Measurement of the Ratio $\sigma(W \to e\nu)/\sigma(Z \to ee)$ 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 at $\sqrt{s}=1.8$ TeV yields $\sigma(W\rightarrow e\nu)/\sigma(Z\rightarrow ee)=10.2\pm0.8(\mathrm{stat})\pm0.4(\mathrm{syst})$. 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 $\bar{p}p$ collisions for W production to that of Z production with subsequent decays into electron(s) can be expressed[1] as

$$R=\frac{\sigma(W\rightarrow e\nu)}{\sigma(Z\rightarrow ee)}=\frac{\sigma(\bar{p}p\rightarrow WX)}{\sigma(\bar{p}p\rightarrow ZX)}\frac{\Gamma(W\rightarrow e\nu)}{\Gamma(Z\rightarrow ee)}\frac{\Gamma(Z)}{\Gamma(W)}\,. \tag{1}$$

From R, the ratio of the total widths, $\Gamma(Z)/\Gamma(W)$, can be extracted since the ratio of the production cross sections, $\sigma(\bar{p}p\rightarrow WX)/\sigma(\bar{p}p\rightarrow ZX)$, and the ratio of the partial widths for electron decays, $\Gamma(W\rightarrow e\nu)/\Gamma(Z\rightarrow ee)$, are predicted from the proton structure functions, standard-model couplings,[2] and the vector-boson masses. Both the theoretical uncertainties in the cross sections and the experimental systematic uncertainties tend to cancel in the ratio of the cross sections. 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 $\bar{p}p$ 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,[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 over the range $-4.2<\eta<4.2$, 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 a 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 BBC's, (ii) a CEM cluster with $E_T>12$ GeV, (iii) a track associated with this cluster with $p_T>6$ GeV/c, and (iv) a ratio of hadronic to electromagnetic E_T in the cluster (H/E) < 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, $I=(E_C-E_T)/E_T$, where E_C is the total transverse energy within a cone of radius 0.4 in η-ϕ 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

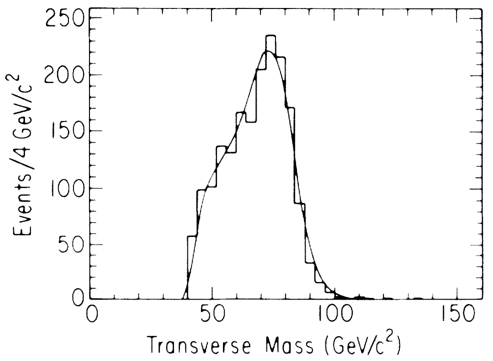

FIG. 1. The transverse-mass spectrum for $W\rightarrow e\nu$ candidates. The curve is a Monte Carlo prediction for $M_W=80$ GeV/c^2.

with a Monte Carlo prediction ($M_T = [2E_T \not\!\!E_T(1-\cos\alpha)]^{1/2}$, 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) $I < 0.2$; (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 $W \to e\nu$ sample is from $W \to \tau\nu$, followed by $\tau \to e\nu\nu$. We have used the ISAJET Monte Carlo program[9] and the observed $W \to e\nu$ rate to estimate this background to be 67 ± 6 events. Another background is $Z \to ee$, with one electron undetected by the calorimeters. ISAJET with a full detector simulation predicts 12 ± 5 events. The W background from $Z \to \tau\tau$ 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 nonisolated 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 $Z \to ee$ 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 $Z \to \tau\tau$ was estimated to be < 0.5 event using ISAJET and the detector simulation.

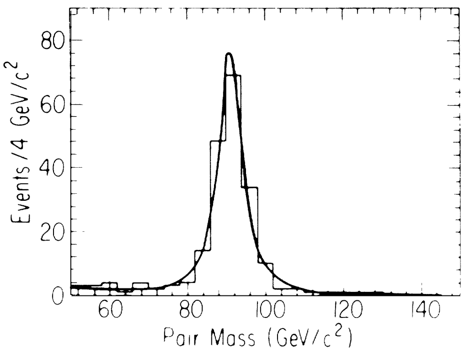

FIG. 2. The invariant-mass spectrum for $Z \to ee$ candidates before the mass cut. Approximately 60% have one electron in the gas calorimeters. The curve is a Monte Carlo prediction using the nominal values for the resolutions, $\sigma(E)/E = 28\%/\sqrt{E} + 2\%$ for the gas calorimeters and $\sigma(E)/E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

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 program[10] with the detector simulation. The W and Z selection is summarized in Table I.

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 simulation which generates W and Z bosons from the leading-order diagram $q\bar{q} \to W(Z)$ using a variety of proton structure functions and simple parametrizations 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 Martin-Roberts-Stirling 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 $\sin^2\theta_W$, where $\sin^2\theta_W \equiv (1 - M_W^2/M_Z^2)$, from 0.229 of ± 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

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

TABLE I. Summary of W and Z event selection and backgrounds. The first uncertainty is statistical and the second is systematic.

	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 II. Summary of W and Z acceptances and efficiencies.

	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	

where F_{cc}, F_{cp}, and 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. In Eq. (3) we have neglected the contribution to ϵ_Z from events where the second central electron has 10 GeV $< E_T <$ 20 GeV because the acceptance for this class of events is negligible.

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 II.

The "zero-jet" requirement is expected to increase the ratio R by $0.8\% \pm 0.5\%$.[13] The changes in R when varying the jet threshold from 5 to 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 I and II we obtain $R = 10.2 \pm 0.8(\text{stat}) \pm 0.4(\text{syst})$. Using this value of R, $\sin^2\theta_W = 0.229 \pm 0.007$,[14] and 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 $M_{\text{top}} > M_W - M_b$ is $\Gamma(W) = 2.07$ GeV.

Recent searches[17] have set lower limits on M_{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_{top} below 41 (35) GeV/c^2 at the 90% (95%) confidence level independent of the decay modes of the top quark.[18]

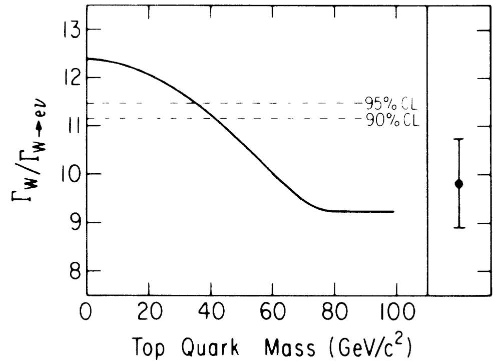

FIG. 3. The predicted value of $\Gamma(W)/\Gamma(W \to e\nu)$ as a function of the top-quark mass for $M_W = 80$ GeV/c^2 and $\alpha_s = 0.13$. The value calculated from Eq. (1) with 90%- and 95%-C.L. limits is shown. We use this ratio since it depends only weakly on the W mass.

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