

Direct Measurement of the W Boson Width in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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A direct measurement of the total decay width of the W boson Γ_W is presented using 350 pb⁻¹ of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV collected with the CDF II detector at the Fermilab Tevatron. The width is determined by normalizing predicted signal and background distributions to 230 185 W candidates decaying to $e\nu$ and $\mu\nu$ in the transverse-mass region $50 < M_T < 90$ GeV and then fitting the predicted shape to 6055 events in the high- M_T region, $90 < M_T < 200$ GeV. The result is $\Gamma_W = 2032 \pm 45_{\text{stat}} \pm 57_{\text{syst}}$ MeV, consistent with the standard model expectation.

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The decay widths of the W and Z bosons that mediate the weak interaction are precisely predicted within the standard model (SM). At Born level the W width Γ_W and mass M_W are related through the precisely determined Fermi coupling constant, G_F . Beyond leading order, higher-order electroweak (EW) and quantum-chromodynamic (QCD) corrections, $\delta_{\text{EW}} \approx -0.4\%$ and $\delta_{\text{QCD}} \approx 2.5\%$, respectively, modify the relation such that

$$\Gamma_W = \frac{3G_F M_W^3}{\sqrt{8}\pi} (1 + \delta_{\text{EW}} + \delta_{\text{QCD}}) \text{ [1,2].}$$
 The uncertainty on the SM prediction $\Gamma_W = 2091 \pm 2$ MeV is dominated by the uncertainty on M_W with smaller contributions from the uncertainties on the higher-order corrections [3]. Uncertainties on SM parameters, such as the Higgs boson mass, affect this prediction very weakly, and so a measurement allows an unambiguous test of the SM that can also be used to constrain other SM parameters such as the V_{cs}

Cabibbo-Kobayashi-Maskawa matrix element [4]. The combination of published direct measurements of Γ_W from $p\bar{p}$ collisions at the Tevatron [5] and e^+e^- collisions at LEP-II [6] has an uncertainty of 2.7% with the most precise determination from a single experiment (ALEPH) having an uncertainty of 5.1%. The most precise indirect determination [7] of Γ_W from a measurement of the ratio $R = \frac{\sigma(p\bar{p} \rightarrow W \rightarrow \ell\nu)}{\sigma(p\bar{p} \rightarrow Z \rightarrow \ell^+\ell^-)}$ has an uncertainty of 2%.

This Letter presents the world's most precise direct determination of Γ_W from a single experiment. The analysis uses $W \rightarrow e\nu(\mu\nu)$ data with integrated luminosities of 370(330) pb^{-1} collected by the CDF II detector at the Fermilab Tevatron.

Neutrinos are undetectable by the CDF II detector and hence the invariant mass of the W boson cannot be reconstructed. Γ_W is therefore determined from a fit to the distribution of the W transverse mass $M_T = \sqrt{2(p_T^\ell p_T^\nu - \vec{p}_T^\ell \cdot \vec{p}_T^\nu)}$, where \vec{p}_T^ℓ and \vec{p}_T^ν are the measured transverse momentum of the charged lepton and the transverse momentum of the neutrino as inferred from the observed missing transverse energy, respectively.

The components of the CDF II detector relevant to this analysis are described briefly here; a more complete description can be found elsewhere [8]. A silicon microstrip detector [9] is used to measure the distance of closest approach in the transverse plane, d_0 , of charged particles to the beam line. The momenta of charged particles are measured using a 96-layer drift chamber (COT) [10] inside a 1.4 T solenoid. Electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, cover the pseudorapidity range $|\eta| < 3.64$ [11]. In the region $|\eta| < 1.0$, a lead/scintillator electromagnetic calorimeter (CEM) [12] measures electron energies and proportional chambers embedded at the shower maximum provide further information on shower shapes and positions. A system of drift chambers outside the calorimeters is used to identify muons in the region $|\eta| < 1.0$ [13].

