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

T. Aaltonen, J. Adelman, P. Akimoto, M. Albgard, B. Álvarez González, S. Amerio, D. Amidei, A. Anastassov, A. Annoo, J. Antos, M. Aoki, G. Apollinari, A. Apresyan, T. Arisawa, A. Artikov, W. Ashman, A. Attal, A. Aurasio, F. Azfar, P. Azzi-Bacchetta, P. Azurri, N. Bacchetta, W. Badger, A. Barbaro-Galtieri, V.E. Barnes, B.A. Barnett, S. Baroiant, V. Bartsch, G. Bauer, P.-H. Beauchemin, F. Bedeschi, P. Bednar, D. Beecher, S. Behari, G. Bellettiini, J. Bellinger, A. Belleni, D. Benjamín, A. Berretta, J. Beringer, T. Berry, A. Bhatti, M. Binkley, D. Bisello, I. Bizjak, R.E. Blair, C. Blocker, B. Blumenfeld, A. Bocci, A. Bodek, V. Boisvert, G. Bolla, A. Bolshov, D. Bortoletto, J. Boudreau, A. Boveia, B. Brau, A. Bridgeman, L. Brigliadori, C. Bromberg, E. Bruhake, J. Budagov, H.S. Budd, K. Burkett, G. Busetto, P. Bussey, A. Buzatu, K.L. Byrum, S. Cabrera, M. Campanelli, M. Campbell, F. Canelli, A. Canepa, D. Carlsmith, E. Brubaker, J. Budagov, H.S. Budd, K. Burkett, G. Busetto, P. Bussey, A. Buzatu, K.L. Byrum, S. Cabrera, M. Campanelli, M. Campbell, F. Canelli, A. Canepa, D. Carlsmiths, R. Carosi, S. Carrillo, B. Carron, I. Cabrera, S. Chang, Y.C. Chen, M. Chertok, G. Chiarelli, G. Chlachidze, F. Chlebana, K. Che, D. Chokheli, J.P. Chou, G. Choudalakis, S.H. Chung, K.L. Chung, W.H. Chung, Y.S. Chung, C.I. Ciobanu, M.A. Ciocci, A. Clark, D. Clark, G. Compagno, M.E. Convery, J. Coway, B. Cooper, K. Copic, M. Cordelli, G. Cortiana, F. Crescioli, C. Cuenca Almenar, J. Cuevas, R. Culbertson, J.C. Cully, D. Dagenhart, M. Datta, T. Davies, P. de Barbaro, S. De Cocco, A. De Cesar, G. De Lentdeckerd, G. De Lorenzo, D. Delmastro, J. Deng, M. Denino, D. De Pedis, P.F. Derwent, G.P. Di Giovanni, C. Dionisi, B. Di Ruza, J.R. Dittmann, M. D’Onofrio, S. Donati, P. Dong, J. Donini, T. Dorigo, S. Dube, J. Efron, R. Erbacher, D. Errede, S. Errede, R. Eusebi, H.C. Fang, S. Farrington, W.T. Fedorik, R.G. Feild, M. Feindt, J.P. Fernandez, C. Ferrarazza, R. Field, G. Flanagan, R. Forrest, S. Forrester, M. Franklin, J.C. Freeman, I. Furic, M. Gallinaro, J. Galyardt, F. Garberson, J.E. Garcia, A.F. Garfinkel, H. Gerberich, D. Gerdes, S. Giagu, V. Giakoumopoulou, P. Giannetti, K. Gibson, J.L. Ginnell, C.M. Ginsburg, N. Giokaris, M. Giordani, P. Giromini, M. Giunta, V. Glagolev, D. Glinkowski, M. Gold, N. Gouloissant, A. Golossanov, G. Gomez, G. Gomez-Ceballos, M. Goncharov, O. Gonzalez, I. Gorelov, A.T. Goshaw, K. Gouloumas, A. Gresele, S. Grinstein, C. Grossos-Pilcher, R.C. Group, U. Glander, J. Guimaraes da Costa, Z. Gunay-Unalan, C. Haber, K. Hahn, S.R. Hahn, E. Halkiadakis, A. Hamilton, B.