Fermi National Accelerator Laboratory

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Measurement of the Ratio $\sigma(W \longrightarrow e\nu)/\sigma(Z \longrightarrow ee)$ in $\bar{p}p$ Collisions at $\sqrt{s}$=1.8 TeV*

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An analysis of W and Z boson production using data from the Collider Detector at Fermilab (CDF) at $\sqrt{s} = 1.8$ TeV yields $\sigma(W \to e\nu)/\sigma(Z \to ee) = 10.2 \pm 0.8$ (stat) $\pm$ 0.4 (sys). The width of the W boson, $\Gamma(W)$, and a limit on the top quark mass independent of decay mode are extracted from this measurement.

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The ratio of the cross section in $\overline{\mathrm{p}}\mathrm{p}$ collisions for W production to that of Z production with subsequent decays into electron(s) can be expressed [1] as

$$\mathrm{R} = \frac{\sigma(W \to e\nu)}{\sigma(Z \to ee)} = \frac{\sigma(\overline{\mathrm{p}}\mathrm{p} \to WX)}{\sigma(\overline{\mathrm{p}}\mathrm{p} \to ZX)} \frac{\Gamma(W \to e\nu)}{\Gamma(Z \to ee)} \frac{\Gamma(Z)}{\Gamma(W)}. \tag{1}$$

From R, the ratio of the total widths, $\Gamma(Z)/\Gamma(W)$, can be extracted since the ratio of the production cross sections, $\sigma(\overline{\mathrm{p}}\mathrm{p} \to WX)/\sigma(\overline{\mathrm{p}}\mathrm{p} \to ZX)$, and the ratio of the partial widths for electron decays, $\Gamma(W \to e\nu)/\Gamma(Z \to ee)$, are predicted from the proton structure functions, Standard Model couplings [2], and the vector boson masses. Theoretical uncertainties in the cross sections and experimental systematic uncertainties tend to cancel. Recent measurements [3] of $\Gamma(Z)$ allow $\Gamma(W)$ to be calculated with a much smaller uncertainty than that obtained by direct measurements.

We present a measurement of R using a data sample from the Collider Detector at Fermilab (CDF) corresponding to an integrated luminosity of 4.4 pb^{-1} in $\overline{\mathrm{p}}\mathrm{p}$ collisions at a center of mass energy $\sqrt{s} = 1.8$ TeV. Previous measurements have been reported at $\sqrt{s} = 630$ GeV, and limits on the number of light neutrino generations and the top quark mass have been extracted from these results [4,5].

In the CDF detector [6] scintillator planes (BBC) located at small angles to the beam directions signal an inelastic event. A vertex time-projection chamber (VTPC) measures the event vertex, and a drift chamber enclosed by a superconducting solenoid allows for precise momentum measurement. Calorimeter coverage extends in a projective tower geometry from $-4.2 < \eta < 4.2$, where $\eta \equiv -\ln(\tan\theta/2)$ [7]. The forward, $2.4 <| \eta |< 4.2$, and plug, $1.1 <| \eta |< 2.4$, calorimeters are constructed with gas proportional chambers. The central calorimeters, $| \eta |< 1.1$, use scintillator as the active medium. A proportional chamber (strip chamber) imbedded near shower maximum in the central electromagnetic calorimeter (CEM) measures the position and shape of electromagnetic showers.

W and Z candidates were selected from a common sample of events with at least one well-

measured, isolated, high transverse momentum (p_T) electron in the CEM. Loose cuts were then adequate to determine with high efficiency whether the other lepton was a neutrino (W decay) or an electron (Z decay) . This strategy cancels systematic uncertainties in the event selection, integrated luminosity, and efficiency of the central electron selection in the W/Z ratio. It was also required that there be no additional clusters with transverse energy (E_T) > 10 GeV other than the electron(s) in the event [8]. This "zero jet" requirement reduces systematic uncertainties and backgrounds.

Events had to pass a hardware trigger requiring: (i) hits in both forward and backward BBCs, (ii) a CEM cluster with $E_T > 12$ GeV, (iii) a track associated with this cluster with $p_T > 6$ GeV/c, and (iv) the ratio of hadronic to electromagnetic E_T in the cluster (H/E) be < 12.5%.

