Direct Measurement of the W Boson Width


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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.

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 enter into $\delta$ and modify $\Gamma_W$ [4].

Direct measurements of $\Gamma_W$ have been previously performed by the CDF and D0 collaborations [5–8]. The width has also been directly measured at the CERN LEP $e^+e^-$ collider [9]. The combined Tevatron average is $\Gamma_W = 2.056 \pm 0.062$ GeV, and the current world average is $\Gamma_W = 2.106 \pm 0.050$ GeV [6].

We present a direct measurement of $\Gamma_W$ using the shape of the transverse mass ($M_T$) distribution of $W \rightarrow e\nu$ candidates from $p\bar{p}$ collisions with center-of-mass energy of 1.96 TeV using data from approximately 1 fb$^{-1}$ of integrated luminosity collected by the D0 detector [10]. 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 in the plane perpendicular to the beam axis, and $p_T^e$ and $p_T^\nu$ are the transverse momenta of the electron and neutrino, respectively. The fraction of events with large $M_T$ is sensitive to $\Gamma_W$, although it is also influenced by the detector responses to the electron and the hadronic recoil. We use a new data-driven method for modeling the hadronic recoil of the W boson using a recoil library of Z boson candidates [11]. Aside from the recoil modeling, the method for extracting $\Gamma_W$ is similar to that described in a recent Letter on a measurement of W boson mass by the D0 collaboration [12].

The D0 detector includes a central tracking system, composed of a silicon microstrip tracker (SMT) and a central fiber tracker, both located within a 2 T superconducting solenoidal magnet and optimized for tracking capability for $|\eta_D| \leq 3$ [13]. Three uranium and liquid argon calorimeters provide coverage for $|\eta_D| \leq 4.2$: a central calorimeter (CC) covering $|\eta_D| \leq 1.1$, and two endcap calorimeters (EC) with a coverage of 1.5 $\leq |\eta_D| \leq 4.2$ for jets and 1.5 $\leq |\eta_D| \leq 3.2$ for electrons. In addition to the preshower detectors, scintillators between the CC and EC cryostats provide sampling of developing showers at 1.1 $\leq |\eta_D| \leq 1.5$. A muon system surrounds the calorimeter and consists of three layers of scintillators and drift tubes, and a 1.8 T iron toroid with a coverage of $|\eta_D| \leq 2$.

The analysis uses $W \rightarrow e\nu$ candidates for the width extraction and $Z \rightarrow ee$ candidates to tune the simulation of the detector response used in the extraction of the W boson width from data. The data sample was collected using a set of inclusive single-electron triggers. The position of the reconstructed vertex of the hard collision along the beam line is required to be within 60 cm of the center of the detector. Throughout this Letter we use “electron” to imply either electron or positron.

Electron candidates are required to have $p_T^e > 25$ GeV and must be spatially matched to a reconstructed track in the central tracking system. We calculate $p_T^e$ 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 $\vec{p}_T^e$ and the transverse momentum of the hadronic recoil ($\vec{u}_T$) using $\vec{E}_T = -[\vec{p}_T^e + \vec{u}_T]$. 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, $E_T > 25$ 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-
erties are modeled by the RESBOS event generator [15] interfaced with PHOTOS [16]. RESBOS uses gluon resumma-
tion at low boson \( p_T \) and a next-to-leading order perturba-
tive 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, includ-
ing 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 exper-
iments [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 system-
atic 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 unsmea-
ring procedure [19] allows the transformation of the two-
dimensional distribution of reconstructed Z boson \( \tilde{p}_T \)
and the measured recoil momentum \( \tilde{u}_T \) to one between the
true Z boson \( \tilde{p}_T \) and the measured recoil \( \tilde{u}_T \). For each
simulated \( W \rightarrow ev \) event with a generator-level transverse
momentum value \( \tilde{p}_T \), we select \( \tilde{u}_T \) randomly from the Z
boson recoil library with the same value of \( \tilde{p}_T \). The un-
certainty 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 re-
coil and detector response. The library method used here
includes the actual detector response for the hadronic
recoil and also the correlations between different compo-
ents 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

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 \( E_T \), and (c) \( W \rightarrow \tau \nu \rightarrow evvvv \) events. The
\( Z \rightarrow ee \) background arises mainly when one of the two
electrons is in the region between the CC and EC calo-
rimeters. 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 \( (0.90 \pm 0.01)\% \)
for \( 50 < M_T < 200 \) GeV. The background fraction from
multijet events is estimated from a loose sample of can-
didate 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 \( E_T \), 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
tables allow us to calculate the fraction of multijet events
in the data set [20]. The background contamination from
multijet events is estimated to be \( (1.49 \pm 0.03)\% \) for
\( 50 < M_T < 200 \) GeV. The \( W \rightarrow \tau \nu \rightarrow evvvv \) background
is determined using a GEANT-based simulation to be
\( (1.60 \pm 0.02)\% \) for \( 50 < M_T < 200 \) GeV and is normal-
ized to the \( W \rightarrow ev \) events in the same simulation. The
overall background fraction is found to be \( (4.36 \pm 0.05)\% \)
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 evalu-
ated using the prescription given by the CTEQ collabora-
tion [17]. Systematic uncertainties from the modeling of
electroweak radiative corrections are obtained by compar-
isons with WGRAD [22] and ZGRAD2 [23]. The systematic
uncertainty due to the \( M_W \) uncertainty is obtained by
varying the input \( M_W \) by \( \pm 23 \) MeV [3].

### 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 $p_T^e$ 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 $\eta_D$, $\bar{\eta}_T \cdot \bar{p}_T(e)$ 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 $W \to e\nu$ events using a recoil library built from $Z \to ee$ 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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\begin{thebibliography}{99}
\bibitem{3} The Tevatron Electroweak Working Group (CDF and D0 Collaborations), arXiv:0908.1374.
\end{thebibliography}
[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.