Precision Mass Measurement of the
W Boson
by the CDF-II Collaboration at FERMILAB

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

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CDF Collaboration *et al.*, *Science* **376**, 170–176 (2022) 8 April 2022

The mass of the *W* boson, a mediator of the weak force between elementary particles, is tightly constrained by the symmetries of the standard model of particle physics. The Higgs boson was the last missing component of the model. After observation of the Higgs boson, a measurement of the *W* boson mass provides a stringent test of the model. We measure the *W* boson mass, M_W, using data corresponding to 8.8 inverse femtobarns of integrated luminosity collected in proton-antiproton collisions at a 1.96 tera–electron volt center-of-mass energy with the CDF II detector at the Fermilab Tevatron collider. A sample of approximately 4 million *W* boson candidates is used to obtain $M_W = 80{,}433.5 \pm 6.4_{\text{stat}} \pm 6.9_{\text{syst}} = 80{,}433.5 \pm 9.4\ \text{MeV}/c^2$, the precision of which exceeds that of all previous measurements combined (stat, statistical uncertainty; syst, systematic uncertainty; MeV, mega–electron volts; *c*, speed of light in a vacuum). This measurement is in significant tension with the standard model expectation.

5.1 Prediction for the W boson mass in the SM

The mass of the signal discovered in the Higgs boson searches at the LHC about a year ago is measured mainly in the $\gamma\gamma$ and the $ZZ^{(*)}$ channels. Currently, the combined mass measurement from ATLAS is $125.5 \pm 0.2 \pm 0.6$ GeV [107] and from CMS $125.7 \pm 0.3 \pm 0.3$ GeV [108]. Adding systematic and statistical errors in quadrature and determining the weighted average between the ATLAS and CMS measurements we get $M_H^{\text{SM}} = 125.64 \pm 0.35$ GeV. Setting the SM Higgs boson mass to this value, the SM prediction for the W boson mass reads (the other SM parameters have been fixed as $G_\mu = 1.1663787 \times 10^{-5}$, $M_Z = 91.1875$ GeV, $\alpha_s(M_Z) = 0.1180$, $\Delta\alpha_{\text{had}} = 0.02757$)

$$M_W^{\text{SM}}(m_t = 173.2 \text{ GeV}, M_H^{\text{SM}} = 125.64 \text{ GeV}) = 80.361 \text{ GeV}. \tag{5.1}$$

Theory paper studies the possibilities of supersymmetric particles on M_W

Accordingly, the SM prediction for M_W turns out to be below the current experimental value, $M_W^{\text{exp}} = 80.385 \pm 0.015$ GeV, by about $1.5\,\sigma$. The dominant theoretical uncertainty of the prediction for M_W arises from the parametric uncertainty induced by the experimental error in the measurement of the top-quark mass. An experimental error of 1 GeV on m_t causes a parametric uncertainty on M_W of about 6 MeV, while the parametric uncertainties induced by the current experimental error of the hadronic contribution to the shift in the fine-structure constant, $\Delta\alpha_{\text{had}}$, and by the experimental error of M_Z amount to about 2 MeV and 2.5 MeV, respectively. The uncertainty of the M_W prediction caused by the experimental error of the Higgs mass $\delta M_H^{\text{exp}} = 0.35$ GeV is significantly smaller (~ 0.2 MeV). The uncertainties from unknown higher-order corrections have been estimated to be around 4 MeV in the SM for a light Higgs boson ($M_H^{\text{SM}} < 300$ GeV) [74].

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Implications of LHC search results on the W boson mass prediction in the MSSM

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Measurement of $W^{\pm}$ and Z-boson production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration *

Measurements of the $W^{\pm} \to \ell^{\pm}\nu$ and $Z \to \ell^{+}\ell^{-}$ production cross sections (where $\ell^{\pm} = e^{\pm}, \mu^{\pm}$) in proton–proton collisions at $\sqrt{s} = 13$ TeV are presented using data recorded by the ATLAS experiment at the Large Hadron Collider, corresponding to a total integrated luminosity of 81 pb^{-1}. The total inclusive $W^{\pm}$-boson production cross sections times the single-lepton-flavour branching ratios are
$\sigma^{\text{tot}}_{W^+} = 11.83 \pm 0.02(\text{stat}) \pm 0.32(\text{sys}) \pm 0.25(\text{lumi})$ nb and
$\sigma^{\text{tot}}_{W^-} = 8.79 \pm 0.02(\text{stat}) \pm 0.24(\text{sys}) \pm 0.18(\text{lumi})$ nb for W^+ and W^-, respectively.