-Y. Han, J.Y. Han, R. Handler, F. Happacher, K. Hara, D. Hare, M. Hare, S. Harper, R.F. Harr, R.M. Harris, M. Hartz, K. Hatakeyama, J. Hauser, C. Hays, M. Heck, M. Heijboer, S. Heinemann, J. Heinrich, C. Henderson, M. Herndon, J. Heuser, S. Hewamanage, D. Hidas, C.S. Hill, D. Hirschiuchel, A. Hocker, S. Hou, M. Houlden, S.-C. Hsu, B.T. Huffman, R.E. Hughes, U. Huebmaier, J. Huston, J. Incandela, G. Introzzi, M. Iori, A. Ivanov, B. Iyutin, E. James, B. Jayatilaka, D. Jeans, E.O. Jeon, S. Jindariani, W. Johnson, M. Jones, K.K. Joo, S.Y. Jun, J.E. Jung, T.R. Junk, T. Kalon, D. Kar, P.E. Karchin, Y. Kato, R. Kephart, U. Kerzel, V. Khitovichov, B. Kilminster, D.H. Kim, H.S. Kim, J.E. Kim, M.J. Kim, S.B. Kim, S.H. Kim, Y.K. Kim, N. Kimura, K. Kirsch, S. Klimentov, K. Klute, B. Knutsen, B.R. Ko, A. Koay, K. Konno, D.J. Kong, J. Konigsberg, A. Korytov, A.V. Kotwal, J. Kraus, M. Krep, J. Kroll, N. Krnmucek, M. Kruse, V. Krutelyov, T. Kubo, M.E. Kulhmann, T. Kuhner, N.P. Kulikarni, Y. Kuskabale, S. Kwang, A.T. Laasanen, S. Lai, S. Lamii, S. Lammel, M. Lancaster, R.L. Lander, K. Lannon, A. Lath, G. Latino, I. Laazzam, T. LeCompte, J. Lee, J. Lee, Y.J. Lee, S.W. Lee, R. Lefèvre, N. Leonardo, S. Leone, S. Levy, J.D. Lewis, C. Lin, C.S. Lin, J. Linacres, M. Lindgren, E. Lipecesac, A. Lister, D.O. Litvintsev, T. Liu, N.S. Lockyer, A. Logino, M. Loretii, R. Llorens, R.-S. Lu, D. Lucchesi, J. Luce, C. Luci, P. Lujan, P. Lukens, G. Lungu, L. Lyons, J. Lys, R. Lysak, E. Lytken, P. Mack, D. MacQueen, R. Madrak, K. Maeshima, K. Makhouli, T. Maki, P. Maksimovic, S. Malde, S. Malik, G. Manca, A. Manousakis, F. Margaroli, G. Marisuv, C.P. Marino, A. Martin, M. Martin, V. Martin, M. Martinez, R. Martinez-Ballarin, M. Maruyama, P. Mastrandrea, T. Masubuchi, M.E. Mattson, P. Mazzaoni, K.S. McFarland, P. McIntyre, R. McNulty, A. Mehta, P. Mehta, S. Menzemer, A. Menzione, P. Merkel, C. Mendoza, A. Messina, T. Miao, N. Miladinovic, J. Miles, R. Miller, R. Mills, M. Milnik, A. Mitra, G. Mitselmakher, H. Miyake, S. Moed, N. Moggio, C.S. Moon, R. Moore, M. Morello, P. Movilla Fernandez, J. Müllerstädt,
A. Mukherjee, J. Naganoma, F. Scuri, S. Tokar, I. Redondo, C. Wolfe, L. Nodulman, A. Robson, T. Spreitzer, R.L. Wagner, A.S. Thompson, M.A. Schmidt, C. Paus, D. Waters, R. Takashima, S.S. Yu, U.K. Yang, V. Rusu, K. Tollefson, T. Wright, T. Vine, A. Sidoti, D.E. Pellett, R. Orava, C. Paus, M.D. Shapiro, J. Strologas, E. Vataga, E. Wicklund, M. Norman, J. Wagner-Kuhr, M. Weinberger, K. Tollefson, T. Wright, 34 X. Wu, 20 S.M. Wyne, 29 A. Yagil, 9 K. Yamamoto, 40 J. Yamashita, C. Yang, 59 U.K. Yang, 13 Y.C. Yang, 27 W.M. Yao, 28 G.P. Yeh, 17 J. Yoh, 17 K. Yorita, 13 T. Yoshida, 40 G.B. Yu, 48 I. Yu, 27 S.S. Yu, 17 J.C. Yun, 17 L. Zanello, 50 A. Zanetti, 53 I. Zaw, 22 X. Zhang, 24 Y. Zheng, 8, and S. Zucchelli

