Fermi National Accelerator Laboratory

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A Measurement of the Production and Muonic Decay Rate of W and Z Bosons in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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A Measurement of the Production and Muonic Decay Rate of W and Z Bosons in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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Abstract

An analysis of proton-antiproton collisions at $\sqrt{s} = 1.8$ TeV recorded with the Collider Detector at Fermilab yields $\sigma(p\bar{p} \to WX) \cdot B(W \to \mu\nu) = 2.21 \pm 0.22$ nb and $\sigma(p\bar{p} \to ZX) \cdot B(Z \to \mu^+\mu^-) = 0.226 \pm 0.032$ nb. The ratio is $R_\mu = \sigma_W \cdot B(W \to \mu\nu)/\sigma_Z \cdot B(Z \to \mu^+\mu^-) = 9.8 \pm 1.2$. Combining with previous CDF electron results gives $\sigma_W \cdot B(W \to l\nu) = 2.20 \pm 0.20$ nb, $\sigma_Z \cdot B(Z \to l^+l^-) = 0.214 \pm 0.023$ nb, and $R_l = 10.0 \pm 0.8$. We extract the ratios of the coupling constants g_μ/g_e and g_τ/g_μ. Using Standard Model assumptions we deduce the inverse branching ratio $BR^{-1}(W \to l\nu)$, the width $\Gamma(W)$, and a decay-mode-independent lower bound on the top quark mass of 45 GeV/c^2 (95% CL).

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Measurements of the W and Z production cross sections and rates for subsequent decay into leptons in $p\bar{p}$ collisions test the consistency of the Standard Model couplings, the contributions from higher-order QCD diagrams, and the proton structure functions. Moreover, in the ratio of W and Z production cross sections times branching ratio,

$$R = \frac{\sigma_W \cdot B(W \to l\nu)}{\sigma_Z \cdot B(Z \to l^+l^-)} = \frac{\sigma(p\bar{p} \to WX)}{\sigma(p\bar{p} \to ZX)} \times \frac{\Gamma(W \to l\nu)}{\Gamma(W)} \times \frac{\Gamma(Z)}{\Gamma(Z \to l^+l^-)}, \tag{1}$$

theoretical and experimental uncertainties each tend to cancel allowing a precise determination of the W width and constraining the possibility of unobserved W decay channels. The previous measurement of R with the Collider Detector at Fermilab (CDF)[1, 2] used the electron decay channels. The UA2 Collaboration at CERN has also recently presented results from the electron channel[3]. In this Letter we present results from the muon channel and test lepton universality in W decays by comparing the electron, muon, and tau rates.

The CDF detector consists of a 1.3 m radius tracking chamber contained in a solenoidal magnet surrounded by projective tower calorimeters of size $(\Delta\phi \times \Delta\eta) = (15° \times 0.1)$ [4]. Muon drift chambers covering $|\eta| < 0.61$ sit behind five absorption lengths of calorimeter at 3.5 m from the beam [5, 6]. The muon trigger is formed when hits in the muon chambers match a track with transverse momentum of $P_T > 9$ GeV/c found by the hardware track processor [7].

The W and Z candidates are selected from a data sample of muon-triggered events passing strict high-P_T muon identification requirements. The track must have $P_T > 20$ GeV/c, match a track segment in the muon chambers to within 2 cm in the $r\phi$-plane, and the track must point at a calorimeter tower with less than 6 GeV of energy in the hadron compartment and 2 GeV in the electromagnetic compartment [8]. The track must be isolated, $I = \frac{E_4 - E_T}{P_T} < 0.1$, where E_T is the transverse energy in the calorimeter tower traversed by the track and E_4 is the transverse energy in a cone of radius $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\phi^2)} = 0.4$ around the track. The event vertex has to be within 60 cm of the center of the interaction region in the z-direction. Track quality requirements reduce decay-in-flight and cosmic ray

backgrounds. These cuts leave 2011 events, from an integrated luminosity of $L = 3.54 \pm 0.24$ pb^{-1}.