Inclusive cross section for W+/- production is the sum, $\sigma_{W^+W^-} = 20.62$ nb at $\sqrt{s} = 13$ TeV

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Assume the W +/- production cross section at 13 TeV is the same as 1.96 TeV

8.8 fb^{-1} of integrated luminosity should produce 1.81×10^8 W bosons.

Decay modes: Γ_μ (W → $\mu\nu$) = 10.63% +/- 0.15
Γ_e (W → $e\nu$) = 10.71% +/- 0.16

Data sample consists of 4×10^6 W bosons, or ~20% of the semileptonic decays

Reconstructed in terms of transverse mass, m_T = sqrt{2($p_T^\ell p_T^\nu - p_T^\ell * p_T^\nu$)}

Leptonic momentum is measured in Central Outer Tracking drift chamber, EM and hadronic calorimeters, and out muon drift chambers.

Neutrino momentum determined from the requirement that the net Transverse momentum be zero.

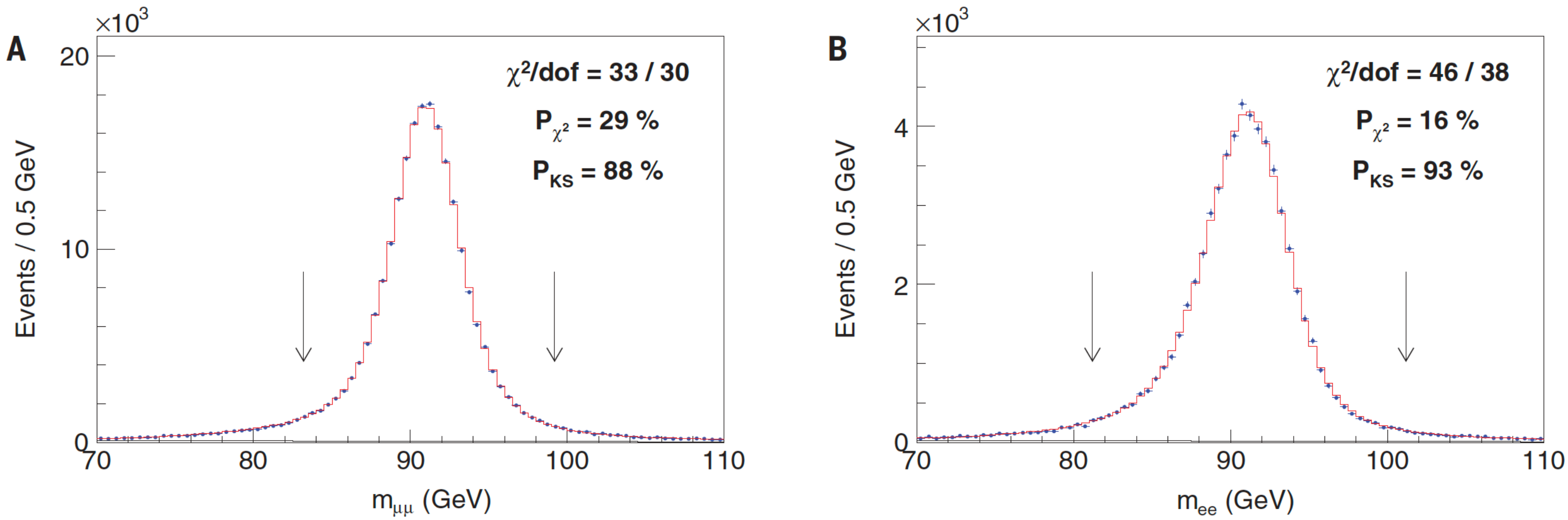
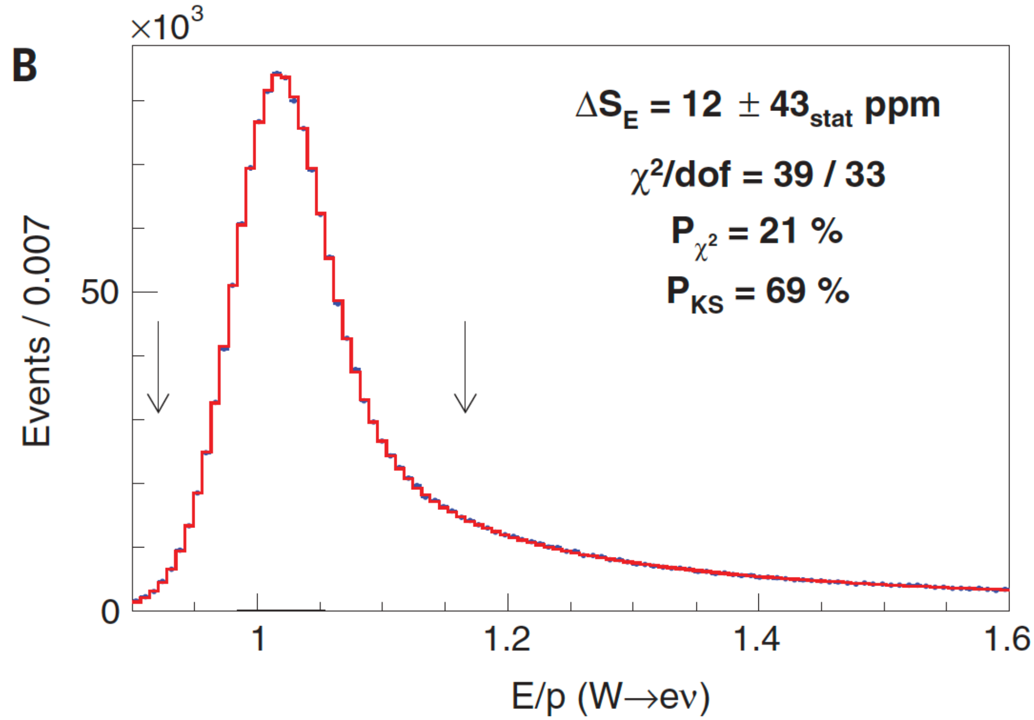


