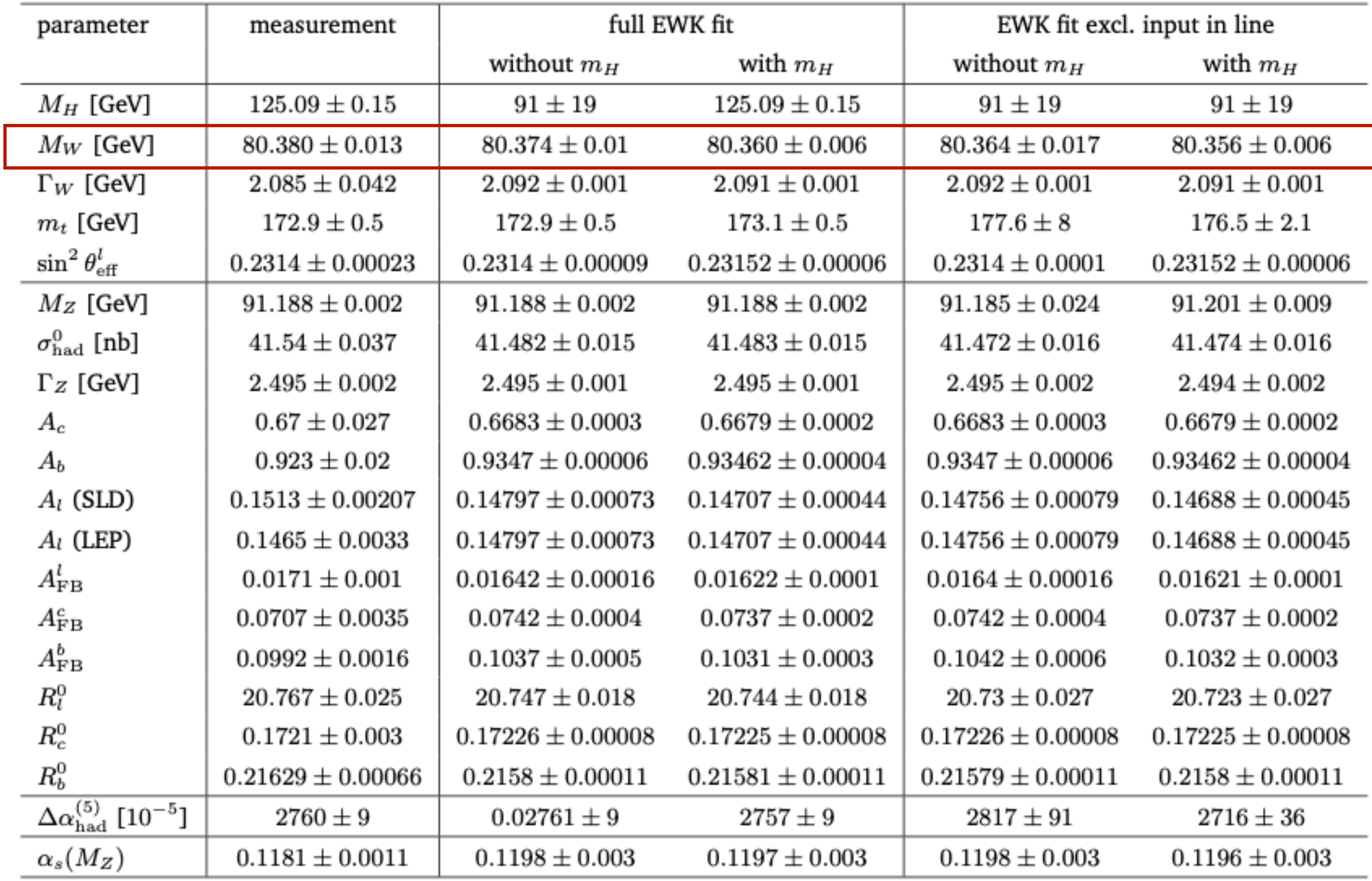
Global fit to EW observables



parameter	measurement	full EWK fit		EWK fit excl. input in line	
		without m_H	with m_H	without m_H	with m_H
M_H [GeV]	125.09 ± 0.15	91 ± 19	125.09 ± 0.15	91 ± 19	91 ± 19
M_W [GeV]	80.380 ± 0.013	80.374 ± 0.01	80.360 ± 0.006	80.364 ± 0.017	80.356 ± 0.006
Γ_W [GeV]	2.085 ± 0.042	2.092 ± 0.001	2.091 ± 0.001	2.092 ± 0.001	2.091 ± 0.001
m_t [GeV]	172.9 ± 0.5	172.9 ± 0.5	173.1 ± 0.5	177.6 ± 8	176.5 ± 2.1
$\sin^2 \theta^l_{\text{eff}}$	0.2314 ± 0.00023	0.2314 ± 0.00009	0.23152 ± 0.00006	0.2314 ± 0.0001	0.23152 ± 0.00006
M_Z [GeV]	91.188 ± 0.002	91.188 ± 0.002	91.188 ± 0.002	91.185 ± 0.024	91.201 ± 0.009
σ^0_{had} [nb]	41.54 ± 0.037	41.482 ± 0.015	41.483 ± 0.015	41.472 ± 0.016	41.474 ± 0.016
Γ_Z [GeV]	2.495 ± 0.002	2.495 ± 0.001	2.495 ± 0.001	2.495 ± 0.002	2.494 ± 0.002
A_c	0.67 ± 0.027	0.6683 ± 0.0003	0.6679 ± 0.0002	0.6683 ± 0.0003	0.6679 ± 0.0002
A_b	0.923 ± 0.02	0.9347 ± 0.00006	0.93462 ± 0.00004	0.9347 ± 0.00006	0.93462 ± 0.00004