Loose cuts identify events with a second high-P_T lepton. A Z-candidate must have a second minimum ionizing track with $|\eta| < 1.0$ and $P_T > 20$ GeV/c which forms an invariant mass $65 < M_{\mu\mu} < 115$ GeV/c^2 with the first track. These cuts select 106 events. Neutrinos are tagged by looking for large missing transverse energy,

$$\vec{\not{E}}_{\mathrm{T}} = -\vec{P}_T^{\mu} - \sum_{|\eta|<3.6} E_i \sin\theta_i \cdot \hat{n}_i, \tag{2}$$

where $\vec{P}_T^{\mu}$ is the transverse component of the muon momentum vector, E_i is the energy in the ith calorimeter tower and $\hat{n}_i$ is a unit vector perpendicular to the beam axis pointing from the event vertex to the tower. We correct the sum over towers for the energy deposition along the muon track. Figure 1 shows the $\not{E}_{\mathrm{T}}$ distribution. W-candidates must have $\not{E}_{\mathrm{T}} > 20$ GeV, leaving 1436 events. The figure also shows the Monte Carlo simulation of the signal and the Z and τ backgrounds discussed below.

The observed number of W-candidates is related to the cross-section times branching ratio by

$$N_W = [\varepsilon_W \cdot A_W \cdot \sigma_W \cdot B(W \to \mu\nu)L + B_W] \cdot \varepsilon_C^W \tag{3}$$

where A_W includes the geometric and kinematic acceptances for both decay leptons, ε_W is the event selection efficiency, $(1-\varepsilon_C^W)$ is the fraction of W events lost when removing cosmic rays, and B_W is the number of background events. The efficiency $\varepsilon_W = \varepsilon_T \cdot \varepsilon_S$ includes the trigger efficiency, ε_T, and the efficiency ε_S for muons to pass the strict identification cuts. For Z events, the efficiency is higher if both muons pass through the muon chambers, and we break ε_Z into two terms,

$$N_Z = \{\frac{\varepsilon_T \cdot \varepsilon_S}{DY}[f(2-\varepsilon_T)(2\varepsilon_L - \varepsilon_S) + (1-f)\varepsilon_L]A_Z \cdot \sigma_Z \cdot B(Z \to \mu^+\mu^-)L + B_Z\}\varepsilon_C^Z \tag{4}$$

where A_Z is the acceptance, f is the fraction of events where both muons pass through the muon chambers and ε_L is the efficiency for muons passing the loose identification requirements. Correlations between ε_L, ε_S, and A_Z are negligible. The factor DY is a 1% correction to remove the contribution of the virtual photon process to the Z-sample.

Acceptances are calculated with a Monte Carlo simulation that generates W and Z bosons from the leading order diagram $q\bar{q} \to W(Z)$ using the HMRS-B proton structure functions [9] and the measured boson P_T spectrum [10]. A simple detector model, with tracking and $\not{E}_{\mathrm{T}}$ resolution determined from data, simulates the effects of detector response on the kinematic cuts. A small correction to the acceptance for higher-order QCD diagrams is made using the Papageno W+1 jet Monte Carlo program[11]. We find $A_W = 19.0 \pm 0.9\%$. The largest contribution to the uncertainty, $\delta A_W = 0.8\%$, is half the variation in the acceptance using different sets of proton structure functions [12, 13]. The boson P_T spectrum and the resolution smearing contribute an additional uncertainty of $\delta A_W = 0.2\%$. For the Z case we find $A_Z = 15.4 \pm 0.9\%$, including a small correction from higher-order effects. The

uncertainty due to structure functions is $\delta A_Z = 0.9\%$, while the boson P_T spectrum and the uncertainty in $\sin^2\theta_W$ contribute $\delta A_Z = 0.3\%$. We calculate $f = 0.310 \pm 0.005$.

