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Determination of the nucleon structure using the weak neutral current

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Abstract

An experimental determination of the neutral current structure functions of the nucleon is obtained by measuring the ratio of the neutral current x distribution to the charged current x distribution. The analysis is based on deep inelastic neutrino nucleon scattering data gathered in a massive fine-grained neutrino detector exposed to a narrow band neutrino beam at Fermilab.

In the Standard Model of electroweak interactions, the nucleon structure probed in neutral current (NC) deep inelastic neutrino-nucleon scattering is expected to be nearly equal to that measured in charged current (CC) scattering. While extensive data exist on the small scale structure of the nucleon determined by deep inelastic CC neutrino scattering,[1] there is comparatively little data on the structure of the nucleon derived from experiments which have studied the NC neutrino-nucleon interaction. The early NC experiments suffered from low statistics or used a statistical method of reconstructing the NC kinematics[2]. We have performed an experiment with increased statistics where the NC kinematics have been reconstructed by a direct analysis.

This experiment recorded 12,400 interactions after acceptance cuts in a 340 metric ton fine-grained calorimeter[3] exposed to the narrow band neutrino beam at Fermilab. We have reconstructed the kinematical variables of the NC and CC events by using the observed energies and angles of the recoil hadronic showers. We present our results as a ratio of the respective x-distributions of the two interactions, where x is the Bjorken scaling variable. A number of the systematic errors of the result are reduced with this ratio comparison.

The differential cross-section for neutrino deep inelastic scattering is given by[4]:

$$(d^2\sigma)/(dxdy) = G^2ME_\nu/\pi \left[(1-y+y^2/2)F_2(x)\pm(y-y^2/2)xF_3(x)\right] \qquad (1)$$

where the (-)+ is for (anti)neutrino scattering, E_ν and E_h are the energies of the incident neutrino and recoil hadronic shower, respectively, $x=Q^2/2M(E_h-M)$ is the fraction of the momentum of the nucleon carried by the struck quark, Q^2 is the square of the four-momentum transferred to the struck quark, M is the nucleon mass, and $y=(E_h-M)/E_\nu$. Equation (1) assumes Bjorken scaling and the Callan-Gross relation,[4] $2xF_1(x)=F_2(x)$.

In the Standard Model, the CC structure functions are:

$$\begin{aligned} F_2(x) &= xq(x) + x\bar{q}(x) \\ xF_3(x) &= xq(x) - x\bar{q}(x) \pm 2\left[xs(x)-xc(x)\right] \end{aligned} \tag{2}$$

where the (-)+ sign corresponds to (anti) neutrinos respectively, and where the quark distributions for an isoscalar target are:

$$\begin{aligned} q(x) &= u(x) + d(x) + s(x) + c(x) \\ \bar{q}(x) &= \bar{u}(x) + \bar{d}(x) + \bar{s}(x) + \bar{c}(x) \quad . \end{aligned} \tag{3}$$

The NC structure functions have different contributions from the participating quarks. They are given by:

$$\begin{aligned} F_2(x) &= (u_L^2+d_L^2+u_R^2+d_R^2)\left[xq(x)+x\bar{q}(x)\right] \\ &\quad -(u_L^2-d_L^2+u_R^2-d_R^2)2\left[xs(x)-xc(x)\right] \\ xF_3(x) &= (u_L^2+d_L^2-u_R^2-d_R^2)\left[xq(x)-x\bar{q}(x)\right] \end{aligned} \tag{4}$$

where u_L, d_L are the up and down quark left handed couplings respectively and u_R, d_R are the right handed couplings, all of which depend on $\sin^2\theta_W$ in the Standard Model.

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[5]. We have used the region dominated by neutrinos from pion decay by requiring the event vertex to be within a radius of 1 meter of the neutrino beam axis. The neutrino energy is correlated with the radius by the two body π and K meson decay kinematics. The fiducial mass of the detector was 55 metric tons.

