# Measurement of the Ratio $\sigma B(W \rightarrow e\nu)/\sigma B(Z^0 \rightarrow e^+e^-)$ in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

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We present a measurement of the ratio $\sigma B(W \to e\nu)/\sigma B(Z^0 \to e^+e^-)$ in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. The data represent an integrated luminosity of 21.7 pb$^{-1}$ from the 1992–1993 run of the Collider Detector at Fermilab. We find $\sigma B(W \to e\nu)/\sigma B(Z^0 \to e^+e^-) = 10.90 \pm 0.32(\text{stat}) \pm 0.29(\text{syst})$. From this value, we extract a value for the $W$ width, $\Gamma(W) = 2.064 \pm 0.061(\text{stat}) \pm 0.059(\text{syst})$ GeV, and the branching ratio, $\Gamma(W \to e\nu)/\Gamma(W) = 0.1094 \pm 0.0033(\text{stat}) \pm 0.0031(\text{syst})$, and we set a decay-mode-independent limit on the top quark mass $m_{\text{top}} > 62$ GeV/$c^2$ at the 95% C.L.

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The ratio of the production cross sections times the branching ratios into electrons of $W$ and $Z^0$ bosons produced in $\bar{p}p$ collisions is related [1] to the $W$ decay width, $\Gamma(W)$, by

$$R \equiv \frac{\sigma B(W \to e\nu)}{\sigma B(Z^0 \to e^+e^-)} = \frac{\sigma(\bar{p}p \to WX)}{\sigma(\bar{p}p \to Z^0X)} \frac{\Gamma(W \to e\nu)}{\Gamma(Z^0 \to e^+e^-)} \frac{\Gamma(Z^0)}{\Gamma(W)}, \quad (1)$$

where $\sigma(\bar{p}p \to WX)/\sigma(\bar{p}p \to Z^0X)$ is the ratio of the production cross sections of $W$'s and $Z^0$'s in $\bar{p}p$ collisions, $\Gamma(W \to e\nu)$ is the $W$ partial width to an electron and neutrino, $\Gamma(Z^0 \to e^+e^-)$ is the $Z^0$ partial width into electrons, and $\Gamma(W)$ and $\Gamma(Z^0)$ are the $W$ and $Z^0$ total decay widths. The ratio of the production cross sections can be calculated using the standard model couplings and parton distribution functions, as can the ratio of partial decay widths. With the LEP [2] measurements of $\Gamma(Z^0)$ and $\Gamma(Z^0 \to e^+e^-)$, a measurement of $R$ yields a measurement of the branching ratio $\Gamma(W \to e\nu)/\Gamma(W)$. One may furthermore use a calculation of $\Gamma(W \to e\nu)$ and this measurement of the branching ratio $\Gamma(W \to e\nu)/\Gamma(W)$ to extract a value for the $W$ decay width, $\Gamma(W)$.

Many theoretical and experimental systematic uncertainties cancel in measuring the ratio, making this the most precise method at present for determining the branching ratio $\Gamma(W \to e\nu)/\Gamma(W)$. An accurate determination of $\Gamma(W \to e\nu)/\Gamma(W)$ is sensitive to decay channels of the $W$ outside the standard model. Previous measurements of $R$ at $\sqrt{s} = 1.8$ TeV [3,4] and at $\sqrt{s} = 0.63$ TeV [5,6] have yielded a combined accuracy on the $W$ width of 5.2%.

We present results using 21.7 pb$^{-1}$ of data from proton-antiproton collisions at a center of mass energy of $\sqrt{s} = 1.8$ TeV collected at the Collider Detector at Fermilab (CDF) during the 1992–1993 run of the Fermilab Tevatron. The CDF Detector is described in detail elsewhere [7]. The components of the detector relevant for this analysis are (i) two scintillator hodoscopes located on either side of the detector, (ii) the Silicon Vertex Detector (SVX) [8], (iii) the time-projection chamber (VTX), (iv) a drift chamber (CTC) immersed in a 1.4 T solenoidal magnetic field, and (v) electromagnetic and hadronic calorimeters. The calorimeters are arranged in projective towers and cover the pseudorapidity ranges $|\eta| < 1.05$ (central calorimeters), $1.1 < |\eta| < 2.4$ (plug calorimeters), and $2.4 < |\eta| < 4.2$ (forward calorimeters). In the central electromagnetic calorimeters, proportional chambers are embedded near shower maximum for fine position measurements. A preshower detector (CPR) is located on the inner face of the central calorimeter.

