

## W BOSON MASS MEASUREMENT AT THE TEVATRON

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The  $W$  boson mass ( $m_W$ ) is a key parameter of the standard model (SM), constraining the mass of the unobserved Higgs boson. Using Tevatron  $p\bar{p}$  collision data from 1992-1995, the CDF and DØ collaborations measured  $m_W$  to  $\delta m_W = 59$  MeV. The ongoing Tevatron Run 2 has produced a factor of 5 more collisions, promising a significant reduction in  $\delta m_W$ . CDF has analyzed the first  $\approx 200$  pb $^{-1}$  of Run 2 data and determined its  $\delta m_W$  to be 76 MeV.

### 1 Introduction

The SM describes all non-gravitational interactions in terms of an  $SU(3)_c \times SU(2)_L \times U(1)_Y$  gauge symmetry. Non-zero particle masses arise from the breaking of the  $SU(2)_L \times U(1)_Y$  electroweak symmetry via the Higgs mechanism. The Higgs boson is the last unobserved SM particle, and the measured electroweak parameters severely constrain its mass ( $m_H$ ). The constraint can be obtained from the radiative correction  $\Delta r$  to the  $W$  boson mass ( $m_W$ )<sup>1</sup>:

$$m_W^2 = \frac{\pi\alpha_{EM}}{\sqrt{2}G_F(1 - m_W^2/m_Z^2)(1 - \Delta r)}. \quad (1)$$

The correction  $\Delta r \approx 0.67\%$  results predominantly from Higgs and  $t\bar{b}$  loops in the  $W$  boson propagator. Because of the precise measurements of the parameters  $\alpha_{EM}$  ( $\delta\alpha_{EM}/\alpha_{EM} = 0.014\%$  at  $Q^2 = m_Z^2$ ),  $G_F$  ( $\delta G_F/G_F = 0.0009\%$ ), and  $m_Z^2$  ( $\delta m_Z^2/m_Z^2 = 0.004\%$ )<sup>1</sup>, the uncertainties on  $m_t$  and  $m_W$  dominate the uncertainty on the inferred  $m_H$ . To obtain equal  $\chi^2$  contributions in a fit to  $m_H$ , the relation  $\delta m_W = 0.007\delta m_t$  must hold<sup>2</sup>. For the Run 1  $\delta m_t$  of 4.3 GeV, the required  $\delta m_W$  is 30 MeV, close to  $\delta m_W(\text{world}) = 34$  MeV<sup>1</sup>. The impending Run 2 top mass measurements will significantly reduce  $\delta m_t$ , making  $\delta m_W$  reduction of primary importance.

The study of ongoing Run 2  $p\bar{p}$  collisions at the Tevatron will achieve this goal. With 2 fb $^{-1}$  of data, the CDF and DØ collaborations expect to complete measurements with  $\delta m_W$  between

40 MeV<sup>3</sup> and 50 MeV<sup>4</sup>. Combining with the measurement from LEP ( $\delta m_W = 42$  MeV) and the Run 2  $\delta m_t \approx 2$  GeV will result in  $\delta m_H/m_H \approx 30\%$ <sup>5</sup>.

The CDF and DØ collaborations are currently analyzing Run 2 data, with DØ finalizing its event selection and precision calorimeter calibration, and CDF performing necessary cross-checks to its full analysis with  $\approx 200$  pb<sup>-1</sup> of data. The CDF collaboration has determined the  $W$  boson mass uncertainty associated with these data to be 76 MeV.

## 2 Measuring the $W$ Boson Mass at the Tevatron

The  $m_W$  measurement in  $p\bar{p}$  data uses  $s$ -channel resonant  $W$  bosons with leptonic decays. The transverse momentum of the decay  $e$  or  $\mu$  ( $p_T^l$ ) can be measured with high precision and thus provides the bulk of the mass information. Additional information comes from the decay  $\nu$  transverse momentum ( $p_T^\nu$ ), which is inferred from the measured energy imbalance in the event. Since the lepton energy is well measured, the dominant uncertainty on  $p_T^\nu$  comes from measuring the hadrons recoiling against the produced  $W$  boson. Because the  $Z$  boson has a similar mass and production mechanism to the  $W$  boson, events with  $Z$  bosons can be used to calibrate and model the detector response to hadronic activity.

The best statistical power for measuring  $m_W$  is obtained by combining  $p_T^l$  and  $p_T^\nu$  into the transverse mass, defined as:

$$m_T = \sqrt{2p_T^l p_T^\nu (1 - \cos(\Delta\phi))}. \quad (2)$$

The transverse mass ignores the unmeasured  $\nu$  momentum along the beam direction ( $\hat{z}$ ). This distribution has a peak at  $m_W$  (if we neglect detector resolution and final-state photon radiation) and a long tail below  $m_W$ , corresponding to events with  $p_z^\nu \neq 0$ .

