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DIRECT MEASUREMENT OF THE W WIDTH IN $p\bar{p}$ COLLISIONS AT $\sqrt{s} = 1.96$ TEV

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This paper describes a direct measurement of the W boson total decay width Γ_W using the DØ detector at the Fermilab Tevatron Collider. The measurement uses an integrated luminosity of 177.3 pb^{-1}, collected during the 2002-2003 run. The width is determined by normalizing the predicted signal and background transverse mass distributions to 75,285 $W \to e\nu$ candidates in the transverse mass region $50 < M_T < 100$ GeV and then fitting the predicted shape to the 625 candidates in the tail region $100 < M_T < 200$ GeV. The W width is determined to be $\Gamma_W = 2.011 \pm 0.093$ (stat) ± 0.107 (syst) GeV.

Keywords: W Width; Transverse Mass; $W \to e\nu$.

1. Introduction

The W boson width Γ_W is precisely predicted to be $\Gamma_W = 2.090 \pm 0.008$ GeV in terms of the masses and coupling constants of the gauge bosons [1]. It has been measured indirectly to be 2.141 ± 0.057 GeV [2] using the W/Z cross section ratio $R = \frac{\sigma(p\bar{p}\to W+X)\times Br(W\to l\nu)}{\sigma(p\bar{p}\to Z+X)\times Br(Z\to ll)} = \frac{\sigma(W)}{\sigma(Z)}\frac{\Gamma(Z)}{\Gamma(Z\to ll)}\frac{\Gamma(W\to l\nu)}{\Gamma_W}$, by assuming SM values for $\sigma(W)/\sigma(Z)$ and $\Gamma(W \to l\nu)$ and using the LEP measurements of the leptonic branching ratio $Br(Z \to ll) = \frac{\Gamma(Z\to ll)}{\Gamma(Z)}$. Recently CDF reported a new indirect measurement at $\sqrt{s} = 1.96$ TeV and the result is 2.079 ± 0.041 GeV [3]. Direct measurement of the W boson width have been obtained from the transverse mass spectrum of $W \to \ell\nu$ decays by the CDF and DØ experiments using data collected during Run I of the Tevatron. The results are $\Gamma_W = 2.05 \pm 0.13$ GeV (CDF) [4] (using $W \to e\nu$ and $W \to \mu\nu$ decays) and $\Gamma_W = 2.231^{+0.175}_{-0.170}$ GeV (DØ) [5] (only $W \to e\nu$ decays). These results have been combined, considering correlations in the systematic uncertainties, to obtain $\Gamma_W = 2.115 \pm 0.105$ GeV [2]. Direct measurements of Γ_W have also been made by measuring the W resonance lineshape in $e^+e^- \to W^+W^-$ events collected at the LEP e^+e^- collider, resulting in an average value $\Gamma_W = 2.150 \pm 0.091$ GeV [6].
This paper presents a direct measurement of Γ_W obtained in studies of the transverse mass spectrum of $W \to e\nu$ events. The W boson transverse mass is

defined as $M_T = \sqrt{2E_T^e E_T^\nu (1 - \cos(\phi_e - \phi_\nu))}$, where E_T^e, E_T^ν are the transverse energies and ϕ_e, ϕ_ν are azimuthal angles of electron and neutrino respectively. The transverse mass distribution exhibits a Jacobian edge near M_W, events with $M_T > M_W$ arise from a combination of the non-zero W width and detector resolutions. Figure 1 shows the Monte Carlo simulated M_T spectra for different W boson widths.

2. DØ Detector

The DØ detector is comprised of the following main elements [7]. Charged particle momenta are measured using a magnetic central-tracking system, which consists of a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located within a 2 T superconducting solenoidal magnet [8]. Central and forward preshower detectors are located just outside of the superconducting coil (in front of the calorimetry). They are constructed from several layers of extruded triangular scintillator strips that are read out using wavelength-shifting fibers and VLPCs, and are used for electron and photon identification. The next layer of detection involves three liquid-argon/uranium calorimeters: a central section (CC) covering $|\eta|$ up to ≈ 1, and two end calorimeters (EC) extending coverage to $|\eta| \approx 4$, all housed in separate cryostats [9]. In addition to the preshower detectors, scintillators between the CC and EC cryostats provide sampling of developing showers at $1.1 < |\eta| < 1.4$.