(CDF Collaboration*)

(*) CDF Collaboration
A direct measurement of the total decay width of the W boson $\Gamma_W$ 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 230185 $W$ 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.

PACS numbers: 13.38.Be, 14.70.Fm
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 $\Gamma_W$ 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, $\delta_{EW} \approx -0.4\%$ and $\delta_{QCD} \approx 2.5\%$ respectively, modify the relation such that

$$\Gamma_W = \frac{3G_F M_W^3}{\sqrt{8\pi}} (1 + \delta_{EW} + \delta_{QCD}) \left[1 + \frac{M_W^2}{\sqrt{s}}\right].$$

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. 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.

Published direct measurements of $\Gamma_W$ from $p\bar{p}$ collisions at the Tevatron and $e^+e^-$ collisions at LEP-II have combined 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 of $\Gamma_W$ from a measurement of the ratio

$$R = \frac{\sigma(p\bar{p} \rightarrow W \rightarrow e\nu)}{\sigma(p\bar{p} \rightarrow Z \rightarrow e^+e^-)}$$

has an uncertainty of 2%.

This Letter presents the world's most precise direct determination of $\Gamma_W$ from a single experiment. The analysis uses $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ data with respective integrated luminosities of 370 pb$^{-1}$ and 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. $\Gamma_W$ is therefore determined from a fit to the distribution of the $W$ transverse mass $M_T = \sqrt{2(\vec{p}_T^e \cdot \vec{p}_T^\nu - \vec{p}_T^e \cdot \vec{p}_T^\nu)}$, where $\vec{p}_T^e$ and $\vec{p}_T^\nu$ 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.

Events with $M_T > M_W$ arise predominantly from a combination of non-zero $W$ width and finite detector resolution. The width component of the high-$M_T$ line-shape falls off more slowly than the resolution component, allowing a precise $\Gamma_W$ measurement from the $M_T > M_W$ events even in the presence of systematic uncertainties on the resolution.

The components of the CDF II detector relevant to this analysis are described briefly here; a more complete description can be found elsewhere. A silicon microstrip detector is used to measure the distance of closest approach in the transverse plane, $d_0$, of charged particles to the beamline. The momenta of charged particles are measured using a 96-layer open-cell drift chamber (COT) inside a 1.4 T solenoid. Optimal $p_T$ resolution is obtained by constraining trajectories to originate from the beamline. Electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, cover the pseudorapidity range $|\eta| < 3.64$. In the region $|\eta| < 1.0$, a lead/scintillator electromagnetic calorimeter (CEM) 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 $|\eta| < 1.0$.