## 3 Run 2 CDF $W$ Boson Mass Measurement

The relevant components of the CDF detector for the  $m_W$  measurement are a large open-cell drift chamber immersed in a 1.4 T magnetic field, surrounded by a lead-scintillator sampling calorimeter. Because of the similar resolutions and acceptances for 40 GeV  $e$  and  $\mu$ , the combination of the two channels nearly doubles the effective statistics for the  $m_W$  measurement.

The CDF strategy for the measurement proceeds as follows: Model  $W$  boson production and decay; calibrate track momentum using high-statistics resonances; calibrate calorimeter energy using  $e$  tracks from  $W$  boson decays; model hadronic response and resolution; estimate backgrounds; and fit the transverse mass distribution to obtain  $m_W$ .

### 3.1 Event Generation

There are two important components of  $W$  boson production for measuring  $m_W$ : the fractional momenta of  $u$  and  $d$  quarks inside the proton, and the  $W$   $p_T$ . The  $u$  and  $d$  momenta determine  $p_z^W$ , which affects the  $m_T$  distribution. The  $u$  and  $d$  fractional momenta are constrained from global fits to high-energy data and embodied in parton distribution functions (PDFs) independently parametrized by the CTEQ<sup>6</sup> and MRST<sup>7</sup> collaborations. Using a CTEQ prescription for obtaining PDF uncertainties, the CDF collaboration has estimated  $\delta m_W(PDF) = 15$  MeV.

The  $W$  boson  $p_T$  distribution is predicted by an event generator (RESBOS<sup>8</sup>) that combines a QCD next-to-leading-log calculation with three non-perturbative parameters fit from high energy data. The dominant constraint on these parameters comes from the  $Z$  boson  $p_T$  measurement in Run 1. The generator and detector simulation predict the observed Run 2  $Z$  boson  $p_T$  spectrum well (Fig. 1). The uncertainty on the RESBOS parameters results in  $\delta m_W(p_T^W) = 13$  MeV.

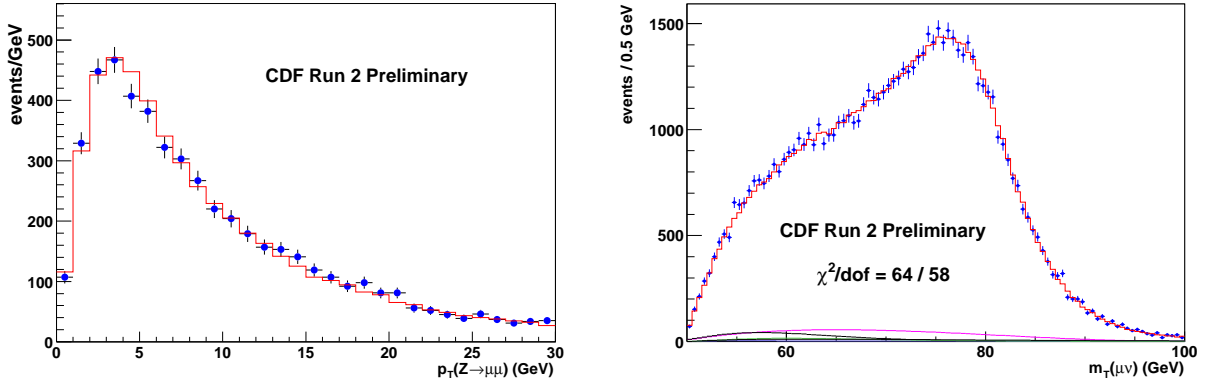


Figure 1: Left: The  $Z$  boson  $p_T$  spectrum in CDF Run 2  $Z \rightarrow \mu\mu$  data (points) compared to the spectrum generated with RESBOS (solid). Right: The  $m_T$  distribution for  $W$  boson decays to  $\mu\nu$ .

In the  $W$  decay, the most important effect for the  $W$  mass measurement is the radiation of a  $\gamma$  from a final-state  $l^\pm$ . This radiation results in a reduced  $l^\pm$  momentum, potentially affecting the inferred mass of the  $W$  boson. CDF bases its simulation of final-state radiation on a QED next-to-leading order event generator (WGRAD). Effects from initial-state radiation, interference, and higher-order terms are not simulated, resulting in a 20 (15) MeV uncertainty for the  $m_W$  measurement in the  $\mu$  ( $e$ ) channel.