$W \rightarrow e\nu$ candidate events are selected by a large transverse energy electron trigger, and the electron shower is required to have transverse energy $E_T^e > 25$ GeV [11] in the CEM. The ratio of the energy measured in the CEM and the charged-track momentum measured in the COT, E/p , must satisfy $0.8 < E/p < 1.3$. The ratio of energy deposited in the hadronic (HAD) and CEM calorimeter towers is required to satisfy $E_{\text{HAD}}/E_{\text{CEM}} < 0.07$. The electron shower must be contained within a fiducial region of the CEM, away from calorimeter cell boundaries, and have a typical electron lateral shower profile. Contamination by $Z \rightarrow e^+e^-$ events is reduced by rejecting events with an additional high p_T track of opposite charge pointing to an uninstrumented region of the calorimeter.

$W \rightarrow \mu\nu$ candidate events are selected by a large p_T muon trigger and are required to contain a COT track, well matched to a track segment in the muon chambers, with

$p_T^\mu > 25$ GeV. The energy deposited in the CEM and HAD must be consistent with the passage of a minimum-ionizing particle. Requirements on the track d_0 and fit χ^2 are imposed to reject background. Events consistent with cosmic rays or those with an additional high- p_T track consistent with $Z \rightarrow \mu^+\mu^-$ decays are removed.

The existence of a neutrino is inferred from a transverse momentum imbalance. The missing transverse momentum, $\vec{p}_T^\nu \equiv -(\vec{p}_T^\ell + \vec{u})$, must satisfy $p_T^\nu > 25$ GeV. The components of the recoil transverse energy vector \vec{u} are defined as $\sum_i E_i \sin\theta_i (\cos\phi_i, \sin\phi_i)$, for calorimeter towers i with $|\eta| < 3.64$, excluding those traversed by and surrounding the charged lepton. \vec{u} receives contributions from initial-state QCD radiation, underlying-event energy, final-state photon radiation, and overlapping $p\bar{p}$ interactions. To reduce backgrounds and improve transverse-mass resolution, the recoil energy must satisfy $u < 20$ GeV. The $W \rightarrow e\nu(\mu\nu)$ sample consists of 127 432 (108 808) candidate events in the range $50 < M_T < 200$ GeV and 3436 (2619) in the high M_T range of $90 < M_T < 200$ GeV.

Since the W and Z bosons share a common production mechanism and the momenta of Z bosons can be directly reconstructed from their decay products, $Z \rightarrow \ell^+\ell^-$ decays are used to model the detector's response to $W \rightarrow \ell\nu$ events. Samples of $Z \rightarrow e^+e^-(\mu^+\mu^-)$ candidates are selected by requiring two charged leptons, with the same requirements as the W lepton candidates, with the exception that the muon chamber track match requirement is removed for one of the muons in the $Z \rightarrow \mu^+\mu^-$ pair. The $\ell^+\ell^-$ invariant mass is required to satisfy $80 < M^{\ell\ell} < 100$ GeV. 2909 (6721) $Z \rightarrow e^+e^-(\mu^+\mu^-)$ events with recoil energy $u < 20$ GeV are used to determine the scale and resolution of the lepton energy and momentum measurements. A second set of $Z \rightarrow e^+e^-(\mu^+\mu^-)$ events with the u cut replaced by a di-lepton transverse momentum cut, $p_T^{\ell\ell} < 50$ GeV, are used to constrain the W boson's transverse momentum spectrum and to provide an empirical model of the recoil.

The W boson M_T spectrum is modeled using a Monte Carlo (MC) simulation. The CTEQ6M [14] parton distribution functions (PDFs) are used, and W boson invariant masses $\sqrt{\hat{s}}$ are generated according to an energy-dependent Breit-Wigner distribution: $\sigma(\hat{s}) \sim [\hat{s}(1 - M_W^2/\hat{s})^2 + \hat{s}\Gamma_W^2/M_W^2]^{-1}$. Higher-order QCD effects are included by generating the W bosons with a p_T distribution from a resummed next-to-leading order (NLO) QCD calculation [15] with the nonperturbative prescription of [16]. Photon radiation from the charged lepton is simulated using a $\mathcal{O}(\alpha)$ matrix-element calculation [17]. Corrections for EW box diagrams are applied from [18].

