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A Direct Measurement of the *W* Boson Width $\Gamma(W)$

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Abstract

This letter describes a direct measurement of the W boson decay width, $\Gamma(W)$, using the high-mass tail of the transverse mass spectrum of $W \to e\nu$ decays recorded by the CDF experiment. We find $\Gamma(W) = 2.11 \pm 0.28(stat.) \pm 0.16(sys.)\ GeV$, and compare this direct measurement with indirect means of obtaining the width.

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The W boson width, $\Gamma(W)$, is a fundamental parameter that is well-predicted in the Standard Model. The W decays with approximately equal probability to each of three lepton and two quark families kinematically available (with a color factor of three on the number of quark families). Hence, its branching ratio into $(\ell,\overline{\nu_\ell})$ is approximately $\frac{1}{9}$. The quark decays are enhanced by $\alpha_s(M_W)/\pi$ to first order in QCD so that the leptonic branching ratio is[1] 0.1084 $\pm$ 0.0002, where the 0.0002 reflects the uncertainty in the value of α_s at $Q^2{=}M_W^2$. The predicted W width may then be predicted by dividing the leptonic partial width $\Gamma(W \to \ell\nu) = (G_F/\sqrt{2})(M_W^3/6\pi)$ by the branching ratio. Using $M_W = 80.14 \pm 0.27\ GeV/c^2$,[2] Rosner *et al.*[1] find $\Gamma(W) = 2.067 \pm 0.021\ GeV$ where the uncertainty in the prediction is dominated by the uncertainty in M_W.

The W width has been obtained experimentally[3] by an indirect method using the ratio $R = \sigma \cdot B(p\overline{p} \to W \to \ell\nu)/\sigma \cdot B(p\overline{p} \to Z^0 \to \ell^+\ell^-)$. A measurement of R, together with a calculation[4] of the ratio of production cross sections $\sigma(p\overline{p} \to W)/\sigma(p\overline{p} \to Z^0)$ and the LEP measurements[5] of $\Gamma(Z^0)$ and $\Gamma(Z^0 \to \ell^+\ell^-)$, is used to obtain a measurement of the W leptonic branching ratio $\Gamma(W \to \ell\nu)/\Gamma(W)$. A calculation of $\Gamma(W \to \ell\nu)$ is then used to obtain the W width. With this method a precision of 85 MeV has been obtained. As Rosner *et al.*[1] have noted, however, loops at the W-fermion vertex involving a Z^0 or scalar Higgs ϕ,[6] could alter the effective W-fermion coupling, and hence $\Gamma(W)$, but not affect the ratio $\Gamma(W\to\ell\nu)/\Gamma(W)$. Thus, a measurement of $\Gamma(W)$ from $\Gamma(W\to\ell\nu)/\Gamma(W)$ assumes that the W coupling to leptons is given by the Standard Model. While in principle such non-standard couplings would also alter the W production cross section and thus affect the value of $\Gamma(W\to\ell\nu)/\Gamma(W)$ extracted from R, a direct measurement of the full width $\Gamma(W)$ is desirable so that these radiative corrections to $\Gamma(W)$ can be observed.

Direct measurements of $\Gamma(W)$ have been reported by the UA1[7] and UA2[8] Collaborations. Including systematic uncertainties, they obtain the values $\Gamma(W) = 2.8\ ^{+1.4}_{-1.5} \pm 1.3\ GeV$ and $\Gamma(W) < 7.0\ GeV$ (90% C.L.) respectively. These direct measurements result from fits of the W transverse mass distribution for the best values of M_W and $\Gamma(W)$. The transverse mass is defined as $M_T = \sqrt{2P_T^e P_T^\nu(1\text{-}\cos(\Delta\phi))}$, where P_T^e and P_T^ν are the transverse momenta[9] of the electron and neutrino and $\Delta\phi$ is the azimuthal angle between them. The fits were performed over a limited range in M_T near the M_W peak.

