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 δm_W. CDF has analyzed the first $\approx$200 pb^{-1} of Run 2 data and determined its δm_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 Δr to the W boson mass (m_W)[1]:

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

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 α_{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 ($\delta m_Z^2/m_Z^2 = 0.004\%$)[1], the uncertainties on m_t and m_W dominate the uncertainty on the inferred m_H. To obtain equal χ^2 contributions in a fit to m_H, the relation $\delta m_W = 0.007 \delta m_t$ must hold[2]. For the Run 1 δm_t of 4.3 GeV, the required δm_W is 30 MeV, close to $\delta m_W(world) = 34$ MeV[1]. The impending Run 2 top mass measurements will significantly reduce δm_t, making δm_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 δm_W between

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

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 ≈200 pb^{-1} 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 μ (p_T^l) can be measured with high precision and thus provides the bulk of the mass information. Additional information comes from the decay ν transverse momentum (p_T^ν), which is inferred from the measured energy imbalance in the event. Since the lepton energy is well measured, the dominant uncertainty on p_T^ν 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^ν into the transverse mass, defined as:

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

The transverse mass ignores the unmeasured ν 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 μ, 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 [6] and MRST [7] 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 [8]) 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.

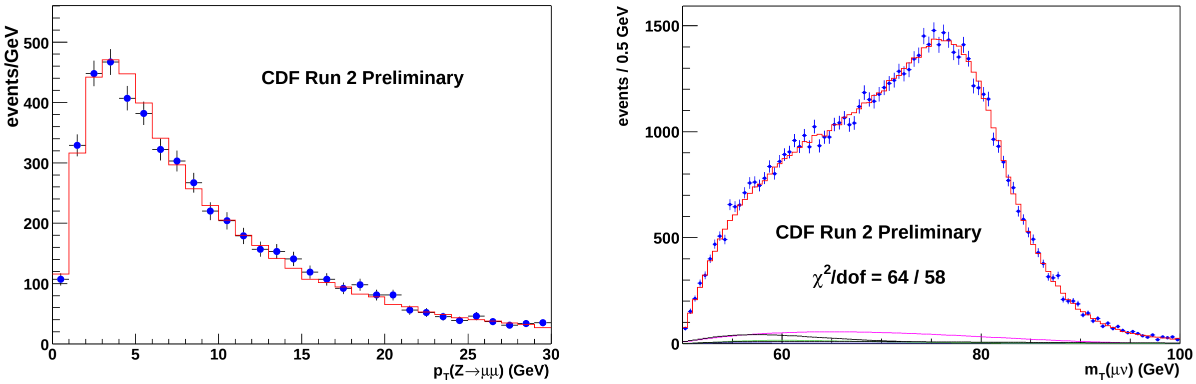

Figure 1: Left: The Z boson p_T spectrum in CDF Run 2 $Z \rightarrow \mu\mu$ data (points) compared to the spectrum generated with RESBOS (solid). Right: The m_T distribution for W boson decays to $\mu\nu$.

In the W decay, the most important effect for the W mass measurement is the radiation of a γ 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 μ (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/ψ 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/ψ decays since they can be separated from the beam line. Instead, Υ 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 $\delta m_W(p_T\ scale) = 25$ 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 $\delta m_W(E\ scale)$ 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 MeV/c^2 using 0.2 fb^{-1} of Run 2 CDF data. The CDF Run 1B uncertainties are shown for comparison.

Sytematic Uncertainty	Electrons (Run 1B [9])	Muons (Run 1B [9])
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)

$R = u_{meas}/u_{true}$, where u_{true} is the recoil energy of the W boson. The response is measured using $Z \to ll$, 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 $Z \to ll$ 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 $W \to e\nu$ and $W \to \mu\nu$ samples are: $Z \to ll$, where one l is not reconstructed; $W \to \tau\nu \to l3\nu$; and dijet production, with one hadronic jet misreconstructed as an l. In addition, the μ 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 $\not{E}_T$ distribution. The data $\not{E}_T$ 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 $\Delta\phi(l, \not{E}_T)$ distribution to a combination of W and decay-in-flight distributions. These estimates result in $\delta m_W(background) = 20$ 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 μ 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 $\delta m_W = 76$ MeV.

References

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