Fig. 3. Decay of the *Z* boson. (**A** and **B**) Distribution of (A) dimuon and (B) dielectron mass for candidate $Z \to \mu\mu$ and $Z \to ee$ decays, respectively. The data (points) are overlaid with the best-fit simulation template including the photon-mediated contribution (histogram). The arrows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



uncorrelated uncertainties (total uncertainty) for the individual boson measurements (combined correction). (**B**) Distribution of E/p for the $W \rightarrow e\nu$ data (points) and the best-fit simulation (histogram) including the small background from hadrons misreconstructed as electrons. The arrows indicate the fitting range used for the electron energy calibration. The relative energy correction ΔS_E, averaged over the calibrated W and Z boson data [see fig. S13 in (*63*)], is compatible with zero. In this and other figures, P_{KS} refers to the Kolmogorov-Smirnov probability of agreement between the shapes of the data and simulated distributions.

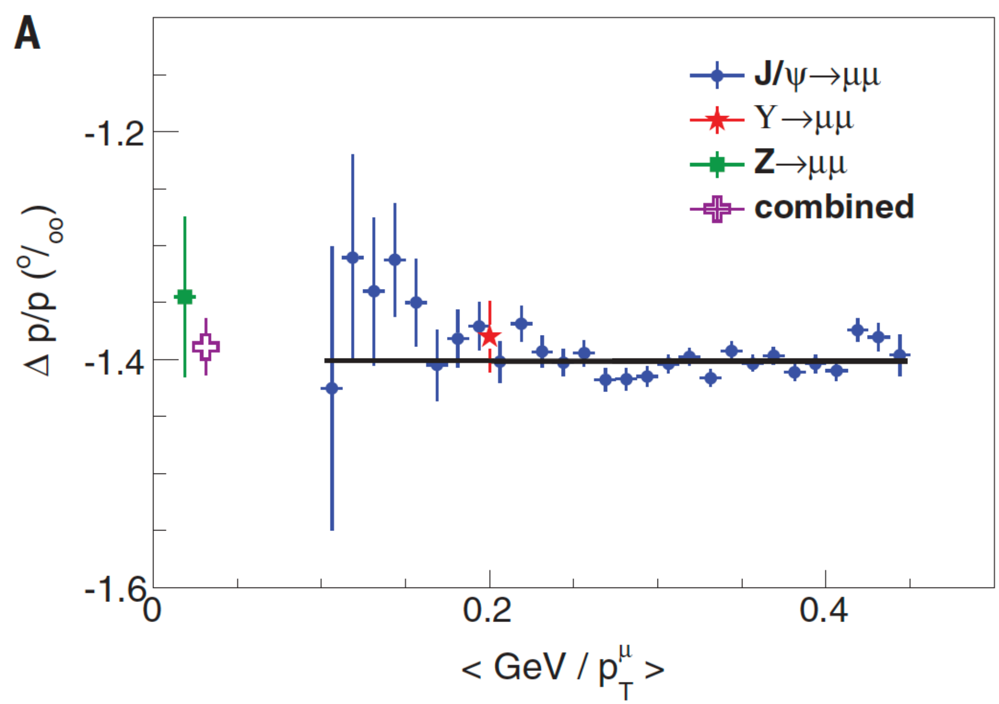


Fig. 2. Calibration of track momentum and electron's calorimeter energy. (**A**) Fractional deviation of momentum $\Delta p/p$ (per mille) extracted from fits to the $J/\psi \rightarrow \mu\mu$ resonance peak as a function of the mean muon unsigned curvature $\langle 1/p_T^{\mu} \rangle$ (blue circles). A linear fit to the points, shown in black, has a slope consistent with zero (17 ± 34 keV). The corresponding values of $\Delta p/p$ extracted from fits to the $\Upsilon \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ resonance peaks are also shown. The combination of all of these $\Delta p/p$ measurements yields the momentum correction labeled "combined," which is applied to the lepton tracks in W boson data. Error bars indicate the