A_l (SLD)	0.1513 ± 0.00207	0.14797 ± 0.00073	0.14707 ± 0.00044	0.14756 ± 0.00079	0.14688 ± 0.00045
A_l (LEP)	0.1465 ± 0.0033	0.14797 ± 0.00073	0.14707 ± 0.00044	0.14756 ± 0.00079	0.14688 ± 0.00045
A^l_{FB}	0.0171 ± 0.001	0.01642 ± 0.00016	0.01622 ± 0.0001	0.0164 ± 0.00016	0.01621 ± 0.0001
A^c_{FB}	0.0707 ± 0.0035	0.0742 ± 0.0004	0.0737 ± 0.0002	0.0742 ± 0.0004	0.0737 ± 0.0002
A^b_{FB}	0.0992 ± 0.0016	0.1037 ± 0.0005	0.1031 ± 0.0003	0.1042 ± 0.0006	0.1032 ± 0.0003
R^0_l	20.767 ± 0.025	20.747 ± 0.018	20.744 ± 0.018	20.73 ± 0.027	20.723 ± 0.027
R^0_c	0.1721 ± 0.003	0.17226 ± 0.00008	0.17225 ± 0.00008	0.17226 ± 0.00008	0.17225 ± 0.00008
R^0_b	0.21629 ± 0.00066	0.2158 ± 0.00011	0.21581 ± 0.00011	0.21579 ± 0.00011	0.2158 ± 0.00011
$\Delta\alpha^{(5)}_{\text{had}}$ $[10^{-5}]$	2760 ± 9	0.02761 ± 9	2757 ± 9	2817 ± 91	2716 ± 36
$\alpha_s(M_Z)$	0.1181 ± 0.0011	0.1198 ± 0.003	0.1197 ± 0.003	0.1198 ± 0.003	0.1196 ± 0.003

1902.05142

Previous W-boson mass measurements

- **LEP measurement $e^+e^- \to W^+W^-$**
  - $M_W = 80{,}376 \pm 33$ MeV (combination, 4 experiments)

