Latest CDF W mass measurement

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

CDF COLLABORATION, T. AALTONEN, S. AMERIO, D. AMIDEI, A. ANASTASSOV, A. ANNOVI, J. ANTOS, G. APOLLINARI, J. A. APPEL, [...], AND S. ZUCCHELLI +388 authors Authors Info & Affiliations

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Yao Fu

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Physics motivation

W boson mass is one of a fundamental physical parameter in the Standard Model.

Direct measurement

Indirect measurement

Measurement of the lepton transverse momentum at hadron collider

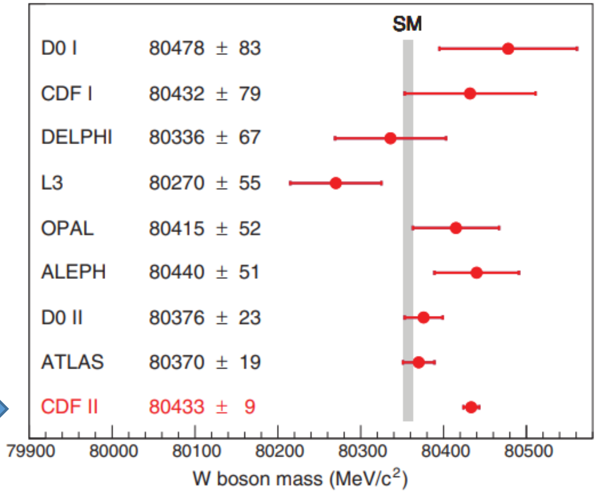
Global fitting from other electroweak parameters

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

New physics beyond the Standard Model would be probed if the discrepancy is found

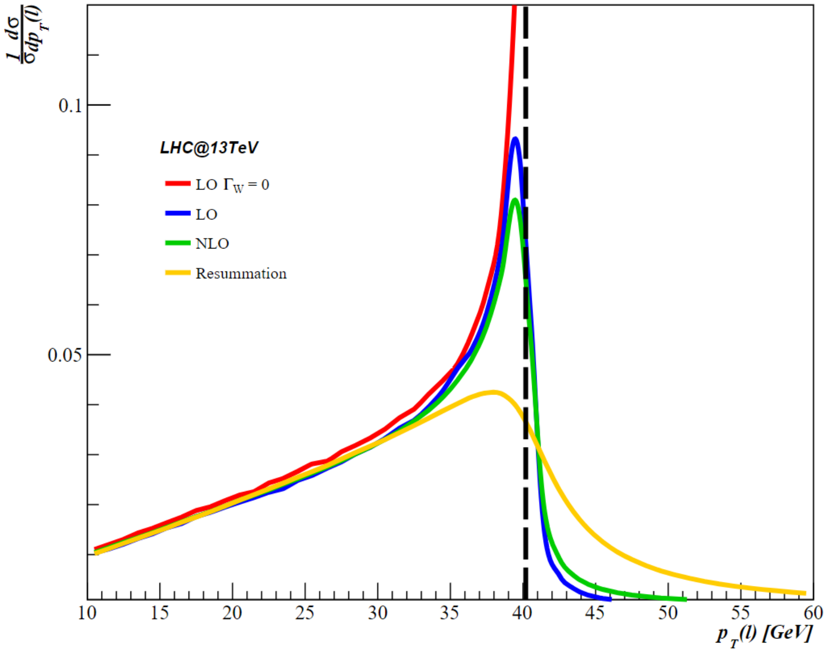
7σ deviation between the world average and the latest measured W mass

CDF W mass result



Jacobian peak in kinematic distribution of W production

Since the neutrino is not able to be detected, W boson mass is extracted from the Jacobian peak



$$\frac{d\sigma}{dp_T^l} \sim \frac{d\sigma}{dcos\theta}\frac{1}{\sqrt{1-\frac{4{p_T^l}^2}{\hat{s}}}}$$

Jacobian peak:

$$p_T^l \sim \frac{M_W}{2}$$

A peak occurred around $\frac{M_W}{2}$ when the width of W boson $\Gamma_W \neq 0$, or the transverse momentum of W boson $p_T(W) \neq 0$

$$p_T^l, p_T^\nu \sim \frac{M_W}{2} \qquad m_T(W) \sim M_W$$

Main uncertainty source:

- **Lepton energy calibration and hadronic recoil calibration**
- **QCD resummation calculation**

