Fermi National Accelerator Laboratory

FERMILAB-Conf-85/107-E
7410.594

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*Submitted to Physical Review Letters and the 1985 International Symposium on Lepton and Photon Interactions at High Energies, Kyoto, Japan, August 19-24, 1985.

A determination of $\sin^2\theta_W$ and ρ in deep inelastic neutrino-nucleon scattering

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June 1985
Submitted to
The 1985 International Symposium on Lepton and Photon
Interactions at High Energies
Kyoto, Japan

Abstract

We have determined the electroweak parameters $\sin^2\theta_W$ and ρ by a measurement of deep inelastic neutrino-nucleon scattering using a fine grained neutrino detector exposed to a narrow band neutrino beam at Fermilab. The unique sampling properties of our detector have permitted neutral current and charged current events to be unambiguously identified over a wide kinematic range, thereby allowing a determination of $\sin^2\theta_W$ and ρ to be made with good statistics and small systematic errors. We have found $\sin^2\theta_W = 0.246 \pm 0.012 \pm 0.013$ in a single parameter fit. The details of the experimental and theoretical systematic errors are given.

In the Standard SU(2)xU(1) Model of Glashow-Weinberg-Salam[1] all of the neutral current neutrino-quark couplings are determined by the quark weak isospin, the quark electric charge, and the free parameter $\sin^2\theta_W$. In the minimal version of the Model, the relative strength, ρ, of the neutral current (NC) neutrino-quark coupling to that of the charged current (CC) neutrino-quark coupling is fixed by the relation: $\rho = M_W^2/M_{Z^0}^2 \cos^2\theta_W = 1$, where M_W and M_Z are the $W^\pm$ and Z^0 gauge boson masses, respectively. The Model is frequently extended[2] to include a more complicated Higgs structure beyond a single isodoublet. In this extension of the theory, ρ can have a value different from 1.

Deep inelastic neutrino-nucleon scattering offers the most statistically potent data from which to determine $\sin^2\theta_W$ and ρ. To exploit this statistical power, it is necessary to minimize the theoretical and experimental systematic uncertainties of the determination. This requires knowledge of the quark structure of the nucleon. In addition, NC and CC events must be unambiguously identified. The nucleon structure complications can be adequately treated in data taken with an isoscalar target,[3] and our fine grained neutrino detector allows the two event types to be distinguished with small corrections on an event-by-event basis.

This experiment recorded 12,400 deep inelastic neutrino interactions, after acceptance cuts, in a 340 metric ton calorimeter[4] exposed in 1982 to a narrow band neutrino beam at Fermilab. Kinematic and fiducial volume cuts were made to optimize the NC and CC identification, and to minimize background events induced by electron neutrinos arising from Ke3 decay in the narrow band parent beam. To reduce the confusion between CC and NC events, we required the inelasticity $y = (E_h-M)/E_\nu < 0.7$, where E_h is the hadron energy, M is the mass of the nucleon, and E_ν is the energy of the incident neutrino inferred from the energy versus angle correlation of the $\pi\mu2$ decay neutrinos from the narrow band beam. The hadron energy was required to satisfy $(E_h-M) > 10$ GeV, so that it is well above the trigger threshold of the calorimeter. The radius of the neutrino-nucleon interaction vertex from the incident neutrino beam axis was required to be less than 1 meter giving a fiducial mass of the detector of 55 metric tons. We used these same cuts for our analysis of the neutral current structure functions.[5]

We studied our classification uncertainties by performing a complete simulation of the experiment. By analyzing these Monte Carlo events with the same analysis package that was used for the data, we found that 1% of the CC events were misidentified as NC events, and approximately 4% of the NC events were misidentified as CC events. These corrections are the integral corrections averaged over all sources of neutrinos, including the electron neutrinos from Ke3 decay, and the neutrinos from wideband backgrounds. The events produced by $K\mu2$ neutrinos comprised about 11% of the NC and CC $\pi\mu2$ data sample. The Ke3 background was roughly 1% of the accepted NC events and the wide band neutrino background was determined to be about 1% of the accepted NC and CC events.

Data were taken at narrow band beam secondary momenta of +165, +200, +250 GeV/c for neutrino production and -165 GeV/c for antineutrino production. Table I indicates the beam conditions, mean values of several kinematic variables, the raw number of events, and the number of events at each beam setting after corrections were made for the NC-CC separation.