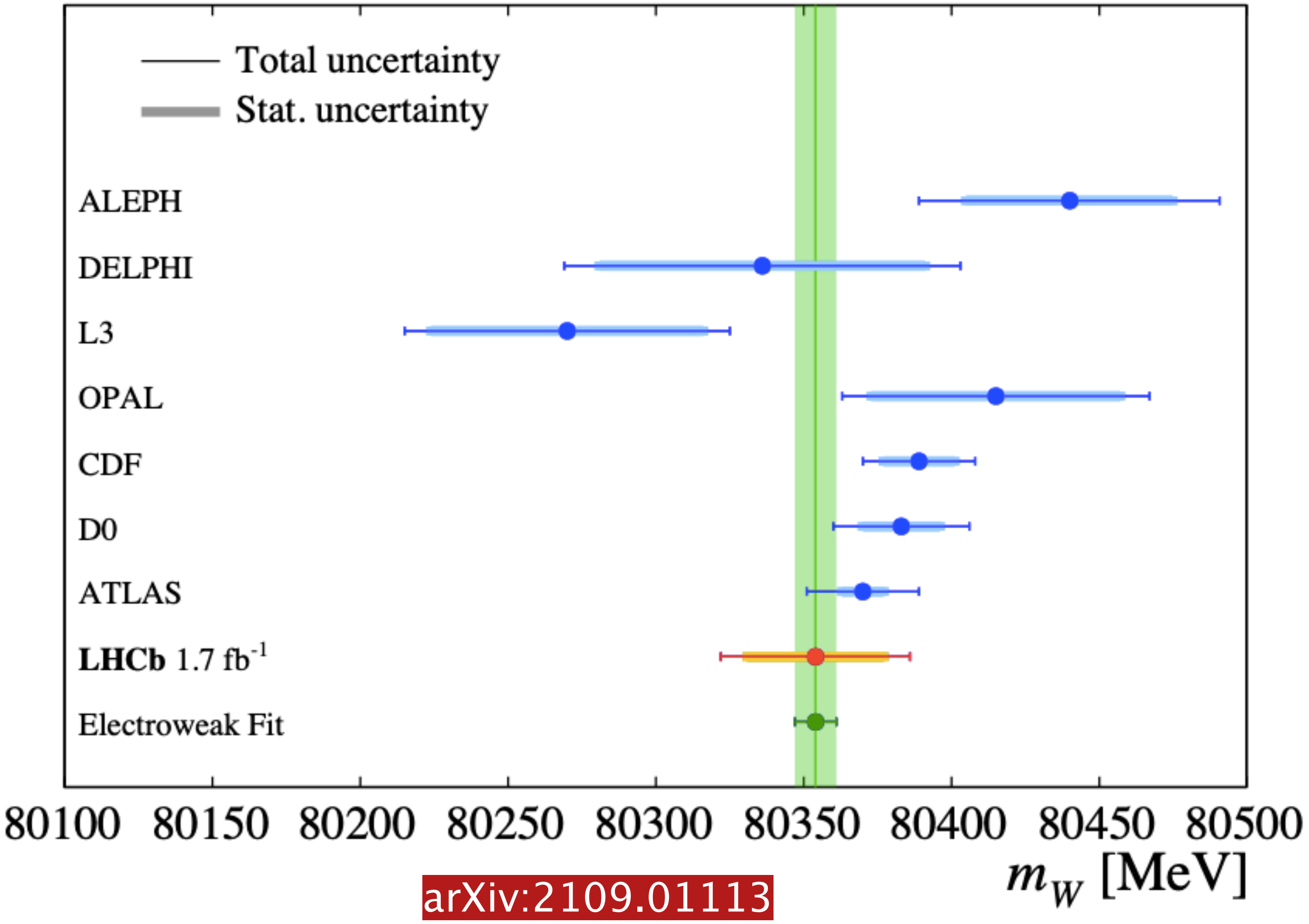
- **Tevatron measurement in $p\bar{p} \to W \to \mu\nu_\mu(e\nu_e)$**
  - $M_W = 80{,}383 \pm 16$ MeV (combination, 2 experiments)

- **LHC measurement $pp \to Wj$**
  - **ATLAS:**
    - $M_W = 80{,}370 \pm 19$ MeV (2017)