Fitting $p_T(l), p_T(\nu), m_T(W)$ to extract the M_W

χ^2 −minimization

Binned likelihood vs M_W ⇐ CDF used

Lepton energy calibration and hadronic recoil calibration

➢ Muon momentum calibration

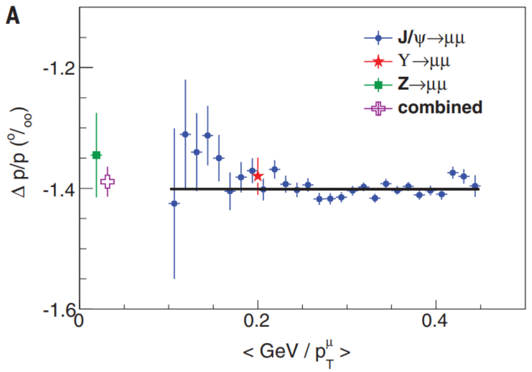


Fig. 2. Calibration of track momentum and electron's calorimeter energy. (**A**) Fractional deviation of momentum $\Delta p/p$ (per mille) extracted from fits to the $J/\psi \to \mu\mu$ resonance peak as a function of the mean muon unsigned curvature $\langle 1/p_T^\mu \rangle$ (blue circles). A linear 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 $\Upsilon \to \mu\mu$ and $Z \to \mu\mu$ 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

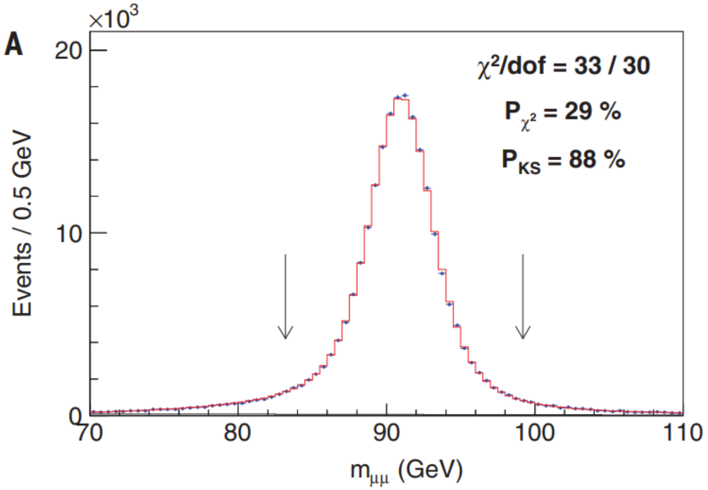
The mass of J/ψ and $\Upsilon(1S)$ are well-known.

$J/\psi \to \mu\mu$ and $\Upsilon(1S) \to \mu\mu$ events are used to calibrate the track momentum.

➢ Z mass measurement from $Z \to \mu\mu$

After track momentum calibration, Z-boson mass is measured using $Z \to \mu\mu$ events

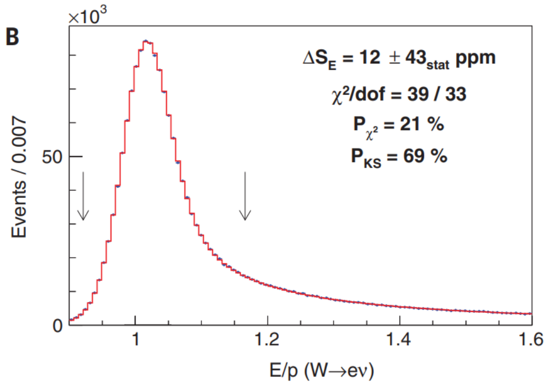
$$M_Z = 91\ 192.0 \pm 6.4_{\text{stat}} \pm 4.0_{\text{syst}}\ \text{MeV}$$



Finally, $J/\psi \to \mu\mu$, $\Upsilon(1S) \to \mu\mu$, $Z \to \mu\mu$ events are used to calibrate the track momentum.

Lepton energy calibration and hadronic recoil calibration

➢ Electron energy calibration



uncorrelated uncertainties (total uncertainty) for the individual boson measurements (combined correction). (**B**) Distribution of E/p for the $W \to e\nu$ 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.

Electron radiates bremsstrahlung photons which degrades its track momentum resolution.