$W \rightarrow e\nu$ candidate events are selected by a large transverse energy electron trigger, and the electron shower is required to have transverse energy $E_T > 25$ GeV 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 calorimeters 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 must have a typical electron lateral shower profile on the projection of the COT track in the CEM. Contamination by $Z \rightarrow e^+e^-$ events is reduced by rejecting events with an additional high $p_T$ track of opposite sign charge pointing to an un-instrumented 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 transverse momentum $p_T^\mu > 25$ GeV. The energy deposited in the electromagnetic and hadronic calorimeters must be consistent with the passage of a minimum-ionizing particle. Requirements on the track $d_0$ and track fit $\chi^2$ 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, $\vec{p}_T^\nu \equiv - (\vec{p}_T^e + \vec{u})$, must satisfy $p_T^\nu > 25$ GeV. The components of the recoil transverse energy vector $\vec{u}$ are defined as $\sum_i E_i \sin \theta_i \cos \phi_i$, 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 $W \rightarrow e\nu (W \rightarrow \mu\nu)$ sample consists of 127432 (108808) 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 reconstituted 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 \(Z \rightarrow e^+e^-\) and \(Z \rightarrow \mu^+\mu^-\) events 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 di-lepton invariant mass is required to satisfy \(80 < M_{\ell\ell} < 110\) GeV. Samples of 2090 \(Z \rightarrow e^+e^-\) and 6271 \(Z \rightarrow \mu^+\mu^-\) 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 \(Z \rightarrow e^+e^-\) and \(Z \rightarrow \mu^+\mu^-\) control samples is defined with the \(u\) cut replaced by a di-lepton transverse momentum cut, \(p_T^{\ell\ell} < 50\) GeV, in order 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 simulation. The CTEQ6M parton distribution functions (PDFs) are used, and \(W\) boson invariant masses \(\sqrt{s}\) are generated according to an energy-dependent Breit-Wigner distribution: \(\sigma(s) \sim \left[ s \left( 1 - M_W^2/s \right)^2 + 8\Gamma_W^2/M_W^2 \right]^{-1}\). Higher order QCD effects are included by generating the \(W\) bosons with a \(p_T\) distribution from a NLO combined with resummation QCD calculation [14] with the non-perturbative prescription of [12]. Photon radiation from the charged lepton is simulated using a \(O(\alpha)\) matrix-element calculation [10]. Corrections for EW box diagrams are applied from the calculation of [17].

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. The simulation produces \(M_T\) spectra for \(\Gamma_W\) values ranging from 1.0 to 3.0 GeV with \(M_W\) fixed at 80.403 GeV [2].

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 \(M_{T_{\text{cut}}}\) values ranging from 80 to 110 GeV. While the statistical uncertainty decreases as \(M_{T_{\text{cut}}}\) is lowered, the systematic uncertainty increases. A value of \(M_{T_{\text{cut}}} = 90\) GeV gives the smallest total uncertainty. Backgrounds are added on top of 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 mass constrained to the world average value [2]. A consistent COT momentum scale is obtained from fits to the invariant mass distributions of \(J/\psi \rightarrow \mu^+\mu^-\) and \(Y \rightarrow \mu^+\mu^-\) events [5]. The difference between the three determinations has a negligible effect on this analysis. The contribution to the uncertainty on \(\Gamma_W\) 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 simulation of the COT to match the observed di-muon invariant mass distribution in \(Z \rightarrow \mu^+\mu^-\) decays, we obtain a momentum resolution of \(\sigma(1/p_T) = (5.4 \pm 0.2) \times 10^{-4}\) GeV\(^{-1}\). A consistent \(\sigma(1/p_T)\) is also 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 the \(Z\) mass constrained to the world average value [2] and to the \(E/p\) distribution of electrons in \(W \rightarrow e\nu\) events, using the calibration of \(p\) described above. The scales determined from the two methods are consistent and are combined to form a weighted average with an uncertainty of 0.04\%. The contribution to the uncertainty on \(\Gamma_W\) in the \(W \rightarrow e\nu\) channel \(\Delta\Gamma_W^{\nu}\) arising from this uncertainty is \(\Delta\Gamma_W^{\nu} = 17\) MeV.

The CEM resolution fits constrain the constant term \(\kappa\) in the CEM resolution function \(\sigma(E)/E = 13.5\%/\sqrt{E_T(\text{GeV})} \oplus \kappa\) [11]. The \(E/p\) and \(Z \rightarrow e^+e^-\) fit results differ by 1.6 standard deviations. 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 \(\Delta\Gamma_W^{\nu} = 31\) 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 parameterized based on the results of a GEANT simulation. In addition to these simulated sources of CEM non-linearity, an additional per-particle intrinsic non-linearity is determined from the \(W \rightarrow e\nu\) and \(Z \rightarrow e^+e^-\) data by fitting the \(E/p\) distribution in bins of \(E_T\). Its uncertainty gives \(\Delta\Gamma_W^{\nu} = 12\) MeV, resulting in a total uncertainty of \(21\) MeV on \(\Gamma_W\) 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 \(\Delta\Gamma_W^{\nu} = 13\) MeV.

