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Direct measurement of the W boson width. — Source link

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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 $W \to e\nu$ 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 ± 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

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

where G_F is the Fermi coupling constant, M_W is the mass of the W boson and $f_{\rm QCD} = 3(1 + \alpha_s(M_W^2)/\pi)$ is a QCD correction factor given to first order of the strong coupling constant α_s. The radiative correction δ 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 δ and modify Γ_W [4].

Direct measurements of Γ_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 Γ_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^ν are the transverse momenta of the electron and neutrino, respectively. The fraction of events with large M_T is sensitive to Γ_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 Γ_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 calorimetry 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^ν, is inferred from the observed missing transverse energy, $\not{E}_T$, reconstructed from $\vec{p}_T^{\,e}$ and the transverse momentum of the hadronic recoil ($\vec{u}_T$) using $\vec{\not{E}}_T = -[\vec{p}_T^{\,e} + \vec{u}_T]$. 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, $\not{E}_T > 25$ 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 Γ_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 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 $W \rightarrow e\nu$ 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 unsmearing procedure [19] allows the transformation of the two-dimensional distribution of reconstructed Z boson $\vec{p}_T$ and the measured recoil momentum $\vec{u}_T$ to one between the true Z boson $\vec{p}_T$ and the measured recoil $\vec{u}_T$. For each simulated $W \rightarrow e\nu$ event with a generator-level transverse momentum value $\vec{p}_T$, we select $\vec{u}_T$ randomly from the Z boson recoil library with the same value of $\vec{p}_T$. 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 Γ_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 Γ_W due to the recoil model is found to be 41 MeV [11].

TABLE I. Systematic uncertainties on the measurement of Γ_W.

Source	$\Delta\Gamma_W$ (MeV)
Electron response model	33
Electron resolution model	10
Hadronic recoil model	41
Electron efficiencies	19
Backgrounds	6
PDF	20
Electroweak radiative corrections	7
Boson p_T	1
M_W	5
Total Systematic	61

The backgrounds to $W \rightarrow e\nu$ 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 $(0.90 \pm 0.01)\%$ 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 $(1.49 \pm 0.03)\%$ 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 $(1.60 \pm 0.02)\%$ for $50 < M_T < 200$ GeV and is normalized to the $W \rightarrow e\nu$ 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 Γ_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 Γ_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 nonperturbative 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].

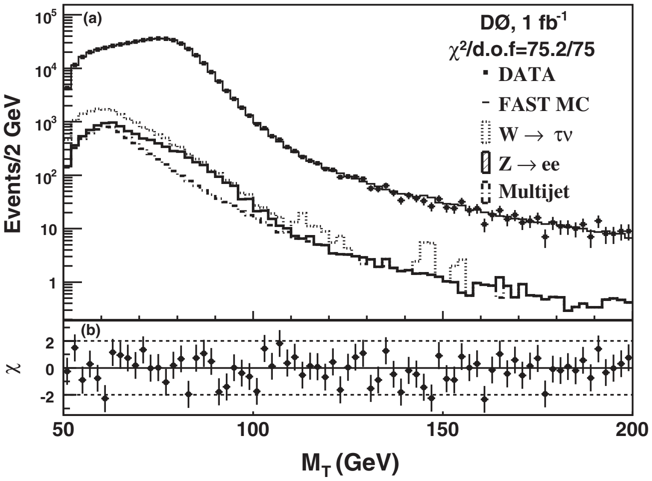

FIG. 1. Comparison of the M_T data distribution with its expectation from a fast MC simulation of $W \to e\nu$ events to which smaller backgrounds have been added (a); χ values for each M_T bin (b). The measured Γ_W value is used for the fast MC prediction. The distribution of the fast MC simulation, including the cumulative contributions of the different backgrounds, is normalized to the data in the region $50 < M_T < 100$ GeV.

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 χ 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 Γ_W value and the input Γ_W value within the statistical precision of the test.

The Γ_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 $\not{E}_T$ 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 η_D, $\vec{u}_T \cdot \hat{p}_T(e)$ 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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