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Direct measurement of 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 $W \rightarrow e\nu$ candidates selected in 1 fb^{-1} of data collected with the D0 detector at the Fermilab Tevatron collider in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. A new method is used to simulate the recoil system in $W \rightarrow e\nu$ events using a recoil library built from $Z \rightarrow ee$ events. Our result, 2.028 ± 0.072 GeV, is in agreement with the predictions of the standard model.

Preliminary Results for Summer 2009 Conferences

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 new physics beyond the SM. The W boson is one of the carriers of the weak force and has a predicted decay width of

$$\Gamma_W = \frac{3G_F M_W^3}{\sqrt{8}\pi}(1+\delta_{SM}), \tag{1}$$

where G_F is the Fermi coupling constant and M_W is the mass of the W boson. The SM radiative correction δ_{SM} is calculated to be about 2.1% with an uncertainty that is less than a half percent [1]. Current world average values for G_F [2] and M_W [3] predict that Γ_W should be 2.089 ± 0.002 GeV. New physics, such as new heavy particles that couple to the W boson, could alter the higher order vertex corrections that enter into δ_{SM}.

Direct measurements of Γ_W have been previously performed by the CDF and D0 collaborations [4–7]. The width has also been measured at the CERN LEP e^+e^- collider [8–11]. 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 [4].

We present a direct measurement of Γ_W using the shape of the transverse mass (M_T) distribution of $W \to e\nu$ candidates from $p\bar{p}$ collisions with center-of-mass energy of 1.96 TeV using 1 fb^{-1} of collisions collected by the D0 detector [12]. 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, 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 [13]. 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 [14].

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 and vertexing capabilities for pseudorapidities $|\eta_D| \leq 3$ [15] and $|\eta_D| \leq 2.5$, respectively. 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 end 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 $W \to e\nu$ candidates for the width extraction and $Z \to ee$ candidates for tuning the simulation. 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 note we use "electron" to denote 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 p_T^ν is inferred from the observed missing transverse energy, $\not\!\!E_T$, as 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 bunch crossing, electronics noise, and residual energy in the detector from previous bunch crossings. Compared with the decay electron, the recoil is difficult to model from first principles.

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 (5,272 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. We use a binned negative log-likelihood method. The fit range used is $100 < M_T < 200$ GeV. The data and Monte Carlo (MC) signal plus backgrounds are normalized to have the same area from 50 to 100 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 mis-reconstructed 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 lower 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 MC simulation [16] and tested using $Z \to ee$ events. Systematic uncertainties are estimated using the precision with which the Z boson data are reproduced.

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 [17] interfaced with PHOTOS [18]. 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) [19, 20] are used. PHOTOS is mainly used for simulation of final state radiation (FSR). Photons and electrons that are nearly collinear are merged using an algorithm that mimics the electromagnetic clustering algorithm.

The detector response, resolution, and energy scale for electrons and photons are simulated using a parameterization from 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 [21], as described in more detail in [14]. The primary control sample is $Z \to ee$ events, although $W \to e\nu$ events are also used in a limited way. The uncertainty on the electron energy scale is dominated by the statistical uncertainty due to the size of the $Z \to ee$ control samples. The modeling of the electron energy resolution and selection efficiencies is described in detail in [14].

The modeling of the recoil is based on the recoil library obtained from $Z \to ee$ events. A Bayesian unsmearing procedure [22] allows the transformation of the two-dimensional distribution of reconstructed Z boson p_T and the measured recoil momentum $\vec{u}_T$ to one between the true Z boson p_T and the measured recoil $\vec{u}_T$. For each simulated $W \to e\nu$ 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 $\vec{p}_T$. Details can be found in [13]. 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, underlying energy corrections 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 parameterizations 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 complex correlations between different components of the hadronic recoil. It requires no first-principles description of the recoil system and has no adjustable parameters.

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 one 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 [23] and propagating them to the W boson width. Systematic uncertainties due to the PDFs are evaluated using the prescription suggested by the CDF collaboration [24]. Systematic uncertainties from the modeling of electroweak radiative corrections are obtained by comparisons with WGRAD [25] and ZGRAD2 [26]. The systematic uncertainty due to the M_W uncertainty is obtained by varying the input M_W by ± 23 MeV [3].