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

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 Monte-Carlo simulation. QCD multi-jet backgrounds arise when one jet mimics a charged lepton and another is mismeasured to produce an energy imbalance. Since the region with apparently low $p_T^{p_F}$ is enriched in QCD background, the background normalization is estimated from a fit to the $p_T^{p_F}$ distribution in events where the $p_T^{p_F}$ and low $M_T$ cut are not applied. The background $p_T^{p_F}$ spectrum is taken from data events in which some of the charged-lepton identification cuts have been reversed, and 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 inside $\mu\nu$ inside the COT, resulting in mismeasured muon momentum and a large $\chi^2$ value between the COT hits assigned to the track and the fitted track trajectory. This background is estimated from a fit to the $\sum$ distribution.

The background spectrum is taken from events with a large $d_0$ and the signal from $Z \rightarrow \mu^+\mu^-$ events, which have negligible background. The background fractions over the entire region $50 < M_T < 200$ GeV are indicated in Figure 1. In the $90 < M_T < 200$ GeV fit region the total background fraction is $4.0 \pm 0.2\%$ ($10.8 \pm 0.3\%$) in the electron (muon) channel. Varying the background predictions within these overall normalization uncertainties, as well as varying their $M_T$ shapes, causes variations in the electron (muon) $\Gamma_W$ of 32 (33) MeV. The backgrounds that contribute the most to the width uncertainty are the QCD multijet (DIF) backgrounds in the electron (muon) channel.

We also investigate small systematic uncertainties due to PDFs, $M_T$, EW corrections, lepton identification, and acceptance. The uncertainty on $\Gamma_W$ arising from PDFs is determined using the variations defined by the CTEQ6M PDF eigenvector basis [12]. The PDF error sets span a 90% confidence interval so the resulting $\Gamma_W$ shifts are divided by 1.6 to obtain $1\sigma$ uncertainties [10], giving an uncertainty of 16 MeV in both channels. A systematic uncertainty of 12 MeV is added in quadrature to this to account for the effect of higher order QCD effects not implemented in the Monte-Carlo simulation which was estimated from a comparison of the width obtained using NLO and NNLO PDFs [20]. Varying $M_W$ by the uncertainty of $\pm 29$ MeV [2] from the central value of 80.403 GeV changes $\Gamma_W$ by $\mp 9$ 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 [21]. Uncertainties on $\Gamma_W^\nu$ ($\Gamma_W^\mu$) 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 the box diagram correction was assigned from the dependence of the correction on the recoil resolution.

The uncertainty in simulating lepton identification variables was constrained from $Z \rightarrow \ell^+\ell^-$ decays and results in a $\Gamma_W$ uncertainty of $10 (6)$ MeV in the electron (muon) channel. Variations in the simulation of the detector acceptance results in a further small uncertainty of $3 (4)$ MeV in the electron (muon) channel. Table I summarizes the sources of uncertainty described above.

A binned likelihood fit to simulated $M_T$ spectra with $\Gamma_W$ as a free parameter over the region $90 < M_T < 200$ GeV gives $\Gamma_W = 2118 \pm 60_{\text{stat}}$ MeV for the electron channel and $\Gamma_W = 1948 \pm 67_{\text{stat}}$ MeV for the muon channel. Figure 1 shows the $M_T$ distributions of the data with the best fits. The electron and muon results have a common uncertainty of 27 MeV and are combined using the BLUE method [22] to give $\Gamma_W = 2032 \pm 45_{\text{stat}} \pm 57_{\text{syst}}$ MeV. The combination has a $\chi^2$ of 1.6 and a total uncertainty of 73 MeV. No statistically significant difference is found between fits using only positively and only negatively charged leptons. As a cross-check, the $W$ width was also determined from a fit to the charged-lepton transverse momentum, which has a different sensitivity to many of the systematics, and a value of $\Gamma_W$ 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 [4] to give a hadron collider 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 [23], gives a new world average value of $\Gamma_W = 2106 \pm 50$ MeV, in good agreement with the SM prediction.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the Korean Science and Engineering Foundation and the Korean Research Foundation; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucléaire et Physique des Particules/CNRS;
TABLE I: The sources of uncertainty (in MeV) on $\Gamma_W$ for the $W \to e\nu$ and $W \to \mu\nu$ 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                          | $\Delta\Gamma_W^{(\text{Stat.})}$ | $\Delta\Gamma_W^{(\text{Syst.})}$ | 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 Syst.                    | 79                                | 71                                | 27  |
| Total (Stat. + Syst.)          | 99                                | 98                                | 27  |

