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# W Boson Mass Measurement at CDF

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**Abstract.** The CDF collaboration has analyzed  $\sim 200 \text{ pb}^{-1}$  of Tevatron Run II data taken with the CDF II detector between February 2002 and September 2003 to measure the  $W$  boson mass. With a sample of 63964  $W \rightarrow e\nu$  decays and 51128  $W \rightarrow \mu\nu$  decays, we measure  $M_W = 80413 \pm 34(\text{stat}) \pm 34(\text{syst}) \text{ MeV}/c^2$ . The total measurement uncertainty of  $48 \text{ MeV}/c^2$  makes this result the most precise single measurement of the  $W$  boson mass to date.

## 1. Introduction

The  $W$  boson mass is an important Standard Model (SM) parameter. It receives self-energy corrections due to vacuum fluctuations involving virtual particles. Thus, the  $W$  boson mass probes the particle spectrum in nature, including particles that have yet to be observed directly. The hypothetical particle of most immediate interest is the Higgs boson. The  $W$  boson mass can be calculated at tree level using the three precise measurements of the  $Z$  boson mass, the Fermi coupling  $G_F$  and the electromagnetic coupling  $\alpha_{em}$ . In order to extract information on new particles, we need to account for the radiative corrections to  $M_W$  due to the dominant top-bottom quark loop diagrams. For fixed values of other inputs, the current uncertainty on the top quark mass ( $m_t$ ) measurement  $170.9 \pm 1.8 \text{ GeV}/c^2$  [1] corresponds to an uncertainty in its  $W$  boson mass correction of  $11 \text{ MeV}/c^2$ . Measurements of the  $W$  boson mass from Run I of the Tevatron and LEP with uncertainties of  $59 \text{ MeV}/c^2$  [2] and  $33 \text{ MeV}/c^2$  [3] respectively, yield a world average of  $80392 \pm 29 \text{ MeV}/c^2$  [3]. It is clearly profitable to reduce the  $W$  boson mass uncertainty further as a means of constraining the Higgs boson mass.

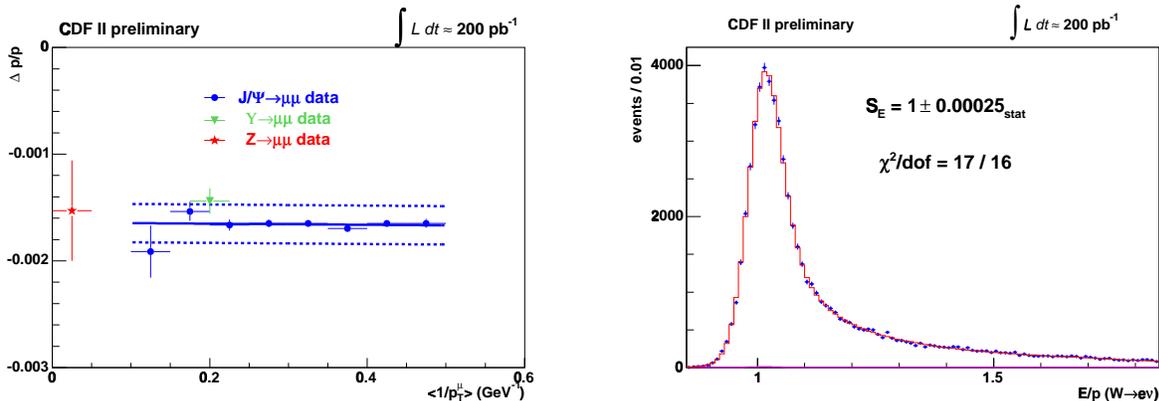
## 2. Measurement Strategy

At the Tevatron,  $W$  bosons are mainly produced by valance quark-antiquark annihilation, with initial state gluon radiation (ISR) generating a transverse boost. The transverse momentum ( $p_T^l$ ) 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 neutrino  $p_T$  ( $p_T^\nu$ ) can be inferred by imposing  $p_T$  balance in the event. The transverse mass, defined as  $m_T = \sqrt{2p_T^l p_T^\nu (1 - \cos[\phi^l - \phi^\nu])}$ , includes both measurable quantities in the  $W$  decay and provides the most precise quantity to measure  $M_W$ . We use the  $m_T$ ,  $p_T^l$  and  $p_T^\nu$  distributions from  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  decays to extract the  $W$  boson mass. These distributions do not lend themselves to analytic parameterizations, which leads us to use a Monte Carlo simulation to predict their shape as a function of  $M_W$ . These lineshape predictions depend on a number of

physical and detector effects, which we constrain from control samples or calculation. By fitting these predictions to the data with a binned maximum-likelihood fit, we extract the  $W$  boson mass [4].