  - **LHCb:**
    - $M_W = 80{,}364 \pm 32$ MeV (2021)

Advantage(s) of Tevatron vs LHC:

- reduced uncertainty in momenta of colliding quark - antiquark pair

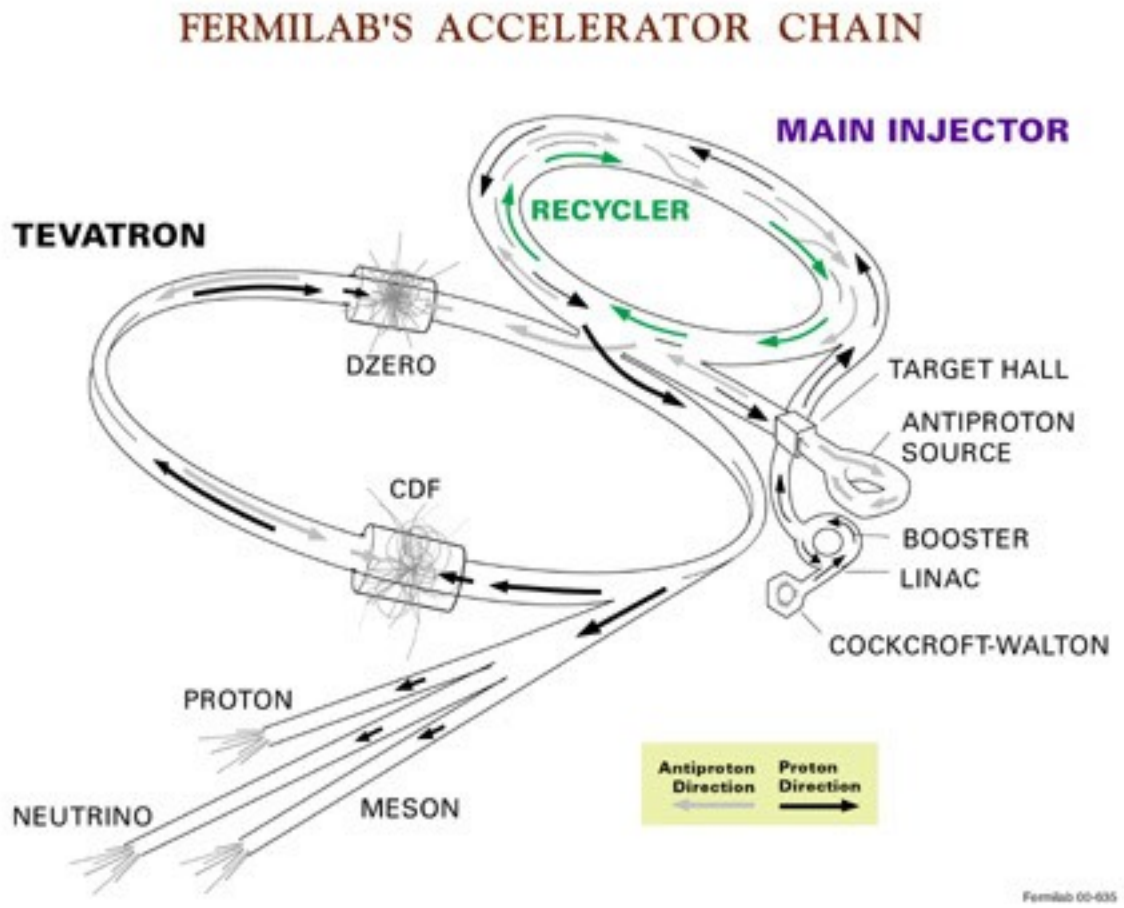
- lower luminosity - lower pile-up?