The tail of the transverse mass distribution of the W contains information on $\Gamma(W)$. Events with $M_T > M_W$ can arise due to the non-zero W width or due to the calorimeter resolution. The resolution, furthermore, degrades for large values of the W transverse momentum, P_T^W. However, a precise measurement of $\Gamma(W)$ from the high-mass tail is possible[10] because the P_T^W distribution is sufficiently well-known and because far above M_W the Breit-Wigner tail dominates over the gaussian resolution of the detector. In this analysis the W width is determined from a binned log-likelihood fit to the transverse mass distribution in the region $M_T > 110\ GeV/c^2$, where a Monte Carlo study indicates there is good sensitivity to the width and the systematic uncertainties are small. Possible non-gaussian tails to the resolution are discussed below.

This measurement is made with $19.7 \pm 0.7\ pb^{-1}$ of data collected by the Collider Detector at Fermilab (CDF) during the 1992-1993 run of the Fermilab Tevatron Collider. The Tevatron produces $p\bar{p}$ collisions at $\sqrt{s} = 1.8\ TeV$. Detailed descriptions of the detector can be found elsewhere.[11] The portions of the detector relevant to this measurement are (i) electromagnetic and hadronic calorimeters covering the pseudorapidity[12] range $|\eta| < 4.2$ and arranged in a projective tower geometry; (ii) a drift chamber (CTC) immersed in a 1.4 T solenoidal magnetic field for tracking charged particles in the range $|\eta| < 1.4$; (iii) a time-projection chamber (VTX) for vertex finding; and (iv) two arrays of scintillator hodoscopes located on either side of the detector for triggering.

To select candidate events we require an electron in the central barrel region of the detector ($|\eta| < 1.05$) with calorimeter transverse energy $E_T > 30\ GeV$[10] and CTC transverse momentum $P_T > 13\ GeV/c$. We require the electron track to be isolated in the CTC, requiring $Iso(trk) < 5\ GeV/c$, where $Iso(trk)$ is defined as the scalar sum of the P_T of all tracks except the electron track within a region in η-ϕ space of $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.25$ centered on the electron. The ratio of energy in the hadron (Had) and electromagnetic (EM) calorimeter towers of the electron cluster is required to satisfy Had/EM $< 0.055 + 0.045 \times \left(\frac{E\ (GeV)}{100}\right)$. A transverse momentum imbalance is required to signal the presence of the neutrino. We require $\not{E}_T > 30\ GeV$, where the missing transverse momentum, or $\not{E}_T$, is defined as the vector sum of the E_T in all calorimeter towers with $|\eta| < 3.6$. Finally, the $p\bar{p}$ interaction point, which is distributed by an approximate gaussian of width $\sigma_Z = 26\ cm$ along the beam direction, is required to satisfy $|Z_{int}| < 60$ cm, and the total accidental calorimeter energy not in time with the $p\overline{p}$ collision is required to be $< 100\ GeV$. There are 10845 events passing these cuts. Of these, 93 events with second isolated, high-P_T tracks pointing to electromagnetic clusters are removed from the W sample as Z^0 candidates, and 226 events with clusters of tracks in the CTC which point at the $\not{E}_T$ vector in ϕ and at calorimeter cracks in η are removed as mismeasured QCD jet events ("dijets"), leaving 10526 events.

Several processes can also mimic the W signal. The process $W \to \tau\nu \to e\nu\nu\nu$ has a signature similar to $W \to e\nu$ decays, but at lower M_T. The process $Z^0 \to e^+e^-$, where one electron is detected and the other is lost because it falls into an uninstrumented region of the detector, can produce the signal of an electron and $\not{E}_T$, as can *QCD* dijet events where one jet is lost and the other passes our electron selection criteria. We use the ISAJET Monte Carlo program[13] and a detector simulation to estimate the number of $Z^0 \to e^+e^-$ and $W \to \tau\nu$ decays contaminating the W sample. We find that the number of Z^0 events remaining in the W sample is 50 ± 15 events and the background from $W \to \tau\nu$ is 150 ± 45 events. The *QCD* dijet background is estimated by studying a data sample of events with an "electron" + $\not{E}_T$ in which the "electron" has $Iso(trk) > 6\ GeV/c$. These events are presumably mismeasured dijet events. We study the efficiency of our dijet removal cuts on this sample and normalize to the number (226) of events in the W sample removed using these cuts. We estimate that the number of dijets left in the sample is 241 ± 40 events. We observe 124 events with $M_T > 110\ GeV/c^2$. We expect that 3.5 ± 0.5 events are due to Z^0 and $W \to \tau\nu$ events and that 53 ± 8 events are from *QCD* dijets .

