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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 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 $1,677,394$ $W \to e\nu$ candidate events, we measure $M_W = 80.367 \pm 0.026$ GeV. This result is combined with an earlier D0 result determined using an independent Run II data sample, corresponding to 1 fb^{-1} of integrated luminosity, to yield $M_W = 80.375 \pm 0.023$ 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 $M_W = 80.399 \pm 0.023$ GeV [10]. This result and the current top quark measurement [11] give a central value for the predicted M_H which is outside the direct search allowed range. 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 fb^{-1}. We use the $W \to e\nu$ 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 50 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^ν. 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

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the event missing transverse momentum ($\vec{\not\!\!E}_T$).

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 θ 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 1.2×10^{32} cm^{-2}s^{-1}, almost three 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 η-dependent miscalibrations of the calorimeter response, a more detailed model of the impact of additional $p\overline{p}$ interactions on the electron energy reconstruction, and a detailed description of electron efficiency in the presence of additional $p\overline{p}$ 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 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 ϕ 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 (η, ϕ) 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. 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 $\not\!\!E_T > 25$ 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 $\vec{\not\!\!E}_T = -(\vec{p}_T^{\,e} + \vec{u}_T)$ defines the missing momentum ascribed to the neutrino. This selection yields 1,677,394 candidate $W \to e\nu$ events.

Candidate $Z \to ee$ 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 $Z \to ee$ 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 $Z \to ee$ events where one electron escapes detection, multijet events (MJ) where a jet is misidentified as an electron with $\not\!\!E_T$ arising from misreconstruction, and $W \to \tau\nu \to e\nu\nu\nu$ 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 $Z \to ee$, 1.02% for MJ, and 1.67% for $W \to \tau\nu \to e\nu\nu\nu$.

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 (FSR) 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 uncertinaty in the M_W measurement due to quantum electrodynamics (QED) corrections. We take the non-perturbative parameter g_2 [21] to be 0.68 ± 0.02 GeV^2 [22] and the uncertainty on g_2 is propagated to the W boson mass uncertainty.

A fast, parameterized 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 $Z \to ee$ 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 $E^{\rm meas} = \alpha\, E^{\rm true} + \beta$ with constants α and β 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, FSR, and energy from the recoil particles that enter the electron selection window. The hadronic response (resolution) is calibrated using the mean (width) of the $\eta_{\rm imb}$ distribution in $Z \to ee$ events in bins of p_T^{ee}. Here, $\eta_{\rm imb}$ is defined as the projections of the 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 $\not\!\!E_T$ 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 $W \to e\nu$ events, generated by PYTHIA [25] event generator and processed through a detailed GEANT MC simulation [26], 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 $\not\!\!E_T$ distributions agree with the input M_W value within the 6 MeV total uncertainty of the test arising from MC statistics. The fitted value of M_Z is 91.185 ± 0.004 (stat) GeV is compared with the input world average value of 91.188 GeV [23].

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 $\not\!\!E_T$. 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 χ^2 distributions, the common offset was removed from the results. The Z boson mass from the fit to data is 91.193 ± 0.017 (stat) GeV. Figure 1 shows a comparison of the m_{ee} distributions for data and FASTMC. The M_W results are given in Table I. The m_T, p_T^e, and $\not\!\!E_T$ distributions showing the data and FASTMC templates with background for the best fit M_W are shown in Fig. 2.

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)	χ^2/dof
m_T	$65 < m_T < 90$	80.371 ± 0.013	37.4/49
p_T^e	$32 < p_T^e < 48$	80.343 ± 0.014	26.7/31
$\not\!\!E_T$	$32 < \not\!\!E_T < 48$	80.355 ± 0.015	29.4/31

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 $Z \to ee$ sample used to derive them. The uncertainties in the propagation of electron energy calibrations from the $Z \to ee$ to the $W \to e\nu$ 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 η 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. Ta-