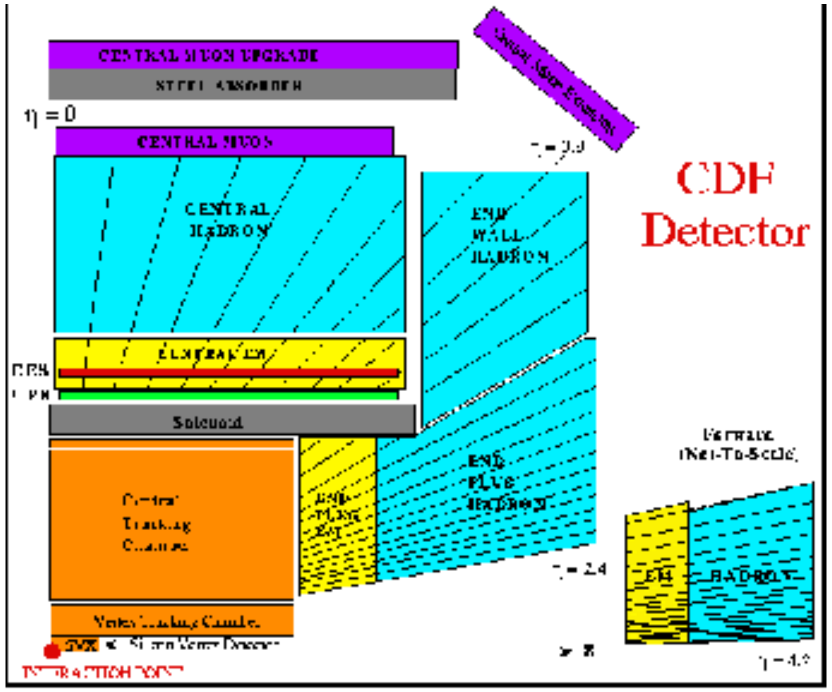


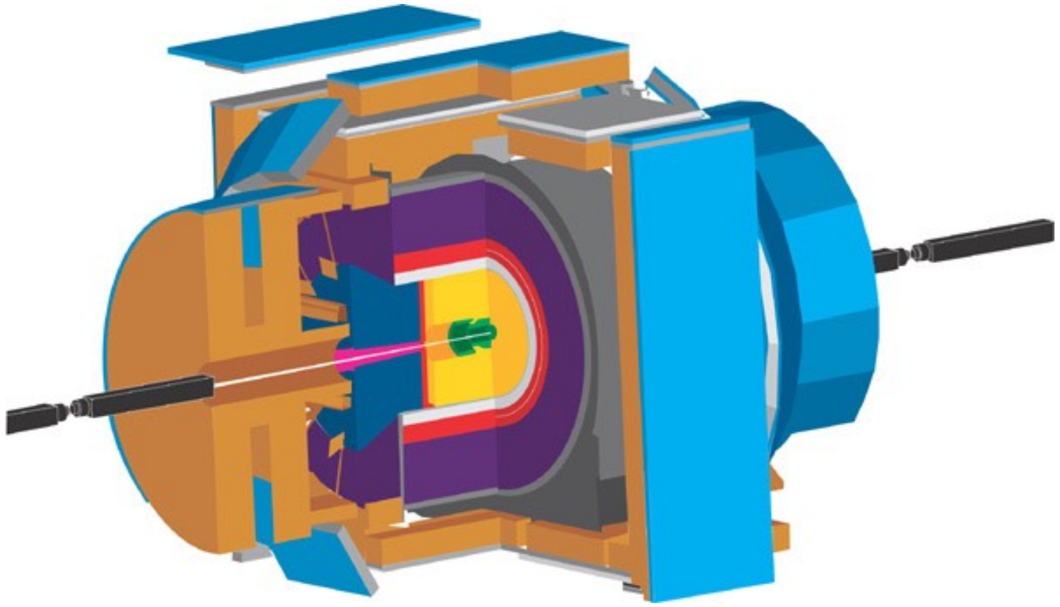
arXiv:2109.01113

Tevatron and CDF detector

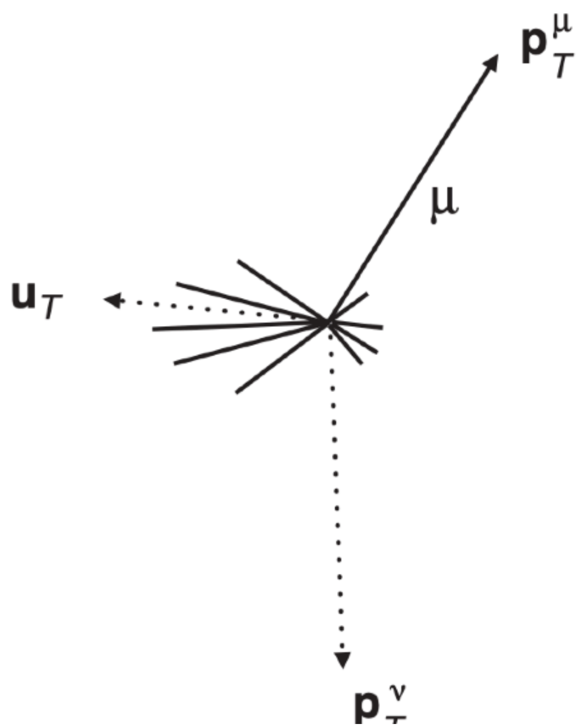
- **Proton-Antiproton accelerator at Fermilab**
- **Center of mass energy $\sqrt{s} = 1.96$ TeV**
- **In operation 1983-2011**
- **Two main detectors**
  - **D0**
  - **CDF (Collider Detector at Fermilab)**
- **Main scientific result:**
  - **top-quark discovery in 1995**
  - **Top-quark mass measurement to 1% precision**







