(D0 Collaboration)

1University de Buenos Aires, Buenos Aires, Argentina
2LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
3Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
4Universidade Federal do ABC, Santo André, Brazil
5Instituto de Física Teórica, Universidade Estadual Paulista, São Paulo, Brazil
6University of Alberta, Edmonton, Alberta, Canada;
   Simon Fraser University, Burnaby, British Columbia, Canada;
   York University, Toronto, Ontario, Canada
7University of Science and Technology of China, Hefei, People’s Republic of China
8University de los Andes, Bogotá, Colombia
9Center for Particle Physics, Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
10Czech Technical University in Prague, Prague, Czech Republic
11Center for Particle Physics, Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
12Universidad San Francisco de Quito, Quito, Ecuador
13LPC, Université Blaise Pascal, CNRS/IN2P3, Clermont, France
14LPSC, Université Joseph Fourier Grenoble 1, CNRS/IN2P3, Institut National Polytechnique de Grenoble, Grenoble, France
15CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
16LAL, Université Paris-Sud, IN2P3/CNRS, Orsay, France
17LPNHE, IN2P3/CNRS, Universités Paris VI and VII, Paris, France
18CEA, Ifre, SPP, Saclay, France
19IPHC, Université de Strasbourg, CNRS/IN2P3, Strasbourg, France
20IPNL, Université Lyon 1, CNRS/IN2P3, Villeurbanne, France and Université de Lyon, Lyon, France
21III. Physikalisches Institut A, RWTH Aachen University, Aachen, Germany
22Physikalisches Institut. Universität Bonn, Bonn, Germany
23Physikalisches Institut, Universität Freiburg, Freiburg, Germany
24II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
25Institut für Physik, Universität Mainz, Mainz, Germany
26Ludwig-Maximilians-Universität München, München, Germany
27Fachbereich Physik, University of Wuppertal, Wuppertal, Germany
28Panjab University, Chandigarh, India
29Delhi University, Delhi, India
30Tata Institute of Fundamental Research, Mumbai, India
31University College Dublin, Dublin, Ireland
32Korea Detector Laboratory, Korea University, Seoul, Korea
33SungKyunKwan University, Suwon, Korea
34CINVESTAV, Mexico City, Mexico
35FOM-Institute NIKHEF and University of Amsterdam/NIKHEF, Amsterdam, The Netherlands
36Radboud University Nijmegen/NIKHEF, Nijmegen, The Netherlands
37Joint Institute for Nuclear Research, Dubna, Russia
38Institute for Theoretical and Experimental Physics, Moscow, Russia
39Moscow State University, Moscow, Russia
We present a direct measurement of the width of the $W$ boson using the shape of the transverse mass distribution of $W \rightarrow e\nu$ candidate events. Data from approximately 1 fb$^{-1}$ of integrated luminosity recorded at $\sqrt{s} = 1.96$ TeV by the D0 detector at the Fermilab Tevatron $p\bar{p}$ collider are analyzed. We use the same methods and data sample that were used for our recently published $W$ boson mass measurement, except for the modeling of the recoil, which is done with a new method based on a recoil library. Our result, $2.028 \pm 0.072$ GeV, is in agreement with the predictions of the standard model.

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The gauge structure of the standard model (SM) of electromagnetic, weak, and strong interactions tightly constrains the properties and interactions of the carriers of these forces, the gauge bosons. Any departure from its predictions would be an indication of physics beyond the SM. The $W$ boson is one of the carriers of the weak force and has a predicted decay width of

$$\Gamma_W = (3 + 2f_{\text{QCD}}) \frac{G_F M_W^3}{6\sqrt{2}\pi} (1 + \delta),$$

where $G_F$ is the Fermi coupling constant, $M_W$ is the mass.
of the W boson and \( f_{\text{QCD}} = 3(1 + \alpha_s(M_W^2) / \pi) \) is a QCD correction factor given to first order of the strong coupling constant \( \alpha_s \). The radiative correction \( \delta \) is calculated to be 2.1% with an uncertainty that is less than 0.5% in the SM [1]. Current world average values for \( G_F \) [2] and \( M_W \) [3] predict \( \Gamma_W = 2.093 \pm 0.002 \) GeV. Physics beyond the SM, such as new heavy particles that couple to the W boson, could alter the higher order vertex corrections that predict \( \Gamma_W \) using the energy from the calorimeter and angles from the matched track. The track must have at least one SMT hit and \( p_T > 10 \) GeV. Electron candidates are further required to pass shower shape and energy isolation requirements and to be in the fiducial region of the CC calorimeter.