To eliminate kinematic regions of poor x resolution or poor NC−CC event separation, cuts were made requiring $E_h > 10$ GeV and $y=(E_h-M)/E_\nu(r) < 0.7$, where E_h is the measured hadron energy, $E_\nu(r)$ is the mean neutrino energy from pion decay at the radius r of the event (computed by Monte Carlo simulation), and M is the nucleon mass. With these cuts, we have estimated by Monte Carlo simulation that the events produced by the muon neutrinos from $K\mu 2$ ($K\mu 3$) decay were 11% (0.5%) of the NC and CC $\pi\mu 2$ events. The events arising from electron neutrinos from Ke3 decay were 1% of the accepted NC sample. The wide band neutrino background was about 1% of both the NC and CC $\pi\mu 2$ data set.

CC and NC events were distinguished by the presence or absence of an outgoing muon track from the neutrino−nucleon interaction vertex. From hadron calibration data and Monte Carlo simulations, we have determined that the average identification efficiencies for accepted NC events and CC events were approximately 0.96 and 0.99, respectively. These values are the effective efficiencies averaged over all incident neutrino species, including electron neutrinos from Ke3 decay. The corrected numbers of accepted events which satisfy the cuts described above are given in Table I.

To reduce the systematic errors in our NC-CC comparison, the scaling variable x for both NC and CC events was computed from the measured hadron recoil energy, the hadron angle with respect to the incident neutrino beam axis, and the inferred $\pi\mu 2$ neutrino energy derived from the simulated properties of the narrow band beam. The x resolution is therefore a function of the hadron energy and angle resolutions[3], and the incident neutrino energy resolution. A typical value of the x resolution is $\sigma_x \approx x$, but it varies over the kinematic region of the experiment. The treatment of this resolution is an integral part of our method of extracting the NC structure functions.

The comparison of the NC and the CC x-distributions is shown in Fig. 1. No correction has been applied for the resolution smearing, but the data have been corrected for the event type misclassification (including Ke3 CC events). The CC data have been normalized in this figure to the same number of NC events at each of the secondary beam settings to make the comparison of the distributions more direct. We see that the x-distributions of the two interactions are the same within statistical errors. Fig. 2 shows the NC/CC ratios for neutrino and antineutrino data as a function of x. For displaying the data, we have combined all of the neutrino energy settings into one plot since there appear to be no systematic differences among the various data sets. The bin at the highest x value included data for reconstructed x>1. The ratios appear to be approximately flat within the statistical errors.

To make a quantitative comparison of the nucleon structure functions of the two interactions, we fit the x dependence of the NC/CC ratios of both the neutrino and antineutrino data simultaneously. We included each of the four beam settings separately so that there were a total of 40 data points in the fit, 10 for each setting. Monte Carlo "data", with all the neutrino beam details and experimental resolutions[3], were matched to the data by varying the shape of the NC structure functions. The resulting errors of the NC structure function parameters were then derived from the statistical uncertainties of the data and the resolution smearing in the scaling variable x.

A simple parameterization of the structure functions was chosen for both the NC and CC interaction which gave a good representation of the world's CC data[1] at our mean $Q^2=11(\mathrm{GeV}/c)^2$. We neglected the Q^2 evolution of the structure functions described by QCD. The forms of the valence and sea structure functions are given by:

$$xV(x) = xq(x)-x\bar{q}(x) = A\,x^{\alpha}\,(1-x)^{\beta} \qquad (5a)$$

$$2x\bar{q}(x) = C\,(1-x)^{\gamma}\ . \qquad (5b)$$

The charm quark sea was neglected and the strange quark sea was assumed to be 20% of the total quark sea, $2x\bar{q}(x)$. The charged current

Monte Carlo simulation included the full Kobayashi - Maskawa quark mixing matrix[6], and the charmed quark kinematic threshold factor (the so-called slow rescaling correction[7]) where the charmed quark mass was taken to be 1.5 GeV/c^2. Radiative effects have been included in the CC simulation[8]. The external bremsstrahlung correction associated with the outgoing muon track and the non-isoscalar correction for our average target material have been considered and found to be negligible.

