A new measurement of the W boson mass from CDF

(CDF Collaboration)

CDF has measured the W boson mass using $\approx$200 pb^{-1} of data collected at $\sqrt{s} = 1.96$ TeV . The preliminary result $m_W = 80.413 \pm 0.034(stat) \pm 0.034(syst)$ GeV supports and strengthens the hypothesis of a light Higgs boson, based on the global electroweak fit in the standard model framework. The total measurement uncertainty of 48 MeV makes this result the most precise single measurement of the W boson mass to date.

The mass of the W boson is a very interesting quantity. Experimentally, it can be measured precisely because of the two-body decay of the W boson into a charged lepton and a neutrino. Theoretically, it receives self-energy corrections due to vacuum fluctuations involving virtual particles. Thus the W boson mass probes the particle spectrum in nature, including those particles that have yet to be observed directly.

The hypothetical particle of most immediate interest is the Higgs boson, representing the quantum of the Higgs field that spontaneously acquires a vacuum-expectation value in the standard model (SM). The interaction of the other SM particles, in particular the W and Z gauge bosons, with the non-zero Higgs field is thought to impart mass to the SM particles while preserving the renormalizability of the theory. Thus the Higgs boson plays a critical role in the SM, and it is very interesting to obtain a Higgs mass prediction using as inputs the W boson mass and other precise measurements, such as the Z boson mass, the Fermi coupling G_F obtained from the muon lifetime, the electromagnetic coupling evolved to the Z pole, and $\sin^2$ theta$_W$.

Further considerations, among them the stability of the Higgs boson mass under radiative corrections, motivate extensions of the SM with additional symmetries. The mass spectrum of new particles such as supersymmetric particles is also constrained via the radiative corrections they induce to the W boson mass.

In order to extract information on new particles, the radiative correction to the W boson mass due to the dominant top-bottom quark loop needs to be accounted for. Analysis of approximately 1/fb of Run 2 data by CDF and D0 have led to the top mass measurement of 171.4 +- 2.1 GeV. For fixed values of other inputs, this top mass uncertainty corresponds to an uncertainty in its W mass correction of 12 MeV. Improved measurements of the top quark mass will reduce this uncertainty further in the future. Measurements of the W mass from Run 1 of the Tevatron [1] and LEP [2] with uncertainties of 59 MeV and 33 MeV respectively, yield a world average of 80392 +- 29 MeV [2]. It is clearly profitable to reduce the W mass uncertainty further as a means of constraining the Higgs boson mass.

At the Tevatron, W bosons are mainly produced by valence quark-antiquark annihilation, with initial state radiation (ISR) generating a typical transverse boost of O(10 GeV). The transverse momentum (p_T) distribution of the decay lepton has a characteristic jacobian edge whose location, while sensitive to the W boson mass, is smeared by the transverse boost of the W boson. The transverse energy of the ISR, denoted by vector(u), is measured inclusively by performing a vector sum over all calorimeter tower energies, excluding those towers with lepton energy contributions. The neutrino p_T is inferred from the lepton p_T and vector(u) by imposing p_T balance in the event. The measurement of boson p_T can be used to sharpen the jacobian edge by computing the W transverse mass (m_T), analogous to an invariant mass but only using the p_T of the lepton and the neutrino. We use the m_T and lepton and neutrino p_T distributions to extract the W boson mass; m_T provides the most precise measurement.

We describe here the latest measurement of the W boson mass from CDF, which uses approx. 200/pb of data collected between February 2002 and September 2003. The data samples consist of 63964 (51128) W boson candidates in the electron (muon) channel, along with important control samples of 2919 (4960) Z boson candidates in the electron (muon) channel. The lepton track momentum is measured in a large cylindrical drift chamber called the COT. The electron energy is measured using the central (barrel) electromagnetic (EM) calorimeter, and its angle measurement is provided by the COT track. The lepton selection criteria of $p_T > 30$ GeV, pseudorapidity < 1 and loose identification requirements, along with u < 15 GeV for W bosons, provide high-purity samples. Backgrounds in the Z boson samples are negligible. Other than the Z $\rightarrow$ mu mu background of 6.6% in the W $\rightarrow$ mu nu sample where one of the decay muons is at high rapidity outside the COT fiducial volume, and is therefore not reconstructed, backgrounds in the W boson samples are less than 0.5%.