A muon system resides beyond the calorimetry, and consists of tracking detectors and scintillation trigger counters before the 1.8 T toroids, followed by two more similar layers after the toroids. Tracking at $|\eta| < 1$ relies on 10 cm wide drift tubes [9], while 1 cm mini-drift tubes are used at $1 < |\eta| < 2$.

The luminosity is measured using plastic scintillator arrays located in front of the EC cryostats, covering $2.7 < |\eta| < 4.4$. The trigger and data acquisition systems are designed to accommodate the large instantaneous luminosity of Run II.

3. Data Sample and Event Selection

The data sample used here was collected with the DØ detector during the 2002-2003 run using a single electron trigger based solely on calorimetric information. Bad quality data are removed from the sample, leaving a total of 177.3 pb^{-1} of integrated luminosity.

Electrons and photons are first identified as electromagnetic (EM) clusters found in the central calorimeter using a simple cone algorithm. The fraction of energy in the EM calorimeter within the cone, f_{EM}, is required to be greater than 0.9. Shower shape and isolation requirements distinguish the EM objects from hadronic jets.

The missing transverse momentum is calculated by taking the vector sum $\vec{\not{E}}_T = -\sum_i E_i \sin\theta_i \hat{u}_i$, where the sum runs over all calorimeter cells that were read out except cells in the coarse hadronic section, E_i is the energy deposited in the ith calorimeter cell, θ_i, $\hat{u}_i$ are the angle and the direction defined by the cell center and the event vertex.

For this analysis, we require a candidate electron in the fiducial region of the central calorimeter with $|\eta^{det}| < 1.05$, $f_{EM} > 0.9$, $f_{iso} < 0.15$, $\chi^2(HM7) < 12$ and transverse energy $E_T > 25$ GeV. The isolation fraction f_{iso} measures the ratio between the energy measured in the ring between $\Delta R = 0.2$ and 0.4 around the electron direction and the energy in the $\Delta R = 0.2$ cone. The $\chi^2(HM7)$ variable measures the consistency of the shower shape with that expected for an electromagnetic shower. The electron candidate is also required to have a track that coincides spatially and to have an E/p ratio consistent with that of an electron.

The $Z \to ee$ candidate events used for tuning the simulation must have at least 2 candidate electrons, one of which must have fired one of the single electron triggers. Both electron candidates are required to pass the same selection criteria used for the selection of the $W \to e\nu$ candidates. This resulted in a sample of 3,169 candidate events with an invariant mass between 0 and 150 GeV.

The $W \to e\nu$ candidate events must have at least 1 electron candidate with a matched track, matching the trigger requirements for the event. In addition we require the events to to have a missing transverse energy $\not{E}_T > 25$ GeV and the W boson to have a transverse momentum $p_T^W < 20$ GeV. To remove the background from non identified $Z \to ee$ decays, we also veto events with a second isolated track event with $p_T > 15$ GeV recoiling against the candidate electron. This selection resulted in a sample of 75,910 candidate events with transverse mass between 50 to 200 GeV, and 625 candidate events with transverse mass between 100 to 200 GeV.

4. Monte Carlo Simulation

We use a parameterized model to simulate the detector response and resolution and thus obtain the prediction for the observed electron and recoil momenta.

To simulate the detector response to an electron of energy E_0, we compute the observed energy as

$$E(e) = R_{EM}(E_0) \otimes \sigma_{EM}(E_0) \tag{1}$$

where $R_{EM}(E_0)$ is the response of the electromagnetic calorimeter and σ_{EM} is the energy resolution of the electromagnetic calorimeter. The energy response $R_{EM}(E_0)$ is modelled using two parameters α and β: $R_{EM}(E_0) = \alpha \times E_0 + \beta$, where α is the EM energy scale and β EM energy offset. The resolution $\sigma_{EM}(E_0)$ is also modelled using two parameters C_{EM} and S_{EM}:
$\sigma_{EM}(E_0)/E_0 = \sqrt{C_{EM}^2 + S_{EM}^2/E_0}$, where C_{EM} is the constant term and S_{EM} the sampling term for the EM calorimeter.

