A Measurement of the W Boson Mass at the Fermilab $p\overline{p}$ Collider

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We report a measurement of the W boson mass based on an integrated luminosity of 82 pb^{-1} from $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV recorded in 1994–1995 by the D0 detector at the Fermilab Tevatron. We identify W bosons by their decays to $e\nu$ and extract the mass by fitting the transverse mass spectrum from 28 323 W boson candidates. A sample of 3563 dielectron events, mostly due to $Z \to ee$ decays, constrains models of W boson production and the detector. We measure $M_W = 80.44 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$ GeV. By combining this measurement with our result form the 1992–1993 data set, we obtain $M_W = 80.43 \pm 0.11$ GeV. [S0031-9007(98)05699-3]

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In the standard model of the electroweak interactions (SM) [1], the mass of the W boson is predicted to be

$$M_W = \left(\frac{\pi\alpha(M_Z^2)}{\sqrt{2}\,G_F}\right)^{1/2} \frac{1}{\sin\theta_w\sqrt{1-\Delta r_W}}\,. \qquad (1)$$

In the "on-shell" scheme [2] $\cos\theta_w = M_W/M_Z$, where M_Z is the Z boson mass. A measurement of M_W, together with M_Z, the Fermi constant G_F, and the electromagnetic coupling constant α, determines the electroweak radiative corrections Δr_W experimentally. Purely electromagnetic corrections are absorbed into the value of α by evaluating it at $Q^2 = M_Z^2$ [3]. The dominant contributions to Δr_W arise from loop diagrams that involve the top quark and the Higgs boson. New particles that couple to the W boson would also contribute to Δr_W. Therefore, a measurement of M_W is one of the most stringent experimental tests of the SM. Deviations from the predictions may indicate new physics. Within the SM, measurements of M_W and the mass of the top quark constrain the mass of the Higgs boson.

This Letter reports a precise new measurement of the W boson mass based on an integrated luminosity of 82 pb^{-1} from $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV, recorded by the D0 detector [4] during the 1994–1995 run of the Fermilab Tevatron. A more complete account of this analysis can be found in Refs. [5–7]. Previously published measurements [8–11], when combined, determine the W boson mass to a precision of 110 MeV.

At the Tevatron, W bosons are produced mainly through $q\overline{q}$ annihilation. We detect their decays into electron-neutrino pairs, characterized by an isolated electron [12] with large transverse momentum (p_T) and significant transverse momentum imbalance $(\not{p}_T)$. The $\not{p}_T$ is due to the undetected neutrino. Many other particles of lower momenta, which recoil against the W boson, are produced in the breakup of the proton and antiproton. We refer to them collectively as the underlying event.

At the trigger level we require $\not{p}_T > 15$ GeV and an energy cluster in the electromagnetic (EM) calorimeter with $p_T > 20$ GeV. The cluster must be isolated and consistent in shape with an electron shower.

During event reconstruction, electrons are identified as energy clusters in the EM calorimeter which satisfy isolation and shower shape cuts and have a drift chamber track pointing towards the cluster centroid. We determine their energies by adding the energy depositions in the first $\approx$40 radiation lengths of the calorimeter in a window, spanning 0.5 in azimuth (ϕ) by 0.5 in pseudorapidity (η) [13], centered on the highest energy deposit in the cluster. Fiducial cuts reject electron candidates near calorimeter module edges and ensure a uniform calorimeter response for the selected electrons. The electron momentum $[\vec{p}(e)]$ is determined by combining its energy with its direction which is obtained from the shower centroid position and the drift chamber track. The trajectories of the electron and the proton beam define the position of the event vertex.

We measure the sum of the transverse momenta of all the particles recoiling against the W boson, $\vec{u}_T = \sum_i E_i \sin\theta_i \hat{u}_i$, where E_i is the energy deposition in the ith calorimeter cell and θ_i is the angle defined by the cell center, the event vertex, and the proton beam. The unit vector $\hat{u}_i$ points perpendicularly from the beam to the cell center. The calculation of $\vec{u}_T$ excludes the cells occupied by the electron. The sum of the momentum components along the beam is not well measured because of particles escaping through the beam pipe. From momentum conservation we infer the transverse neutrino momentum, $\vec{p}_T(\nu) = -\vec{p}_T(e) - \vec{u}_T$, and the transverse momentum of the W boson, $\vec{p}_T(W) = -\vec{u}_T$.