We used the integral NC to CC ratios for both neutrino and antineutrino data to determine $\sin^2\theta_W$ and ρ. These ratios are defined by:

$$R_{\overset{(-)}{\nu}} = I(\overset{(-)}{\nu}+N\to\overset{(-)}{\nu}+X)/I\ (\overset{(-)}{\nu}+N\to\mu^{\pm}+X) \qquad (1)$$

where $I(\overset{(-)}{\nu}+N\to\overset{(-)}{\nu}+X)$ is the accepted number of NC events which satisfy the cuts described above, and $I(\overset{(-)}{\nu}+N\to\mu^{\pm}+X)$ is the corresponding number of accepted CC events. The ratios were calculated separately for all four secondary momentum settings shown in Table I. The neutrino ratios have the greater sensitivity to $\sin^2\theta_W$. The additional consideration of the antineutrino ratio allows $\sin^2\theta_W$ and ρ to be decoupled partially, and thus to be determined simultaneously. Use of these ratios avoids neutrino flux normalization uncertainties.

The extraction of $\sin^2\theta_W$ and ρ in deep inelastic neutrino scattering is based on the assumption that the quark scaled momentum distributions in the NC structure functions are the same as those of the CC structure functions. In a separate work[5] we tested this assumption by showing that the NC nucleon structure functions are equal within errors to the charged current structure functions. Thus, in the present analysis we used the QCD parameterization of the quark distributions given by Duke and Owens[6] for both the NC and the CC structure functions. However, we found that the extracted values of $\sin^2\theta_W$ and ρ were not very sensitive to the detailed Bjorken x dependence of the quark distribution functions as long as the quark x distributions were the same for both the NC and the CC interaction.

To account for the flavor mixing and heavy quark effects in our computation of the theoretical CC cross section, we included the Kobayashi-Maskawa mixing matrix[7] terms, and the so-called slow rescaling terms[8] for charmed quark production. In the slow rescaling calculation the charmed quark mass was taken to be 1.5 GeV/c^2. Radiative corrections along the external muon leg were made according to the prescription of De Rujula et al.[9] We have not corrected for isospin symmetry breaking bremsstrahlung effects associated with the quark legs since these effects are estimated to be an order of magnitude smaller[10] and thus are negligible. The value of ρ has been modified by the prescription of Sirlin and Marciano[11] to correct for the radiative effects from box diagrams. External bremsstrahlung and non-isoscalar[12] corrections for our target material have been found to be negligible.

The measured value of R_ν is plotted against $R_{\bar{\nu}}$ in Figure 1. We averaged the three neutrino ratios given in Table I for the plotted value of R_ν. In this figure we show the theoretical prediction of R_ν

versus $R_{\bar{\nu}}$ as a function of $\sin^2\theta_W$. The theoretical curve was computed with all of the effects mentioned above, as well as the resolutions and cuts of this experiment.

The values of $\sin^2\theta_W$ and ρ were determined by a minimum χ^2 fitting procedure[13] which matched a Monte Carlo simulation to the data. All four NC/CC ratios were included in the fit as four separate data points. The Monte Carlo simulation included all known details of the incident neutrino beam, the experimental resolutions,[4] the backgrounds, and the experimental cuts. In our fit for $\sin^2\theta_W$ alone we found:

$$\sin^2\theta_W = 0.246 \pm 0.012 \pm 0.013 \tag{2}$$

where the first error is statistical and the second is systematic. The value of ρ was fixed to 0.9915 according to the calculation of Sirlin and Marciano[14] for the box diagram radiative correction. The χ^2/degrees of freedom of the fit was 3.9/3. The two dimensional fit, with the muon leg and box diagram radiative corrections , yielded:

$$\sin^2\theta_W = 0.279 \pm 0.027 \pm 0.019 \tag{3}$$
$$\rho = 1.027 \pm 0.023 \pm 0.026 \quad .$$

The χ^2/degrees of freedom for the fit was 2.5/2. We note that the magnitude of ρ in this fit is consistent with the Standard Model value of 1.0. In the two dimensional fit, the parameters $\sin^2\theta_W$ and ρ are strongly correlated. This is illustrated in Figure 2.

The systematic errors of this calculation arise from both experimental and theoretical sources and are listed in Table II. The experimental systematic errors for the single parameter fit are dominated by the NC-CC separation corrections, and the systematic error from theoretical sources arises primarily from the slow rescaling correction in the calculation of the CC cross section.

To compare our one parameter result with other experiments and with theory, we computed $\sin^2\theta_W$ in two renormalization conventions. In the convention where $\sin^2\theta_W$ is defined in terms of the physical boson masses[11] by the relation $\sin^2\theta_W=1-M_W^2/M_Z^2$, we found:

$$\sin^2\theta_W = 0.247 \pm 0.012 \pm 0.013 \quad . \tag{4}$$

In the $\overline{MS}$ scheme with the 't Hooft unit of mass chosen to be M_W[11] which is appropriate for the SU(5) theories, we computed:

$$\sin^2\theta_W = 0.245 \pm 0.012 \pm 0.013 \quad . \tag{5}$$

The errors quoted above are the statistical and systematic errors, respectively.