Two fits of the NC/CC ratios under different assumptions have been performed. In Fit 1, the values of A, β, and C have been determined under the constraint α = 1/2 in accordance with CC data[1] and the prediction of Regge Theory[9]. The fit has little sensitivity to the shape of the NC sea quark term, so we fixed $\gamma_{nc} = \gamma_{cc}$ in agreement with CC data[1] at our mean Q^2 and in conformity with counting rule arguments[10]. We have used our value of $\sin^2\theta_W = 0.246 \pm 0.012$ determined by a one parameter fit to the integral NC/CC ratios for neutrinos and antineutrinos[11]. The results of Fit 1, which do not depend on assumptions about the Gross Llewellyn-Smith sum rule[4], are consistent with the sum rule prediction. In Fit 2, we included this sum rule constraint and required $\gamma_{nc} = \gamma_{cc}$ to determine α, β, and C thereby testing the self-consistency of our procedure.

The results of the fits[12] are shown in Table II. It is important to note that only the differences between the assumed values of the CC parameters and the determined NC parameters are significant. In this manner we have determined the NC structure functions relative to those of the CC interaction. The fits indicate that the NC and the CC parameters agree to within one standard deviation.

In estimating the systematic errors of the fits, we have considered the sensitivities to different values of $\sin^2\theta_W$, the hadronic energy scale, the event classification , and the upper y cut. Systematic errors from the uncertainties of the strange sea, the slow rescaling threshold, the radiative corrections, and the Kobayashi-Maskawa matrix have also been included, although they are smaller than the errors from the sources listed above.

The values of the fit parameters yield an integral quark sea content of $\overline{Q}/(Q+\overline{Q})=0.16\pm0.04$ for Fit 1 and 0.17 ± 0.04 for Fit 2 where: $\overset{(-)}{Q} = \int_0^1 x\overset{(-)}{q}(x)dx$. The value of this ratio is 0.136 for the CC interaction using the parameters of Table II. For Fit 1, we find $\int_0^1 V(x)dx = 3.1 \pm 0.5$ indicating that the Gross Llewellyn-Smith sum rule is satisfied.

Finally, we note that the fit parameters are highly correlated and only the diagonal errors are noted in Table II. The off-diagonal elements of the covariance matrix are for Fit 1 $C_{A\beta} = 0.239$, $C_{Ac} = -0.098$ and $C_{\beta c} = -0.050$, and for Fit 2 $C_{\alpha\beta} = 0.057$, $C_{\alpha c} = -0.013$, $C_{\beta c} = -0.072$.

In summary, we have measured the x distributions for deep inelastic neutrino-nucleon scattering for both the NC and the CC interaction. From a ratio comparison of these distributions, the NC nucleon structure functions relative to those of the CC interaction have been extracted. We find no significant difference of the nucleon structure measured in the two interactions, thereby confirming the expectation of the Standard Model.

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Table I

Number of Accepted Events Corrected for Event Type Misclassification.

The (-) + momentum settings correspond to (anti) neutrino beams.

The errors in the ratios are statistical only.

Secondary Momentum (GeV/c)	NC	CC	NC/CC
+165	966	3219	0.300±0.011
+200	647	2175	0.297±0.013
+250	677	2072	0.327±0.014
-165	740	1928	0.384±0.017

Table II

Results of The Fits to The NC Structure Functions

The first error for each NC parameter is the statistical error determined by the fitting procedure, and the second error is an estimate of the systematic error. The entries with no errors are the input parameters.

CC Parameters		Fit 1 NC Parameters	Fit 2 NC Parameters
Valence			
A	3.28	3.59 ± 0.63 ± 0.62	$A=3\Gamma(\alpha+\beta+1)/\Gamma(\alpha)\Gamma(\beta+1)$
α	0.50	0.50	0.48 ± 0.10 ± 0.10
β	3.0	3.54 ± 0.40 ± 0.41	3.38 ± 0.62 ± 0.54
Sea			
C	1.0	1.16 ± 0.18 ± 0.13	1.21 ± 0.16 ± 0.13
γ	7.0	7.0	7.0
χ^2/degrees of freedom		32.0/37	32.0/37

FIGURE CAPTIONS

Fig. 1. The NC and CC x distributions for the four beam conditions of this measurement: neutrino data (a),(b),(c); antineutrino data (d). The CC data have been normalized to the same integral number of events as the NC data at each beam setting. The NC data are indicated by the error bars and the CC data by the histogram. The corresponding statistical errors for the CC data are about 1.8 times smaller than the NC statistical errors.