The calorimeter position resolution is modelled using two parameters σ_η and σ_ϕ:

$\eta_{smear} = \eta_{gen} + x * \sigma_\eta$ and $\phi_{smear} = \phi_{gen} + y * \sigma_\phi$, where σ_η and σ_ϕ are η and ϕ resolutions, x and y are random variables from a normal distribution.

The model for the particles recoiling against the W/Z boson has two components, a "hard" component, that models the p_T of the W/Z boson, and a "soft" component, that models detector noise and underlying events. For the latter we use the transverse momentum imbalance $\vec{\not{p}}_T^{mb}$ from minimum bias events recorded in the detector. The observed recoil transverse momentum is then given by

$$\vec{u}_T = -[R_{rec}(q_T) \otimes \sigma_{rec}(q_T)]\hat{q}_T - \Delta u_{\|}\hat{p}_T(e) + \alpha_{mb}\vec{\not{p}}_T^{mb} \tag{2}$$

where q_T is the generated value of the boson transverse momentum, R_{rec} is the response, σ_{rec} the resolution of the hadronic calorimeter, $\Delta u_{\|}$ is the transverse energy flow into the electron window from the underlying event and pileup events, $\hat{p}_T(e)$ is the electron direction, and α_{mb} is a correction factor that allows us to adjust the resolution to the data. The hadronic momentum response is modelled with one parameter κ: $R_{rec}(q_T) = \kappa \times q_T$ and the hadronic energy resolution is modelled with two parameters S_{HAD} (sampling term) and C_{HAD} (constant term): $\sigma_{rec}(q_T)/q_T = \sqrt{C_{HAD}^2 + S_{HAD}^2/q_T}$.

We generate $Z \to ee$, $Z/\gamma^* \to ee$ and $W \to e\nu$ events with the PYTHIA generator and CTEQ6 parton distribution function (PDF) sets [10], then smear the generated $\vec{p}_T(e)$ and $\vec{u}_T$ vectors using the formulae described above and apply selection efficiencies introduced by the trigger and event selection requirements. The model parameters are adjusted to match the data.

The electron energy scale and energy offset are obtained by plotting the di-electron invariant mass of $Z \to ee$ events and adjusting the two parameters until the Monte Carlo distribution agrees with the data; the energy scale is determined to be $\alpha = 1.0054 \pm 0.0010$ and the energy offset is $\beta = 0.038 \pm 0.048$ GeV.

The energy resolution for electrons is described by sampling and constant terms. In the Monte Carlo simulation, we use a sampling term of 15% $\mathrm{GeV}^{1/2}$ derived from Run I beam tests, and assign a 3% uncertainty to this value. We constraint the constant term to $C_{EM} = (4.20 \pm 0.23)\%$ by requiring that the width of the dielectron invariant mass spectrum predicted by the Monte Carlo simulation be consistent with the Z data. Figure 2 shows the invariant mass distribution for data and Monte Carlo.

The response of the detector to the underlying event relative to its response to electrons is also determined using $Z \to ee$ events. Loosening the rapidity cuts so that one electron is required to be in the central region, while the other electron can be in central or endcap region, brings the rapidity distribution of the Z bosons closer to that of the W bosons (since there is no rapidity cut on the unobserved neutrinos in W events). In $Z \to ee$ decays, momentum conservation requires $\vec{p}_T^{\,ee} = -\vec{p}_T^{\,rec}$, where $\vec{p}_T^{\,ee}$ is the sum of the two electron p_T vectors. To minimize sensitivity to the electron energy resolution, we project $\vec{p}_T^{\,ee}$ and $\vec{p}_T^{\,rec}$ on the inner bisector of the two electron directions, called the η axis, ξ axis is the axis orthogonal to the η axis. The hadronic momentum response is determined to be

$\kappa = 0.67 \pm 0.02$ by plotting $\vec{p}_T^{ee} \bullet \hat{\eta}$ as function of $< \vec{p}_T^{rec} \bullet \hat{\eta} >$ and then fitting with a linear function. The sampling term for the hadronic calorimeter is determined to be $S_{HAD} = 0.80 \pm 0.20$ GeV$^{1/2}$, and the constant term is determined to be $C_{HAD} = 0.05 \pm 0.01$ using di-jet and γ+jet events.