We select a W boson sample of 28 323 events by requiring $p_T(\nu) > 25$ GeV, $u_T < 15$ GeV and an electron candidate with $|\eta| < 1.0$ and $p_T(e) > 25$ GeV.

Since we do not measure the longitudinal momentum components of the neutrinos from W boson decays, we cannot reconstruct the $e\nu$ invariant mass. Instead, we extract the W boson mass from the spectra of the electron p_T and the transverse mass, $m_T = \sqrt{2p_T(e)p_T(\nu)(1-\cos\Delta\phi)}$, where $\Delta\phi$ is the azimuthal separation between the two leptons. We perform a maximum likelihood fit to the data using probability density functions from a Monte Carlo program. Since neither m_T nor $p_T(e)$ are Lorentz invariants, we have to model the production dynamics of W bosons to correctly predict the spectra. The m_T spectrum is insensitive to transverse boosts and is therefore less sensitive to the W boson production model than the $p_T(e)$ spectrum. On the other hand, it depends strongly on the detector response to the underlying event and is therefore more sensitive to detector effects than the $p_T(e)$ spectrum.

Z bosons decaying to electrons provide an important control sample to calibrate the detector response to the underlying event to the electrons, and to constrain the model for intermediate vector boson production used in the Monte Carlo simulations. We trigger on events with at least two EM clusters with $p_T > 20$ GeV. We define two samples of $Z \to ee$ decays in this analysis. For both Z samples, we require two electron candidates with $p_T >$ 25 GeV. For sample 1, we loosen the pseudorapidity cut for one of the electrons to $|\eta| < 2.5$. This selection accepts 2341 events. For sample 2, we require both electrons with $|\eta| < 1.0$ but allow one electron without a matching drift chamber track. Relaxing the track requirement for electrons with $|\eta| < 1.0$ increases the efficiency without a significant increase in background. Sample 2 contains 2179 events, of which 1225 are in common with sample 1.

For this measurement we developed a fast Monte Carlo program that generates W and Z bosons with the rapidity and p_T spectra given by a calculation using soft gluon resummation [14] and the MRSA$'$ [15] parton distribution functions. The line shape is a relativistic Breit-Wigner, skewed by the mass dependence of the parton luminosity. The angular distribution of the decay electrons includes a $p_T(W)$-dependent $\mathcal{O}(\alpha_s)$ correction [16]. The program

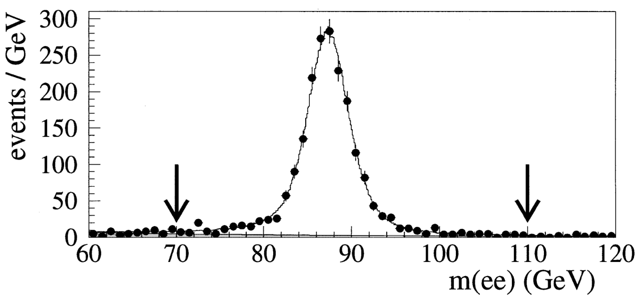

FIG. 1. The dielectron invariant mass distribution of the Z data for sample 2 (●). The solid line shows the fitted signal plus background shape and the small shaded area the background. The arrows indicate the fit window.

also generates $W \to e\nu\gamma$ [17], $Z \to ee\gamma$ [17], and $W \to \tau\nu \to e\nu\overline{\nu}\nu$ decays.

The program smears the generated $\vec{p}(e)$ and $\vec{u}_T$ vectors using a parametrized detector response model and applies inefficiencies introduced by the trigger and event selection requirements. The model parameters are adjusted to match the data and are discussed below.

The energy resolution for electrons with $|\eta| < 1.0$ is described by sampling, noise, and constant terms. In the Monte Carlo simulation we use a sampling term of $13\%/\sqrt{p_T/\text{GeV}}$, derived from beam tests. The noise term is determined by pedestal distributions derived from the W data sample. We constrain the constant term to $c_{\text{EM}} = 1.15^{+0.27}_{-0.36}\%$ by requiring that the width of the dielectron invariant mass spectrum predicted by the Monte Carlo simulation is consistent with the Z data (Fig. 1).

