Measurement of the W Boson Mass

We present a measurement of the W boson mass in $W \rightarrow e\nu$ decays using 1 fb$^{-1}$ of data collected with the D0 detector during Run II of the Fermilab Tevatron collider. With a sample of 499830 $W \rightarrow e\nu$ candidate events, we measure $M_W = 80.401 \pm 0.043$ GeV. This is the most precise measurement from a single experiment.

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Knowledge of the W boson mass ($M_W$) is currently a limiting factor in our ability to tighten the constraints on the mass of the Higgs boson as determined from internal consistency of the standard model (SM) [1]. Improving the measurement of $M_W$ is an important contribution to our understanding of the electroweak (EW) interaction, and, potentially, of how the electroweak symmetry is broken. The current world-average measured value is $M_W = 80.399 \pm 0.025$ GeV [1] from a combination of measurements from the ALEPH [2], DELPHI [3], L3 [4], OPAL [5], D0 [6], and CDF [7, 8] collaborations.

In this Letter we present a measurement of $M_W$ using data collected from 2002 to 2006 with the D0 detector [9], corresponding to a total integrated luminosity of 1 fb$^{-1}$ [10]. We use the $W \rightarrow e\nu$ decay mode because the D0 calorimeter is well-suited for a precise measurement of electron energies, providing an energy resolution of 3.6% for electrons with an energy of 50 GeV. The components of the initial state total momentum and of the neutrino momentum along the beam direc-
tion are unmeasurable, so $M_W$ is measured using three kinematic variables measured in the plane perpendicular to the beam direction: the transverse mass $m_T$, the electron transverse momentum $p_T^e$, and the neutrino transverse momentum $p_T^\nu$. The transverse mass is defined as

$$m_T = \sqrt{2p_T^e p_T^\nu (1 - \cos \Delta \phi)},$$

where $\Delta \phi$ is the opening angle between the electron and neutrino momenta in the plane transverse to the beam. The magnitude and direction of $p_T^e$ are inferred from the event missing transverse energy ($\not{E}_T$). The $M_W$ measurement is made by comparing data spectra of $m_T$, $p_T^e$, and $E_T$ with probability density functions (templates) for these spectra constructed from Monte Carlo simulation with varying input $M_W$ values.

The D0 detector [9] contains tracking, calorimeter, and muon systems. Silicon microstrip tracking detectors (SMT) near the interaction point cover pseudorapidity $|\eta| \leq 3$ to provide tracking and vertex information. The central fiber tracker surrounds the SMT, providing coverage to $|\eta| \approx 2$. A 2 T solenoid surrounds these tracking detectors. Three uranium, liquid-argon calorimeters measure particle energies. The central calorimeter (CC) covers $|\eta| < 1.1$, and two end calorimeters (EC) extend coverage to $|\eta| \approx 4$. The CC is segmented in depth into eight layers. The first four layers are used primarily to measure the energy of photons and electrons and are collectively called the electromagnetic (EM) calorimeter. The remaining four layers, along with the first four, are used to measure the energy of hadrons. Intercryostat detectors (ICD) provide added sampling in the region $1.1 < |\eta| < 1.4$ where the CC and EC cryostat walls degrade the calorimeter energy resolution. A three level trigger system selects events for recording with a rate of 100 Hz.

Events are initially selected using a trigger requiring at least one EM cluster found in the CC with transverse energy threshold varying from 20 GeV to 25 GeV depending on run conditions. Additionally, the position of the reconstructed production point of a $W$ or $Z$ boson along the beam line is required to be within 60 cm of the center of the detector.

Candidate $W$ boson events are required to have one EM cluster reconstructed in the CC, with $p_T^e > 25$ GeV and $|\eta| < 1.05$ where $\eta$ is the pseudorapidity measured with respect to the center of the detector. The EM cluster must pass electron shower shape and energy isolation requirements in the calorimeter, be within the central 80% of the electromagnetic section of each CC module, and have one track matching in $(\eta, \phi)$ space, where the track has at least one SMT hit and $p_T > 10$ GeV. The central 80% requirement is applied to the $\phi$ coordinate only and excludes regions with slightly degraded energy resolution. The event must satisfy $E_T > 25$ GeV, $u_T < 15$ GeV, and $50 < m_T < 200$ GeV. Here $E_T$ is the magnitude of the vector sum of the transverse energy of calorimeter cells above read out threshold, excluding those in the coarse hadronic layer and in the intercryostat detector, and $u_T$ is the magnitude of the vector sum of the transverse component of the energies measured in calorimeter cells excluding those associated with the reconstructed electron. This selection yields 499,830 candidate $W \rightarrow e\nu$ events. Throughout this Letter we use “electron” to imply either electron or positron.

