We report a measurement of the $W$ boson mass based on an integrated luminosity of 82 pb$^{-1}$ from $p\bar{p}$ 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 $Z \rightarrow ee$ 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 from the 1992–1993 data set, we obtain $M_W = 80.43 \pm 0.11$ GeV. [S0031-9007(98)05699-3]
In the standard model of the electroweak interactions (SM) [1], the mass of the W boson is predicted to be

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

In the “on-shell” scheme [2] \( \cos \theta_c = M_W/M_Z \), 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 \( \alpha \), determines the electroweak radiative corrections \( \Delta r_W \) experimentally. Purely electromagnetic corrections are absorbed into the value of \( \alpha \) by evaluating it at \( Q^2 = M_Z^2 \) [3]. The dominant contributions to \( \Delta r_W \) 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 \( \Delta r_W \). 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 \( p\bar{p} \) 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 \( q\bar{q} \) 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 \( (\Delta p_T) \). The \( \Delta p_T \) 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 \( \Delta p_T > 15 \) 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 (\( \phi \)) by 0.5 in pseudorapidity (\( \eta \)) [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, \( \vec{u}_T = \sum_i E_i \sin \theta_i \vec{u}_i \), where \( E_i \) is the energy deposition in the \( i \)th calorimeter cell and \( \theta_i \) is the angle defined by the cell center, the event vertex, and the proton beam. The unit vector \( \vec{u}_i \) 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 \( Z \rightarrow ee \) 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 \( O(\alpha_s) \) correction [16]. The program
also generates $W \to e\nu\gamma$ [17], $Z \to ee\gamma$ [17], and $W \to \tau\nu \to e\nu\bar{\nu}\nu$ 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}/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 $c_{EM} = 1.15^{+0.23}_{-0.36}$% by requiring that the width of the dielectron invariant mass spectrum predicted by the Monte Carlo simulation is consistent with the invariant mass spectrum predicted by the Monte Carlo simulation for the fitted values of $c_{EM}$, $\alpha_{EM}$, and $\delta_{EM}$.

We calibrate the response of the detector to the underlying event, relative to the EM response, using sample 1. 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.

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

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 $\alpha_{mb}$ by a factor of $1.03 \pm 0.01$ to account for this effect in the W boson model.

Backgrounds in the W sample are $W \rightarrow \tau \nu \rightarrow e \nu \bar{\nu}$ 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 $\chi^2$ 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 $\chi^2$ 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 $p\bar{p}$ 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 $u_T$, 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-4' [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 $\Lambda_{QCD}$ [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 $80.44 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})$ GeV and the fit to the $p_T(e)$ spectrum results in $80.48 \pm 0.11(\text{stat}) \pm 0.09(\text{syst})$ GeV. The good agreement of the two fits shows that our simulation models the W boson

![Figure 3](image-url)
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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