We select $W$ and $Z^0$ candidates from a common set of inclusive electrons with transverse energy $E_T > 20$ GeV in the central region [9]. We also require that the event was triggered by the central electron [10]. Requiring both $W$'s and $Z^0$'s to pass this requirement reduces systematic uncertainties in the selection efficiencies when taking the ratio. Placing tight selection criteria on this first, central electron also allows us to place loose, highly efficient selection criteria on the second lepton (either $\nu$ or $e$). The selection criteria for electrons at CDF can be found in Ref. [10]. These selection criteria include an isolation (Iso) cut [11] on the amount of energy in the calorimeter near the electron cluster.

The $Z^0$ candidates are selected from the inclusive electron sample by requiring a second electron and an invariant mass of the electron pair in the pass range 66–116 GeV/$c^2$. The second electron is required to have $E_T > 20$ GeV if in the central, $E_T > 15$ GeV if in the plug, or $E_T > 10$ GeV if in the forward. Other selection criteria are as listed in [10]. Figure 1(a) shows the invariant mass spectrum of all electron pairs satisfying our electron criteria; of these, 1312 in the mass range 66–116 GeV/$c^2$ are $Z^0$ candidates.

$W$ candidates are selected from the inclusive electron sample by requiring that the event is not a $Z^0$ candidate and that the event has a transverse energy imbalance ($\not{E}_T \equiv$ "missing $E_T$") of $\not{E}_T > 20$ GeV, where $\not{E}_T$ is the magnitude of the vector sum of all calorimeter tower transverse energies using towers with $|\eta| < 3.6$. Figure 1(b) shows the transverse mass spectrum of the 13 796 $W$ candidates, where $M_T \equiv \sqrt{2E_T^{\mathrm{ele}}\not{E}_T[1 - \cos(\Delta\phi)]}$, and $\Delta\phi$ is the azimuthal angle between the electron and the $\not{E}_T$ vector.

The dominant background to the $W$ candidates comes from the hadron jets, where one jet produces an isolated high-$P_T$ electron and the other jet is mismeasured in the calorimeters, creating $\not{E}_T$. The jet fragmentations which produce isolated [11], high-$P_T$ clusters which pass our electron criteria are photon conversions to $e^+e^-$ pairs in the material within the tracking volume, semileptonic decays of heavy quarks, $b \to ce\nu$, and hadrons which shower early in the calorimeter. We estimate the sum of these backgrounds by comparing the number of events in three background-dominated regions, $\not{E}_T < 10$ GeV, Iso $> 0.3$, $\not{E}_T < 10$ GeV, Iso $< 0.1$, and $\not{E}_T > 20$ GeV, Iso $> 0.3$, and using the ratios to extrapolate into the signal region, $\not{E}_T > 20$ GeV, Iso $< 0.1$. We calculate the number of hadron jet events with an electron and $\not{E}_T > 20$ GeV to be 2100 $\pm$ 350 events, and the number to contaminate the $W$ region with Iso $< 0.1$ to be 898 $\pm$ 155 events. As a check of this method, the backgrounds from conversions, semileptonic $b$ decays, and hadron showers are studied separately. Conversions are identified by searching for oppositely signed charged tracks in the tracking chamber near the electron for which the pair forms a small invariant mass. Semileptonic $b$ decays can be identified statistically using the SVX to search for electrons that come from a displaced vertex. Hadrons showering early in the calorimeter were identified by a minimum ionizing pulse in the CPR. From these studies, we estimate the number of conversions at $\not{E}_T > 20$ GeV to be 910 $\pm$ 80, the number of electrons from $b$ decays to be 850 $\pm$ 360, and the number of fake electrons from hadron showers to be 580 $\pm$ 370, which add up to 2340 $\pm$ 520, consistent with the 2100 $\pm$ 350 events above.