The W transverse mass spectrum is modeled using a Monte Carlo program that generates zeroth order diagrams of W production, $q\overline{q} \to W$, according to an energy-dependent Breit-Wigner distribution:[14]

$$\sigma(\hat{s}) \sim \frac{\hat{s}}{[(\hat{s} - M_W^2)^2 + \hat{s}^2\Gamma_W^2/M_W^2]}$$

where $\sqrt{\hat{s}}$ is the (possibly off-shell) $\ell\nu$ mass. This form of the cross section includes vacuum polarization contributions to the W propagator. We use the MRSD-' structure functions.[15] The effects of higher order diagrams for W production are mimicked by giving the bosons P_T according to a previous measurement[16] of the P_T^W spectrum. The lepton momenta are passed through a simulation of the detector response. The same kinematic and geometric cuts as in the data are applied.

A cut of $P_T^W < 20$ GeV/c is imposed in order to suppress many of the expected backgrounds in the fit region ($M_T > 110$ GeV/c^2) and in order to suppress the broader calorimeter resolution which arises at large P_T^W. With this cut, the number of $W \rightarrow e\nu$ candidates is reduced from 10526 to 9701 and the total background is reduced from 441 ± 62 events to 224 ± 44 events. The background in the fit region is reduced to ~ 10% of the 58 events observed. Furthermore, Monte Carlo studies indicate that the uncertainty in $\Gamma(W)$ due to the P_T^W shape is reduced from 700 MeV to 120 MeV. Figure 1 shows the transverse mass distribution of the 9701 candidate events after the $P^W_T < 20$ GeV/c cut, along with the expected background.

To obtain $\Gamma(W)$ a binned log-likelihood fit to the W M_T distribution, binned in 1 GeV/c^2 bins, is performed for $M_T > 110$ GeV/c^2. Monte Carlo templates are generated with values of $\Gamma(W)$ between 0.667 and 3.667 GeV at 200 MeV intervals. In the templates the M_T shapes are the sum of W Monte Carlo and of backgrounds, where the background is normalized to 224 events and the W Monte Carlo is normalized to 9701 - 224 = 9477 events. The data are fit to each template and a likelihood curve *vs.* $\Gamma(W)$ is made. Figure 2 shows the likelihood curve for the data. The most likely value is $\Gamma(W)$ = 2.04 ± 0.28 GeV. The uncertainty is purely statistical and is determined by the point where the likelihood decreases by 0.5.

As a check of the fitting technique, we generate an ensemble of Monte Carlo "experiments" of 9477 W events each, add 224 background events, and fit to the Monte Carlo templates above. The mean returned value of $\langle\Gamma(W)\rangle$ = 2.10 ± 0.02 GeV is obtained from the ensemble of "experiments," to be compared to the input value of 2.07 GeV. Furthermore, the r.m.s. = 250 ± 17 MeV of the fitted values is consistent with the 280 MeV statistical uncertainty estimated from the data.

The systematic uncertainties in this determination of the W width are due to effects that alter the shape of the transverse mass distribution. They are: the P_T^W distribution, the electron resolution, the neutrino resolution, the backgrounds, and the electron energy scale. To estimate the uncertainties due to these effects, we allow these parameters to vary in our Monte Carlo program and then re-fit the Monte Carlo transverse mass spectrum with the varied input parameters to the original Monte Carlo templates.