### 3.2 Track Momentum Calibration

A charged particle's momentum is measured through its observed curvature in the tracker. Since the momentum is inversely proportional to curvature, the momentum scale is measured as a function of the mean inverse momentum of  $J/\psi$  muons and fit to a line. The line has zero slope, verifying the applicability of the extracted scale to  $W$  boson decays.

To improve momentum resolution, muon tracks from  $W$  and  $Z$  decays use the beam position as a point in the track fit. This constraint cannot be applied to  $J/\psi$  decays since they can be separated from the beam line. Instead,  $\Upsilon$  decays are used to verify that the beam constraint produces no bias on the momentum calibration. A systematic uncertainty of 15 MeV accounts for the observed difference in scale. Including the uncertainty due to tracker alignment, CDF estimates an uncertainty of  $\delta m_W(p_T \text{ scale}) = 25$  MeV.

### 3.3 Calorimeter Energy Calibration

Given the momentum calibration, electron tracks from  $W$  decays are used to calibrate the electromagnetic calorimeter. The calorimeter energy is scaled such that the ratio of energy to track momentum ( $E/p$ ) is equal to 1. To correct for an energy-dependent scale, the  $E/p$  distribution is fit as a function of electron  $E_T$  and a correction applied.

The significant amount of material in the silicon detector inside the tracker affects the position of the  $E/p$  peak. An uncertainty on the amount of material translates into an uncertainty on the measured  $E$  scale. The fraction of events in the region  $1.19 < E/p < 1.85$  is a measure of the material. The extent to which this region is not well modelled results in a 55 MeV uncertainty on the  $W$  mass. This uncertainty dominates the total  $\delta m_W(E \text{ scale})$  of 70 MeV.

### 3.4 Hadronic Recoil Measurement and Simulation

The hadronic recoil energy is measured by vectorially summing all the energy in the calorimeter, excluding that contributed by the  $l$ . The detector response to the hadronic energy is defined as

Table 1: The uncertainties on the  $W$  boson mass measurement in  $\text{MeV}/c^2$  using  $0.2 \text{ fb}^{-1}$  of Run 2 CDF data. The CDF Run 1B uncertainties are shown for comparison.

Systematic Uncertainty	Electrons (Run 1B <sup>9</sup> )	Muons (Run 1B <sup>9</sup> )
Production and Decay Model	30 (30)	30 (30)
Lepton $E$ Scale and Resolution	70 (80)	30 (87)
Recoil Scale and Resolution	50 (37)	50 (35)
Backgrounds	20 (5)	20 (25)
Statistics	45 (65)	50 (100)
Total	105 (110)	85 (140)

$R = u_{\text{meas}}/u_{\text{true}}$ , where  $u_{\text{true}}$  is the recoil energy of the  $W$  boson. The response is measured using  $Z \rightarrow ll$ , since the  $l$  is measured more precisely than the hadronic energy.

The hadronic energy resolution is modelled as having a component from the underlying event (independent of recoil) and a component from the recoiling hadrons. The model parameters are tuned using the resolution of  $Z \rightarrow ll$  along the axis bisecting the leptons. This axis is the least susceptible to fluctuations in  $l$  energy. The recoil response and resolution uncertainty on the  $W$  mass is 50 MeV, of which 37 MeV is due to the model of the underlying energy resolution.

### 3.5 Backgrounds

The backgrounds common to the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  samples are:  $Z \rightarrow ll$ , where one  $l$  is not reconstructed;  $W \rightarrow \tau\nu \rightarrow l3\nu$ ; and dijet production, with one hadronic jet misreconstructed as an  $l$ . In addition, the  $\mu$  sample includes background from cosmic rays and decays in flight. The  $W$  and  $Z$  backgrounds are estimated using Monte Carlo. The dijet background estimation uses events with significant energy surrounding the  $l$  to enhance hadronic background and obtain a background  $\cancel{E}_T$  distribution. The data  $\cancel{E}_T$  distribution is then fit using the  $W$  and jet distributions as input. The cosmic ray background is determined using track hit timing information and the decay-in-flight background estimated by fitting the  $\Delta\phi(l, \cancel{E}_T)$  distribution to a combination of  $W$  and decay-in-flight distributions. These estimates result in  $\delta m_W(\text{background}) = 20 \text{ MeV}$ .

### 3.6 Mass Fit and Systematics

Given the energy calibrations, recoil model, and background estimation, the  $m_T$  distribution is fit for the  $e$  and  $\mu$  channels. The predicted line shape agrees with that of the data (Fig. 1). The central value is blinded while CDF cross-checks the analysis with independent data sets and simulation. Combining the two channels (Table 1) results in  $\delta m_W = 76 \text{ MeV}$ .

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