We use $Z \rightarrow e\nu$ events for calibration. Candidate $Z$ boson events are required to have two EM clusters satisfying the requirements above. Both electrons must have $p_T^e > 25$ GeV. One must be reconstructed in the CC and the other in either the CC or EC ($1.5 < |\eta| < 2.5$). The associated tracks must be of opposite charge. Events must also have $u_T < 15$ GeV and $70$ GeV $\leq m_{ee} \leq 110$ GeV, where $m_{ee}$ is the invariant mass of the dielectron pair. Events with both electrons in the CC are used to determine the EM calibration. There are 18,725 candidate $Z \rightarrow e\nu$ events in this category.

The backgrounds in the $W$ boson sample are $Z \rightarrow e\nu$ events in which one electron escapes detection, multijet events (MJ) in which a jet is misidentified as an electron with $E_T$ arising from misreconstruction, and $W \rightarrow \tau\nu \rightarrow e\nu\nu$ events. The background from $Z$ boson events arises from electrons which traverse the gap between the CC and EC. The tracking efficiency in this region is high, so this background is estimated by selecting data events passing the $W$ boson selection in which an additional track is pointing at the gap region. The MJ background is determined using a sample obtained by removing the track matching requirement for the electron candidates. The probabilities for background and $W$ boson signal events in this sample to have a matching track are measured in control samples. The number of events in the sample without the track requirement and the two probabilities are then used to determine the number of MJ background events in the final $W$ boson sample. The $W \rightarrow \tau\nu \rightarrow e\nu\nu$ contribution is determined from detailed simulation of the process using the D0 GEANT [11]-based simulation. The backgrounds expressed as a fraction of the final sample are $(0.90 \pm 0.01)\%$ from $Z \rightarrow ee$, $(1.49 \pm 0.03)\%$ from MJ, and $(1.60 \pm 0.02)\%$ from $W \rightarrow \tau\nu \rightarrow e\nu\nu$.

$W$ and $Z$ boson production and decay kinematics are simulated using the RESBOS [12] next-to-leading order generator which includes non-perturbative effects at low boson $p_T$. These effects are parametrized by three constants ($g_1$, $g_2$, and $g_3$) whose values are taken from global fits to data [13]. The radiation of one or two photons is performed using the PHOTOS [14] program.

Detector efficiencies and energy response and resolution for the electron and hadronic energy are applied to the RESBOS+PHOTOS events using a fast parametric Monte Carlo simulation (FASTM) developed for this analysis. The FASTM parameters are determined using a combination of detailed simulation and control data
samples. The primary control sample used for both the electromagnetic and hadronic response tuning is $Z \to ee$ events. $W$ boson events are also used in a limited manner, as are events recorded in random beam crossings, with or without requiring hits in the luminosity counters.

Since the $Z$ boson mass and width are known with high precision from measurements [15] at the CERN $e^+e^-$ collider (LEP), these values are used to calibrate the electromagnetic calorimeter response assuming a form $E_{\text{true}} = E_{\text{true}} \pm \beta$ with $\alpha$ and $\beta$ constants determined by calibration. The $M_W$ measurement presented here is effectively a measurement of the ratio of $W$ and $Z$ boson masses. Figure 1 shows a comparison of the $m_{ee}$ distributions for data and FastMC, as well as the $\chi$ distribution defined as the difference between data and the FastMC prediction divided by the statistical uncertainty on the difference.

The other major calibration is that of the hadronic energy in the event, which includes energy recoiling against the boson. The hadronic response (resolution) is tuned using the mean (width) of the $n_{\text{imb}}$ distribution in $Z \to ee$ events in bins of $p_T$. Here $n_{\text{imb}}$ is defined as the sum of all the vectors in the transverse plane on the axis bisecting the dielectron opening angle [16].

A test of the analysis procedure is performed using events produced by the detailed GEANT Monte Carlo simulation treated as collider data. The methods used for the data analysis are applied to the simulated events, including the FastMC tuning using the simulated $Z \to ee$ events. Each of the $M_W$ fit results using the $m_T$, $p_T$, and $E_T$ distributions agree with the input $M_W$ value within the 20 MeV total uncertainty of the test arising from Monte Carlo statistics.

During the FastMC tuning performed to describe the collider data, the $M_W$ values returned from fits are blinded by the addition of an unknown constant offset. The same offset was used for $m_T$, $p_T$, and $E_T$. This allowed the full tuning on the $W$ and $Z$ boson events and internal consistency checks to be performed without knowledge of the final result. Once the important data and FastMC comparison plots have acceptable $\chi$ distributions, the results are unblinded. The $Z$ boson mass value from the post-tuning fit is $91.185 \pm 0.033$ (stat) GeV, in agreement with the world average of 91.188 GeV used for the tuning. The $M_W$ results from data after unblinding are given in Table I. The $m_T$, $p_T$, and $E_T$ distributions showing the data and FastMC template with background for the best fit $M_W$ are shown in Fig. 2.