Fig. 2. NC/CC ratio as function of x for (a) neutrinos, where all three settings have been combined for display, and (b) antineutrinos. The solid line indicates the results from both Fits 1 and 2 described in the text. The data have been corrected for the event misclassification.

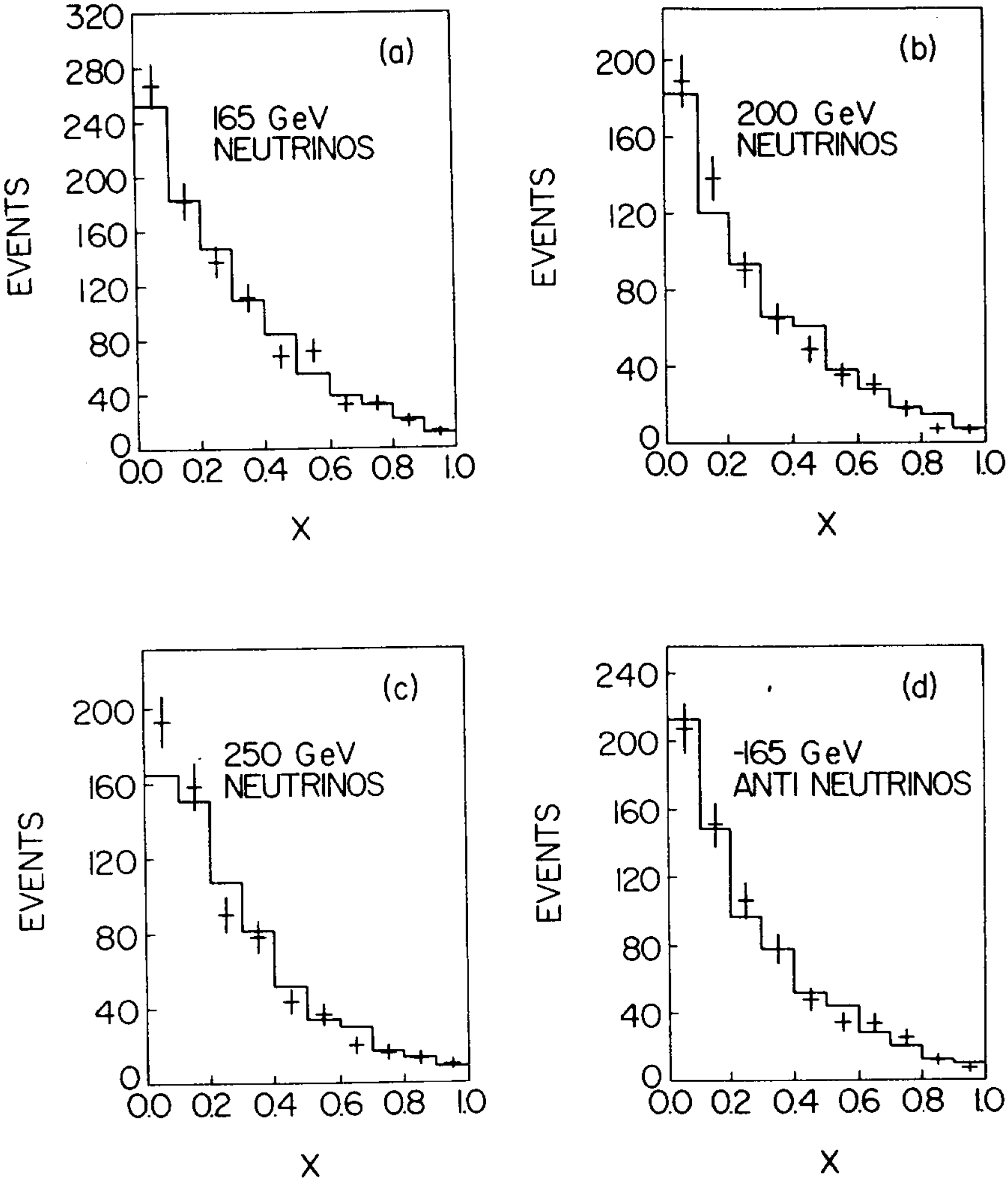
(a)
165 GeV
NEUTRINOS
EVENTS
X
(b)
200 GeV
NEUTRINOS
EVENTS
X
(c)
250 GeV
NEUTRINOS
EVENTS
X
(d)
165 GeV
ANTI NEUTRINOS
EVENTS
X