The charged leptons and radiated photons are passed through a custom detector simulation that models in detail the energy loss due to ionization and bremsstrahlung. The simulation also includes a parametric model of the \vec{u}

measurement as a function of the boson p_T , tuned on data as described below. The same kinematic and geometric cuts used to select candidate events in the data are applied to the simulation.

This measurement relies on the accurate modeling of the M_T distribution over a wide range. The most important sources of systematic uncertainty affecting the M_T shape arise from the charged-lepton energy and momentum scales and resolutions, the recoil modeling, and the presence of backgrounds. All systematic uncertainties are evaluated by varying parameters in the simulation and then fitting the resulting M_T spectra with the nominal spectra. Uncertainties have been calculated separately for the fit region $M_T^{\text{cut}} < M_T < 200$ GeV for M_T^{cut} values ranging from 80 to 110 GeV. While the statistical uncertainty decreases as M_T^{cut} is lowered, the systematic uncertainty increases. A value of $M_T^{\text{cut}} = 90$ GeV gives the smallest total uncertainty. Backgrounds are added to the simulation M_T spectra which are then normalized to the number of data events in the region $50 < M_T < 90$ GeV.

The COT momentum scale is determined from a fit to the $Z \rightarrow \mu^+ \mu^-$ invariant-mass distribution with the Z mass M_Z constrained to the world average value [3]. A consistent COT momentum scale is obtained from fits to the $\mu^+ \mu^-$ invariant-mass distributions from J/ψ and Y decays [8]. The difference between the three determinations has a negligible effect on this analysis. The contribution to the uncertainty on Γ_W in the $W \rightarrow \mu\nu$ channel $\Delta\Gamma_W^{\mu\nu}$ arising from the 0.04% uncertainty in the COT momentum scale, due to the $Z \rightarrow \mu^+ \mu^-$ statistics, is $\Delta\Gamma_W^{\mu\nu} = 17$ MeV.

By scaling the resolutions predicted by a GEANT [19] simulation of the COT to match the observed di-muon invariant-mass distribution in $Z \rightarrow \mu^+ \mu^-$ decays, a momentum resolution of $\sigma(1/p_T) = (5.4 \pm 0.2) \times 10^{-4} \text{ GeV}^{-1}$ is obtained. A consistent $\sigma(1/p_T)$ is determined using the E/p distribution of the $W \rightarrow e\nu$ data. The combined uncertainties from the $Z \rightarrow \mu^+ \mu^-$ and E/p fits for the COT resolution give $\Delta\Gamma_W^{\mu\nu} = 26$ MeV.

The CEM energy scale and resolution are determined from fits to the $Z \rightarrow e^+ e^-$ invariant-mass distribution with M_Z constrained to the world average value [3] and to the E/p distribution of electrons in $W \rightarrow e\nu$ events. The scales determined from the two methods are consistent and are combined with an uncertainty of 0.04%. The contribution to the uncertainty on Γ_W in the $W \rightarrow e\nu$ channel $\Delta\Gamma_W^{e\nu}$ arising from this uncertainty is $\Delta\Gamma_W^{e\nu} = 17$ MeV.

Determinations of the CEM resolution term κ defined by the CEM resolution function $\sigma(E)/E = 13.5\%/\sqrt{E_T(\text{GeV})} \oplus \kappa$ [12] from E/p and $Z \rightarrow e^+ e^-$ fits differ by 1.6σ . They are combined and an uncertainty is assigned that spans both values, as well as the values obtained when the E/p fit region is varied, to give $\kappa = 1.1 \pm 0.4\%$. This uncertainty on the CEM resolution gives $\Delta\Gamma_W^{e\nu} = 31$ MeV.

Energy loss by electrons and photons in the solenoid coil and associated material prior to the CEM, as well as energy leakage into the hadronic calorimeter, are parametrized based on the results of a GEANT simulation. In addition to these simulated sources of CEM nonlinearity, an additional per-particle intrinsic nonlinearity is determined from the $W(Z) \rightarrow e\nu(e^+ e^-)$ data by fitting the E/p distribution in bins of E_T . Its uncertainty gives $\Delta\Gamma_W^{e\nu} = 12$ MeV, resulting in a total uncertainty of 21 MeV on $\Gamma_W^{e\nu}$ from the uncertainties on the electron energy scale determination. Finally, uncertainties in the modeling of very low-energy photons and the amount of passive material prior to the COT give $\Delta\Gamma_W^{e\nu} = 13$ MeV.