Beam tests show that the electron energy response of the calorimeter can be parametrized by a scale factor α_{EM} and an offset δ_{EM}. We determine these *in situ* using $\pi^0 \to \gamma\gamma$, $J/\psi \to ee$, and $Z \to ee$ decays. We obtain $\delta_{\text{EM}} = -0.16^{+0.03}_{-0.21}$ GeV and $\alpha_{\text{EM}} = 0.9533 \pm 0.0008$ by fitting the observed mass spectra while constraining the resonance masses to their measured values [18,19]. The uncertainty in α_{EM} is dominated by the finite size of the Z sample. Figure 1 shows the observed dielectron mass spectrum from sample 2, and the line shape predicted by the Monte Carlo simulation for the fitted values of c_{EM}, α_{EM}, and δ_{EM}.

We calibrate the response of the detector to the underlying event, relative to the EM response, using sample 1. The looser rapidity cut on one electron brings the rapidity distribution of the Z bosons closer to that of the W bosons, since there is no rapidity cut on the unobserved neutrino in W events. In $Z \to ee$ decays, momentum conservation requires $\vec{p}_T(ee) = -\vec{u}_T$, where $\vec{p}_T(ee)$ is the sum of the two electron p_T vectors. To minimize sensitivity to the electron energy resolution, we project $\vec{u}_T$ and $\vec{p}_T(ee)$ on the inner bisector of the two electron directions, called the η axis (Fig. 2). We call the projections u_η and $p_\eta(ee)$.

Detector simulations based on the GEANT program [20] predict a detector response to the recoil momentum of the form $\text{R}_{\text{rec}} = \alpha_{\text{rec}} + \beta_{\text{rec}} \ln(p_T/\text{GeV})$. We constrain α_{rec} and β_{rec} by comparing the mean value of $u_\eta + p_\eta(ee)$ with Monte Carlo predictions for different values of the parameters. We measure $\alpha_{\text{rec}} = 0.693 \pm 0.060$ and $\beta_{\text{rec}} = 0.040 \pm 0.021$ with a correlation coefficient of -0.98.

The recoil momentum resolution has two components. We smear the magnitude of the recoil momentum with a resolution of $s_{\text{rec}}/\sqrt{p_T/\text{GeV}}$. We describe the detector noise and pileup, which are independent of the boson p_T and azimuthally symmetric, by adding the $\not{p}_T$ from a random $p\overline{p}$ interaction, scaled by a factor α_{mb}, to the smeared boson p_T. To model the luminosity dependence of this resolution component correctly, the sample of $p\overline{p}$ interactions was chosen to have the same luminosity

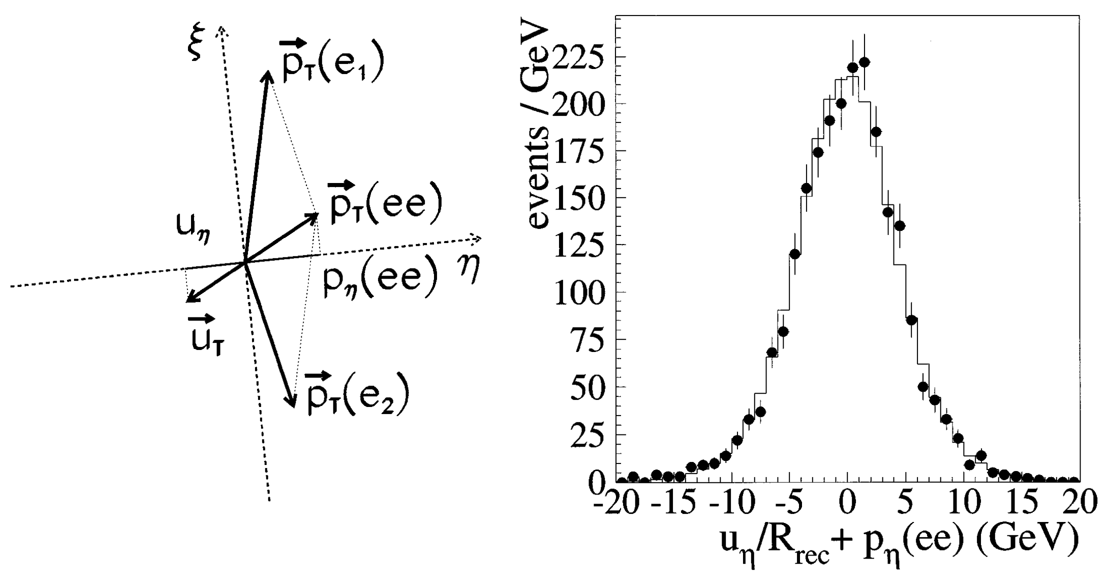

FIG. 2. The definition of the η axis (left). The plot of $u_\eta/\text{R}_{\text{rec}} + p_\eta(ee)$ (right) for the data (●) and simulation (—).

