Low-$Q^2$ low-$x$ Structure Function Analysis of CCFR data for $F_2$

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Analyses of structure functions (SFs) from neutrino and muon deep inelastic scattering (DIS) data have shown discrepancies in $F_2$ for $x < 0.1$. A new SF analysis of the CCFR collaboration data examining regions in $x$ down to $x = 0.0015$ and $0.4 < Q^2 < 1.0$ is presented. Comparison to corrected charged lepton scattering results for $F_2$ from the NMC and E665 experiments are made. Differences between $\mu$ and $\nu$ scattering allow that the behavior of $F_2^\mu$ could be different from $F_2^\nu$ as $Q^2$ approaches zero. Comparisons between $F_2^\mu$ and $F_2^\nu$ are made in this limit.

High-energy neutrinos are a unique probe for understanding the parton properties of nucleon structure. Combinations of $\nu$ and $\bar{\nu}$ DIS data are used to determine the $F_2$ and $xF_3$ SFs which determine the valence, sea, and gluon parton distributions in the nucleon $^{89}$. The universalities of parton distributions can also be studied by comparing neutrino and charged lepton scattering data. Past measurements have indicated that $F_2^\nu$ differs from $F_2^e/\mu$ by 10-15% in the low-$x$ region $^{89}$. These differences are larger than the quoted combined statistical and systematic errors of the measurements and may indicate the need for modifications of the theoretical modeling to include higher-order or new physics.
contributions. We present a new analysis of the CCFR collaboration \( \nu N \) DIS data in a previously unexplored kinematic region. In this low-\( x \) and low-\( Q^2 \) region, the discrepancy between \( F_2^{\nu} \) and \( F_2^{\mu} \) persists. However, in this kinematic region some differences in \( F_2 \) from neutrino and charged lepton data may result from differences in the properties of weak and electromagnetic interactions. Within the PCAC nature of \( \nu N \) DIS, \( F_2^{\nu} \) should approach a constant as \( Q^2 \) approaches zero, while \( F_2^{e/\mu} \) for charged lepton DIS should approach zero. A determination of this constant is presented.

The \( \nu \) DIS data were taken in two high-energy high-statistics runs, FNAL E744 and E770, in the Fermilab Tevatron fixed-target quadrupole triplet beam (QTB) line by the CCFR collaboration. The detector, described in Refs. [4,5], consists of a target calorimeter instrumented with both scintillators and drift chambers for measuring the energy of the hadron shower \( E_{HAD} \) and the \( \mu \) angle \( \theta_\mu \), followed by a toroid spectrometer for measuring the \( \mu \) momentum \( p_\mu \). There are 950,000 \( \nu_\mu \) events and 170,000 \( \tau_\mu \) events in the data sample after fiducial-volume cuts, geometric cuts, and kinematic cuts of \( p_\mu > 15 \text{ GeV}, \theta_\mu < 150 \text{ mr}, E_{HAD} > 10 \text{ GeV}, \) and \( 30 < E_\nu < 360 \text{ GeV} \), to select regions of high efficiency and small systematic errors in reconstruction.

In order to extract the SFs from the number of observed \( \nu_\mu \) and \( \tau_\mu \) events, determination of the flux was necessary [7,6,8]. The cross-sections, multiplied by the flux, are compared to the observed number of \( \nu N \) and \( \tau N \) events in each \( x \) and \( Q^2 \) bin to extract \( F_2(x, Q^2) \) and \( x F_3(x, Q^2) \). Determination of muon and hadron energy calibrations from the previous CCFR analysis were used in the present analysis. These calibrations were determined from test beam data collected during the course of the experiment [6,5]. Changes in the SF extraction to extend the analysis into the low-\( Q^2 \), low-\( x \) region include incorporation of an appropriate model below \( Q^2 \) of 1.35 GeV\(^2 \), in this case we chose the GRV [1] model of PDFs. The data have been corrected using the leading order Buras-Gaemers model [4] for slow rescaling [12,13], with charm mass of 1.3 GeV and for the difference in \( x F_3^{\nu} - x F_3^{\mu} \). In addition, corrections for radiative effects [10], non-isoscalarity of the Fe target, and the mass of the W-boson propagator were applied. Due to the systematic uncertainty in the model, the radiative correction error dominates in the lowest \( x \) bins. Other significant systematics across the entire kinematic region include the value of \( R \), which comes from a global fit to the world’s measurements [11].