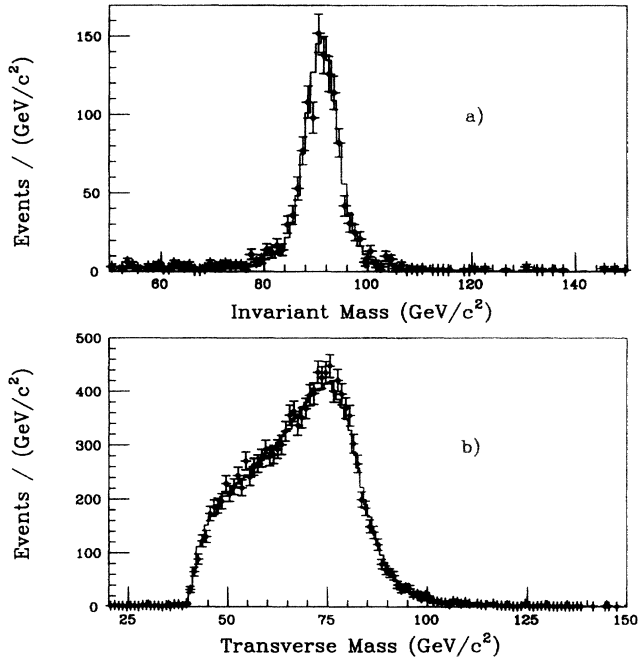


FIG. 1. (a) Observed distribution of invariant mass of $e^+e^-$ pairs satisfying our electron selection criteria. $Z^0$ candidates are taken to lie in the range 66–116 GeV/$c^2$. (b) Observed distribution of transverse mass of the $W$ candidates. The curves in both plots are the sum of the expected background shape and the predicted spectrum from the Monte Carlo used in the acceptance calculation.

Other backgrounds to the $W$ come from $W^\pm \to \tau^\pm\nu \to e^\pm\nu\nu\nu$, from $Z^0 \to \tau^+\tau^-$, where one $\tau$ decays to an $e$, from $Z^0 \to e^+e^-$ where one $e$ is lost, and possibly from heavy top quark decays. We estimate all of these backgrounds using the ISAJET [12] Monte Carlo and a detector simulation. The upper limit on the top background comes from the expected number of events if $m_{top} = 120\ \text{GeV}/c^2$, which is the 68% C.L. limit from CDF [13]. The $W$ backgrounds are summarized in Table I.

The dominant background to $Z^0$ candidates also comes from hadron jets that fluctuate to pass our $Z^0$ selection criteria. This background is estimated by a similar study of the isolation variable [10] to that of the $W$'s to be 20 ± 9 events. The other background is from the process $Z^0 \to \tau^+\tau^-$, where the $\tau$'s decay into electrons. We estimate this background using ISAJET plus a detector simulation to be 1 ± 1 event. A correction of (0.5 ± 0.2)% was applied to the number of $Z^0$ candidates to account for the $e^+e^-$ pairs produced by the Drell-Yan $\gamma$ continuum and not from resonant $Z^0$ production. The $Z^0$ backgrounds are summarized in Table I.

In terms of experimentally measured quantities, the ratio $R$ is

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

where $N_W$ is the number of $W$ candidates after background subtraction, $A_W$ is the geometric and kinematic acceptance for $W$ decays, and $\epsilon_W$ is the lepton selection efficiency for the $W$, and similarly for the $Z^0$'s.

The ratio of efficiencies in Eq. (2) is

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

where $c_1$ is the efficiency for the central electron to pass our inclusive electron selection (including the trigger efficiency), and $c_2$, $p$, and $f$ are the efficiencies for the second $Z^0$ electrons in central, plug, and forward regions. $F_{cc}$, $F_{cp}$ , and $F_{cf}$ are the fractions of the $Z^0$'s in which the second electron falls in the central, plug, and forward regions. The efficiency $c_1$ cancels almost completely in the ratio. The selection efficiencies are determined from the second electrons in a sample of $Z^0$ candidates where no cuts are imposed on the second electron. The ratio of efficiencies is determined to be $\epsilon_W/\epsilon_Z = 1.035 \pm 0.016$ (see Table I).