The W boson mass is extracted by performing maximum likelihood fits using templates created by a custom fast Monte Carlo simulation of the detector. We perform a first-principles simulation of the lepton tracks at the COT hit-level, including complete calculations of ionization and radiative energy loss and multiple scattering. We incorporate a detailed model of the passive material which we validate using our data. Bremsstrahlung photons and conversion electrons are generated and propagated to the calorimeter. Extensive validation of the custom simulation is performed by cross-checking control distributions between the data and the simulation.

The generator-level input to the custom simulation is provided by the RESBOS [4] program. RESBOS generates the lepton and neutrino momentum vectors in W and Z boson events according to a QCD calculation of the quintuple differential cross section in boson mass, p_T, rapidity, and decay angles. It provides tunable parameters for the non-perturbative form factor which describes the boson p_T spectrum at low p_T. We tune this form factor on the well-measured Z boson p_T spectrum using leptons. QED radiative photons are generated according to the calculation of the WGRAD [5] program, which includes all O(alpha) electroweak processes.

The key aspect of the measurement is the calibration of the lepton momentum. The COT track measurement sets the momentum scale for this analysis. We perform the internal alignment of the COT (which contains about 30,000 sense wires) using high-p_T cosmic rays that traverse diametrically the entire drift chamber. By fitting a cosmic ray's complete trajectory to a single helix [3] and measuring hit residuals with respect to this helix, we align individual cells (containing 12 sense wires) to better than 5 microns, and also strongly constrain baises due to COT endplate rotations and gravitational and electrostatic deflections of the wires. The alignment is cross-checked and final curvature corrections are made based on the observed difference in the ratio (E/p) of calorimeter energy to track momentum for electrons vs positions from the W boson signal sample.

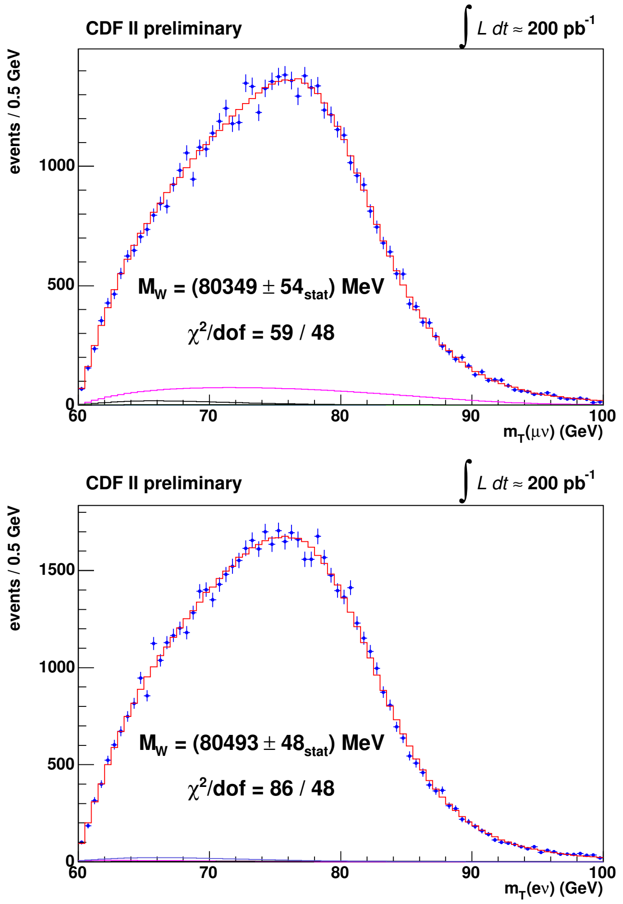

FIG. 1. The m_T fit for muon (top) and electron (bottom) channels.