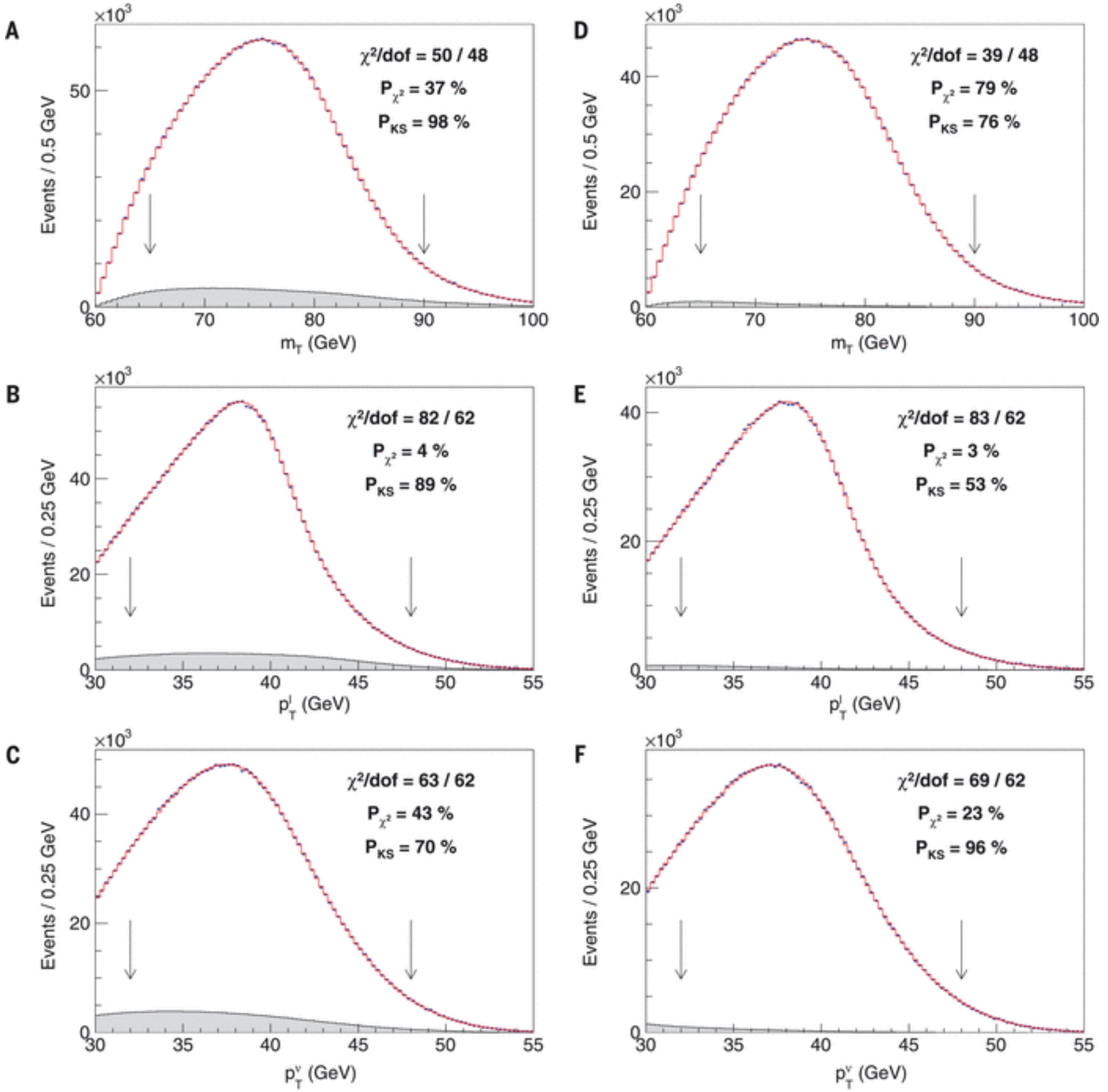
New CDF measurement



$$m_T = \sqrt{2(p_T^l p_T^\nu - \overrightarrow{p}_T^l \cdot \overrightarrow{p}_T^\nu}$$

$$\overrightarrow{p}_T^\nu = - \overrightarrow{p}_T^l - \overrightarrow{u}$$

The dataset (8.8 fb^{-1}) recorded between 2002 and 2011 is about four times larger than that used in previous analysis