The recoil transverse energy vector \vec{u} is used to determine \vec{p}_T^{ν} and hence M_T . Since \vec{u} comes predominantly from initial-state QCD radiation, which is balanced by the W or Z p_T , we form an empirical model of \vec{u} as a function of $p_T^{\ell\ell}$. The parameters of the model are varied according to the covariance matrices obtained in fits to Z data. The resulting uncertainties on \vec{u} from the recoil model give $\Delta\Gamma_W^{e\nu}(\Delta\Gamma_W^{\mu\nu}) = 54(49)$ MeV. The uncertainty in the modeling of the p_T^{ν} distribution is determined by fitting the $p_T^{\ell\ell}$ distribution in $Z \rightarrow \ell^+ \ell^-$ decays and results in a 7 MeV common uncertainty on Γ_W .

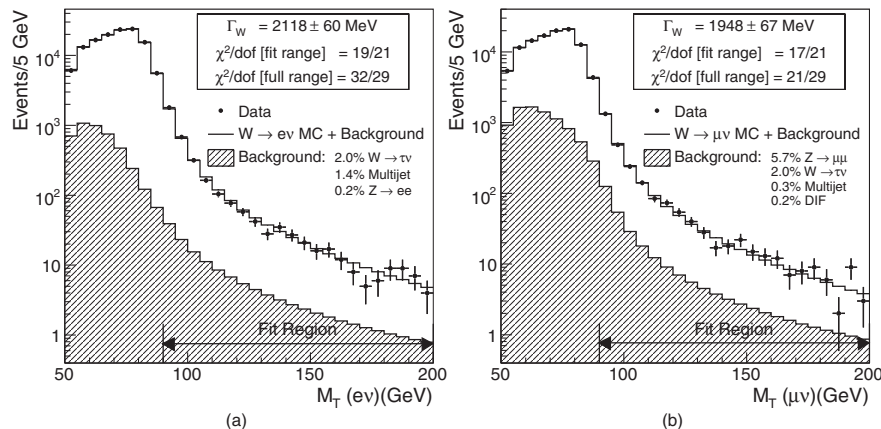


FIG. 1. The transverse-mass distributions of the $W \rightarrow e\nu$ data (a) and $W \rightarrow \mu\nu$ data (b) compared to the best fit.

Several background processes can mimic the W signal. The process $W \rightarrow \tau\nu \rightarrow \ell\nu\nu\nu$ has a signature similar to $W \rightarrow \ell\nu$ decays, but with lower M_T . $Z \rightarrow \ell^+\ell^-$ events, where only one lepton is identified, can be reconstructed as W candidates. These two backgrounds can be accurately determined from MC simulation. QCD multijet backgrounds arise when one jet mimics a charged lepton and another is mismeasured to produce an energy imbalance. Since the region with apparently low p_T^ν is enriched in QCD background, the background is estimated from a fit to the p_T^ν distribution in events where the p_T^ν and low M_T cut are not applied and in which some of the charged-lepton identification cuts have been reversed. The signal spectrum is taken from the simulation. A decay-in-flight (DIF) background to the $W \rightarrow \mu\nu$ signal arises when kaons or pions decay to $\mu\nu$ inside the COT, resulting in mismeasured p_T^μ and a large χ^2 value between the COT hits assigned to the track and the fitted track trajectory. This background is estimated from the χ^2 and d_0 distributions of $W \rightarrow \mu\nu$ events using $Z \rightarrow \mu^+\mu^-$ events as a reference sample with negligible background. The background fractions over the entire region $50 < M_T < 200$ GeV are indicated in Fig. 1. In the $90 < M_T < 200$ GeV fit region the background fraction is $4.0 \pm 0.2\%$ ($10.8 \pm 0.3\%$) in the $e\nu(\mu\nu)$ channel. Varying the backgrounds within these overall normalization uncertainties, as well as varying their M_T shapes, gives $\Delta\Gamma_W^{e\nu}(\Delta\Gamma_W^{\mu\nu}) = 32(33)$ MeV.

