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## Measurement of the $W$ Boson Mass with the D0 Detector

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We present a measurement of the  $W$  boson mass using data corresponding to  $4.3 \text{ fb}^{-1}$  of integrated luminosity collected with the D0 detector during Run II at the Fermilab Tevatron  $p\bar{p}$  collider. With a sample of 1 677 394  $W \rightarrow e\nu$  candidate events, we measure  $M_W = 80.367 \pm 0.026 \text{ GeV}$ . This result is combined with an earlier D0 result determined using an independent Run II data sample, corresponding to  $1 \text{ fb}^{-1}$  of integrated luminosity, to yield  $M_W = 80.375 \pm 0.023 \text{ GeV}$ .

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In the context of the standard model (SM), there is a relationship between the  $W$  boson mass ( $M_W$ ) and the hypothetical Higgs boson mass (and other observables such as the top quark mass). Accurate measurement of the  $M_W$  is thus a key ingredient in constraining the SM Higgs boson mass and comparing that constraint with the results of direct Higgs boson searches. Precise measurements of  $M_W$  have been reported by the ALEPH [1], DELPHI [2], L3 [3], OPAL [4], D0 [5,6], and CDF [7,8] collaborations. The  $W$  boson mass experimental methods and measurements are discussed in Ref. [9]. The current world average measured value is  $M_W = 80.399 \pm 0.023 \text{ GeV}$  [10]. This result and the current measurement [11] of the top quark mass,  $M_t$ , give a range for the predicted  $M_H$  which is centered on a value outside the direct search allowed range. The predicted range is, however, large and does have some overlap with the regions allowed by direct searches. The limiting factor in the predictions is the experimental precision on  $M_W$ . It is therefore of great interest to improve the precision of the  $W$  boson mass measurement so as to further probe the validity of the SM.

In this Letter, we present a measurement of  $M_W$  using data collected from 2006 to 2009 with the D0 detector [12],

corresponding to a total integrated luminosity of  $4.3 \text{ fb}^{-1}$ . We use the  $W \rightarrow e\nu$  decay mode because the D0 calorimeter is well suited for a precise measurement of electron [13] energies. For the data considered in this analysis, the average energy resolution is 4.2% for electrons of 45 GeV. The longitudinal components of the colliding partons and of the neutrino cannot be determined, so  $M_W$  is determined 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 vector  $\vec{p}_T^\nu$  is equal to the event missing transverse momentum ( $\vec{\cancel{E}}_T$ ).

The D0 detector [12] comprises a tracking system, calorimeters and a muon system with an iron toroid magnet. Silicon microstrip tracking detectors (SMT) near the interaction point cover  $|\eta| < 3$ , where  $\eta \equiv -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle with respect to the proton beam direction, to provide tracking and vertex information. The central fiber tracker surrounds the SMT, providing coverage to  $|\eta| \approx 2$ . A 1.9 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 allow for a precise measurement of the energy of photons and electrons. The remaining four layers, along with the first four, are used to measure the energy of hadrons. A three-level trigger system selects events for recording with a rate of  $\approx 100$  Hz.

The present analysis builds on the techniques developed in Ref. [6]. Additional studies are necessary to cope with the consequences of the increased instantaneous luminosities (on average  $1.2 \times 10^{32} \text{ cm}^{-2} \text{ S}^{-1}$ , almost 3 times higher than in Ref. [6]). The main developments include a new model of dependence of the gains of the D0 calorimeter on the instantaneous luminosity. This dependence had been predicted [14] before the start of Run II and has been studied in detail in the data used for this Letter. The other important additions are a correction for residual  $\eta$ -dependent miscalibrations of the calorimeter response, a more detailed model of the impact of additional  $p\bar{p}$  interactions on the electron energy reconstruction, and a detailed description of electron efficiency in the presence of additional  $p\bar{p}$  interactions. Using the same method as Ref. [6] we obtain the amount of material preceding the calorimeter from a fit to the longitudinal energy profile in the electromagnetic calorimeter.