The recoil of the W boson may affect the electron identification, especially if the recoil system is close to the electron. A measurement of the event selection biases due to the electron isolation cut can be obtained by studying the projection of the hadronic recoil momentum along the electron direction $u_{\|} = \vec{p}_T^{rec} \bullet \hat{e}$, where $\hat{e}$ is a unit vector in the electron direction. The efficiency as a function of $u_{\|}$ is fit to a function of the form:

$$\epsilon(u_{\|}) = \epsilon_0 \begin{cases} 1 & \text{for } u_{\|} < u_0; \\ 1 - s(u_{\|} - u_0) & \text{otherwise.} \end{cases}$$

The parameter ϵ_0 is an overall efficiency which is inconsequential for this measurement, u_0 is the value of $u_{\|}$ at which the efficiency starts to decrease as a function of $u_{\|}$, and s is the rate of decrease. We obtain the best fit for $\epsilon_0 = (98.48 \pm 0.06)\%$, $u_0 = -0.908 \pm 0.599$ GeV and $s = 0.004364 \pm 0.000587$ GeV^{-1}.

The recoil u_T is corrected for the momentum that is lost by excluding the electron window. The momentum that is lost points in direction of the electron and therefore biases $u_{\|}$ towards negative values. Since for $p_T^W \ll M_W$, $m_T \approx 2p_T(e) + u_{\|}$, any $u_{\|}$ bias directly propagates into a bias on the transverse mass. The $u_{\|}$ correction ($\Delta u_{\|}$) is very sensitive to the ratio of W events with $u_{\|} > 0$ and $u_{\|} < 0$. We change the $u_{\|}$ correction in the Monte Carlo simulation until it gives the same ratio as in data, giving a $u_{\|}$ correction of -1.78 ± 0.01 GeV. As described above, to model the detector noise and pileup, we add $\vec{p}_T^{mb}$ from a random $p\bar{p}$ interaction to the smeared boson p_T. Since the instantaneous luminosity profile for the recorded W and minimum bias events are different, we weight the minimum bias events so that their instantaneous luminosity approximates that of the W events. α_{mb} is determined to be 0.95 ± 0.05 by varying α_{mb} in MC until the simulated $u_{\|}$ and $u_{\perp}$ distributions agree with the data distributions. Finally, the distribution of the transverse momentum of W bosons p_T^W obtained in the Monte Carlo is reweighted to match the one obtained from data.

5. Likelihood Fitting

We generate a set of Monte Carlo M_T templates with Γ_W varying from 1.6 GeV to 3.6 GeV at intervals of 50 MeV. These templates are normalized to the number of $W \to e\nu$ data events in the region of $50 < M_T < 100$ GeV. The background distributions of QCD, $Z \to ee$ and $W \to \tau\nu$ events are added to the templates and a binned maximum likelihood is calculated for data. The fitting region is chosen to be 100 GeV $< M_T <$ 200 GeV. From the dependence of the likelihood on Γ_W (Fig.

3), we obtain the W boson width and its error as $\Gamma_W = 2.011 \pm 0.093$ GeV. Figure 4 shows the data and MC comparison plots for M_T with the fitted W width.

6. Systematic Uncertainties

The systematic uncertaines in the determination of the W width are due to effects that could alter the transverse mass distribution. Uncertainties in each input parameter of the Monte Carlo can affect the measurement of Γ_W. These parameters are constrained in most cases by the $Z \to ee$ data. Since there is only a finite Z sample, there is an error associated with each part of the detector model. Although these errors are considered as systematic errors for the width measurement, they are really statistical errors which depend on the number of Z events.

To estimate the effects, we allow these input parameters to vary by one standard deviation and then re-generate the transverse mass spectrum with the same procedure used to determine the mean value of W width. If the variation of the W boson width with respect to a parameter is not linear, the error is symmetrized by assigning the larger value. A 100% uncertainty is assigned to the shift of the W width obtained when reweighting the distribution of the transverse momentum of the W boson, p_T^W.

Additional uncertainties arise from uncertainties in the value of the W mass (constrained to its world average) and from uncertainties in the production model, the parton distribution and from the effects of final state photon radiation. Pending further investigation these uncertainties are taken from our previous measurement [5].

Table 1 lists the uncertainties in the measured W width caused by each individual source.