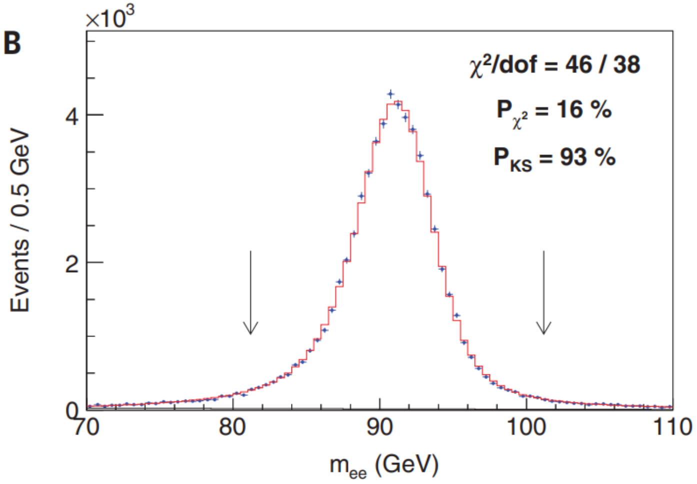
After track momentum calibration, the peak of E/p distribution is used to calibrate the electron energy.

➢ Z mass measurement from $Z \to ee$

After energy calibration, Z-boson mass is measured using $Z \to ee$ events

$$M_Z = 91\ 194.3 \pm 13.8_{\text{stat}} \pm 7.6_{\text{syst}}\ \text{MeV}$$

Final energy calibration is obtained by combining the E/p calibration and Z mass calibration



Lepton energy calibration and hadronic recoil calibration

Missing transverse energy and $p_T(W)$ reconstruction

The vector transverse momentum sum of all detectable collision products accompanying the W or Z boson is defined as the hadronic recoil.

The neutrino transverse momentum vector is inferred from p_T conservation:

$$p_T(\nu) \equiv -p_T(l) - u \qquad\qquad p_T(W) = -u$$

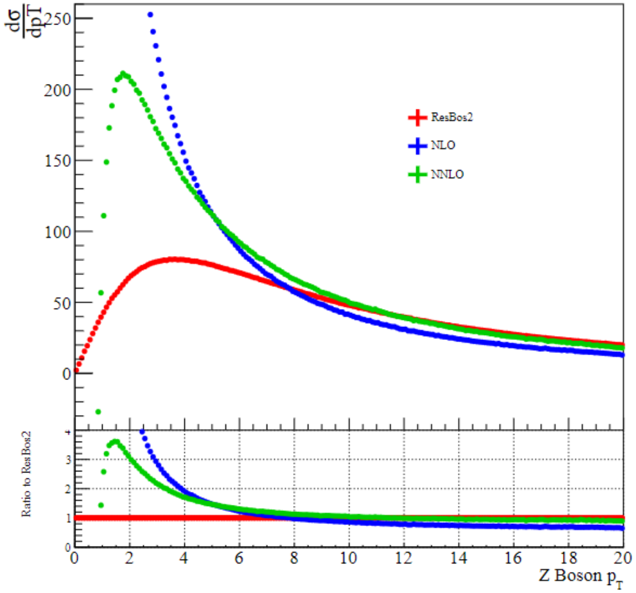
Hadronic recoil calibration

There are no high-p_T neutrinos in Z-boson data.

u in $Z \to ll$ events is used to measure the calorimeter response.

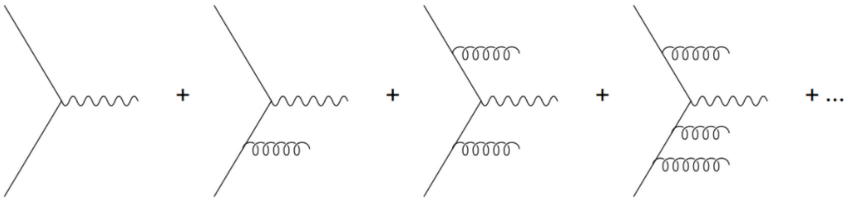
Resummation calculation and nonperturbative refitting

➢ Break down of fixed order calculation



$$\frac{d\sigma}{dq_T^2} \sim \alpha_s^n \frac{1}{q_T^2} \log^m\left(\frac{Q^2}{q_T^2}\right)$$

Fixed order calculation breaks down when $q_T \to 0$,
After q_T resummation, the q_T distribution can agree with data.