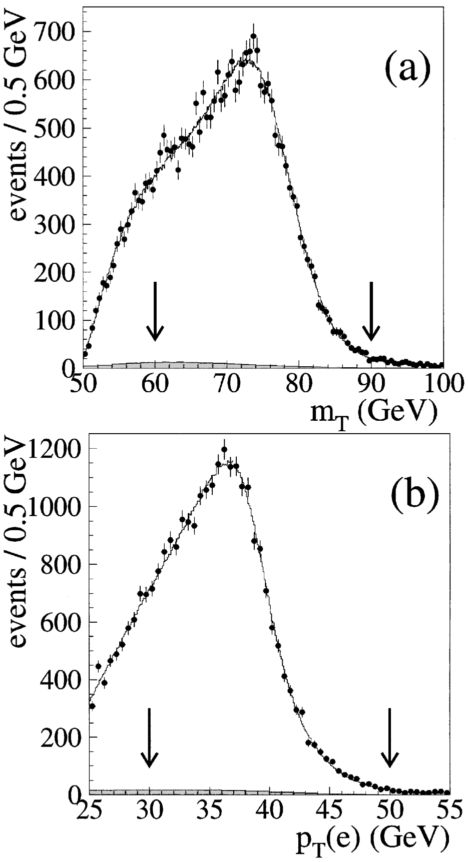

FIG. 3. Spectra of (a) m_T and (b) $p_T(e)$ from the data (●), the fit (—), and the backgrounds (shaded). The arrows indicate the fit windows.

spectrum as the W sample. We constrain the parameters by comparing the observed rms of $u_\eta/\mathrm{R}_{\mathrm{rec}} + p_\eta(ee)$ with Monte Carlo predictions and measure $s_{\mathrm{rec}} = 0.49 \pm 0.14$ and $\alpha_{\mathrm{mb}} = 1.032 \pm 0.028$ with a correlation coefficient of -0.60. Figure 2 shows a plot of $u_\eta/\mathrm{R}_{\mathrm{rec}} + p_\eta(ee)$.

Excluding the cells occupied by the electrons, the average transverse energy flow, $S_T = \sum_i E_i \sin\theta_i$, is 7.7 GeV higher for the W sample than for the Z sample. This bias is caused by requiring the identification of two electrons in the Z sample versus one in the W sample. The larger energy flow translates into a slightly broader recoil momentum resolution in the W sample. We correct α_{mb} by a factor of 1.03 ± 0.01 to account for this effect in the W boson model.

Backgrounds in the W sample are $W \rightarrow \tau\nu \rightarrow e\nu\overline{\nu}\nu$ decays (1.6%), hadrons misidentified as electrons (1.3% $\pm$ 0.2%), $Z \rightarrow ee$ decays (0.42% $\pm$ 0.08%), and $W \rightarrow \tau\nu \rightarrow$ hadrons + X decays (0.24%), as determined from data or Monte Carlo depending on the source. Their shapes are included in the fits.

The fit to the m_T distribution [Fig. 3(a)] yields $M_W = 80.44$ GeV with a statistical uncertainty of 70 MeV. A Kolmogorov-Smirnov (KS) test gives a confidence level of 28% that the parent distribution of the data is the probability density function given by the Monte Carlo program. A χ^2 test gives $\chi^2 = 79.5$ for 60 bins which corresponds to a confidence level of 3%. The fit to the $p_T(e)$ distribution [Fig. 3(b)] yields $M_W = 80.48$ GeV with a statistical uncertainty of 87 MeV. The confidence level of the KS test is 83% and that of the χ^2 test is 35%.