![FIG. 1: (a) The dielectron invariant mass distribution in $Z \to ee$ data and from the fast simulation FastMC and (b) the $\chi$ values where $\chi_i = (P_i = \text{FASTMC}_i)/\sigma_i$ for each point in the distribution. $N_i$ is the data yield in bin $i$ and $\sigma_i$ is the statistical uncertainty in bin $i$.](image)

<table>
<thead>
<tr>
<th>Variable Fit Range (GeV)</th>
<th>$M_W$ (GeV)</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_T$ 65 &lt; $m_T$ &lt; 90</td>
<td>80.401 ± 0.023</td>
<td>48/49</td>
</tr>
<tr>
<td>$p_T$ 32 &lt; $p_T$ &lt; 48</td>
<td>80.400 ± 0.027</td>
<td>39/31</td>
</tr>
<tr>
<td>$E_T$ 32 &lt; $E_T$ &lt; 48</td>
<td>80.402 ± 0.023</td>
<td>32/31</td>
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</tbody>
</table>

The systematic uncertainties in the $M_W$ measurement arise from a variety of sources, and can be categorized as those from experimental sources and those from uncertainties in the production mechanism. The systematic uncertainties are summarized in Table II.

The uncertainties on the electron energy calibration and the hadronic recoil model are determined by simultaneously varying the parameters determined in the tuning to $Z \to ee$ events by one statistical standard deviation including correlation coefficients. The electron energy resolution systematic uncertainty is determined by varying resolution parameters determined in the fit to the width of the observed $Z \to ee$ $m_{ee}$ distribution. The shower modeling systematic uncertainties are determined by varying the amount of material representing the detector in the detailed simulation within the uncertainties found by comparing the electron showers in the simulation to those observed in data. No effect was seen when studying possible systematic bias for the energy loss differences arising from the differing $E$ or $\eta$ distributions for the electrons from $W$ and $Z$ boson decay. The quoted systematic uncertainty is due to the finite statistics of the event samples from the tuned detailed simulation that are...
used to transport calibrations from the $Z$ to the $W$ sample. The electron efficiency systematic is determined by varying the efficiency by one standard deviation. Table II also shows the $M_W$ uncertainties arising from variation of the background uncertainties indicated above.

Among the production uncertainties, the parton distribution function (PDF) uncertainty is determined by generating $W$ boson events with the PYTHIA [17] program using the CTEQ6.1M [18] PDF set. The CTEQ prescription [18] is used to determine a one standard deviation uncertainty [8] on $M_W$. The QED uncertainty is determined using WGRAD [19] and ZGRAD [20], varying the photon-related parameters and assessing the variation in $M_W$ and by comparisons between these and PHOTOS. The boson $p_T$ uncertainty is determined by varying $g_2$ by its quoted uncertainty [13]. Variation of $g_1$ and $g_3$ has negligible impact.

The quality of the simulation is indicated by the good $\chi^2$ values computed for the difference between the data and FASTMC shown in the figures. The data are also sub-divided into statistically independent categories based on instantaneous luminosity, time, the total hadronic transverse energy in the event, the vector sum of the hadronic energy, and electron pseudorapidity range. The fit ranges are also varied. The results are stable to within the measurement uncertainty for each of these tests.

The results from the three methods have combined statistical and systematic correlation coefficients of 0.83, 0.82, and 0.68 for $(m_T, p_T^e)$, $(m_T, E_T)$, and $(p_T^e, E_T)$ respectively. The correlation coefficients are determined using ensembles of simulated events. The results are combined [21] including these correlations to give the final result

$$M_W = 80.401 \pm 0.021 \text{ (stat)} \pm 0.038 \text{ (syst)} \text{ GeV}$$

$$= 80.401 \pm 0.043 \text{ GeV}.$$

The dominant uncertainties arise from the available statistics of the $W \rightarrow e\nu$ and $Z \rightarrow ee$ samples. Thus, this measurement can still be expected to improve as more data are analyzed. The $M_W$ measurement reported here agrees with the world average and the individual measurements and is more precise than any other single measurement. Its introduction in global electroweak fits is expected to lower the upper bound on the SM Higgs mass, although it is not expected to change the best fit value [1].

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**TABLE II: Systematic uncertainties of the $M_W$ measurement.**

<table>
<thead>
<tr>
<th>Source</th>
<th>$\Delta m_T$ (MeV)</th>
<th>$\Delta p_T^e$ (MeV)</th>
<th>$\Delta E_T$ (MeV)</th>
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<tbody>
<tr>
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<tr>
<td>Total</td>
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</table>
CNSF (China); and the Alexander von Humboldt Foundation (Germany).

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[c] Visitor from The University of Liverpool, Liverpool, UK.
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[e] Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacán, Mexico.
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