### 3. Energy Scale Calibration

The key aspect of the measurement is the calibration of the lepton energy. The trajectory of the charged lepton is measured in a cylindrical drift chamber. The momentum scale is set by measuring the  $J/\Psi$  and  $\Upsilon(1S)$  masses using the dimuon mass peaks. The  $J/\Psi$  sample spans a range of muon  $p_T$  (2-10 GeV/c), which allows us to tune our ionization energy loss model. We obtain consistent calibrations from the  $J/\Psi$ ,  $\Upsilon(1S)$  and  $Z$  boson mass fits shown in Fig. 1 (left). The tracker resolution is tuned on the observed width of the  $\Upsilon(1S)$  and  $Z$  boson mass



**Figure 1.** Left: Momentum scale summary:  $\Delta p/p$  vs  $1/p_T$  for  $J/\Psi$ ,  $\Upsilon(1S)$  and  $Z$  boson dimuon data. The dotted line represents the independent uncertainty between  $J/\Psi$  and  $\Upsilon(1S)$ . Right: Energy scale calibration using  $E/p$  distribution from  $W \rightarrow e\nu$  events.

peaks. Given the tracker momentum calibration, we fit the peak of the  $E/p$  distribution of the signal electrons in the  $W \rightarrow e\nu$  sample, shown in Fig. 1 (right), in order to calibrate the energy measurement in the electromagnetic (EM) calorimeter. The model for radiative energy loss is tuned using the radiative tail of the  $E/p$  distribution. The calorimeter energy calibration is performed in bins of electron  $p_T$  to constrain the calorimeter non-linearity. The calibration yields a  $Z \rightarrow ee$  mass measurement of  $M_Z = 91190 \pm 67_{stat}$  MeV/ $c^2$ , in very good agreement with the world average ( $91187.6 \pm 2.1$  MeV/ $c^2$  [3]); we obtain the most precise calorimeter calibration by combining the results from the  $E/p$  method and the  $Z \rightarrow ee$  mass measurement. The EM calorimeter resolution model is tuned on the widths of the  $E/p$  and  $Z \rightarrow ee$  mass peaks.

### 4. Hadronic Recoil Calibration

The recoil is the vector sum of transverse energy over all calorimeter towers, where the towers associated with the leptons are explicitly removed from the calculation. The response of the calorimeter to the recoil is described by a response function which scales the true recoil magnitude to simulate the measured magnitude. The hadronic resolution receives contributions from ISR jets and the underlying event. The latter is independent of the boson transverse momentum and modeled using minimum bias data. The recoil response and resolution parameterizations are tuned on the mean and  $rms$  of the  $p_T$ -imbalance in  $Z \rightarrow ll$  events as a function of boson  $p_T$ . Cross-checks of the recoil model using  $W$  and  $Z$  boson data show good agreement and validate the model.

## 5. Event Generation

We generate  $W$  and  $Z$  events with RESBOS [5], which captures the QCD physics and models the  $W$   $p_T$  spectrum. The RESBOS parametrization of the non-perturbative form factor is tuned on the dilepton  $p_T$  distribution in the  $Z$  boson sample. Photons radiated off the final-state leptons (FSR) are generated according to WGRAD [6]. The FSR photon energies are increased by 10% to account for 2-photon radiation [7]. We use the CTEQ6M [8] set of parton distribution functions (PDFs) at NLO to evaluate the systematic uncertainty on the  $W$  boson mass. The set of 40 PDFs covers the  $\pm 1.6\sigma$  (90% C.L.) uncertainties for the eigenvectors of the parametrization.

## 6. Backgrounds

Backgrounds passing the event selection have different kinematic distributions from the  $W$  signal and are included in the template fit according to their normalizations. Backgrounds arise in the  $W$  boson samples from misidentified jets containing high- $p_T$  tracks and EM clusters,  $Z \rightarrow ll$  where one of the leptons is not reconstructed and mimics a neutrino,  $W \rightarrow \tau\nu$ , kaon and pion decays in flight (DIF), and cosmic ray muons. The latter two are backgrounds in the muon channel only. Jet, DIF, and cosmic ray backgrounds are estimated from the data to be together less than 0.5%. The  $W \rightarrow \tau\nu$  background is 0.9% for both channels, and the  $Z \rightarrow ll$  is 6.6% (0.24%) in the muon (electron) channel, as estimated from Monte Carlo.

## 7. Results and Conclusions

The fits to the three kinematic distributions  $m_T$ ,  $p_T^l$  and  $p_T^\nu$  in the electron and muon channels give the  $W$  boson mass results shown in Table 1.