We estimate systematic uncertainties in M_W from the Monte Carlo parameters by varying them within their uncertainties (Table I). In addition to the parameters described above, the calibration of the electron polar angle measurement contributes a significant uncertainty. We use muons from $p\overline{p}$ collisions and cosmic rays to calibrate the drift chamber measurements and $Z \rightarrow ee$ decays to align the calorimeter with the drift chambers. Smaller uncertainties are due to the removal of the cells occupied by the electron from the computation of $\vec{u}_T$, the uniformity of the calorimeter response, and the modeling of trigger and selection biases [7].

The uncertainty due to the model for W boson production and decay consists of several components (Table I). We assign an uncertainty that characterizes the range of variations in M_W obtained when employing several recent parton distribution functions: MRSA′, MRSD-′ [21], CTEQ2M [22], and CTEQ3M [23]. We allow the $p_T(W)$ spectrum to vary within constraints derived from the $p_T(ee)$ spectrum of the Z data [7] and from Λ_{QCD} [19]. The uncertainty due to radiative decays contains an estimate of the effect of neglecting double photon emission in the Monte Carlo simulation [24].

The fit to the m_T spectrum results in a W boson mass of 80.44 $\pm$ 0.10(stat) $\pm$ 0.07(syst) GeV and the fit to the $p_T(e)$ spectrum results in 80.48 $\pm$ 0.11(stat) $\pm$ 0.09(syst) GeV. The good agreement of the two fits shows that our simulation models the W boson

TABLE I. Uncertainties in the W boson mass measurement in MeV, rounded to the nearest 5 MeV.

Source of uncertainty	m_T fit	$p_T(e)$ fit
W sample size	70	85
Z sample size (α_{EM})	65	65
Total statistical uncertainty	95	105
Calorimeter linearity (δ_{EM})	20	20
Calorimeter uniformity	10	10
Electron resolution (c_{EM})	25	15
Electron angle calibration	30	30
Electron removal	15	15
Selection bias	5	10
Recoil resolution ($\alpha_{\mathrm{mb}}, s_{\mathrm{rec}}$)	25	10
Recoil response ($\alpha_{\mathrm{rec}}, \beta_{\mathrm{rec}}$)	20	15
Total detector systematics	60	50
Total backgrounds	10	20
$p_T(W)$ spectrum	10	50
Parton distribution functions	20	50
Parton luminosity	10	10
Radiative decays	15	15
W boson width	10	10
Total W boson model	30	75
Total	115	140

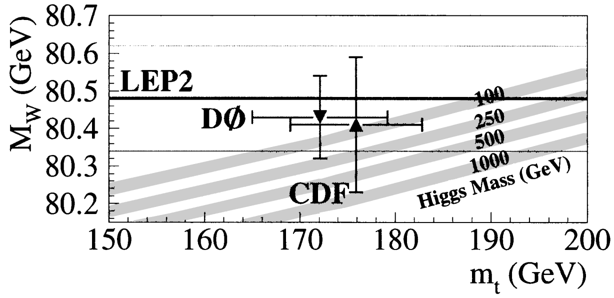

FIG. 4. Direct *W* boson and top quark mass measurements by the D0 [25], CDF [9,26], and LEP [11,18] experiments. The bands show SM predictions for the indicated Higgs masses [27].

production dynamics and the detector response well. We have performed additional consistency checks. A fit to the $p_T(\nu)$ distribution yields $M_W = 80.37 \pm 0.12(\text{stat}) \pm 0.13(\text{syst})$ GeV, consistent with the m_T and $p_T(e)$ fits. Fits to the data in bins of luminosity, $\phi(e)$, $\eta(e)$, and u_T do not show evidence for any systematic biases.

We combine the results from the m_T fit and the data collected by D0 in 1992–1993 [10] to obtain $M_W = 80.43 \pm 0.11$ GeV. This is the most precise measurement of the *W* boson mass to date. Using Eq. (1) we find $\Delta r_W = -0.0288 \pm 0.0070$, which establishes the existence of electroweak corrections to M_W at the level of four standard deviations. Fitting the SM to all other electroweak data [18] predicts $M_W = 80.329 \pm 0.041$ GeV or $\Delta r_W = -0.0224 \pm 0.0026$. Figure 4 compares the direct measurements of the *W* boson and top quark masses to SM predictions.

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