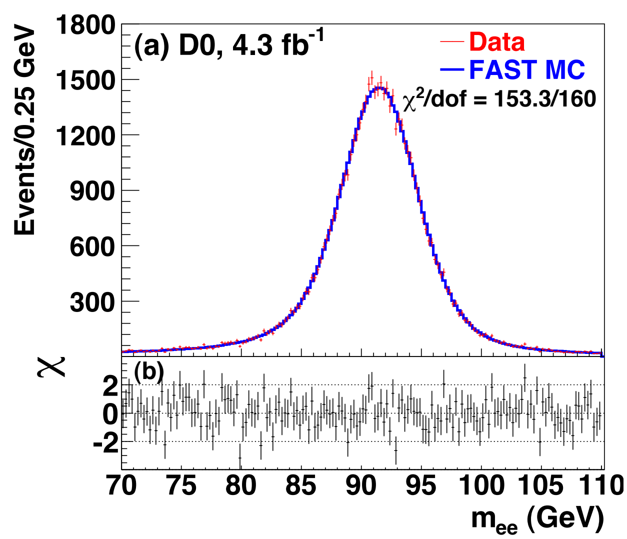

FIG. 1: (a) The dielectron invariant mass distribution in $Z \to ee$ data and from the FASTMC and (b) the χ values, where $\chi_i = [N_i - (\text{FASTMC}_i)]/\sigma_i$ for each bin in the distribution, N_i and FASTMC_i are the data and FASTMC template yields in bin i, respectively, and σ_i is the statistical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

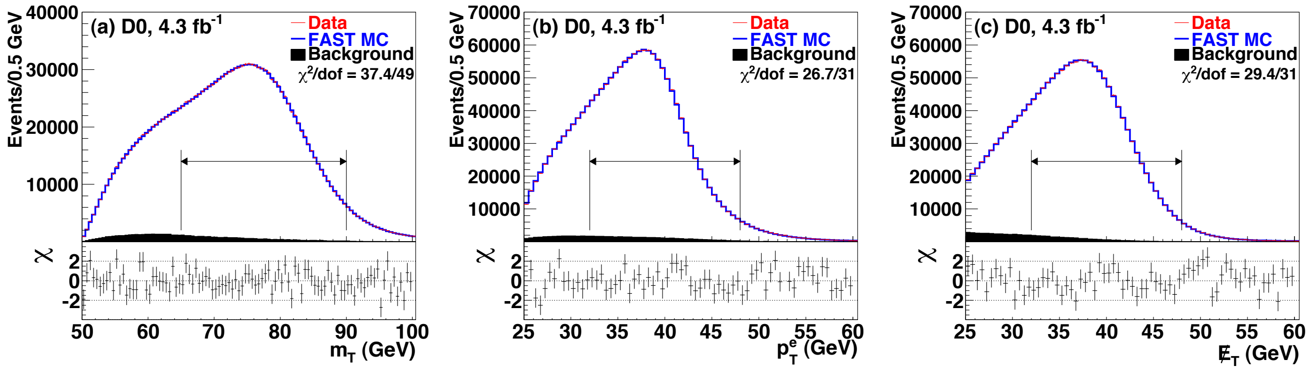

FIG. 2: The (a) m_T, (b) p_T^e, and (c) $\not\!\!E_T$ distributions for data and FASTMC simulation with backgrounds. The χ values are shown below each distribution, where $\chi_i = [N_i - (\text{FASTMC}_i)]/\sigma_i$ for each bin in the distribution, N_i and FASTMC$_i$ are the data and FASTMC template yields in bin i, respectively, and σ_i is the statistical uncertainty in bin i. The fit ranges are indicated by the double-ended horizontal arrows.

TABLE II: Systematic uncertainties of the M_W measurement.

	ΔM_W (MeV)		
Source	m_T	p_T^e	$\not\!\!E_T$
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

ble 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. These affect the M_W measurement since a change in the momentum fraction carried by the quarks in the p or $\overline{p}$ results in a change in acceptance of the electrons from W boson decay after application of the electron pseudorapidity requirements. The uncertainties in the PDF are propagated to a one 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 χ^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 $\not\!\!E_T$ distributions. The data are also divided into statistically independent categories based on instantaneous luminosity, time, electron η, 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 covariance 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 non-statistical 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 ($m_T, \not\!\!E_T$) and 0.75 ($p_T^e, \not\!\!E_T$). When considering only the uncertainties which are allowed to decrease in the combination, we find that the $\not\!\!E_T$ measurement has negligible weight. We therefore combine the m_T and p_T^e measurements using the method [28] and obtain

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

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

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

The dominant uncertainties arise from the available statistics of the $W \to e\nu$ and $Z \to ee$ samples. Thus, a future measurement with the full D0 dataset is expected to be more precise. The M_W measurement reported here agrees with the world average [29] and the previous individual measurements and has an uncertainty that significantly improves upon previous D0 measurements.

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