muon
2424486 candidates

electron
1811700 candidates

New CDF measurement

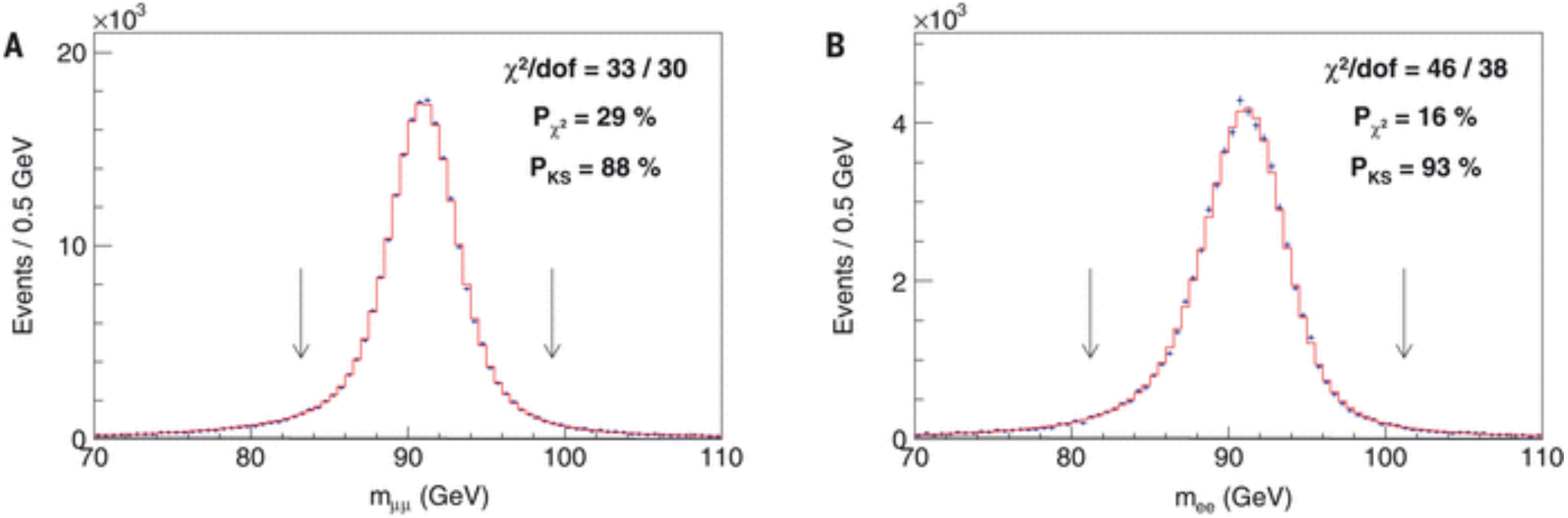
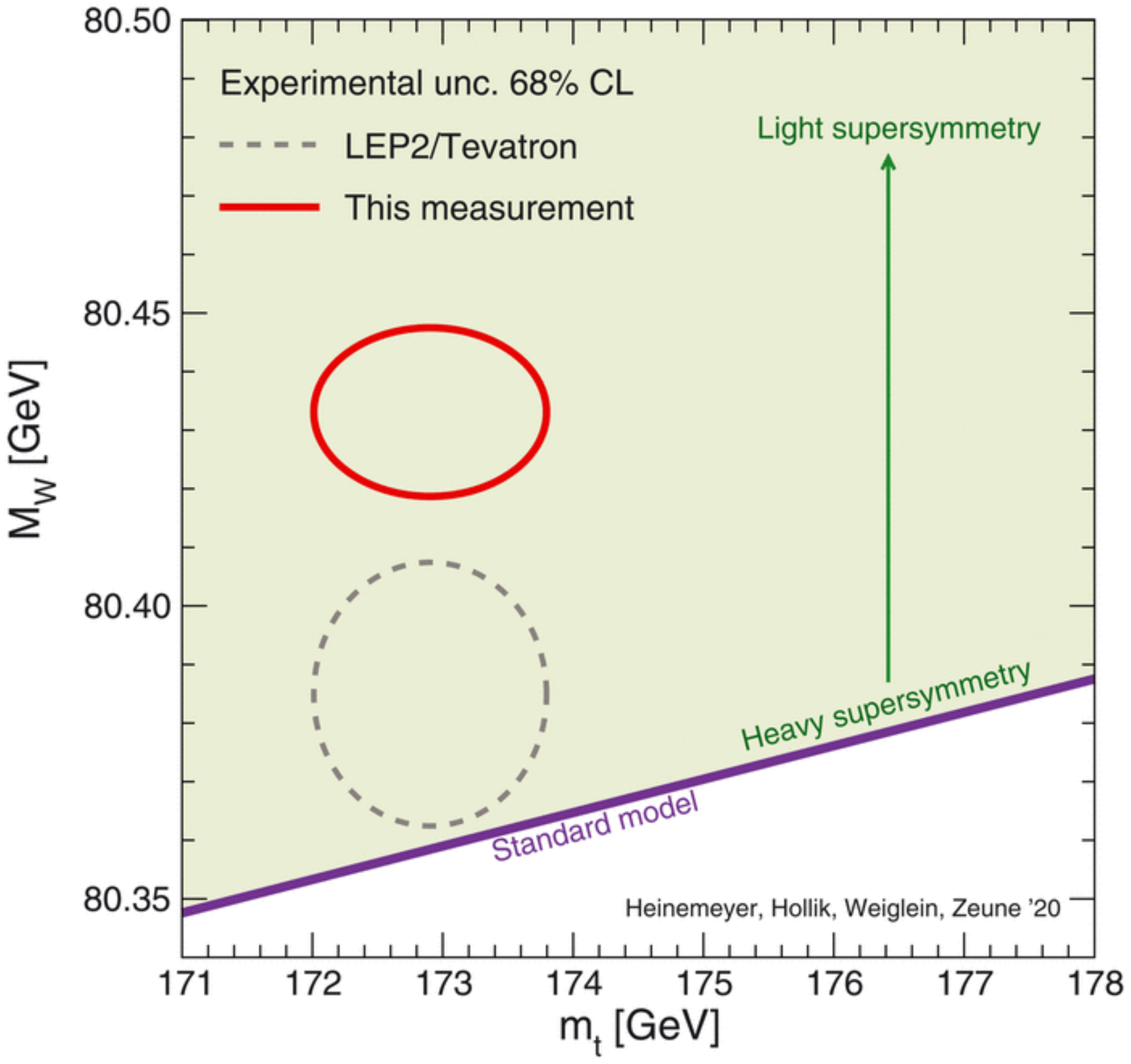


Fig 3. from the article. Decay of the *Z* boson.(**A** and **B**) Distribution of (A) dimuon and (B) dielectron mass for candidate $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$ decays, respectively. The data (points) are overlaid with the best-fit simulation template including the photon-mediated contribution (histogram).

Calibration by Z-boson mass measurements $M_Z = 91{,}192 \pm 6.4_{stat} \pm 4.0_{syst}$ **MeV**