W → μ ν

W → e ν

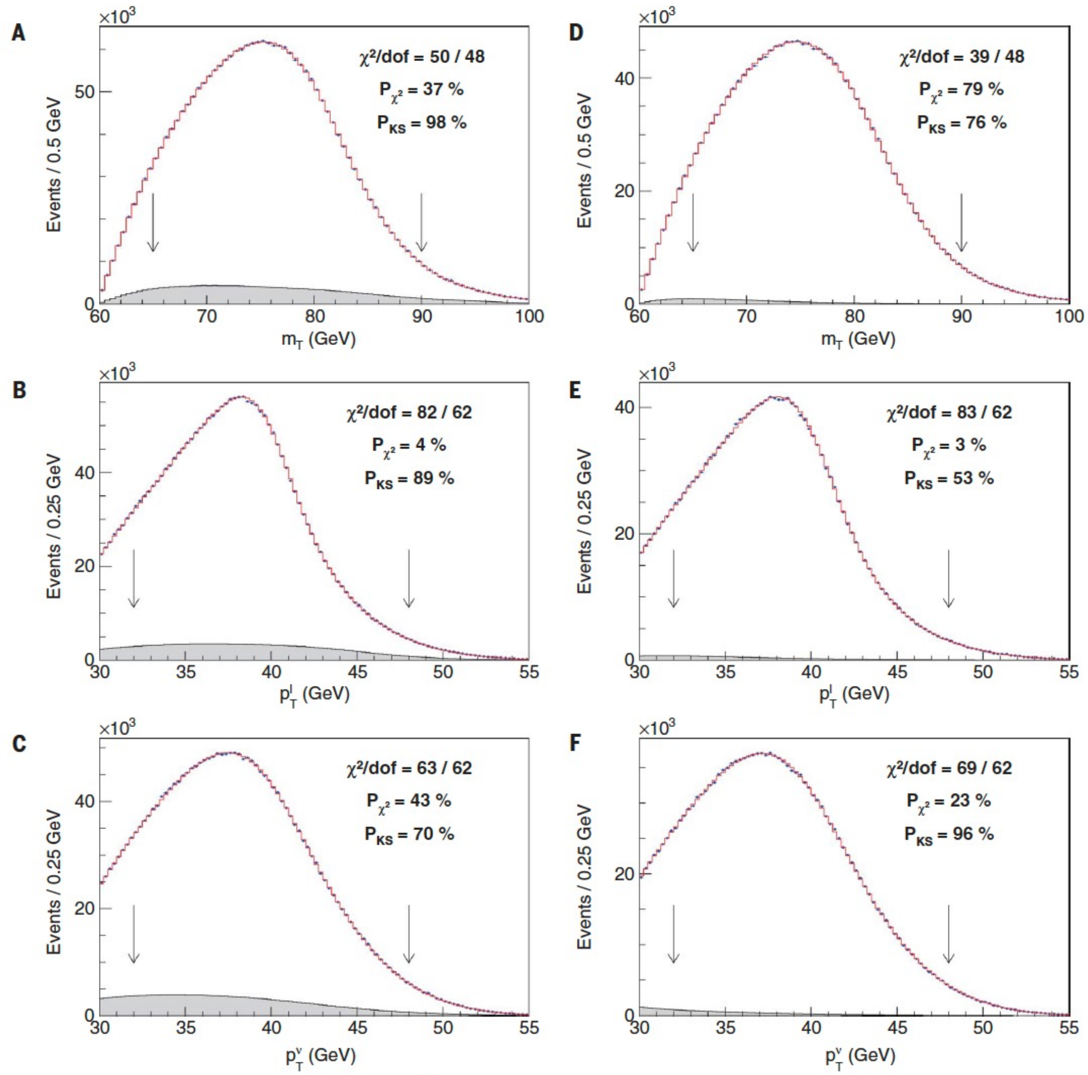


Fig. 4. Decay of the *W* boson. (**A** to **C**) Distributions for m_T (A), p_T^ℓ (B), and p_T^ν (C) for the muon channel. (**D** to **F**) Same as in (A) to (C) but for the electron channel. The data (points) and the best-fit simulation template (histogram) including backgrounds (shaded regions) are shown. The arrows indicate the fitting range.

Shaded regions are backgrounds.

Arrows show fitting region.