The central electron sample was selected by requiring that: (i) there exist a CEM cluster with $|\eta| < 1.0$ and $E_T > 20$ GeV, (ii) the cluster be away from calorimeter edges so that its energy is well measured, (iii) the ratio of cluster energy to track momentum, E/P, be in the range $0.5 < E/P < 2.0$, (iv) the strip chamber shower profile in the z direction and the lateral energy sharing between calorimeter towers be consistent with an electron shower, (v) $H/E < 0.05$, (vi) there be a good match between the strip chamber shower and the extrapolated track positions, and (vii) a measure of isolation, Iso = $(E_C - E_T)/E_T$ where E_C is the total transverse energy within a cone of radius 0.4 in $\eta - \phi$ space centered on the cluster, be < 0.1. Finally, the event vertex had to be within 60 cm (2σ) of the center of the interaction region in the z direction. A total of 4777 events satisfy these criteria.

W candidates were selected by requiring that the missing transverse energy ($\not{E}_T$), defined as the magnitude of the vector sum of transverse energy over all calorimeter towers in the region $|\eta| < 3.6$, be > 20 GeV, and there exist no additional clusters with $E_T > 10$ GeV. There are 1828 events satisfying these criteria. Figure 1 shows the transverse mass (M_T) spectrum of these events

along with a Monte Carlo prediction ($M_T = \sqrt{2E_T \not{E}_T(1-\cos\alpha)}$ where α is the azimuthal angle between the $\not{E}_T$ vector and the electron).

Z candidates were selected by requiring that: (i) there be a second electromagnetic cluster with $E_T > 10$ GeV in any of the regions $0.05 <| \eta |< 1.0$, $1.3 <| \eta |< 2.2$, or $2.4 <| \eta |< 3.7$, (ii) the cluster be away from calorimeter edges, (iii) $H/E < 0.1$, (iv) Iso < 0.2, (v) if the cluster is in the central region, $0.5 < E/P < 2.0$, and (vi) if the cluster is in the plug region, the transverse energy profile be consistent with electron test beam results. We required no additional clusters with $E_T >$ 10 GeV. Figure 2 shows the invariant mass distribution of these events. Finally, the invariant mass of the two electromagnetic clusters was required to be between 65 and 115 GeV/c^2. There are 193 events satisfying these criteria.

The largest background in the $W \rightarrow e\nu$ sample is from $W \rightarrow \tau\nu$, followed by $\tau \rightarrow e\nu\nu$. We have used the ISAJET Monte Carlo [9] and the observed $W \rightarrow e\nu$ rate to estimate this background to be 67 ± 6 events. Another background is $Z \rightarrow ee$, with one electron undetected by the calorimeters. ISAJET with a full detector simulation predicts 12 ± 5 events. The W background from $Z \rightarrow \tau\tau$ was similarly found to be 4 ± 1 events. Background from jet production was estimated to be 18 ± 9 events by comparing the rates of isolated and non-isolated electrons in events passing the $\not{E}_T$ cut (i.e. the W sample) to the rates for a sample with the same electron cuts but with $\not{E}_T < 10$ GeV.

From a study of the isolation of the second electron we estimate the background in the $Z \rightarrow ee$ sample from jet production to be 5 ± 3 events with no contribution in the central region where we have momentum determination. The background due to $Z \rightarrow \tau\tau$ was estimated to be < 0.5 events using ISAJET and the detector simulation. The background due to QCD production of W events with jets was estimated to be 1 ± 1 event by comparing the $\not{E}_T$ distribution of our Z sample to the $\not{E}_T$ distribution of W plus jet events produced from the PAPAGENO Monte Carlo [10] with the detector simulation. The W and Z selection is summarized in Table 1.

Using experimentally measured quantities, R can be written

$$R = \frac{N_W}{N_Z}\frac{A_Z}{A_W}\frac{\epsilon_Z}{\epsilon_W}, \tag{2}$$

where N_W and N_Z are the background-subtracted number of W and Z candidates, A_Z and A_W are the geometrical acceptances including the electron E_T cut, and ϵ_Z and ϵ_W are the detection efficiencies for $Z \to ee$ and $W \to e\nu$ decays. The acceptances were calculated with a Monte Carlo which generates W and Z bosons from the leading order diagram $q\overline{q} \to W(Z)$ using a variety of proton structure functions and simple parameterizations of the boson p_T. A simple detector model, with nominal energy resolutions [6] and with $\not{E}_T$ resolution determined from the W data, was used to check that the decay leptons passed the E_T cuts, and that the electrons passed fiducial cuts. Using the MRSB structure functions [11], we find $A_W = 35.1\%$ and $A_Z = 37.4\%$. Different structure functions [12] can change A_Z/A_W by up to $\pm$ 2.5%; we take this to be the contribution to the systematic uncertainty from the structure functions. A change in $\sin^2\theta_W$ from 0.229 of $\pm$ 0.007 changes A_Z/A_W by $\pm$ 0.8% and variations in the p_T spectrum of the bosons affect A_Z/A_W at the $\pm$ 0.6% level. We assign an additional 1% uncertainty due to higher order corrections to the W and Z rapidity distributions. The acceptances agree with results from the ISAJET program.