Events are selected using a trigger requiring at least one electromagnetic (EM) cluster found in the CC with the transverse energy threshold varying from 25 to 27 GeV depending on run conditions. The offline selection of candidate  $W$  boson events is similar to that used in Ref. [6], except that the veto on electrons in  $\phi$  regions with degraded energy response is now based on extrapolation of the track to the third calorimeter layer instead of the position of the calorimeter cluster. We require at least one candidate electron reconstructed as an EM cluster in the CC, matched in  $(\eta, \phi)$  space to a track including at least one SMT hit and  $p_T > 10$  GeV to reject jets misidentified as electrons and to ensure a precise measurement of the electron direction. The length of the electron three-momentum vector is defined by the cluster energy, and the direction by the track. We require an electron with  $p_T^e > 25$  GeV that passes shower shape and isolation requirements and points to the central 80% in azimuth of a CC ( $|\eta| < 1.05$ ) module. The event must satisfy  $\cancel{E}_T > 25$  GeV,  $u_T < 15$  GeV, and  $50 < m_T < 200$  GeV. Here  $u_T$  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. The relation  $\vec{\cancel{E}}_T = -(\vec{p}_T^e + \vec{u}_T)$  defines the missing momentum ascribed to the neutrino. This selection yields 1 677 394 candidate  $W \rightarrow e\nu$  events.

Candidate  $Z \rightarrow ee$  events are required to have two EM clusters satisfying the above requirements, except that one

of the two may be reconstructed within an EC ( $1.5 < |\eta| < 2.5$ ). The associated tracks must be of opposite curvature. Events must also have  $u_T < 15$  GeV and  $70 \leq m_{ee} \leq 110$  GeV, where  $m_{ee}$  is the invariant mass of the electron pair. Events with both electrons in the CC are used to determine the calibration of the electron energy scale. There are 54 512 candidate  $Z \rightarrow ee$  events in this category. Events with one electron in EC are only used for the efficiency measurement.

The backgrounds in the  $W$  boson candidate sample are  $Z \rightarrow ee$  events where one electron escapes detection, multijet events where a jet is misidentified as an electron with  $\cancel{E}_T$  arising from misreconstruction, and  $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$  events. The backgrounds are estimated using refined versions of the techniques in Ref. [6], and their impact on the measurement of  $M_W$  is small. The fractions of the backgrounds in the  $W$  boson candidate sample are 1.08% for  $Z \rightarrow ee$ , 1.02% for multijet events, and 1.67% for  $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$ .

The RESBOS [15] event generator, combined with PHOTOS [16] is used to simulate the kinematics of  $W$  and  $Z$  boson production and decay. RESBOS is a next-to-leading order event generator including next-to-next-to-leading logarithm resummation of soft gluons [17], and PHOTOS generates up to two final state radiation photons. Parton distribution functions (PDF) are described using CTEQ6.6 [18]. This combination provides a good description of the most important effects in the  $M_W$  measurement, namely, the boson transverse momentum spectrum (influenced by the emission of multiple soft gluons) and radiation from the electrons in the final state. We use comparisons to the WGRAD [19] and ZGRAD [20] event generators, which provide a more complete treatment of electroweak corrections at the one radiated photon level, in order to assess the uncertainty in the  $M_W$  measurement due to quantum electrodynamics (QED) corrections. We take the nonperturbative parameter  $g_2$  [21] to be  $0.68 \pm 0.02 \text{ GeV}^2$  [22] and the uncertainty on  $g_2$  is propagated to the  $W$  boson mass uncertainty.

A fast, parametrized Monte Carlo (MC) simulation (FASTMC) is used to simulate electron identification efficiencies and the energy response and resolutions of the electron and recoil system in the generated events. The FASTMC 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  $Z \rightarrow ee$  events. Events recorded in random beam crossings are overlaid on  $W$  and  $Z$  events in the detailed simulation to quantify the effect of additional collisions in the same or nearby bunch crossings.

The  $Z$  boson mass and width are known with high precision from measurements at LEP [23]. These values are used to calibrate the electromagnetic calorimeter response assuming a form  $E^{\text{meas}} = \alpha E^{\text{true}} + \beta$  with

constants  $\alpha$  and  $\beta$  determined from fits to the dielectron mass spectrum and the energy and angular distributions of the two electrons. The  $M_W$  measurement presented here is effectively a measurement of the ratio of  $W$  and  $Z$  boson masses.