The absolute momentum scale for the tracker is set by measuring the J/psi and upsilon masses using the dimuon mass peaks. The J/psi sample spans a range of muon p_T, which allows us to tune the ionization energy loss model such that the measured mass is independent of muon p_T. We obtain consistent calibrations from the J/psi and Upsilon mass fits, whose combined measurement of the momentum scale is dominated by the systematic uncertainties due to QED radiative corrections and magnetic field non-uniformities. In the future we anticipate reductions in these systematics by improving our corrections for these effects. The momentum scale extracted independently from the Z $\rightarrow$ mu mu mass fit is also consistent, albeit with a larger, statistics-dominated uncertainty. The tracker resolution model is tuned on the observed widths of the upsilon and Z boson mass peaks.

Channel	Distribution	Fit Result (MeV)	chi^2/DoF
Electron	m_T	80493 +- 48	86/48
Electron	electron p_T	80451 +- 58	63/62
Electron	neutrino p_T	80473 +- 57	63/62
Muon	m_T	80349 +- 54	59/48
Muon	muon p_T	80321 +- 66	72/62
Muon	neutrino p_T	80396 +- 66	44/62

TABLE I. Fit results and statistical errors for electrons and muons from the three kinematic distributions used to extract the W mass.

The EM calorimeter is calibrated with respect to the tracker by template-fitting the peak of the E/p distribution of the signal electrons in the W $\rightarrow$ e nu sample. The model for radiative energy loss is checked by comparing the number of events in the radiative tail of the E/p distribution between data and simulation, and found to be statistically consistent. The calorimeter energy calibration is performed in bins of electron p_T to also constrain the calorimeter non-linearity. The calibration yields a Z $\rightarrow$ ee mass measurement that is statistically consistent with the world average; we obtain the most precise calorimeter calibration by combining the results from the E/p method and the Z $\rightarrow$ ee mass method. The EM calorimeter resolution model is tuned on the observed widths of the E/p peak and the Z $\rightarrow$ ee mass peak, separately for non-radiative and radiative electrons.

Systematic (MeV)	Electrons	Muons	Common
Lepton Energy Scale	30	17	17
Lepton Energy Resolution	9	3	0
Recoil Energy Scale	9	9	9
Recoil Energy Resolution	7	7	7
selection bias	3	1	0
Lepton Removal	8	5	5
Backgrounds	8	9	0
p_T(W) model	3	3	3
Parton Distributions	11	11	11
QED radiation	11	12	11
Total	39	27	26

TABLE II. Table of systematic uncertainties for the transverse mass fits.

The response and resolution parameterizations for the hadronic recoil (u) are obtained by fitting the p_T balance distributions in Z boson events. The hadronic resolution

Experiment	Mass (MeV/c^2)
DELPHI	80336 ± 67
L3	80270 ± 55
OPAL	80416 ± 53
ALEPH	80440 ± 51
CDF-I	80433 ± 79
D0-I	80483 ± 84
LEP Average	80376 ± 33
Tevatron-I Average	80454 ± 59
Previous World Average	80392 ± 29
CDF-II	80413 ± 48
New Tevatron Average	80429 ± 39
New World Average	80398 ± 25

TABLE III. Current world's best W mass measurements.

receives contributions from the underlying event (which is independent of $p_T(Z)$ and modelled using minimum-bias data) and from jets. The p_T balance is studied in bins of dilepton p_T to fit both the $p_T(Z)$-independent and $p_T(Z)$ dependent components of the hadronic response and resolution. The model gives a consistent description of the W and Z boson data.

The fits to the three kinematic distributions in the electron and muon channels give the W mass results and statistical errors shown in Table I. The results are consistent and this is an important cross-check. The m_T fits are shown in Fig. 1, and their systematic uncertainties are summarized in Table II. The uncertainty due to parton distribution functions (PDFs) is evaluated using the CTEQ6 [6] ensemble of PDFs that captures the uncertainties in the PDF parameters. The uncertainty due to QED radiative corrections is dominated by the higher order contributions. The six fit results are combined taking all correlations into account, to obtain the preliminary result m_W = 80.413 +- 0.034 (stat) +- 0.034 (stat). The fit values were hidden during the analysis by adding an unknown random offset in the [-100, 100] MeV range in the fitting program; this offset was removed after the analysis was completely frozen.