New CDF result

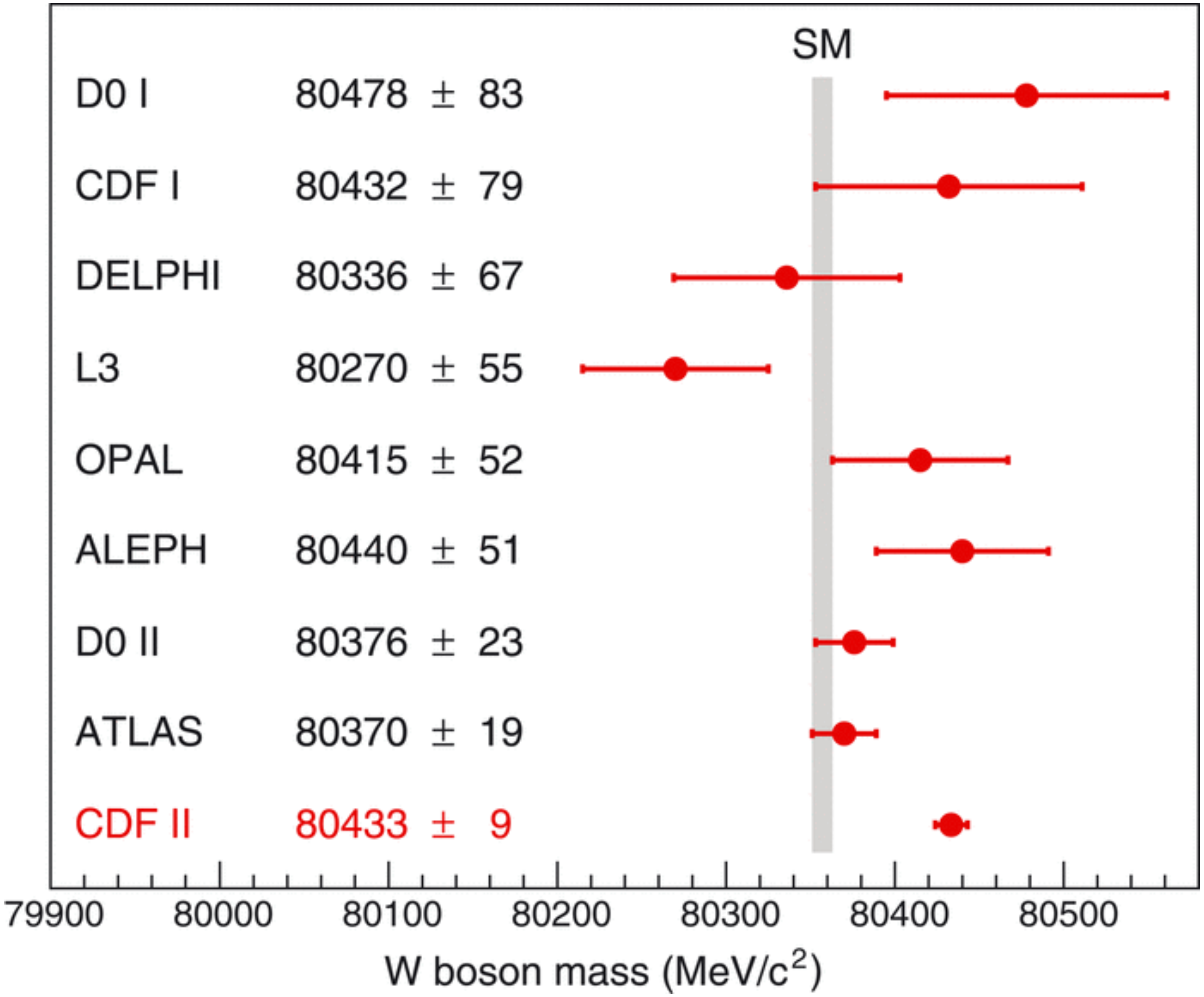
Fig 1. Experimental measurements and theoretical predictions for the *W* boson mass. The red continuous ellipse shows the *MW* measurement reported in this paper and the global combination of top-quark mass measurements, $m_t = 172.89 \pm 0.59$ GeV. The correlation between the M_W and m_t measurements is negligible. The gray dashed ellipse, shows the 68% confidence level (CL) region allowed by the previous LEP-Tevatron combination $M_W = 80.385 \pm 15$ MeV. That combination includes the *MW* measurement published by CDF in 2012, which this paper both updates (increasing M_W by 13.5 MeV) and subsumes. As an illustration, the green shaded region shows the predicted mass of the *W* boson as a function of the top-quark mass m_t in the minimal supersymmetric extension (one of many possible extensions) of the standard model (SM), for a range of supersymmetry model parameters as described. The thick purple line at the lower edge of the green region corresponds to the SM prediction with the Higgs boson mass measured at the LHC used as input.



$$M_W^{CDF} = 80{,}433.5 \pm 6.9_{stat} \pm 6.9_{syst} \text{ MeV}$$

New CDF result

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



$$M_W^{SM} = 80{,}357 \pm 4_{input} \pm 4_{theory} \text{ MeV}$$

Conclusions?

- The announced CDF measurement are in “significant tension with the SM” (7 sigma?)

$$M_W^{CDF} = 80{,}433.5 \pm 6.9_{stat} \pm 6.9_{syst}\ \text{MeV}$$

- Yet, we need an independent confirmation from other experiments (LHC or future colliders)

- Many theoretical papers appeared (42 citations since 8th of April) with different options to account for the discrepancy….