➢ CSS Resummation formalism

$$\frac{d\sigma}{dQ^2 dq_T^2 dy} = \frac{H}{(2\pi)^2} \int d^2 b e^{i\vec{q}_T \cdot \vec{b}} e^{-\mathcal{S}(Q,b)}$$

$$\times \sum_j C_j\left(\frac{C_1}{C_2 b}, Q, x_1\right) C_j\left(\frac{C_1}{C_2 b}, Q, x_2\right) + Y(q_T, Q, x_1, x_2),$$

$$\mathcal{S}(Q,b) = \int_{C_1^2/b^2}^{C_2^2 Q^2} \frac{d\mu^2}{\mu^2}\left(A\left(g_s(\mu), C_1\right)\log\frac{C_2^2 Q^2}{\mu^2} + B(\mu), C_1, C_2\right).$$

Resummation calculation and nonperturbative refitting

➢ Nonperturbative function

When $b \to \infty$, $q_T \to 0$, the calculation is nonperturbative.

$$b^* = \frac{b}{\sqrt{1+\frac{b^2}{b_{max}^2}}},$$

$$\mathcal{S}\left(Q,b\right) = \int_{C_1^2/b^2}^{C_2^2Q^2} \frac{d\mu^2}{\mu^2} \left(A\left(g_s\left(\mu\right),C_1\right) \log \frac{C_2^2Q^2}{\mu^2} + B\left(\mu\right), C_1, C_2 \right).$$

Final resummation formalism is

$$\frac{d\sigma}{dQ^2 dq_T^2 dy} = \sum_{i,j} \frac{H}{(2\pi)^2} \int d^2 b e^{i\vec{q_T}\cdot\vec{b}} e^{-S_{\text{pert}}} e^{-S_{NP}} C \otimes f_i C \otimes f_j,$$

➢ Nonperturbative refitting

BLNY formalism: $\exp\left[-g_1 - g_2 \ln\left(\frac{Q}{2Q_0}\right) - g_1 g_3 \ln\left(100 x_1 x_2\right)\right] b^2.$

The nonperturbative parameters g_1, g_2, g_3 are obtained by a global fitting from the various fixed target and collider data.

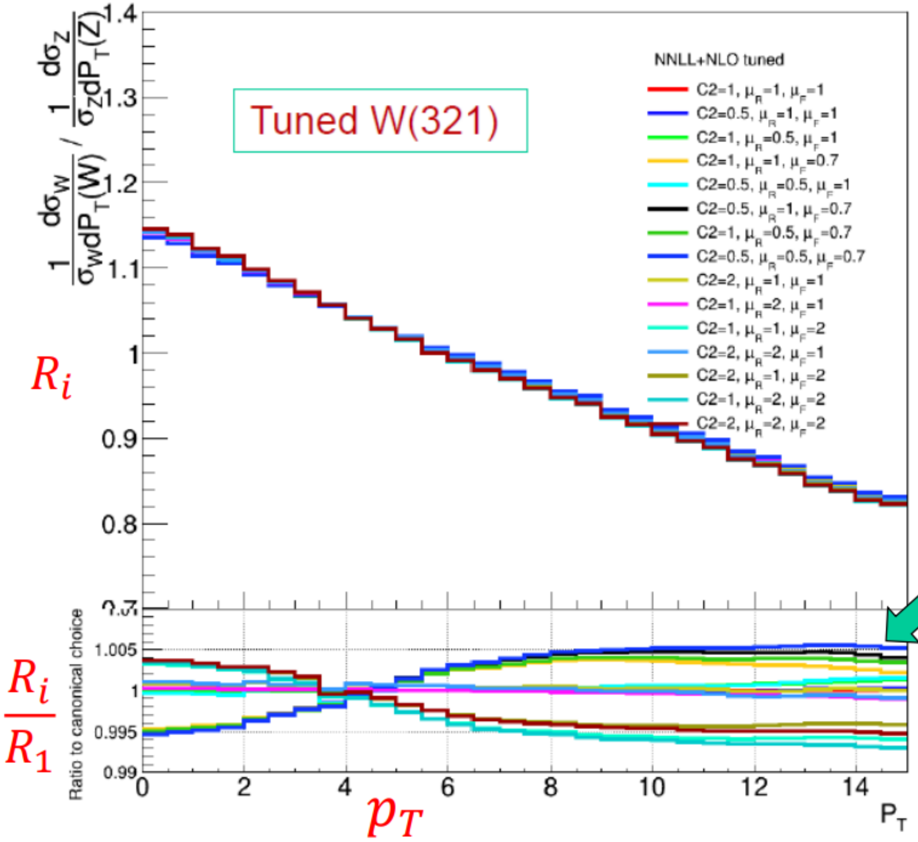
In CDF experiment, g_2, α_s are refitted using the $p_T(Z)$ data. Refitted ResBos generator is used to generate the theory prediction and perform simulation.