The Monte Carlo model of the $\not{E}_T$ resolution is compared to the $\not{E}_T$ observed in $Z^0 \rightarrow e^+e^-$ decays, where any $\not{E}_T$ in the event is due to the energy response of the calorimeter and not due to neutrinos. Varying the gaussian width of the $\not{E}_T$ resolution by the amount allowed by the Z^0 data leads to a 4.9% variation in $\Gamma(W)$. Possible non-gaussian tails in the calorimeter $\not{E}_T$ resolution, which have been checked using minimum bias data, lead to negligible variations in $\Gamma(W)$. The calorimeter electron energy scale and resolution are determined using the mass peak position and width of $Z^0 \rightarrow e^+e^-$ decays. Allowing the scale and resolution to vary in the Monte Carlo leads to 2.0% and 0.6% variations in $\Gamma(W)$, respectively. Allowing the background to vary within its estimated uncertainty causes 0.8% variations in $\Gamma(W)$.

Distorting the input P_T^W distribution in the Monte Carlo within its uncertainty and fitting the Monte Carlo with the distorted P_T^W to the nominal templates, we find a variation of 6%, or 120 MeV, in $\Gamma(W)$. A different kind of P_T^W uncertainty arises because of the theoretical expectation[17] that the P_T^W distribution varies logarithmically, $\sim \frac{\alpha_w \times \alpha_s}{P_T^2}\log(\frac{M^2}{P_T^2})$, with the mass M of the $\ell\nu$ pair. We have checked this possible source of bias in two ways: first, we fit a Monte Carlo sample with this new P_T^W distribution to the Monte Carlo templates generated with the nominal distribution and observe a shift of 23 MeV in $\Gamma(W)$. Second, we have performed the entire analysis with a cut of $P_T^W < 10$ GeV/c, observing a shift of 0 MeV. The contribution of these shifts, when combined in quadrature with the 120 MeV uncertainty from the input W P_T spectrum, is negligible.

Finally, we apply a shift to $\Gamma(W)$ due to the effect of radiative decays of the W, $W \rightarrow e\nu\gamma$, not accounted for in our Monte Carlo. While most of the radiated γ 's are collinear with the electron and, hence, are clustered in with the electron energy, some of the photons are radiated at wide angles. These wide angle photons carry away some of the W mass, and, hence, shift the M_T distribution downward. We have used a Monte Carlo program[18] to estimate that we must shift our value for $\Gamma(W)$ up by 70 $\pm$ 28 MeV to correct for radiative decays.

Assembling the results, the final result for the W width is:

$$\Gamma(W) = 2.11 \pm 0.28(stat.) \pm 0.16(sys.)\ GeV.$$

As a check, we instead fit over the region $M_T > 120\ GeV/c^2$, and obtain a value of $\Gamma(W) = 2.15 \pm 0.34(stat.) \pm 0.09(sys.)\ GeV$. Here the systematic uncertainty is smaller because the cut-off for the fit is farther from the falling edge of the resolution. Note that the $M_T > 110\ GeV/c^2$ sample has 58 events and the $M_T > 120\ GeV/c^2$ sample has 35 events.

In conclusion, we have reported on a direct measurement of the W boson decay width, $\Gamma(W) = 2.11 \pm 0.28(stat.) \pm 0.16(sys.)\ GeV$, using the tail of the transverse mass distribution of $W \rightarrow e\nu$ decays in 19.7 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1800\ GeV$. With the combined data set of 200 pb^{-1} from both the CDF and DØ detectors anticipated in the next year, a 100 MeV measurement may be anticipated. This may be compared with the expected uncertainty[19] from the LEP-200 experiments of 200 MeV, which will be obtained after five years of data-taking. With future runs of the Fermilab collider, a 30 MeV measurement is possible, which approaches the level of the radiative corrections to the width.