The efficiencies are summarized in Table 1. We measure most efficiencies using cosmic rays, $J/\psi \to \mu^+\mu^-$ events, and Z events where both tracks pass through the muon chambers. We obtain the isolation cut efficiency from the E_T distribution inside cones randomly placed in (η, ϕ) in W events selected without the isolation cut. The over-efficiency of the cosmic ray filter, $1 - \varepsilon_C$, is determined by scanning a large independent track sample. The overall muon identification efficiency is $\varepsilon_S = 90.4 \pm 3.8\%$ for the strict selection cuts, and $\varepsilon_L = 97.4 \pm 1.1\%$ for the loose cuts. The trigger efficiency is $\varepsilon_T = 91 \pm 2\%$ for a single muon. The overall result is $\varepsilon_W \cdot A_W = 0.156 \pm 0.010$ and $\varepsilon_Z \cdot A_Z = 0.132 \pm 0.010$.

The largest background in the $W \to \mu\nu$ sample comes from $Z \to \mu^+\mu^-$ events where one muon hits the chambers and the other is beyond the range of the tracking acceptance. Calculating the acceptance for these events and normalizing to the observed number of Z's, we predict 134 ± 13 such events. The choice of structure functions gives an additional ± 8 event systematic uncertainty. The backgrounds from $W \to \tau\nu$ and $Z \to \tau\tau$ events where τ's produce a muon candidate are estimated using the ISAJET Monte Carlo [14] and a full detector simulation to calculate acceptances, and are normalized to the observed $W \to \mu\nu$ and $Z \to \mu^+\mu^-$ rates. We expect 47 ± 9 $W \to \tau\nu$ and 3 ± 1 $Z \to \tau\tau$ events in the W sample, and 0^{+1}_{-0} $Z \to \tau\tau$ events in the Z sample. Similarly, a top quark at the current 95% confidence level lower limit, $M_{top} = 91$ GeV/c^2 [15], would contribute 15 W candidates, which we assign as the uncertainty on this background. The W background due to QCD jet events of 30 ± 20 events is found by extrapolating the $\not{E}_T$ distribution for isolated muons into our signal region, using the shape of the $\not{E}_T$ distribution for non-isolated muons. Figure 1 shows the falling QCD distribution at low $\not{E}_T$. For the jet background to the Z sample, we count events where the muon forms an invariant mass $65 < M < 115$ GeV/c^2 with a non-minimum ionizing track, and scale by the probability for a pion to pass the minimum ionizing cut [8]. We predict 0^{+1}_{-0} dijet events and 0^{+1}_{-0} W+jet events in the Z sample. Z events where the second leg fails the 'loose' cuts add another 3 ± 3 background events to the W sample. The fraction of cosmic ray events remaining in the W sample was found by scanning to be 0.4%. The backgrounds are summarized in Table 1.

From these numbers,

$$\sigma_W \cdot B(W \to \mu\nu) = 2.21 \pm 0.07\ (stat.) \pm 0.21\ (sys.)\ \text{nb}$$

and

$$\sigma_Z \cdot B(Z \to \mu^+\mu^-) = 0.226 \pm 0.022\ (stat.) \pm 0.023\ (sys.)\ \text{nb}.$$

The ratio is $R_\mu = 9.8 \pm 1.1\ (stat.) \pm 0.4\ (sys.)$ where common systematic uncertainties such as the luminosity do not contribute to the ratio.

The muon results can be compared with the previous CDF electron and tau results to test lepton universality. In the standard model the ratio of the coupling constants is related to the ratio of the W branching ratios into leptons, and with the values in Table 2