Data driven method to reduce the theoretical uncertainty

- **Scale uncertainty of $p_T(W)/p_T(Z)$**

Scale uncertainty should be included by varying the calculation scale:

Fixed order scale: μ_R, μ_F Resummation scale: C_1, C_2, C_3



- The upper panel shows

$$R_i = \frac{\left(\frac{d\sigma}{\sigma dp_T}\right)_W}{\left(\frac{d\sigma}{\sigma dp_T}\right)_Z} \quad \text{for scale choice } i = 1,2,\ldots 15$$

- The lower panel shows the ratio $\frac{R_i}{R_1}$

($i = 1$ is the canonical scale choice.)

The envelope of $\frac{R_i}{R_1}$ is found to be covered by the scale choice $(C_2,\ C_1 = C_3 = \mu_F,\ \mu_R) = (0.5, 0.7, 0.5)$, after symmetrizing it about 1.
Later, we shall refer this curve as $En(p_T)$.

Data driven method to reduce the theoretical uncertainty

➢ Reduce the scale uncertainty of $p_T(W)/p_T(Z)$

- ➢ Reweight the normalized pT(W) distribution (with i=1) by

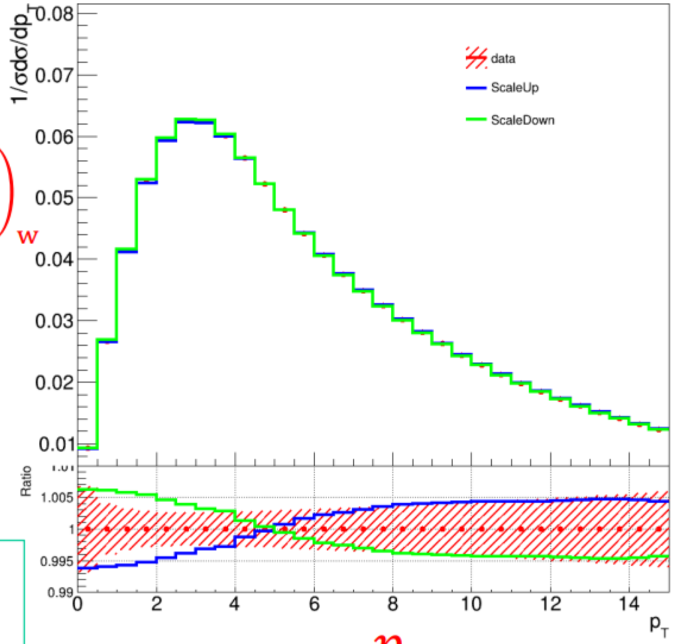
$$a * (En(p_T) - 1) + 1$$

with a varying from -1 to 1, for every pT bin.

- ➢ Generate the normalized pT(W) distribution after reweighting the (i=1) result by applying the weight a. The result of a=0 corresponds to the result of i=1, i.e. D_1.

- ➢ For a given $p_T(W)$, after reweighting, one can extract M_W, from the corresponding $m_T, p_T(e), p_T(\nu)$ distributions.

- ❖ Lower panel shows the normalized pT(W) ratio to D_1 (with $a = 0$).
- ❖ ScaleUp is for $a = 1$, and ScaleDown is for $a = -1$, which are derived from the $\frac{R_i}{R_1}$ ratio plot.
- ❖ The shaded band shows the statistical error of the CDF data.



$$\left(\frac{d\sigma}{\sigma dp_T}\right)_W$$

p_T

Background

- **Estimated by data driven method**

  QCD jet production with a hadron misidentified a lepton.