Several aspects of our determination of $\sin^2\theta_W$ have been investigated by considering only the neutrino data, or by changing various elements of the theory. When we use only the neutrino data in our fit, thereby reducing the sensitivity to the antiquark sea, we found $\sin^2\theta_W = 0.246 \pm 0.015$ (statistical error) with a χ^2/degrees of freedom=2.5/2. Using all the neutrino and antineutrino data, but with the slow rescaling correction relaxed by setting the charmed quark mass to zero, we obtained a value of $\sin^2\theta_W = 0.228 \pm 0.012$(statistical error). This is in better agreement with previous measurements[15], but the fit had a poor χ^2/degrees of freedom = 8.0/3. The value of $\sin^2\theta_W$ with no radiative corrections (ρ=1 and no muon leg bremsstrahlung) was found to be 0.257 ± 0.012 (statistical error).

The Grand Unified Theory based on minimal SU(5) predicts[16] a value of $\sin^2\theta_W = 0.214 ^{+0.004}_{-0.003}$, which is smaller than our value. Supersymmetric Grand Unified Theories[17] can accomodate larger values of $\sin^2\theta_W$ and are in better agreement with our determination, but the predictions of these models are flexible.

In summary, we determined $\sin^2\theta_W$ and ρ by fitting the integral ratios of NC events to CC events. Radiative corrections and slow rescaling corrections have been performed. The analysis employed strict kinematic and fiducial volume cuts to reduce the backgrounds in the data. We found for the single parameter fit $\sin^2\theta_W = 0.246 \pm 0.012 \pm 0.013$.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of the National Science Foundation and the Department of Energy. The generous technical assistance provided by Fermilab staff, especially D.Burandt and R.Olsen, is gratefully acknowledged. Special thanks to Professor M.Peters, University of Hawaii, who helped with the offline software and data taking, and to Dr. S. Mori, Dr. T. Ohsugi, and Dr. J. Wolfson who helped in the early phases of this work.

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Table I

The Number of Accepted Events at Various Beam Conditions

P_0 is the central momentum of the narrow band train. The (-) + momentum settings correspond to (anti) neutrino beams. The mean true neutrino energy, E_ν, and the mean true 4-momentum transferred to the struck quark, Q^2, for the experimental cuts of $y < 0.7$ and $(E_h - M) > 10$ GeV have been estimated by the Monte Carlo simulation of the experiment. The raw and corrected number of accepted events correspond to before and after the event classification correction, respectively. The errors of $R_{\overset{(-)}{\nu}}$ are the statistical uncertainties.

			Number of Events				
			raw		corrected		
P_0(GeV/c)	E_ν(GeV)	Q^2(GeV/c)^2	NC	CC	NC	CC	$R_{\overset{(-)}{\nu}}$
165	61.3	11.0	950	3235	966	3219	0.300 ± 0.011
200	74.7	12.2	638	2184	647	2175	0.298 ± 0.013
250	92.4	13.8	656	2093	677	2072	0.327 ± 0.014
-165	61.5	8.6	723	1945	740	1928	0.384 ± 0.017