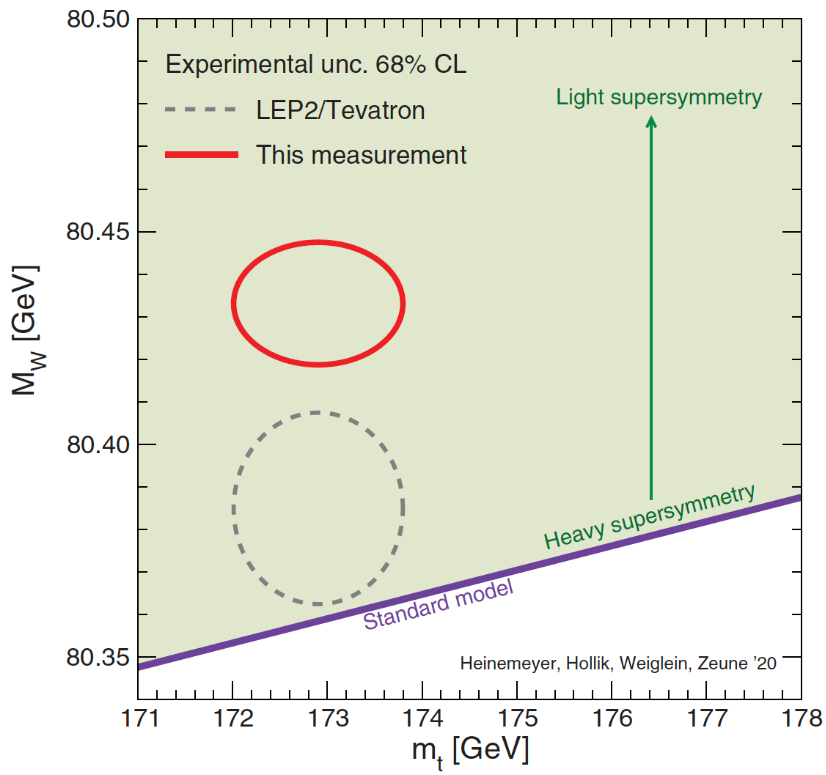


Fig. 1. Experimental measurements and theoretical predictions for the *W* boson mass. The red continuous ellipse shows the M_W measurement reported in this paper and the global combination of top-quark mass measurements, $m_t = 172.89 \pm 0.59$ GeV (*10*). The correlation between the M_W and m_t measurements is negligible. The gray dashed ellipse, updated (*16*) from (*15*), shows the 68% confidence level (CL) region allowed by the previous LEP-Tevatron combination $M_W = 80{,}385 \pm 15$ MeV (*45*) and m_t (*10*). That combination includes the M_W measurement published by CDF in 2012 (*41*, *43*), which this paper both updates (increasing M_W by 13.5 MeV) and subsumes. As an illustration, the green shaded region (*15*) 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 in (*15*). 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 (*10*) used as input. The arrow indicates the variation of the predicted *W* boson mass as the mass scale of supersymmetric particles is lowered. The supersymmetry model parameter scan is for illustrative purposes and does not incorporate all exclusions from direct searches at the LHC. unc., uncertainty.

Table 1. Individual fit results and uncertainties for the M_W measurements. The fit ranges are 65 to 90 GeV for the m_T fit and 32 to 48 GeV for the p_T^ℓ and p_T^ν fits. The χ^2 of the fit is computed from the expected statistical uncertainties on the data points. The bottom row shows the combination of the six fit results by means of the best linear unbiased estimator (*66*).

Distribution	*W* boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80{,}429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^\ell(e)$	$80{,}411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^\nu(e)$	$80{,}426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu,\nu)$	$80{,}446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^\ell(\mu)$	$80{,}428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^\nu(\mu)$	$80{,}428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

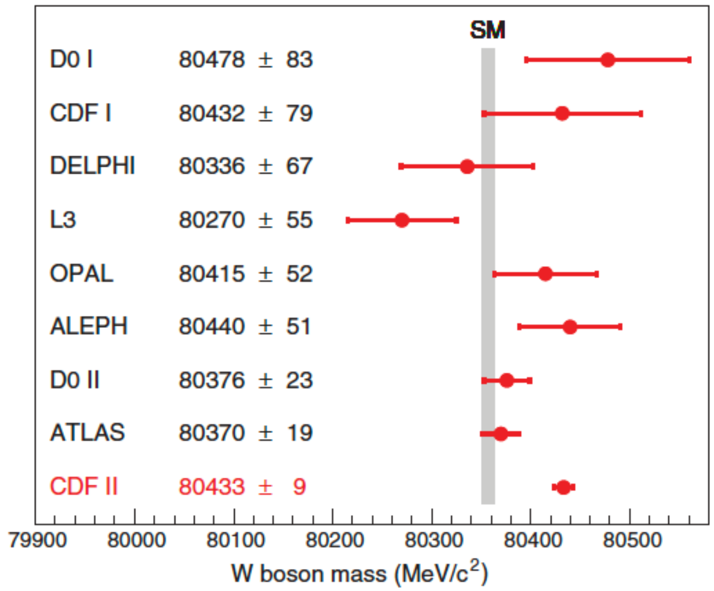


Fig. 5. Comparison of this CDF II measurement and past M_W measurements with the SM expectation. The latter includes the published estimates of the uncertainty (4 MeV) due to missing higher-order quantum corrections, as well as the uncertainty (4 MeV) from other global measurements used as input to the calculation, such as m_t. c, speed of light in a vacuum.

Table 2. Uncertainties on the combined M_W 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