The SF \( F_2 \) from \( \nu \) DIS on iron can be compared to \( F_2 \) from charged lepton DIS on isoscalar targets. To make this comparison, two corrections must be made to the charged lepton data. For deuterium data, a heavy nuclear target correction must be made to convert \( F_2^{dD} \) to \( F_2^{tFe} \) [13]. Second, a correction was made to account for the different quark charge involved in the charged lepton DIS interactions [3]. The errors on the nuclear and charge corrections are small compared to the statistical and systematic errors on both the CCFR and NMC data. The corrected SF, \( F_2 \), from \( \mu \) DIS experiments NMC and E665 [15,16] along with CCFR for lowest \( x \)-bins is shown in Fig. [4]. The new analysis allows comparison to E665 data, which is in the low-\( x \), low-\( Q^2 \) region. Error bars for CCFR and E665 data are large in the \( x \)-bin, \( x = 0.0015 \). However, In the next \( x \)-bin, \( x = 0.0045 \), there is clearly as much as a 20% discrepancy between the NMC \( F_2^{\mu} \) and the CCFR \( F_2^{\nu} \) and an approximately 10% discrepancy between CCFR and E665. As the value of \( x \) increases, the discrepancy decreases; there is agreement between CCFR and the charged lepton experiments above \( x = 0.1 \).
The discrepancy between CCFR and NMC at low-$x$ is outside the experimental systematic errors quoted by the groups. Several suggestions for an explanation have been put forward. One suggestion [17], that the discrepancy can be entirely explained by a large strange sea, is excluded by the CCFR dimuon analysis which directly measures the strange sea [18]. Another is that the strange sea may not be the same as the anti-strange sea distribution. Data from both NMC and CCFR do not support this possibility [19]. Another possibility is that the heavy nuclear target correction may be different between neutrinos and charged leptons. Heavy target corrections used in this paper are determined by NMC for charged lepton-nucleon DIS data and applied to NMC and E665 only; no charged lepton correction data is applied to $\nu$ data. Another possibility that has been proposed would have a large symmetry violation in the sea quark [20], but recently the model has been ruled out by the CDF $W$ charge asymmetry measurements [21]. Finally, in the low-$x$ and low-$Q^2$ region, some of the discrepancy may be accounted for by the differences in behavior of $F_2$ as $Q^2$ approaches zero, although this can only address the $x < 0.0175$ region.

In charged lepton DIS, the SF, $F_2$, is constrained by gauge invariance to vanish linearly with $Q^2$ at $Q^2 = 0$. Donnachie and Landshoff predict that in the low-$Q^2$ region, $F_2^\mu$ will follow the form [22] $C \left( \frac{Q^2}{Q^2 + A^2} \right)$. However, in the case of neutrino DIS, the PCAC nature of the weak interaction contributes a nonzero component to $F_2$ as $Q^2$ approaches zero. Donnachie and Landshoff predict that $F_2^\nu$ should follow a form with a non-zero contribution at $Q^2 = 0$: $C \left( \frac{Q^2}{Q^2 + A^2} + \frac{Q^2 + D}{Q^2 + B^2} \right)$. Using NMC data we fit to the form predicted
Table 1
Fit results for NMC and CCFR data. NMC is fit to Eq. 3 and parameter $A$ extracted: $A = 1.00 \pm 0.17$. CCFR data is fit to Eq. 4 with $A$ extracted from NMC fit. $B$, $C$, $D$ and $F_2$ at $Q^2$ results shown below.

| $x$   | $B$          | $C$          | $D$          | $F_2^\nu (Q^2 = 0)$ | $\chi^2$ |
|-------|--------------|--------------|--------------|---------------------|----------|
| 0.0045| 1.54 $\pm$ 0.03 | 2.57 $\pm$ 0.29 | 0.40 $\pm$ 0.23 | 0.22 $\pm$ 0.13    | 1.01     |
| 0.0080| 1.51 $\pm$ 0.04 | 2.34 $\pm$ 0.06 | 0.64 $\pm$ 0.06 | 0.33 $\pm$ 0.04    | 1.04     |
| 0.0125| 1.50 $\pm$ 0.04 | 2.28 $\pm$ 0.05 | 0.70 $\pm$ 0.06 | 0.36 $\pm$ 0.04    | 0.70     |
| 0.0175| 1.51 $\pm$ 0.04 | 2.31 $\pm$ 0.05 | 0.64 $\pm$ 0.06 | 0.33 $\pm$ 0.04    | 0.80     |

for $e/\mu$ DIS, extracting the parameter $A$. Inserting this value for $A$ into the form predicted for $\nu$ DIS, we fit CCFR data to extract parameters $B,C,D$, and determine the value of $F_2$ at $Q^2 = 0$. Only data below $Q^2 = 1.35$ GeV$^2$ are used in the fits. The CCFR $x$-bins having enough data for a good fit in this $Q^2$ region are $x = 0.0045$, $x = 0.0080$, $x = 0.0125$, $x = 0.0175$. Table I shows the results of the fits. The values of $F_2$ at $Q^2=0$ in the three highest $x$-bins are statistically significant and in agreement with each other. The lowest $x$-bin is consistent with the other results.

In summary, a comparison of $F_2$ from $\nu$ DIS to that from $\mu$ DIS continues to show good agreement above $x = 0.1$ but a difference at smaller $x$ that grows to 20% at $x = 0.0045$. The experimental systematic errors between the two experiments, and improved theoretical analyses of massive charm production in both neutrino and muon scattering are both presently being investigated as possible reasons for this discrepancy. Some of this low-$x$ discrepancy may be explained by the different behavior of $F_2$ from $\nu$ DIS to that from $e/\mu$ DIS at $Q^2 = 0$. CCFR $F_2^\nu$ data appear to approach a non-zero constant at $Q^2 = 0$.

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