The neutrino transverse momentum, \( p_T^\nu \), is inferred from the observed missing transverse energy, \( \vec{E}_T \), reconstructed from \( \vec{p}_T^\nu \) and the transverse momentum of the hadronic recoil (\( \vec{u}_T \)) using \( \vec{E}_T = -[\vec{p}_T^\nu + \vec{u}_T] \). The recoil vector \( \vec{u}_T \) is the vector sum of energies in calorimeter cells outside those cells used for defining the electron. The recoil is a mixture of the “hard” recoil that balances the boson transverse momentum and “soft” contributions from particles produced by the spectator quarks, other \( p\bar{p} \) collisions in the same beam crossing, electronics noise, and residual energy in the detector from previous beam crossings.

W boson candidate events are required to have a CC electron with \( p_T^e > 25 \) GeV, \( \vec{E}_T > 25 \) GeV, \( u_T < 15 \) GeV, and \( 50 < M_T < 200 \) GeV. Z boson candidate events are required to have two CC electrons with \( p_T^e > 25 \) GeV and \( u_T < 15 \) GeV. These selections yield 499,830 W boson candidates (5272 candidates with \( 100 < M_T < 200 \) GeV) and 18,725 Z boson candidates with the invariant mass \( (M_{ee}) \) of the two electrons between 70 and 110 GeV.

The W boson width is extracted by comparing the \( M_T \) data distribution with distributions in simulated templates generated at different width values. The prediction (in number of events) of signal-plus-background is normalized to the data in the \( 50 < M_T < 100 \) GeV window. A binned negative log-likelihood method is used to extract \( \Gamma_W \) in the range \( 100 < M_T < 200 \) GeV.

There are two main sources of events with high \( M_T \): events that truly contain a high mass W boson, and events with a W boson whose mass is close to the W boson mass central value but are produced with large \( u_T \). This second category of events can be misreconstructed at high \( M_T \) because of resolution effects and also because the magnitude of the recoil vector is systematically underestimated due to the response of the calorimeter to low energy hadrons, energy thresholds on the calorimeter energies, and magnetic field effects.

Another experimental challenge arises from the \( p_T \) dependence of the electron identification efficiency, which can alter the shape of the \( M_T \) distribution. The electron isolation requirement used in this analysis has a non-negligible dependence on the electron \( p_T \) which is measured using a detailed GEANT-based Monte Carlo (MC) simulation [14] and tested using \( Z \rightarrow ee \) events.

A fast MC simulation is used for the production of the \( M_T \) templates. W and Z boson production and decay prop-
properties are modeled by the RESBOS event generator [15] interfaced with PHOTOS [16]. RESBOS uses gluon resummation at low boson \( p_T \) and a next-to-leading order perturbative QCD calculation at high boson \( p_T \). The CTEQ6.1M parton distribution functions (PDFs) [17] are used. PHOTOS is used for simulation of final state radiation (FSR). Photons and electrons that are nearly collinear are merged using an algorithm that mimics the calorimeter clustering algorithm.

The detector response for electrons and photons, including energy calibration, showering and energy loss models, is simulated using a parameterization based on collider data control samples, a detailed GEANT-based simulation of the detector, and external constraints, such as the precise measurement of the Z boson mass from the LEP experiments [18]. The primary control sample is \( Z \rightarrow ee \) events, although \( W \rightarrow ev \) events are also used in a limited way. The modeling of the electron energy response, resolution and selection efficiencies is described in [12]. The number of Z boson candidates in data sets the scale for the systematic uncertainties related to the electron modeling in the simulation, which are listed in detail in Table I.