The ratio of efficiencies in Eq. 2 can be written:

$$\frac{\epsilon_Z}{\epsilon_W} = \frac{F_{cc}c_1(2c_2 - c_1) + F_{cp}c_1 p + F_{cf}c_1 f}{c_1\epsilon_\nu}, \tag{3}$$

where F_{cc},F_{cp},F_{cf} are the fraction of Z events with the second electron in the central, plug, and forward regions extracted from the acceptance studies, ϵ_ν is the efficiency for the $\not{E}_T$ cut for a W decay with an electron of $E_T > 20$ GeV, and c_1, c_2, p, and f are the efficiencies for the common central, loose central, plug, and forward electron selections.

The efficiency c_1 almost cancels completely because a central electron is required for every event. The term $(2c_2 - c_1)$ arises because Z events with both electrons in the central region can

have either electron satisfy the common electron cuts. The neutrino efficiency was studied with the Monte Carlo generator by varying the p_T spectrum of the W and the $\not{E}_T$ resolution of the detector. The electron efficiencies were measured using a W sample selected on the basis of $\not{E}_T$ and by studying the second electron in Z decays. The results obtained from the two methods agree well. The values of the acceptances and the efficiencies are summarized in Table 2.

The "zero jet" requirement is expected to increase the ratio R by 0.8% ±0.5% [13]. The changes in R when varying the jet threshold from 5–15 GeV are consistent with statistical fluctuations. A second effect, due to the Drell-Yan continuum, increases the number of Z candidates and thus decreases the ratio R by an estimated 0.5%. We therefore multiply R by the factor 0.997 for the combined effects.

From the numbers of Tables 1 and 2 we obtain R = 10.2 ± 0.8 (stat) ± 0.4 (sys). Using this value of R, $\sin^2\theta_W = 0.229$ [14], predicted values for $\sigma(W)/\sigma(Z) = 3.23 \pm 0.03$ [15], and $\Gamma(W \to e\nu)/\Gamma(Z \to ee) = 2.70 \pm 0.02$ [16], we extract $\Gamma(W)/\Gamma(Z) = 0.85 \pm 0.08$. Using the measured value of $\Gamma(Z) = 2.57 \pm 0.07$ GeV [3], we find $\Gamma(W) = 2.19 \pm 0.20$ GeV. The Standard Model prediction with $M_W = 80.0$ GeV/c^2, $\alpha_s = 0.13$, and $M_{\rm top} > M_W - M_{\rm b}$ is $\Gamma(W) = 2.07$ GeV.

Recent searches [17] have set lower limits on $M_{\rm top}$ up to 77 GeV/c^2 assuming Standard Model decays. Figure 3 shows a prediction for the ratio $\Gamma(W)/\Gamma(W \to e\nu)$ as a function of the top quark mass. From the values quoted above we find $\Gamma(W)/\Gamma(W \to e\nu) = 9.8 \pm 0.9$. This value excludes $M_{\rm top}$ below 41 (35) GeV/c^2 at the 90% (95%) confidence level independent of the decay modes of the top quark [18].

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	W events	Z events
Inclusive e	4777	
Candidates	1828	193
Background		
$W \to \tau\nu$	67 ± 6	–
$Z \to ee$	12 ± 5	–
$Z \to \tau\tau$	4 ± 1	< 0.5
W + jet	–	1 ± 1
QCD	18 ± 9	5 ± 3
Total Bkgd	101 ± 12	6 ± 3
Total	$1727 \pm 43 \pm 12$	$187 \pm 14 \pm 3$

Table 1: Summary of W and Z event selection and backgrounds. The first uncertainty is statistical and the second is systematic.

	W events	Z events
A_Z/A_W	1.065 ± 0.031	
F_{cc}	–	0.39
F_{cp}	–	0.47
F_{cf}	–	0.14
c_1	0.86 ± 0.03	0.86 ± 0.03
c_2	–	0.96 ± 0.02
p	–	0.96 ± 0.03
f	–	0.97 ± 0.03
ϵ_ν	0.965 ± 0.005	–
ϵ_Z/ϵ_W	1.04 ± 0.03	

Table 2: Summary of W and Z acceptances and efficiencies.