Table II

Estimate of the Systematic Errors

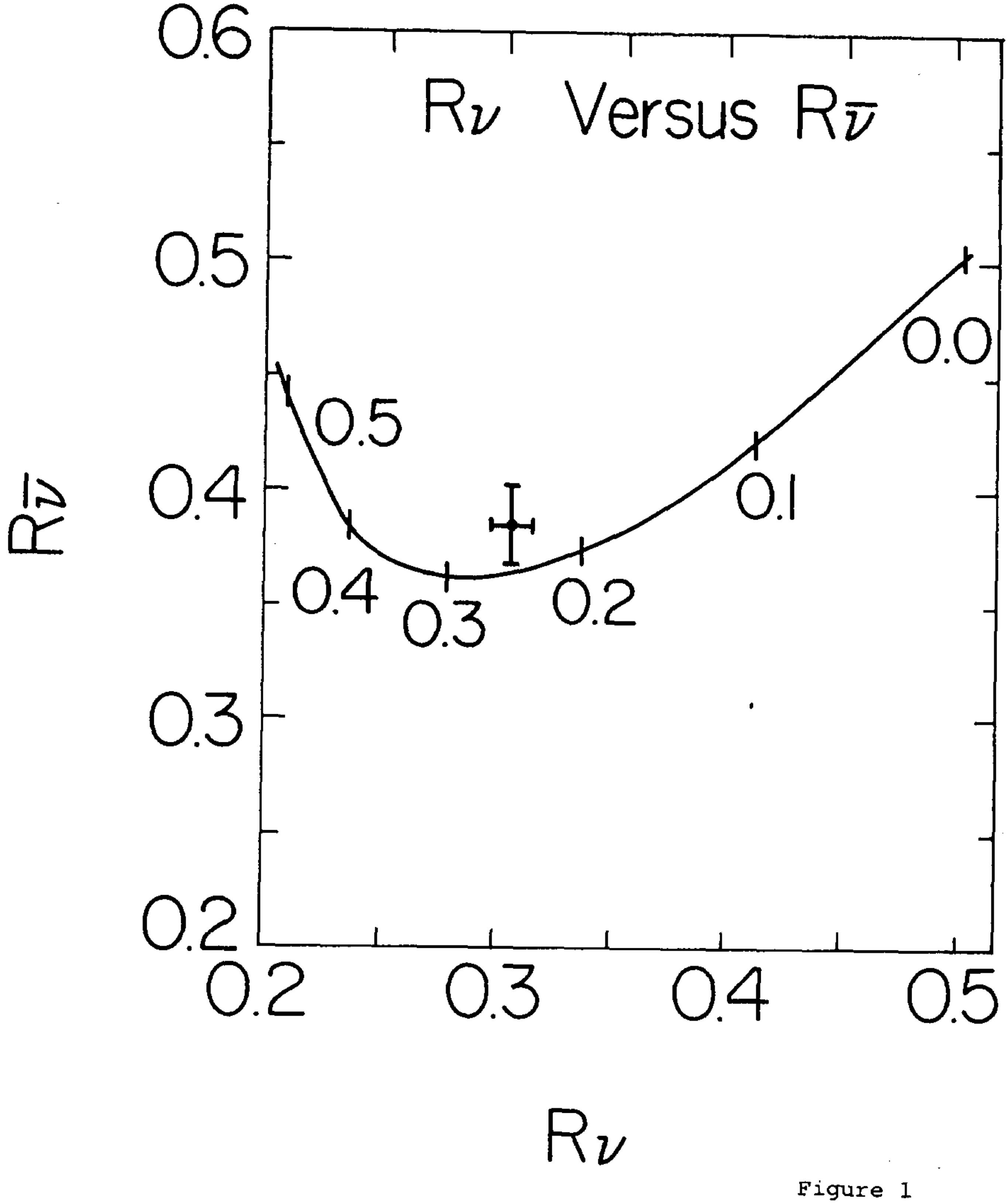
The major sources of experimental and theoretical systematic errors are tabulated. The total systematic error was computed by adding all sources in quadrature. The systematic errors for the single parameter $\sin^2\theta_W$ fit are enclosed in parentheses ( ) and the errors for $\sin^2\theta_W$ for the two parameter fit are recorded in the second column. The two parameter fit errors are correlated.

Experimental sources	$\Delta\sin^2\theta_W/\sin^2\theta_W$		$\Delta\rho/\rho$
Neutral current/Charged current separation	(±4.2%)	±3.9%	±1.3%
Muon track elimination in Charged current hadron energy determination	(±2.0%)	±5.4%	±1.8%
Experimental Error	(±4.7%)	±6.7%	±2.2%
Theoretical sources	$\Delta\sin^2\theta_W/\sin^2\theta_W$		$\Delta\rho/\rho$
Strange sea magnitude ($xs(s)=(0.50\pm 0.20)x\bar{u}(x)$)	(±0.4%)	±0.4%	±0.1%
QCD corrections ($\Lambda_{lo}=200^{+200}_{-100}$ MeV/c)	(±0.1%)	±0.05%	±0.05%
Slow Rescaling (M_c=1.5±0.4 GeV/c²)	(±2.0%)	±1.8%	±1.1%
Theoretical Error	(±2.0%)	±1.8%	±1.1%
Total Systematic Error	(±5.1%)	±6.9%	±2.5%