	W events	Z events
Inclusive μ	2011	
W/Z Candidates	1436	106
Background:		
$Z \to \mu^+\mu^-$	$134 \pm 13 \pm 8$	-
$W \to \tau\nu$	$47 \pm 1.5 \pm 8.4$	-
QCD	30 ± 20	0^{+1}_{-0}
Cosmic rays	6 ± 3	0.4 ± 0.2
$Z \to \tau\tau$	$2.8 \pm 0.3 \pm 0.9$	0^{+1}_{-0}
Top	0^{+15}_{-0}	-
Total bkgd.	220^{+31}_{-27}	$0.4^{+1}_{-0.2}$
Total events	$1216 \pm 38\ ^{+27}_{-31}$	$106 \pm 10^{+0.2}_{-1}$
ε_L	$97.4 \pm 1.1\%$	
ε_S	$90.4 \pm 3.8\%$	
ε_C	$99.7 \pm 0.3\%$	$99.7 \pm 0.3\%$
ε_T	$91 \pm 2\%$	
DY	-	0.99 ± 0.01
$\varepsilon \cdot A$	0.156 ± 0.010	0.132 ± 0.010
$\sigma \cdot B$	$2.21 \pm 0.07 \pm 0.21$ nb	$0.226 \pm 0.022 \pm 0.023$ nb

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

we obtain

$$\frac{g_\mu}{g_e} = \sqrt{\frac{\sigma_W \cdot B(W \to \mu\nu)}{\sigma_W \cdot B(W \to e\nu)}} = 1.01 \pm 0.04,$$

consistent with lepton universality. The luminosity, structure function, and some background uncertainties cancel in the ratio. CDF has also measured the rate for W bosons decaying into tau leptons [16], giving $g_\tau/g_\mu = 0.96 \pm 0.07$.

We combine these muon results with the electron results in [1, 2] to reduce the statistical and systematic uncertainties, and obtain $\sigma_W \cdot B(W \to l\nu) = 2.20 \pm 0.04\ (stat.) \pm 0.20\ (sys.)$ nb and $\sigma_Z \cdot B(Z \to l^+l^-) = 0.214 \pm 0.011\ (stat.) \pm 0.020\ (sys.)$ nb. The ratio becomes $R_l = \sigma_W \cdot B(W \to l\nu)/\sigma_Z \cdot B(Z \to l^+l^-) = 10.0 \pm 0.6\ (stat.) \pm 0.4\ (sys.)$.

We extract the W width using Equation 1 and the Z total and partial widths as measured at CERN [17]. Uncertainties are small in the theoretical calculation of the ratio of W and Z production cross sections, $\frac{\sigma(p\bar{p}\to WX)}{\sigma(p\bar{p}\to ZX)} = 3.23 \pm 0.03$ at $\sqrt{s} = 1.8$ TeV [18]. We find $\Gamma(W)/\Gamma(W \to l\nu) = 9.6 \pm 0.7$. Figure 2 shows the measured inverse branching ratio and a calculation of its top mass dependence. We extract a limit on the top quark mass of $M_{top} > 45(49)$ GeV/c^2 at the 95% (90%) confidence level independent of how the top quark

decays. Using $\Gamma(W \to l\nu)/\Gamma(Z \to l^+l^-) = 2.71 \pm 0.03$ [19] along with equation 1, we find

$$\Gamma(W)/\Gamma(Z) = 0.87 \pm 0.07, \qquad \Gamma(W) = 2.16 \pm 0.17 \text{ GeV}.$$

Table 2 summarizes the CDF muon, electron, and combined results.

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	Muons	Electrons	Combined
	Statistical, systematic, and luminosity errors.		
$\sigma(W) \cdot B$ (nb)	$2.21 \pm 0.07 \pm 0.14 \pm 0.15$	$2.19 \pm 0.04 \pm 0.14 \pm 0.15$	$2.20 \pm 0.04 \pm 0.13 \pm 0.15$
$\sigma(Z) \cdot B$ (pb)	$226 \pm 22 \pm 18 \pm 15$	$209 \pm 13 \pm 9 \pm 14$	$214 \pm 11 \pm 14 \pm 15$
R	$9.8 \pm 1.1 \pm 0.4$	$10.2 \pm 0.8 \pm 0.4$	$10.0 \pm 0.6 \pm 0.4$
$B.R.^{-1}(W)$	9.9 ± 1.2	9.5 ± 0.9	9.6 ± 0.7
M_{top}, 90% C.L.	-	> 48 GeV/c^2	> 49 GeV/c^2
M_{top}, 95% C.L.	> 22 GeV/c^2	> 43 GeV/c^2	> 45 GeV/c^2
$\Gamma(W)/\Gamma(Z)$	0.89 ± 0.11	0.86 ± 0.08	0.87 ± 0.07
g_μ/g_e			1.01 ± 0.04

Table 2: Muon, electron, and combined results.