7. Results

We have described a direct measurement of the W boson total decay width Γ_W, the result is $\Gamma_W = 2.011 \pm 0.093$ (stat) ± 0.107 (syst) GeV. Figure 5 shows the W boson width results compared with the SM prediction.

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Table 1. Uncertainties for the W width measurment.

Source	$\Delta\Gamma_W$ (MeV)
EM Energy Scale	15
EM Energy Offset	17
EM Energy Resolution, Sampling	30
EM Energy Resolution, Constant	41
HAD Momentum Response	40
HAD Energy Resolution, sampling	50
HAD Energy Resolution, constant	7
Primary Vertex	10
Position Resolution σ_η	5
Position Resolution σ_ϕ	5
Underlying Event	47
$u_{\|\|}$ Correction ($\Delta u_{\|\|}$)	4
$u_{\|\|}$ Efficiency s	1
$u_{\|\|}$ Efficiency u_0	1
Selection Bias	10
QCD Backgrounds	3
$Z \to ee$ Backgrounds	negligible
$W \to \tau\nu$ Backgrounds	negligible
p_T^W	29
M_W	15
PDF	27
Radiactive Decays $\Delta R(e\gamma)$	3
Total Systematic Uncertainty	107
Total Statistical Uncertainty	93
Total Uncertainty	142

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7. We use a coordinated system (ρ, θ, ϕ) where ρ is the perpendicular sdistance from the beam line, θ is the polar angle measured relative the the proton beam direction z, and ϕ is the azimuthal angle. The pseudorapidity η is defined as $-\ln(\tan\theta/2)$.

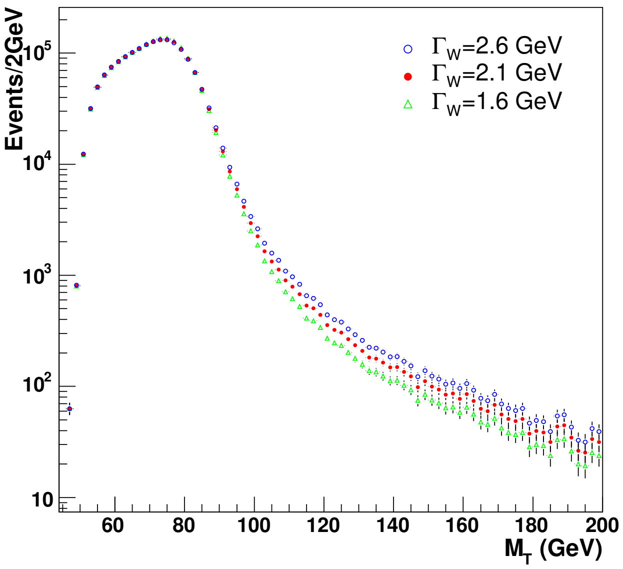

Fig. 1. Transverse mass spectra from Monte Carlo simulation with different W widths with an arbitrary normalization. The triangles are for $\Gamma_W = 1.6$ GeV, the dots are for $\Gamma_W = 2.1$ GeV and the circles are for $\Gamma_W = 2.6$ GeV.

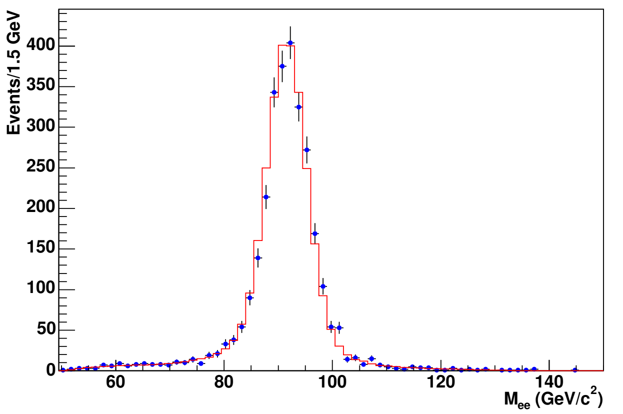

Fig. 2. Invariant Mass distribution for $Z \to ee$ events (Blue dots for data, Red line for MC).