We also investigate small systematic uncertainties due to PDFs, M_W , EW corrections, lepton identification, and acceptance. The uncertainty on Γ_W arising from PDFs is determined using the variations defined by the CTEQ6M PDF eigenvector basis [14] which span a 90% confidence interval. The resulting Γ_W shifts are divided by 1.6 to obtain 1σ uncertainties [20], giving $\Delta\Gamma_W = 16$ MeV in both channels. A systematic uncertainty of 12 MeV is added in quadrature to this to account for higher-order QCD effects not implemented in the MC simulation. These were estimated from a comparison of the width obtained using NLO and next-to-next-to-leading order (NNLO) PDFs [21]. Varying M_W by the uncertainty of ± 29 MeV [3] from the central value of 80.403 GeV changes Γ_W by ∓ 9 MeV in each channel.

The impact of higher-order EW corrections is determined by comparing simulated samples of $W \rightarrow \ell\nu\gamma$ and $W \rightarrow \ell\nu\gamma\gamma$ events generated by PHOTOS [22]. Uncertainties on $\Gamma_W^{e\nu}(\Gamma_W^{\mu\nu})$ of 8(1) MeV were obtained. The correction due to EW box diagrams was determined to be 12 MeV in both channels. A systematic uncertainty of 6 MeV in this correction was assigned from its dependence on the recoil resolution.

The uncertainty in simulating lepton identification variables was constrained from $Z \rightarrow \ell^+\ell^-$ decays and gives $\Delta\Gamma_W^{e\nu}(\Delta\Gamma_W^{\mu\nu}) = 10(6)$ MeV. Variations in the simulation of the detector acceptance results in further small uncertainties of 3(4) MeV in the $e\nu(\mu\nu)$ channel. Table I summarizes the sources of uncertainty described above.

TABLE I. The sources of uncertainty (in MeV) on Γ_W for the $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ measurements. If there is a correlated source of error between the two measurements its contribution to each measurement is listed in the third column, labeled C.

Source	$\Delta\Gamma_W^{e\nu}$	$\Delta\Gamma_W^{\mu\nu}$	C
Statistics	60	67	
Lepton E or p scale	21	17	12
Lepton E or p resolution	31	26	
Electron energy loss simulation	13		
Recoil model	54	49	
p_T^W	7	7	7
Backgrounds	32	33	
PDFs	20	20	20
M_W	9	9	9
EW radiative corrections	10	6	6
Lepton ID/acceptance	10	7	
Total systematic	79	71	27
Total (statistic + systematic)	99	98	27

A binned likelihood fit to simulated M_T spectra with Γ_W as a free parameter over the region $90 < M_T < 200$ GeV gives $\Gamma_W^{e\nu} = 2118 \pm 60_{\text{stat}}$ MeV and $\Gamma_W^{\mu\nu} = 1948 \pm 67_{\text{stat}}$ MeV. Figure 1 shows the M_T distributions of the data with the best fits. The two results have a common uncertainty of 27 MeV and are combined using the BLUE method [23] to give $\Gamma_W = 2032 \pm 45_{\text{stat}} \pm 57_{\text{sys}}$ MeV. The combination has a χ^2 of 1.6 and a total uncertainty of 73 MeV. No statistically significant difference is found between fits using positively or negatively charged leptons. As a cross-check, Γ_W was also determined from a fit to p_T^ℓ , which has a different sensitivity to many of the systematics, and a value of Γ_W consistent with the M_T fit at the $< 1\sigma$ level was obtained.

The result presented in this Letter is the most precise direct measurement of the W width. It can be combined with published Tevatron direct width measurements [5] to give a Tevatron average of $\Gamma_W = 2056 \pm 62$ MeV. A further combination with the preliminary value obtained from e^+e^- collisions, $\Gamma_W = 2196 \pm 84$ MeV [24], gives a new world average value of $\Gamma_W = 2106 \pm 50$ MeV, in good agreement with the SM prediction.

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