**Table 1.** Fit results from the distributions used to extract  $M_W$  with uncertainties.

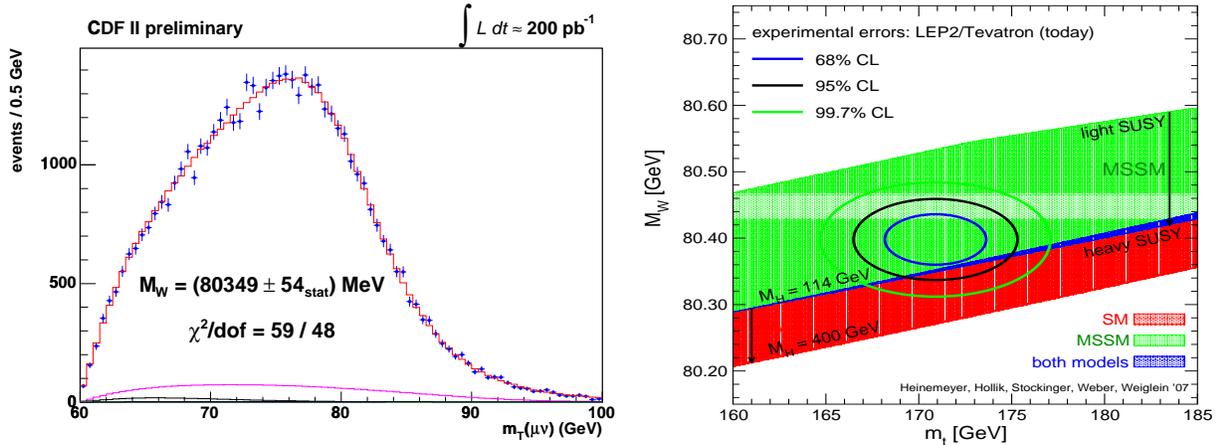
Distribution	$W \rightarrow e\nu$ (MeV/ $c^2$ )	$\chi^2/\text{dof}$	$W \rightarrow \mu\nu$ (MeV/ $c^2$ )	$\chi^2/\text{dof}$
$m_T$	$80493 \pm 48_{stat} \pm 39_{syst}$	86/48	$80349 \pm 54_{stat} \pm 27_{syst}$	59/48
$p_T^l$	$80451 \pm 58_{stat} \pm 45_{syst}$	63/62	$80321 \pm 66_{stat} \pm 40_{syst}$	72/62
$p_T^\nu$	$80473 \pm 57_{stat} \pm 54_{syst}$	63/62	$80396 \pm 66_{stat} \pm 46_{syst}$	44/62

The transverse mass fit in the  $W \rightarrow \mu\nu$  channel is shown in Fig. 2 (left). The uncertainties for the  $m_T$  fits in both channels are summarized in Table 2. We combine the six  $W$  boson mass fits including all correlations to obtain  $M_W = 80413 \pm 34(\text{stat}) \pm 34(\text{syst})$  MeV/ $c^2$ . Inclusion of this result increases the world average  $W$  boson mass to  $M_W = 80398 \pm 25$  MeV/ $c^2$  [3], reducing its uncertainty by 15%. The updated world average impacts the global precision electroweak fits, reducing the preferred Higgs boson mass fit by 6 GeV/ $c^2$  to  $M_H = 76_{-24}^{+33}$  GeV/ $c^2$ . The 95% CL upper limit on the Higgs mass is 144 GeV/ $c^2$  (182 GeV/ $c^2$ ) with the LEP II direct limit excluded (included) [3] [9]. The direction of this change has interesting theoretical implications: as Fig 2 (right) shows, the  $M_W$  vs  $m_t$  ellipse moves a little deeper into the light-Higgs region excluded by LEP II, and into the region favored by the minimal supersymmetry model (MSSM). While this is a one-sigma effect, it arouses further interest in higher precision measurements of  $M_W$  (and  $m_t$ ).

Most of the systematic uncertainties in this measurement (Table 2) are limited by the statistics of the control samples used. CDF has now accumulated an integrated luminosity of over 2 fb $^{-1}$  and we look forward to a  $W$  boson mass measurement with precision better than the current world average of 25 MeV/ $c^2$ , with the dataset in hand.

**Table 2.** Systematic and total uncertainties for the  $m_T$  fits. The last column shows the correlated uncertainties between the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  channel.

Systematic ( $\text{MeV}/c^2$ )	$W \rightarrow e\nu$	$W \rightarrow \mu\nu$	Common
Lepton Energy Scale and Resolution	31	17	17
Recoil Energy Scale and Resolution	11	11	11
Lepton Removal	9	5	5
Backgrounds	8	9	0
$p_T(W)$ Model	3	3	3
Parton Distributions	11	11	11
QED radiation	11	12	11
Total Systematics	39	27	26
Total Uncertainty	62	60	26



**Figure 2.** Left: Transverse mass fit in the muon decay channel. Right: Constraint on  $M_H$  from direct  $M_W$  and  $m_t$  measurements along with SM and MSSM calculations.

## Acknowledgments

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