The modeling of the recoil is based on the recoil library obtained from \( Z \rightarrow ee \) events [11]. A Bayesian unsmeared procedure [19] allows the transformation of the two-dimensional distribution of reconstructed Z boson \( \hat{p}_T \) and the measured recoil momentum \( \vec{u}_T \) to one between the true Z boson \( \hat{p}_T \) and the measured recoil \( \vec{u}_T \). For each simulated \( W \rightarrow ev \) event with a generator-level transverse momentum value \( \hat{p}_T \), we select \( \vec{u}_T \) randomly from the Z boson recoil library with the same value of \( \hat{p}_T \). The uncertainty on the recoil system simulation from this method is dominated by the limited statistics of the Z boson sample; other systematic uncertainties originate from the modeling of FSR photons, acceptance differences between \( W \) and Z boson events, corrections for underlying energy beneath the electron cluster, residual efficiency-related correlations between the electron and the recoil system, and the unfolding procedure. Previous \( M_W \) and \( \Gamma_W \) measurements have relied upon parametrizations of the recoil kinematics based on phenomenological models of the recoil and detector response. The library method used here includes the actual detector response for the hadronic recoil and also the correlations between different components of the hadronic recoil. This method does not rely on the GEANT-based simulation of the recoil system and does not have any tunable parameters. The overall systematic uncertainty on \( \Gamma_W \) due to the recoil model is found to be 41 MeV [11].

The backgrounds to \( W \rightarrow ev \) events are (a) \( Z \rightarrow ee \) events in which one electron is not detected, (b) multijet production in which one jet is misidentified as an electron and mismeasurement of the hadronic activity in the event leads to apparent \( \not{E}_T \), and (c) \( W \rightarrow \tau\nu \rightarrow e\nu\nu\nu \) events. The \( Z \rightarrow ee \) background arises mainly when one of the two electrons is in the region between the CC and EC calorimeters. It is estimated from events with one electron with a high-\( p_T \) track opposite in azimuth pointing towards the gap. The estimated background fraction is (0.90 ± 0.01)% for 50 < \( M_T \) < 200 GeV. The background fraction from multijet events is estimated from a loose sample of candidate events without track match requirements and then selecting a subset of events which satisfy the final tighter track match requirement. From \( Z \rightarrow ee \) events, and a sample of multijet events passing the preselection but with low \( \not{E}_T \), we determine the probabilities with which real and misidentified electrons will pass the track match requirement. These two probabilities, along with the numbers of events selected in the loose and tight samples allow us to calculate the fraction of multijet events in the data set [20]. The background contamination from multijet events is estimated to be (1.49 ± 0.03)% for 50 < \( M_T \) < 200 GeV. The \( W \rightarrow \tau\nu \rightarrow e\nu\nu\nu \) background is determined using a GEANT-based simulation to be (1.60 ± 0.02)% for 50 < \( M_T \) < 200 GeV and is normalized to the \( W \rightarrow ev \) events in the same simulation. The overall background fraction is found to be (4.36 ± 0.05)% with \( M_T \) between 100 and 200 GeV. The uncertainties on the normalization and shape of the backgrounds cause a 6 MeV systematic uncertainty on \( \Gamma_W \).

The systematic uncertainties in the determination of the \( W \) boson width are due to effects that could alter the \( M_T \) distribution. Uncertainties in the parameters of the fast MC simulation can affect the measurement of \( \Gamma_W \). To estimate the effects, we allow these parameters to vary by 1 standard deviation and regenerate the \( M_T \) templates. Systematic uncertainties resulting from the boson \( p_T \) spectrum are evaluated by varying the \( g_2 \) parameter of the RESBOS non-perturbative prescription within the uncertainties obtained from a global fit [21] and propagating them to the \( W \) boson width. Systematic uncertainties due to the PDFs are evaluated using the prescription given by the CTEQ collaboration [17]. Systematic uncertainties from the modeling of electroweak radiative corrections are obtained by comparisons with WGRAD [22] and ZGRAD2 [23]. The systematic uncertainty due to the \( M_W \) uncertainty is obtained by varying the input \( M_W \) by ±23 MeV [3].