The hadronic energy in the event contains the hadronic system recoiling from the  $W$  boson, the effects of low energy products from spectator parton collisions and other beam collisions, final state radiation, and energy from the recoil particles that enter the electron selection window. The hadronic response (resolution) is calibrated using the mean (width) of the  $\eta_{\text{imb}}$  distribution in  $Z \rightarrow ee$  events in bins of  $p_T^{ee}$ . Here,  $\eta_{\text{imb}}$  is defined as the projections of the sum of dielectron transverse momentum ( $\vec{p}_T^{ee}$ ) and  $\vec{u}_T$  vectors on the axis bisecting the dielectron directions in the transverse plane [24].

The combination of event generator and FASTMC is used to predict the shapes of  $m_T$ ,  $p_T^e$ , and  $\cancel{E}_T$  for a given  $M_W$  hypothesis.  $M_W$  is determined separately for each of the three observables by maximizing a binned likelihood between the data distribution and the predicted distribution normalized to the data. The fit ranges are optimized as indicated in Table I.

A test of the analysis procedure is performed using  $W \rightarrow e\nu$  events, generated by the PYTHIA [25] event generator and processed through a detailed GEANT MC simulation [26], which are treated as collider data. The FASTMC is separately tuned to give agreement with the GEANT events in the same way as for the data comparison. Each of the  $M_W$  fit results using the  $m_T$ ,  $p_T^e$ , and  $\cancel{E}_T$  distributions agree with the input  $M_W$  value within the 6 MeV total uncertainty of the test arising from MC statistics.

During the FASTMC tuning performed to describe the collider data, the  $M_W$  values returned from fits had an unknown constant offset added. The same offset was used for  $m_T$ ,  $p_T^e$ , and  $\cancel{E}_T$ . 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 had acceptable  $\chi^2$  distributions, the common offset was removed from the results. The  $Z$  boson mass from the fit to the data corresponds to the input that was used in the determination of the calorimeter response described above. The statistical uncertainty from the fit is 0.017 GeV, quoted here as a quantitative illustration of the statistical power of the  $Z \rightarrow ee$  sample. Figure 1 shows a comparison of the  $m_{ee}$  distributions for data and FASTMC. The  $M_W$  results are

TABLE I. Results from the fits to data. The uncertainty is solely due to the statistics of the  $W$  boson sample.

Variable	Fit Range (GeV)	$M_W$ (GeV)	$\chi^2/\text{dof}$
$m_T$	$65 < m_T < 90$	$80.371 \pm 0.013$	37.4/49
$p_T^e$	$32 < p_T^e < 48$	$80.343 \pm 0.014$	26.7/31
$\cancel{E}_T$	$32 < \cancel{E}_T < 48$	$80.355 \pm 0.015$	29.4/31

given in Table I. The  $m_T$ ,  $p_T^e$ , and  $\cancel{E}_T$  distributions showing the data and FASTMC templates with background for the best fit  $M_W$  are shown in Fig. 2.

The systematic uncertainties in the  $M_W$  measurement are summarized in Table II. They can be categorized as those from experimental sources and those from uncertainties in the production mechanism. The uncertainties on the electron energy calibration, the electron energy resolution, and the hadronic recoil model arise from the finite size of the  $Z \rightarrow ee$  sample used to derive them. The uncertainties in the propagation of electron energy calibrations from the  $Z \rightarrow ee$  to the  $W \rightarrow e\nu$  sample are determined by the difference in energy loss in the uninstrumented material in front of the calorimeter. The energy loss as a function of electron energy and  $\eta$  is derived from a dedicated detailed GEANT simulation of the D0 detector. The shower modeling systematic uncertainties reflect the uncertainties in the amount of uninstrumented material, and the energy loss systematic uncertainties arise from the finite precision of our simulations of electron showers based on a detailed model of the detector geometry. The systematic uncertainties of electron efficiency, hadronic recoil model, and backgrounds are determined by varying the corresponding parameters within the statistical uncertainties of their measurements. Table II also shows the  $M_W$  uncertainties arising from the backgrounds.