TABLE I. Summary of results.

| | $W$ events | $Z$ events |
|---|---|---|
| Candidates | 13796 | 1312 |
| Backgrounds: | | |
| Hadron jets | 898 ± 155 | 20 ± 9 |
| $W^\pm \to \tau^\pm \nu$ | 473 ± 29 | ... |
| $Z^0 \to \tau^+\tau^-$ | 48 ± 7 | 1 ± 1 |
| $Z^0 \to e^+e^-$ | 281 ± 42 | ... |
| Top | 0 + 52 − 0 | ... |
| Total | 1700 + 171 − 163 | 21 ± 9 |
| Signal | 12096 ± 117 + 163 − 171 | 1291 ± 36 ± 9 |
| Acceptance | 0.342 ± 0.008 | 0.409 ± 0.005 |
| $A_W/A_Z$ | 0.835 ± 0.013 | |
| $F_{cc}$ | ... | 0.372 ± 0.007 |
| $F_{cp}$ | ... | 0.509 ± 0.007 |
| $F_{cf}$ | ... | 0.120 ± 0.005 |
| $c_1$ | 0.754 ± 0.011 | 0.754 ± 0.011 |
| $c_2$ | ... | 0.917 ± 0.008 |
| $p$ | ... | 0.909 ± 0.014 |
| $f$ | ... | 0.859 ± 0.044 |
| $\epsilon_W, \epsilon_Z$ | 0.754 ± 0.011 | 0.729 ± 0.016 |
| $\epsilon_W/\epsilon_Z$ | 1.035 ± 0.016 | |
| Drell-Yan correction | ... | 1.005 ± 0.002 |
| $\sigma B(W \to e\nu)/\sigma B(Z^0 \to e^+e^-)$ | 10.90 ± 0.32(stat) | ±0.29(syst) |

The fractions $F_{cc}$, $F_{cp}$, and $F_{cf}$ and the acceptances $A_W$ and $A_Z$ are determined from a Monte Carlo which generates bosons from the lowest order diagram, $q\bar{q} \to W$ or $Z^0$, using various parton distribution functions. The bosons are given a $P_T$ according to the distribution measured previously by CDF [14]. The electron and neutrino energies are smeared with the calorimeter energy resolutions. The fiducial and kinematic cuts are then placed on the leptons. Using the MRS $D'$-parton distribution functions [15] and the world averages [2] for the electroweak parameters, we obtain $A_W/A_Z = 0.835$. Using other current parton distribution functions varies $A_W/A_Z$ by 1.1%. Variations in the input $P_T$ distribution lead to 0.2% variation in $A_W/A_Z$. Variations of $M_W = 80.24 \pm 0.10\ \text{GeV}/c^2$ within its uncertainty leads to a 0.1% variation in $A_W/A_Z$. The uncertainty in the modeling of the detector response to $\not{E}_T$ leads to a 0.6% uncertainty in $A_W/A_Z$. The uncertainty in the energy scale of the calorimeter leads to 0.4% variations in $A_W/A_Z$. Finally, from a comparison with a next-to-leading-order calculation [16] of $W$ and $Z^0$ production, we estimate the systematic uncertainty on using only the lowest-order matrix element plus the boson $P_T$ to model higher-order diagrams to be 0.8%. The overall systematic uncertainty in $A_W/A_Z$ is taken to be the sum of the above variations, namely, ±1.6%.