  Pion and Kaon decays in flight to muon

  Cosmic ray muons

- **Estimated by MC simulation**

  $Z \rightarrow ll$ decays with only one reconstructed lepton

  $W \rightarrow \tau\nu \rightarrow l\nu\bar{\nu}\nu$

Results

➢ W and Z data samples

- Cuts:
  - $p_T(Z) < 15$ GeV, $p_T(W) < 15$ GeV
  - $30 < p_T(\ell) < 55 GeV$, $30 < p_T(\nu) < 55$ GeV
  - $|\eta(\ell)| < 1$
  - $66 < M_{\ell\ell} < 116$ GeV (Z events), $60 < m_T < 100$ GeV (W events)
- Number of Events:
  - 1,811,700 $W \to e\nu$
  - 66,180 $Z \to ee$
  - 2,424,486 $W \to \mu\nu$
  - 238,534 $Z \to \mu\mu$

➢ M_W result and uncertainties

$$M_W = 80433.5 \pm 9.4 \text{ MeV}$$

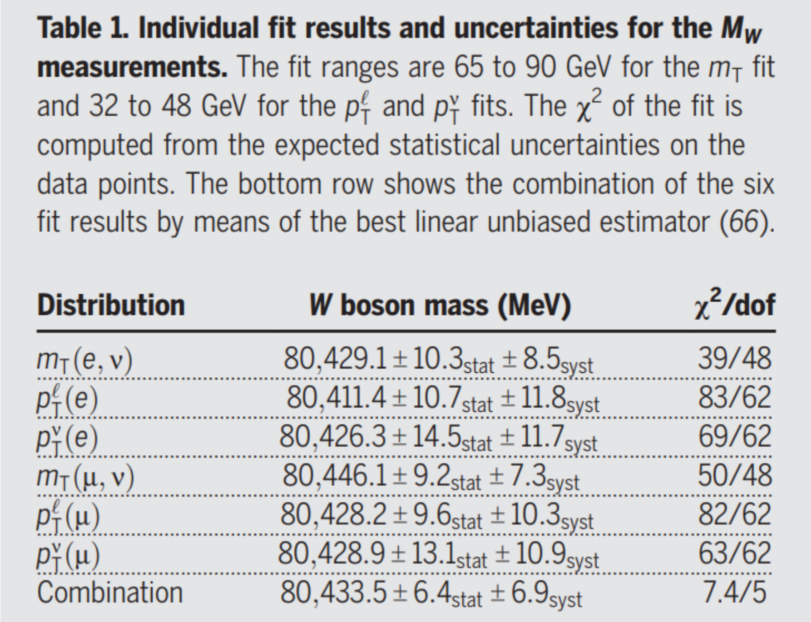


Table 1. Individual fit results and uncertainties for the M_W measurements. The fit ranges are 65 to 90 GeV for the m_T fit and 32 to 48 GeV for the p_T^ℓ and p_T^ν fits. The χ^2 of the fit is computed from the expected statistical uncertainties on the data points. The bottom row shows the combination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

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

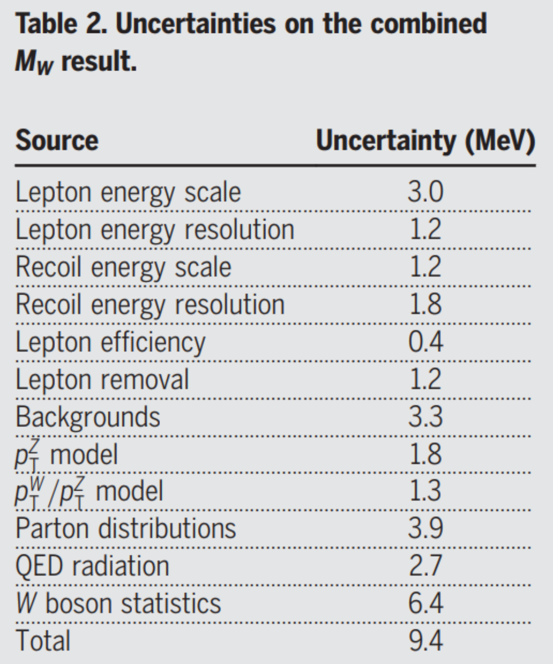


Table 2. Uncertainties on the combined M_W result.

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

Discussions

- **7σ deviated from standard model global fitting**

- **Out-of-date low order ResBos generator is used to give prediction**

  Nonperturbative refitting reduces the higher order effect

  Data driven method reduces the scale uncertainty

- **New electroweak global fitting needs to be performed**