Figure 1: The transverse mass spectrum for $W \rightarrow e\nu$ candidates. The curve is a Monte Carlo prediction for $M_W = 80$ GeV/c^2.

Figure 2: The invariant mass spectrum for $Z \rightarrow ee$ candidates before the mass cut. Approximately 60% have one electron in the gas calorimeters. The curve is a Monte Carlo prediction using the nominal values for the resolutions, $\sigma(E)/E = 28\%/\sqrt{E} + 2\%$ for the gas calorimeters and $\sigma(E)/E = 13.5\%/\sqrt{E} + 1.7\%$ for the central calorimeter. Radiative effects are not included. The Monte Carlo events away from the peak are due to the Drell-Yan continuum.

Figure 3: The predicted value of $\Gamma(W)/\Gamma(W \rightarrow e\nu)$ as a function of the top quark mass for $M_W = 80$ GeV/c^2 and $\alpha_s = 0.13$. The value calculated from Eq. 1 with 90% and 95% C.L. limits is shown. We use this ratio since it depends only weakly on the W mass.

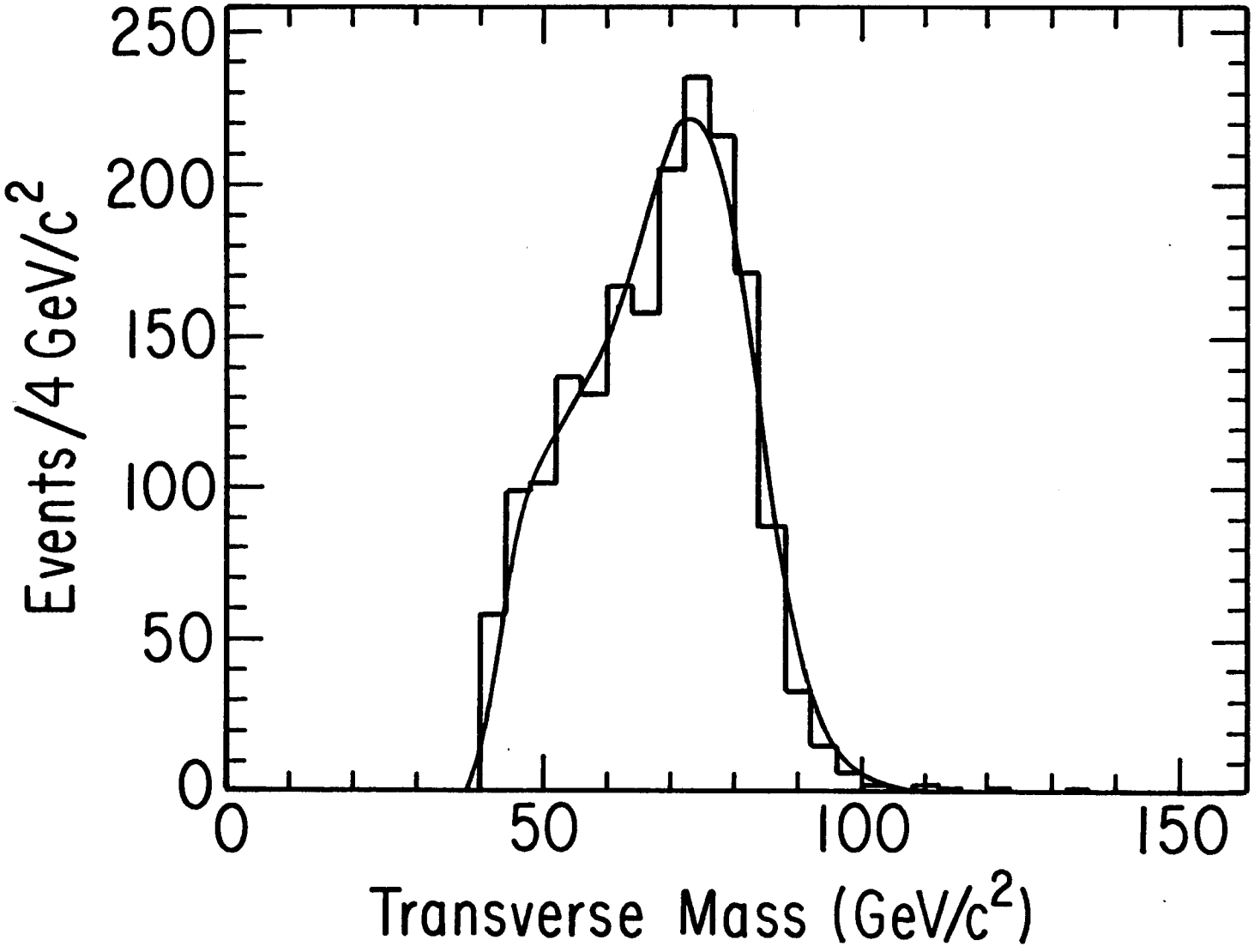
250
200
150
100
50
0
Events /4 GeV/c^2
0
50
100
150
Transverse Mass (GeV/c^2)