The uncertainties due to the production mechanism are dominated by the uncertainties due to the PDFs. The transverse observables ( $m_T$ ,  $p_T^e$ , and  $\cancel{E}_T$ ) used in the measurement of  $M_W$  are invariant under longitudinal boosts, and their use therefore minimizes the sensitivity to PDF uncertainties. However, a limited sensitivity to PDF uncertainties does arise from the electron pseudorapidity requirements that are used in the measurement of  $M_W$  reported here. These requirements are not invariant under longitudinal boosts, and changes in the PDF can therefore

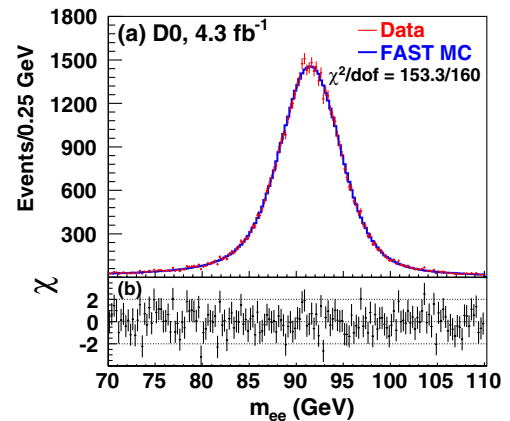


FIG. 1 (color online). (a) The dielectron invariant mass distribution in  $Z \rightarrow ee$  data and from the FASTMC and (b) the  $\chi$  values, where  $\chi_i = [N_i - (\text{FASTMC}_i)]/\sigma_i$  for each bin in the distribution,  $N_i$  and  $\text{FASTMC}_i$  are the data and FASTMC template yields in bin  $i$ , respectively, and  $\sigma_i$  is the statistical uncertainty in bin  $i$ .

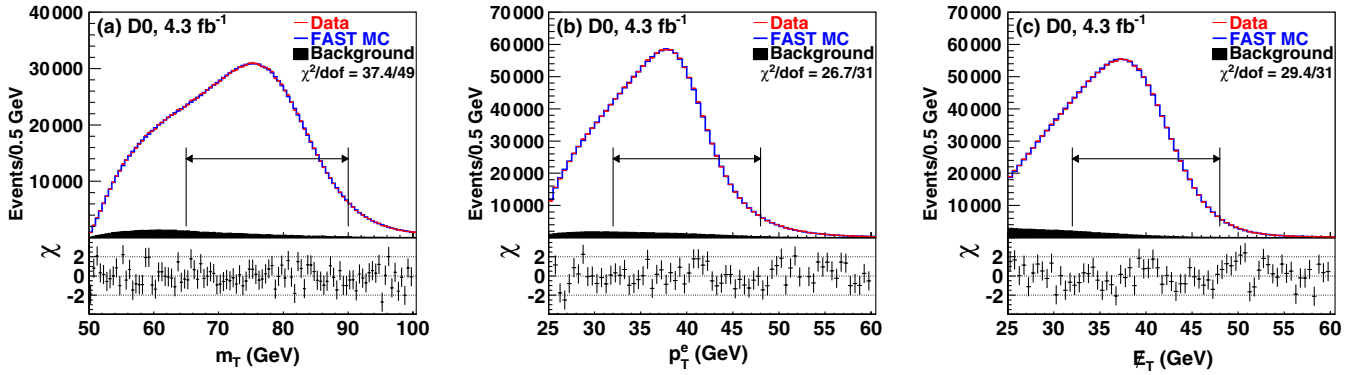


FIG. 2 (color online). The (a)  $m_T$ , (b)  $p_T^e$ , and (c)  $E_T$  distributions for data and FASTMC simulation with backgrounds. The  $\chi$  values are shown below each distribution, where  $\chi_i = [N_i - (\text{FASTMC}_i)]/\sigma_i$  for each bin in the distribution,  $N_i$  and  $\text{FASTMC}_i$  are the data and FASTMC template yields in bin  $i$ , respectively, and  $\sigma_i$  is the statistical uncertainty in bin  $i$ . The fit ranges are indicated by the double-ended horizontal arrows.

result in changes of the shapes of our transverse observables. The uncertainties in the PDF are propagated to a 1 standard deviation uncertainty in  $M_W$  by generating ensembles of  $W$  boson events using PYTHIA with the CTEQ6.1 [27] prescription. The other production uncertainties have been discussed above.

The quality of the simulation is indicated by the  $\chi^2$  values computed for the differences between the data and FASTMC shown in Figs. 1 and 2. We perform a variety of consistency checks of the stability of our results. We vary the fit ranges for the  $m_T$ ,  $p_T^e$ , and  $E_T$  distributions. The data are also divided into statistically independent categories based on instantaneous luminosity, time, electron  $\eta$ , and the projection of  $\vec{u}_T$  on the electron direction. The exclusion region near CC module edges is varied, and the selection requirement on  $u_T$  is varied. The results are stable to within the measurement uncertainty for each of these tests.