Figure 1

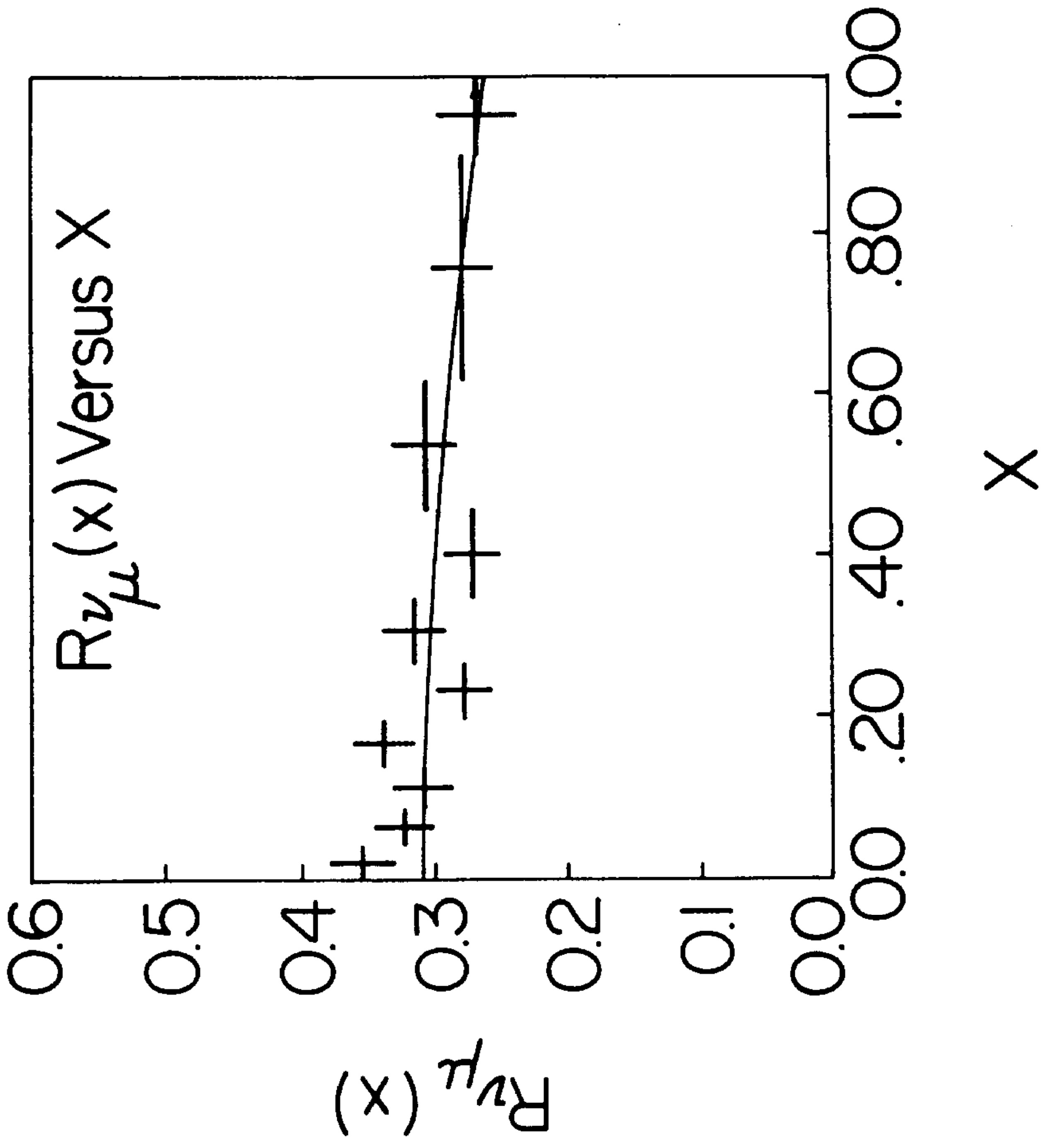

Figure 2A

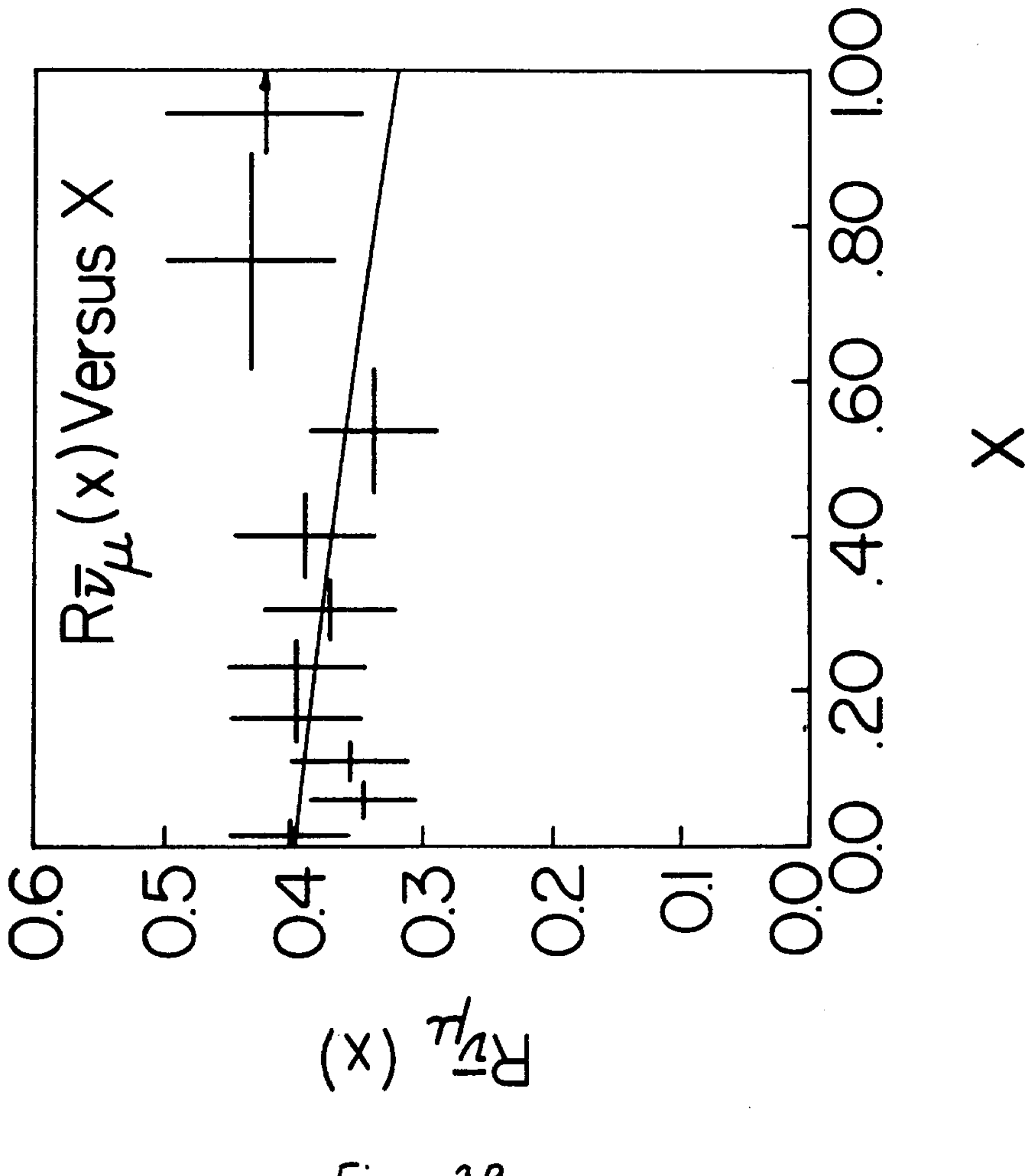
$R\bar{\nu}_\mu$(x) Versus X
0.6
0.5
0.4
0.3
0.2
0.1
0.0
$R\bar{\nu}_\mu$ (x)
0.0
.20
.40
.60
.80
1.00
X

Figure 2B