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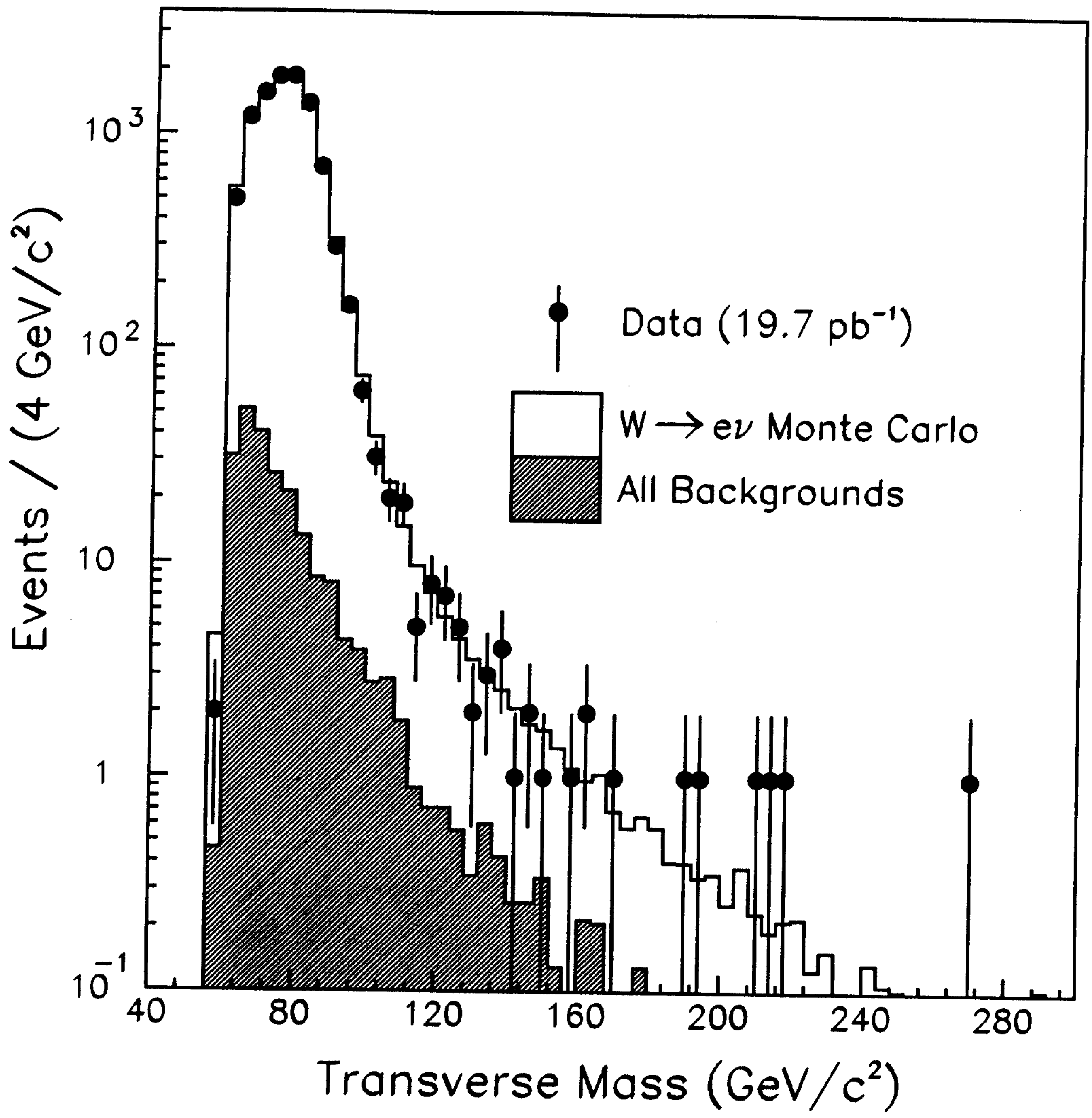
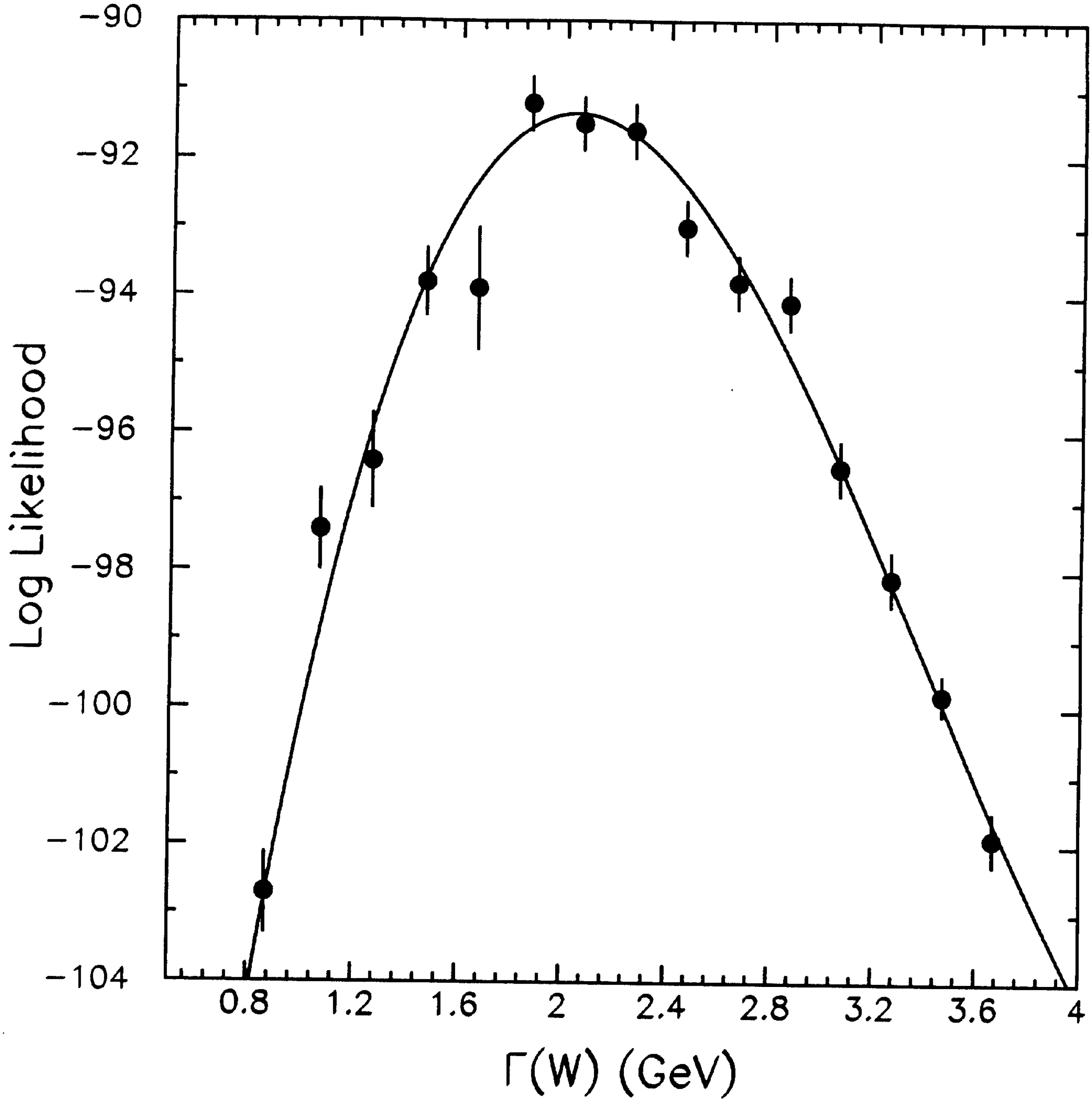
Figure Captions

Figure 1: Transverse mass distribution of the 9701 W candidates surviving a cut of $p_T^W < 20\ GeV/c$, along with the expectation for the background and the expected W shape from the Monte Carlo program. In the Monte Carlo, $\Gamma(W) = 2.067\ GeV$ was used.

Figure 2: Results of the log likelihood fit of the data to Monte Carlo templates of different W widths. Each point represents a log-likelihood fit performed over the range $M_T > 110\ GeV/c^2$. The curve is the best fit of the likelihood points to a cubic polynomial. The most likely value is at $\Gamma(W) = 2.04\ GeV$.



Data (19.7 pb^{-1})
W → eν Monte Carlo
All Backgrounds
Events / (4 GeV/c^2)
10^3
10^2
10
1
10^{-1}
40
80
120
160
200
240
280
Transverse Mass (GeV/c^2)



-90
-92
-94
-96
-98
-100
-102
-104
Log Likelihood
0.8
1.2
1.6
2
2.4
2.8
3.2
3.6
4
Γ(W) (GeV)