The total correlations among the three  $W$  boson mass measurements are determined by combining the covari-

ance matrices for each source of uncertainty. For uncertainties which arise from sample statistics, such as the electron energy scale, the full covariance matrices are determined using ensemble studies. For uncertainties which are nonstatistical in nature, such as the QED uncertainty, the correlations among the three observables are defined as 100% to prevent these uncertainties from being decreased in the combination. The resulting total correlations, including both categories of uncertainties, are 0.89 ( $m_T$ ,  $p_T^e$ ), 0.86 ( $m_T$ ,  $E_T$ ), and 0.75 ( $p_T^e$ ,  $E_T$ ). When considering only the uncertainties which are allowed to decrease in the combination, we find that the  $E_T$  measurement has negligible weight. We therefore combine the  $m_T$  and  $p_T^e$  measurements using the method [28] and obtain

$$\begin{aligned} M_W &= 80.367 \pm 0.013(\text{stat.}) \pm 0.022(\text{syst.}) \text{ GeV} \\ &= 80.367 \pm 0.026 \text{ GeV.} \end{aligned}$$

The probability to observe a larger difference than observed between these two measurements is 2.8%. The probability to observe a larger difference than observed when all three measurements are combined is 5%. We combine this measurement with the earlier D0 measurement [6] to obtain

$$\begin{aligned} M_W &= 80.375 \pm 0.011(\text{stat.}) \pm 0.020(\text{syst.}) \text{ GeV} \\ &= 80.375 \pm 0.023 \text{ GeV.} \end{aligned}$$

The dominant uncertainties arise from the available statistics of the  $W \rightarrow e\nu$  and  $Z \rightarrow ee$  samples. Thus, a future measurement with the full D0 data set is expected to be more precise. The  $M_W$  measurement reported here agrees with the world average [10,29] and the previous individual measurements and has an uncertainty that significantly improves upon previous D0 measurements. Our new measurement of  $M_W$  and the most recent world average measurement of  $M_t$  are compared in Fig. 3 with the regions that are still allowed, at the 95% C.L., after direct searches for the Higgs boson at LEP, the Tevatron, and the

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

Source	$\Delta M_W(\text{MeV})$		
	$m_T$	$p_T^e$	$E_T$
Electron energy calibration	16	17	16
Electron resolution model	2	2	3
Electron shower modeling	4	6	7
Electron energy loss model	4	4	4
Hadronic recoil model	5	6	14
Electron efficiencies	1	3	5
Backgrounds	2	2	2
Experimental subtotal	18	20	24
PDF	11	11	14
QED	7	7	9
Boson $p_T$	2	5	2
Production subtotal	13	14	17
Total	22	24	29

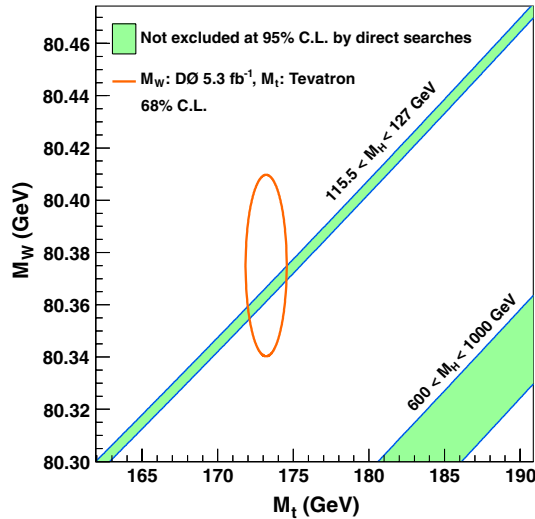


FIG. 3 (color online). Contour curves of 68% probability in the  $(M_t, M_W)$  plane. The ellipse represents the measurement of  $M_t$  from Ref. [11] and the measurement of  $M_W = 80.375 \pm 0.023$  GeV reported in this Letter. The bands show the SM prediction for different Higgs boson mass hypotheses that are not yet ruled out by direct searches [30] for the Higgs boson.

LHC. Our new measurement of  $M_W$  is in good agreement with one of the regions allowed by direct searches for the Higgs boson.

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