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[19] In the Standard model, $\frac{\Gamma(W\to l\nu)}{\Gamma(Z\to l^+l^-)} = (\frac{M_W}{M_Z})^3 \frac{2}{1-4\sin^2\theta_W+8\sin^4\theta_W}$. We use $M_W/M_Z = 0.8791 \pm 0.0034$ and $\sin^2\theta_W = 0.2327 \pm 0.00085$.

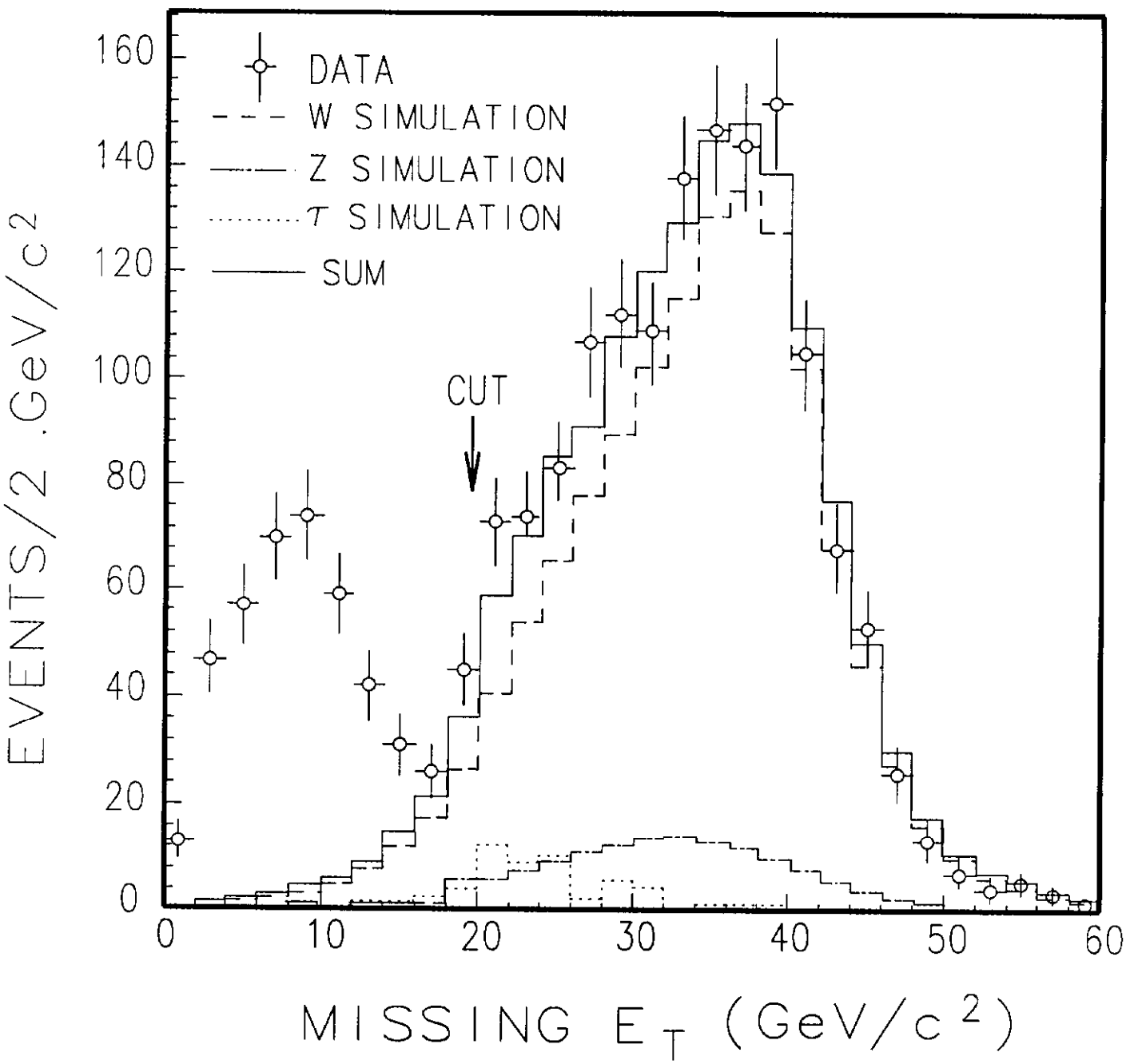

Figure 1: The missing transverse energy distribution for muon trigger events (circles). The histogram shows the Monte Carlo prediction for W signal, including Z and τ backgrounds. The peak at low missing transverse energy comes from QCD backgrounds.

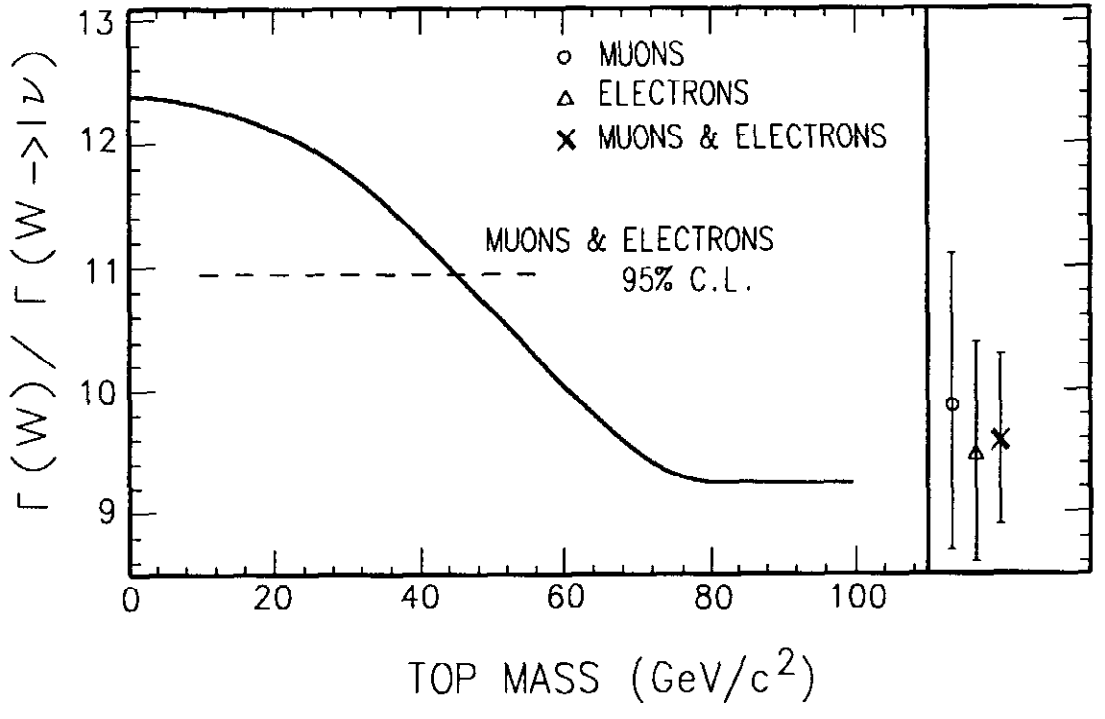

Figure 2: The theoretical prediction for the inverse of the W branching ratio to leptons as a function of the top quark mass, along with the muon, electron, and combined measurements.