The backgrounds to $W \to e\nu$ events are (a) $Z \to ee$ events in which one electron is not detected; (b) multijet production in which one jet is misidentified as an electron and mis-measurement of the hadronic activity in the event leads to apparent $\not\!\!E_T$; (c) $W \to \tau\nu \to e\nu\nu\nu$ events. The $Z \to ee$ background arises mainly when an electron is in the region between the CC and EC calorimeters. It is estimated from events with one good electron with a high-p_T track opposite in azimuth pointing towards the gap. The estimated background fraction is $(0.80 \pm 0.01)\%$. 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 $Z \to ee$ 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 dataset. The background contamination from multijet events is estimated to be $(1.49 \pm 0.03)\%$. The $W \to \tau\nu \to e\nu\nu\nu$ background is determined using a GEANT-based simulation to be $(1.60 \pm 0.02)\%$ and is normalized to the $W \to e\nu$ events in the same simulation.

We fit the M_T data distribution to a set of templates 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 test 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 reaches for a lower M_T cut of 100 GeV with $\Gamma_W = 2.028 \pm 0.038$ (stat) $\pm\, 0.061$ (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 uncertainty. The detailed breakdown of the systematic uncertainties is given in Table I.

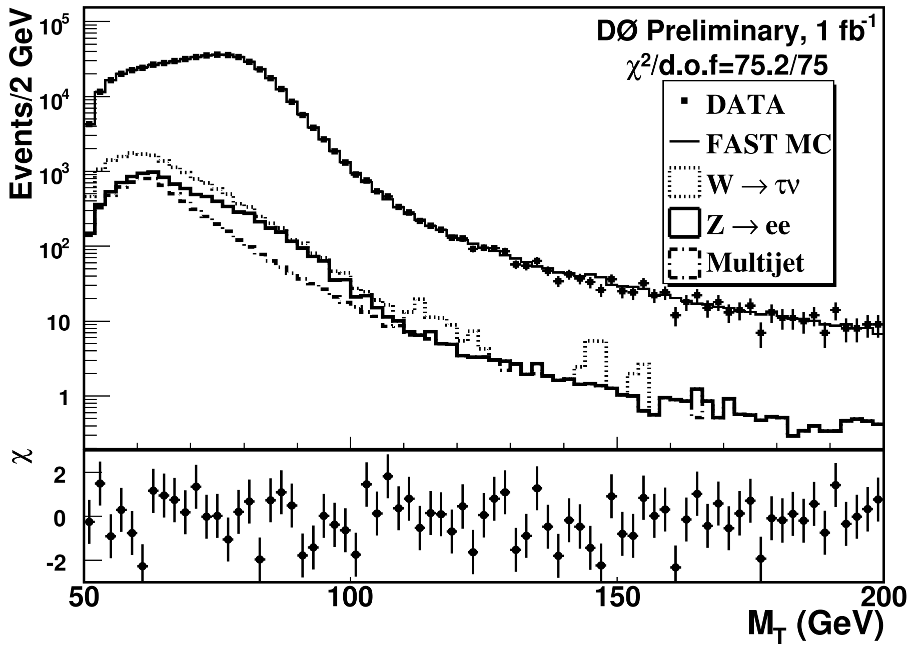

FIG. 1: The M_T distributions for data and fast MC simulation with background added (top) and the χ values for each bin (bottom). The fitted Γ_W value is used for the fast MC prediction. The distribution of the fast MC simulation with background added is normalized to the number of data events in the region $50 < M_T < 100$ GeV.

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

TABLE I: Systematic uncertainties on the measurement of Γ_W.

The methodology used to extract the width in this note is tested using W and Z boson events produced by a PYTHIA/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 27 MeV statistical precision of the test.

The Γ_W result obtained using the M_T spectrum is in agreement with the predictions of the SM. Results from fits to the p_T^e and to the $\not\!\!E_T$ spectra give consistent results: 2.012 ± 0.046 (stat) GeV and 2.058 ± 0.036 (stat) GeV, respectively. The width can also be estimated directly from the fraction of events with $M_T > 100$ GeV, and this gives $\Gamma_W = 2.020 \pm 0.040$ (stat) GeV. The results are stable within errors when the data sample is divided into different regions of instantaneous 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.

We also use the recoil library method to measure the W boson mass using the M_T distribution over the region $65 < M_T < 90$ GeV. A value of $M_W = 80.404 \pm 0.023$ (stat) ± 0.038 (syst) GeV is found, in good agreement with the previous result from D0, $M_W = 80.401 \pm 0.023$ (stat) ± 0.037 (syst) GeV, obtained using the same data set and the parameterized recoil model [14].

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 new method to simulate the recoil system in $W \to e\nu$ events using a recoil library built from $Z \rightarrow ee$ events was developed and used for the first time on the width measurement. Our result, 2.028 ± 0.072 GeV, is in agreement with the prediction of the SM and is the most precise direct measurement result from one single experiment to date.

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