Interministerial de Ciencia y Tecnología, Spain; the European Community’s Human Potential Programme; the Slovak R&D Agency; and the Academy of Finland.

[1] J. L. Rosner, M. P. Worah, and T. Takeuchi, Phys. Rev. D 49, 1363 (1994).
[2] W.-M. Yao et al., J. Phys. G 33, 1 (2006).
[3] P. B. Renton, Rept. Prog. Phys. 65, 1271 (2002).
[4] V. Abazov et al., (CDF Collaboration), D0 Collaboration, Tevatron EW Working Group), Phys. Rev. D 70, 092008 (2004).
[5] S. Schael et al. (ALEPH Collaboration), Eur. Phys. J. C 47, 309 (2006); G. Abbiendi et al. (OPAL Collaboration), ibid. 45, 307 (2006); P. Achard et al. (L3 Collaboration), ibid. 45, 569 (2006); P. Abreu et al. (DELPHI Collaboration), Phys. Lett. B 511, 159 (2001).
[6] D. Acosta et al. (CDF Collaboration), Phys. Rev. Lett. 94, 091803 (2005).
[7] T. Aaltonen et al. (CDF Collaboration), arXiv:0708.3642 [hep-ex].
[8] A. Sill et al., Nucl. Instrum. Methods A 447, 1 (2000); A. Affolder et al., ibid. 453, 84 (2000).
[9] A. Affolder et al., Nucl. Instrum. Methods A 526, 249 (2004).
[10] Throughout this Letter units of $\hbar = c = 1$ are used such that momenta and masses are in units of MeV or GeV.

![FIG. 1: The transverse mass distributions of the $W \to e\nu$ data (a) and $W \to \mu\nu$ data (b) compared to the best fit.](image)

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

[11] L. Balka et al., Nucl. Instrum. Methods A 267, 272 (1988).
[12] G. Ascoli et al., Nucl. Instrum. Methods A 268, 33 (1998).
[13] J. Pumplin et al., J. High Energy Phys. 0207, 012 (2002).
[14] P. B. Arnold and R. P. Kaufman, Nucl. Phys. B349, 381 (1991); P. B. Arnold and M. H. Reno, ibid. 319, 37 (1989); P. B. Arnold, R. K. Ellis, and M. H. Reno, Phys. Rev. D 40, 912 (1989).
[15] F. Landry et al., Phys. Rev. D 67, 073016 (2003).
[16] F. A. Berends et al., Z. Phys. C 27, 155 (1985); F. A. Berends and R. Kleiss, ibid. 27, 365 (1985).
[17] U. Baur and D. Wackeroth, Phys. Rev. D 70, 073015 (2004).
[18] R. Brun and F. Carminati, CERN Program Library Long Writeup, W5013, 1993 (unpublished), version 3.15.
[19] J. M. Campbell, J. W. Huston, and W. J. Stirling, Rep. Prog. Phys. 70, 89 (2007).
[20] A.D. Martin, R.G. Roberts, W.J. Stirling, and R.S. Thorne, Phys. Lett. B 604, 61 (2004).
[21] E. Barberio and Z. Was, Comput. Phys. Commun. 79, 291 (1994); E. Barberio, B. van Eijk, and Z. Was, ibid. 66, 115 (1991).
[22] L. Lyons, D. Gibaut, and P. Clifford, Nucl. Instrum. Methods A 270, 110 (1988).
[23] J. Alcaraz et al. (LEP Electroweak Working Group), arXiv:hep-ex/0612034.