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**Table I. Systematic uncertainties on the measurement of \( \Gamma_W \).**

<table>
<thead>
<tr>
<th>Source</th>
<th>( \Delta \Gamma_W ) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron response model</td>
<td>33</td>
</tr>
<tr>
<td>Electron resolution model</td>
<td>10</td>
</tr>
<tr>
<td>Hadronic recoil model</td>
<td>41</td>
</tr>
<tr>
<td>Electron efficiencies</td>
<td>19</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>6</td>
</tr>
<tr>
<td>PDF</td>
<td>20</td>
</tr>
<tr>
<td>Electroweak radiative corrections</td>
<td>7</td>
</tr>
<tr>
<td>Boson ( p_T )</td>
<td>1</td>
</tr>
<tr>
<td>( M_W )</td>
<td>5</td>
</tr>
<tr>
<td>Total Systematic</td>
<td>61</td>
</tr>
</tbody>
</table>
We fit the $M_T$ data distribution to a set of templates generated with an input $W$ boson mass of 80.419 GeV at different assumed widths between a lower $M_T$ value and $M_T = 200$ GeV. The lower $M_T$ cut is varied from 90 to 110 GeV to demonstrate the stability of the fitted result. While the statistical uncertainty decreases as the lower $M_T$ cut is reduced, the systematic uncertainty increases. The lowest overall uncertainty is obtained for a lower $M_T$ cut of 100 GeV yielding $\Gamma_W = 2.028 \pm 0.039(\text{stat}) \pm 0.061(\text{syst})$ GeV. The $M_T$ distributions for the data and the MC template with backgrounds for the best fit value are shown in Fig. 1, which also shows the bin-by-bin $\chi$ values defined as the difference between the data and the template divided by the data statistical uncertainty.

The methodology used to extract the width in this Letter is tested using $W$ and $Z$ boson events produced by a PYTHIA- or GEANT-based simulation and the same analysis methods used for the data. The fast MC simulation is separately tuned for this study. Good agreement is found between the fitted $\Gamma_W$ value and the input $\Gamma_W$ value within the statistical precision of the test.

The $\Gamma_W$ result obtained using the $M_T$ spectrum is in agreement with the predictions of the SM. We get consistent values of the $W$ boson width from fits to the $p_T$ distribution ($2.012 \pm 0.046(\text{stat})$ GeV) and the $E_T$ distribution ($2.058 \pm 0.036(\text{stat})$ GeV). The width can also be estimated directly from the fraction of events with $M_T > 100$ GeV, and this gives $\Gamma_W = 2.020 \pm 0.040(\text{stat})$ GeV. The results are stable within errors when the data sample is divided into different regions of instantaneous Tevatron luminosity, run epoch, and different restrictions on $u_T$, electron $\eta_D$, $\vec{u}_T \cdot \vec{p}_T(e)$ and fiducial cuts on electron azimuthal angle.

As a further cross check of the recoil library method we also use it to measure the $W$ boson mass using the $M_T$ distribution over the region $65 < M_T < 90$ GeV. A value of $M_W = 80.404 \pm 0.023(\text{stat}) \pm 0.038(\text{syst})$ GeV is found, in good agreement with the result, $M_W = 80.401 \pm 0.023(\text{stat}) \pm 0.037(\text{syst})$ GeV, obtained using the same data set and the parameterized recoil model [12].

In conclusion, we have presented a new direct measurement of the width of the $W$ boson using 1 fb$^{-1}$ of data collected by the D0 detector at the Tevatron collider. A method to simulate the recoil system in $W \rightarrow e\nu$ events using a recoil library built from $Z \rightarrow ee$ events is used for the first time. Our result, $\Gamma_W = 2.028 \pm 0.039(\text{stat}) \pm 0.061(\text{syst}) = 2.028 \pm 0.072$ GeV, is in agreement with the prediction of the SM and is the most precise direct measurement result from a single experiment to date.

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*Visitor from Augustana College, Sioux Falls, SD, USA.
†Visitor from Rutgers University, Piscataway, NJ, USA.
‡Visitor from The University of Liverpool, Liverpool, United Kingdom.
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**Visitor from ECFM, Universidad Autonoma de Sinaloa, Culiacan, Mexico.
***Visitor from UC/CEM, Laboratoire d'Annecy de l'Université de Savoie, France.
[13] The polar angle $\theta$ is defined with respect to the positive $z$ axis, which is defined along the proton beam direction. Pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$. $\eta_D$ is the pseudorapidity measured with respect to the center of the detector.