FIGURE CAPTIONS

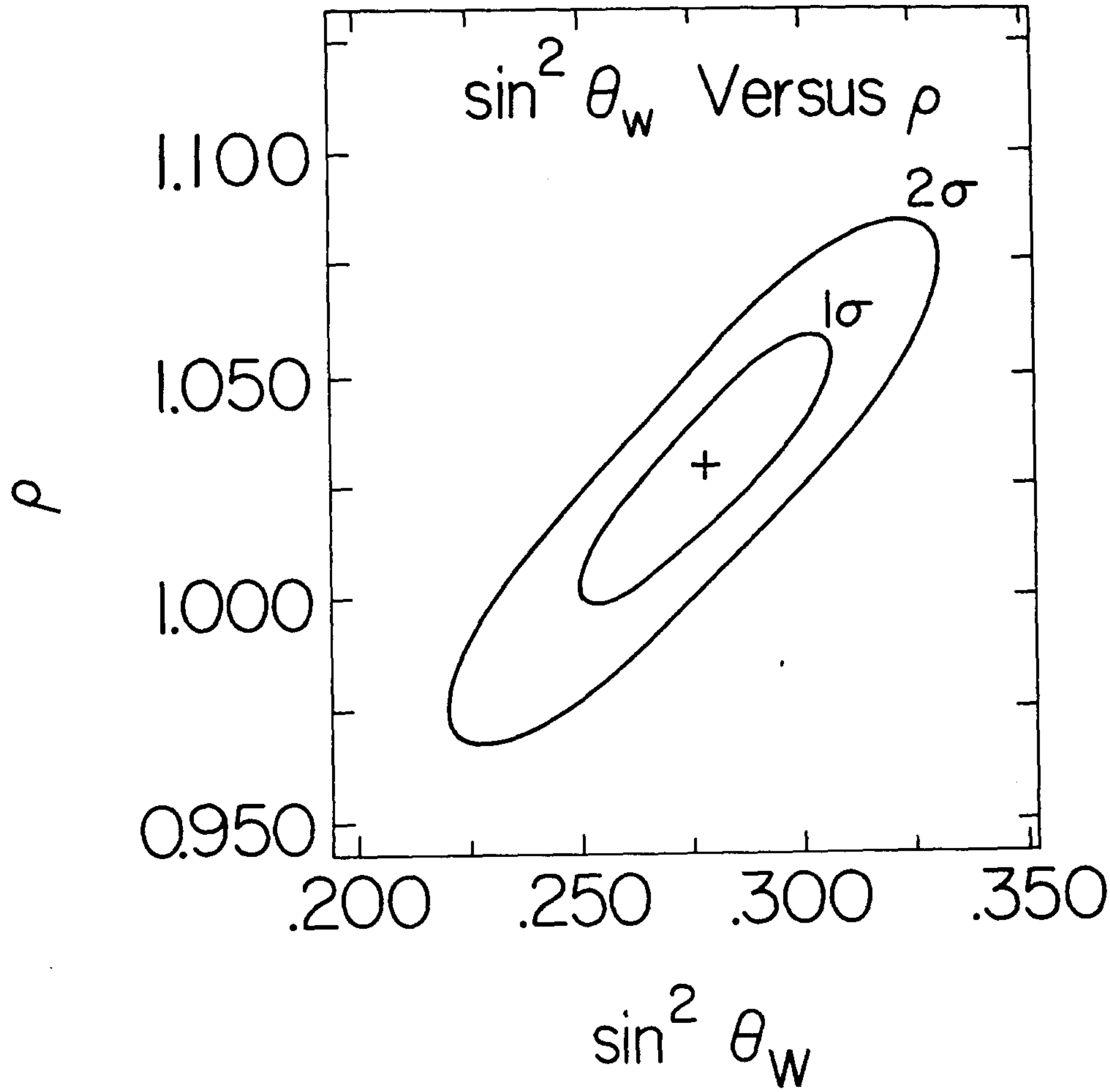
Fig. 1. The averaged value of the NC/CC ratio R_ν for the three neutrino beam settings is plotted against the value of the NC/CC ratio $R_{\bar{\nu}}$ for antineutrinos. The error bars on R_ν and $R_{\bar{\nu}}$ represent the statistical uncertainties. The curve is the theoretical relation between R_ν and $R_{\bar{\nu}}$ as a function of $\sin^2\theta_W$ with all the radiative effects, slow rescaling corrections, experimental cuts, and resolution smearing described in the text.

Fig. 2. The 1 and 2 standard deviation contours[13] for the simultaneous fit of $\sin^2\theta_W$ and ρ are indicated. The value of ρ has been shifted by the radiative correction factor discussed in the text.



R_ν Versus $R_{\bar\nu}$
0.6
0.5
0.4
0.3
0.2
$R_{\bar\nu}$
0.0
0.1
0.2
0.3
0.4
0.5
0.2
0.3
0.4
0.5
R_ν

Figure 1



$\sin^2\theta_W$ Versus ρ
2σ
1σ
1.100
1.050
1.000
0.950
ρ
.200
.250
.300
.350
$\sin^2\theta_W$

Figure 2