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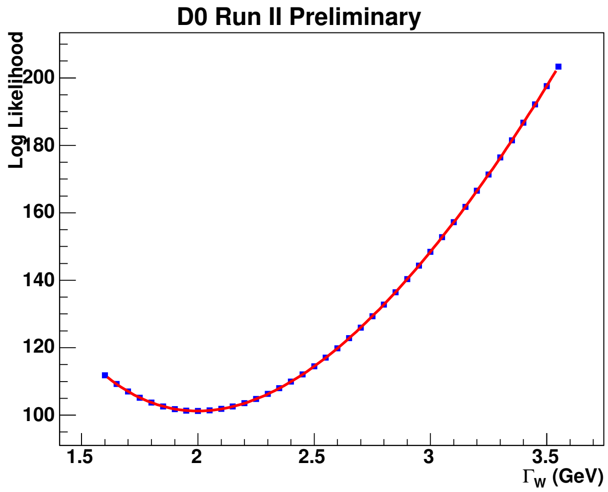

Fig. 3. Results of the maximum likelihood fit of the data to Monte Carlo templates. Monte Carlo templates are generated with Γ_W between 1.6 and 3.6 GeV at 50 MeV intervals. Each point represents a log-likelihood fit performed over the range $100 < M_T < 200$ GeV. The curve is the best fit of the likelihood points to a fourth order polynomial. The best value is 2.011 ± 0.093 GeV.

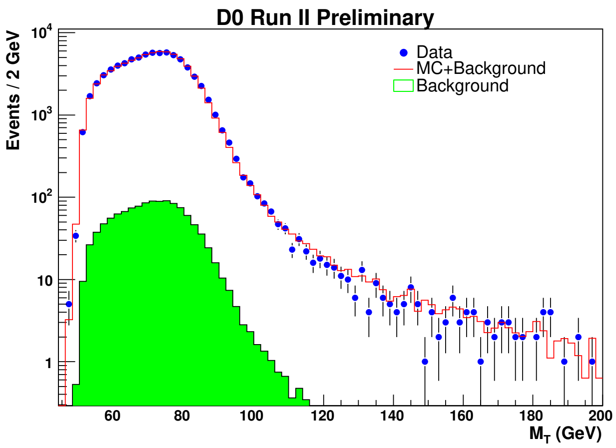

Fig. 4. Comparison of data to Monte Carlo templates for the transverse mass shape. The dots with error bars are data, the shadowed area is QCD background and the line corresponds to the sum of the $W \to e\nu$ and $W \to \tau\nu$ Monte Carlo samples and of the QCD background for the fitted value of the W width. The normalization of the Monte Carlo samples i s obtained from the transverse mass distribution in the [50, 100] GeV region, while the W width is obtained by the li kelihood fit in the [100, 200] GeV region.

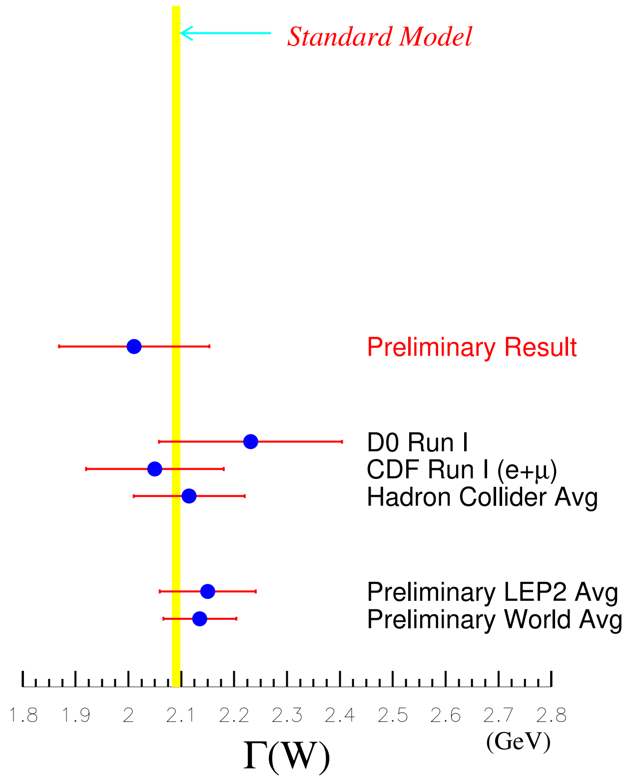

Fig. 5. Comparison of this measurement with previously published direct measurements of the W boson width. The shaded region indicates the predicted W width value.

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