Fig. 1

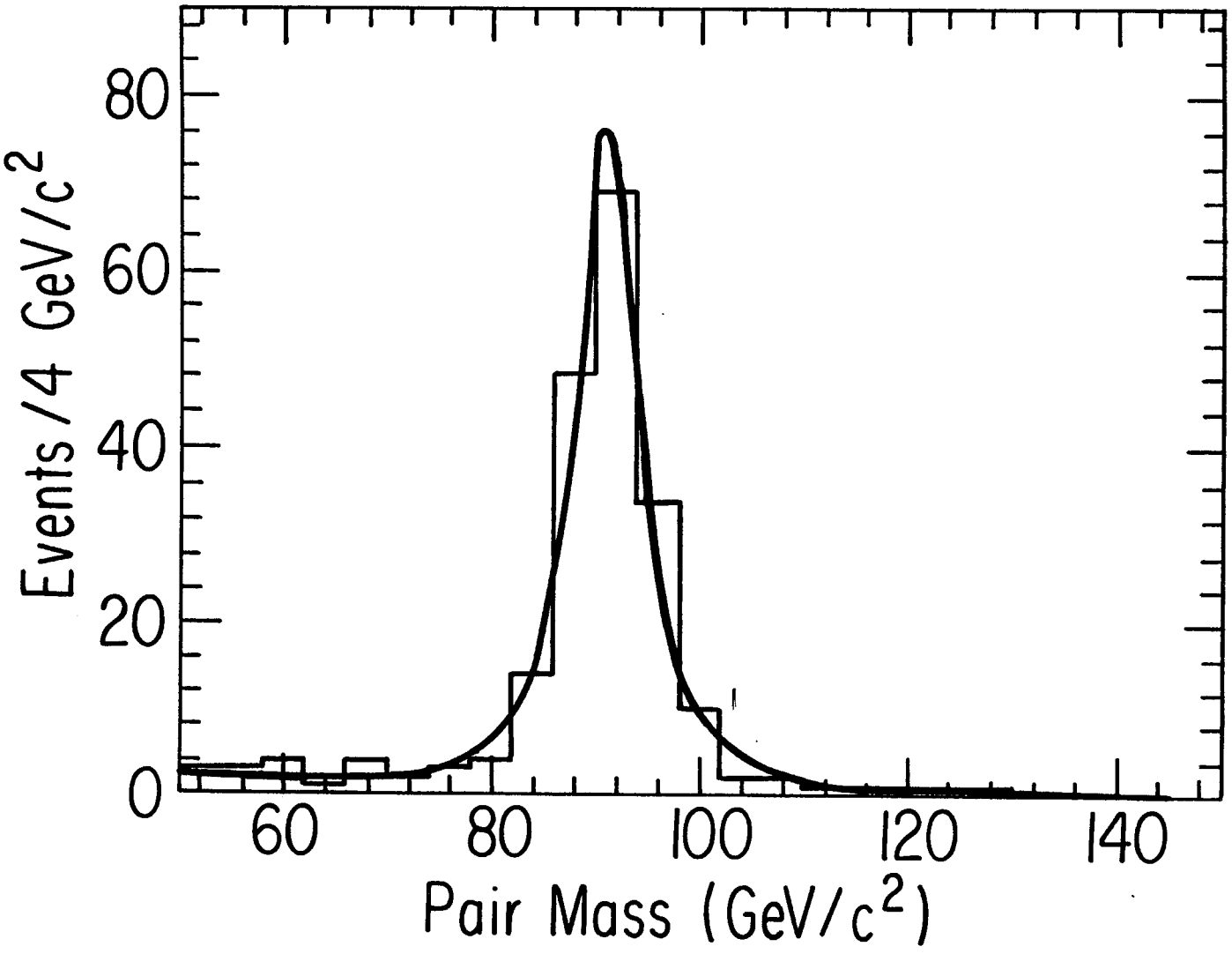

Fig. 2

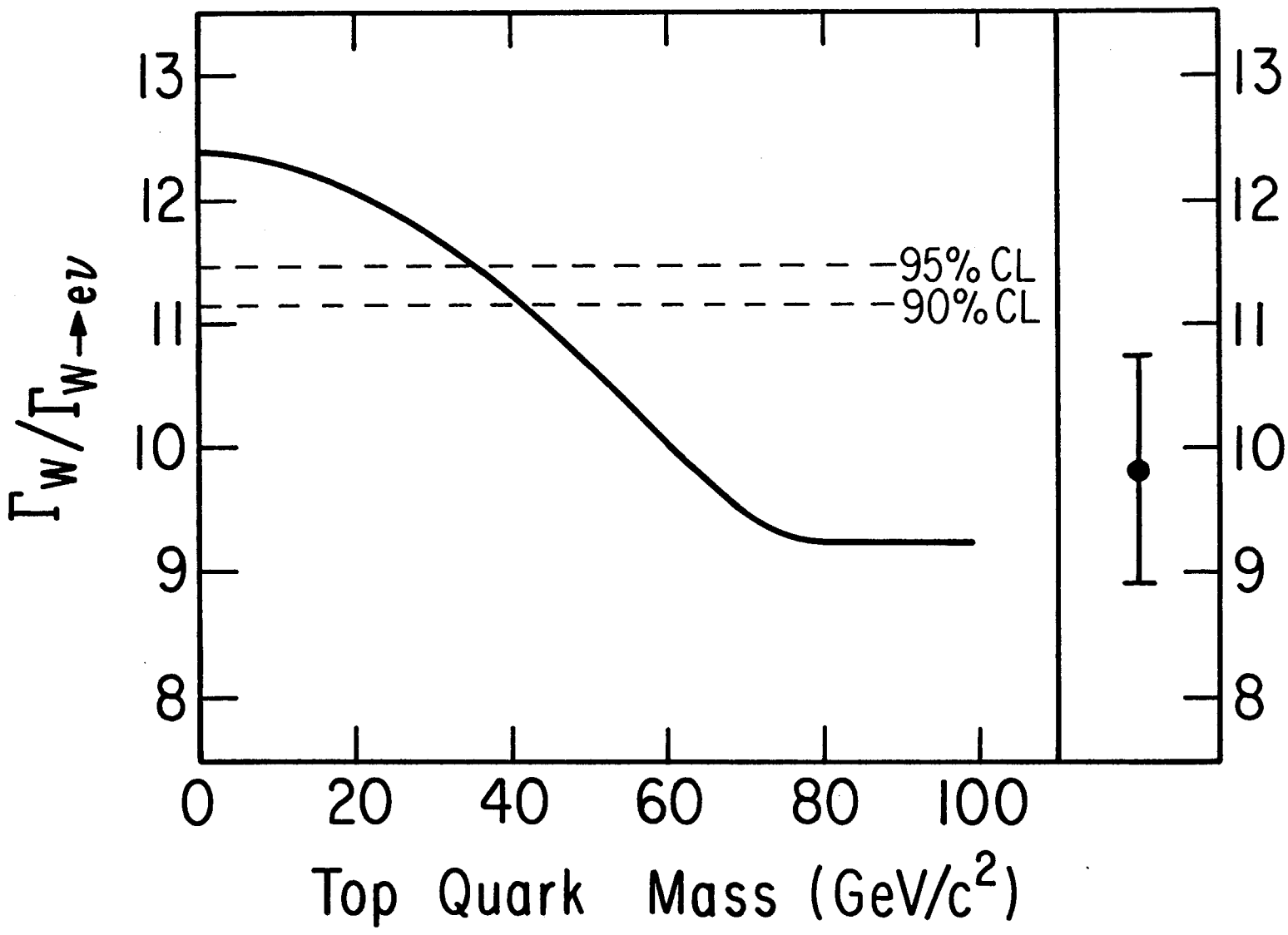
13
12
11
10
9
8
95% CL
90% CL
$\Gamma_W/\Gamma_{W\to e\nu}$
0
20
40
60
80
100
Top Quark Mass (GeV/c^2)

Fig. 3