The results for $R$ are summarized in Table I. We find

$$R = 10.90 \pm 0.32\,(\text{stat}) \pm 0.29\,(\text{syst}). \tag{4}$$

Using the theoretical calculation [17] $\sigma(\bar{p}p \to WX)/\sigma(\bar{p}p \to Z^0X) = 3.33 \pm 0.03$, and the LEP measurements [2] of $\Gamma(Z^0) = 2.492 \pm 0.007$ GeV and $\Gamma(Z^0 \to e^+e^-) = 83.33 \pm 0.30$ MeV, we obtain an absolute measure of the $W$ branching ratio into $e\nu$:

$$\frac{\Gamma(W \to e\nu)}{\Gamma(W)} = 0.1094 \pm 0.0033\,(\text{stat}) \pm 0.0031\,(\text{syst}). \tag{5}$$

For comparison, the standard model prediction [18] is $0.1084 \pm 0.0002$. This is a 4.1% measurement of the $e\nu$ branching ratio. If we furthermore use the calculation [19] $\Gamma(W \to e\nu) = 225.8 \pm 0.9$ MeV, we extract a value for the $W$ width of

$$\Gamma(W) = 2.064 \pm 0.061\,(\text{stat}) \pm 0.059\,(\text{syst})\ \text{GeV}. \tag{6}$$

For comparison, the standard model prediction [18] is $2.067 \pm 0.021$ GeV.

This measurement of the branching ratio is sensitive to new decay modes of the $W$. One such decay mode

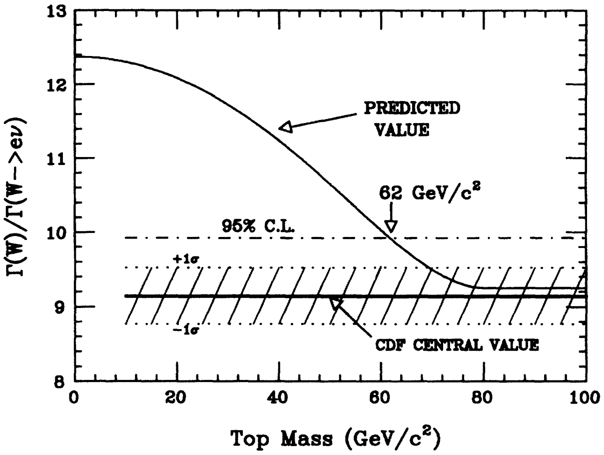


FIG. 2. The predicted value for $\Gamma(W)/\Gamma(W \rightarrow e\nu)$ from the standard model and this measurement. The curve is the standard model prediction. The solid horizontal line is our central value; the $1\sigma$ error bars are denoted by the dotted lines. The 95% C.L. upper limit is the dot-dashed line. The 95% C.L. lower limit on $m_{\mathrm{top}}$ is 62 GeV/$c^2$.

would be $W \rightarrow t\bar{b}$. While CDF [13] has set a limit on the top quark mass of $m_{\mathrm{top}} > 91$ GeV/$c^2$ (95% C.L.), this limit assumes standard model decays of the top quark. If, however, the top should decay in a manner outside the standard model, for example via charged Higgs ($t \rightarrow H^+ b$), then the assumptions that go into previous direct searches are no longer valid [20]. The present result sets a limit on the top quark mass independent of presumed top decay channels. Figure 2 shows the standard model expectation for $\Gamma(W)/\Gamma(W \rightarrow e\nu)$ as a function of the top quark mass, $m_{\mathrm{top}}$, along with our result. Using the prediction and this measurement, we set a decay-mode-independent limit [21] on the top quark mass of $m_{\mathrm{top}} > 62$ GeV/$c^2$ (95% C.L.). The previous CDF [3,4] and UA 1/2 [5,6] limits with this technique are 45 and 53 GeV/$c^2$, respectively. With the data anticipated at future collider runs and further understanding of the $u/d$ ratio as obtained in measurements of the $W$ charge asymmetry, this technique could be extended to a 1% precision in the $W \rightarrow e\nu$ branching ratio, giving a sensitivity to top masses of up to 77 GeV/$c^2$.

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[11] An isolated electron is defined to be one for which the transverse energy in the calorimeter in the cone of radius 0.4 in $\eta$-$\phi$ space around the electron cluster is less than 10% of the electron transverse energy. The isolation variable used is Iso $= (E_T^{\mathrm{Cone}} - E_T^{\mathrm{Cluster}})/E_T^{\mathrm{Cluster}}$.

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