Table III gives a summary of other recent W mass measurements and averages. With a total uncertainty of 48 MeV, this measurement is the most precise single measurement to date. The updated world average impacts the global precision electroweak fits: the new fitted Higgs mass is m_H = 80 +36 -26 GeV [7] (updated from m_H = 85 +39 -28 GeV [2]). The 95% CL upper limit on the Higgs mass is updated from 199 GeV (166 GeV) to 189 GeV (153 GeV) with the LEP II direct limit included (excluded) [2,7]. The direction of this change has interesting theoretical implications: as Fig. 2 shows, the m_W vs m_{top} ellipse moves a little deeper into the light-Higgs region excluded by LEP II, and into the region [8] favored by the Supersymmetry (MSSM) model. While this is a one-sigma effect, it arouses further interest in higher precision measurements of the W mass (and the top mass) at the Tevatron in the near future, and ultimately the LHC. Also, the increased likelihood of the 'light-Higgs' scenario adds to the interest in direct Higgs searches ongoing at the Tevatron.

Most of the systematic uncertainties in this measurement (Table II) are limited by the statistics of the calibration samples. Improvements in the detector model, and the production and decay model (e.g. QED radiative corrections) are likely to shrink the other systematics as well. CDF has now accumulated about 1.5/fb, and we look forward to a W mass measurement with precision better than 25 MeV (surpassing the current world average) with this dataset which is already in hand.

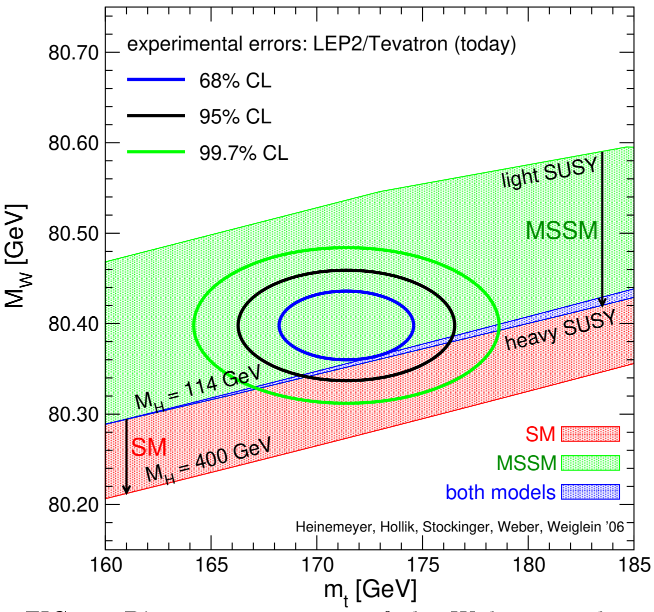

FIG. 2. Direct measurements of the W boson and top quark masses, along with SM and MSSM calculations [8].

Precise measurements of the W boson and top quark masses are of enduring interest as the direct searches for the Higgs, Supersymmetry and other new physics come to fruition. For example, when the Higgs is discovered, one can immediately ask whether its mass is consistent with the SM fit. In either case, the measured Higgs mass becomes an input to the SM fit, and the W mass can provide constraints on other new physics. Thus, the complementarity of direct searches and precision measurements like the W mass will continue in the post-Higgs-discovery era.

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[1] CDF Collaboration and D0 Collaboration (V.M. Abazov et al.), Phys. Rev. D **70** , 092008 (2004), and references therein.

[2] LEP collaborations and LEP Electroweak Working Group, http://lepewwg.web.cern.ch/LEPEWWG/, and references therein.

[3] A. V. Kotwal, H. K. Gerberich and C. Hays, Nucl. Instrum. Meth. Phys. Res. A **506**, 110 (2003).

[4] C. Balazs and C.-P. Yuan, Phys. Rev. D **56**, 5558 (1997); G. A. Ladinsky and C.-P. Yuan, Phys. Rev. D **50**, 4239 (1994); F. Landry, R. Brock, P. M. Nadolsky and C.-P. Yuan, Phys. Rev. D **67**, 073016 (2003).

[5] U. Baur, S. Keller and D. Wackeroth, Phys. Rev. D **59**, 013002 (1998).

[6] J. Pumplin *et al.*, JHEP **0207**, 012 (2002).

[7] M. Grunewald, private communication.

[8] S. Heinemeyer et. al., JHEP **0608** , 052 (2006).