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New Measurements of Nucleon Structure Functions from the CCFR/NuTeV Collaboration

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Abstract. We report on the extraction of the structure functions F_2 and $\Delta xF_3 = xF_3^{\nu}$-$xF_3^{\overline{\nu}}$ from CCFR ν_μ-Fe and $\overline{\nu}_\mu$-Fe differential cross sections. The extraction is performed in a physics model independent (PMI) way. This first measurement for ΔxF_3, which is useful in testing models of heavy charm production, is higher than current theoretical predictions. The F_2 (PMI) values measured in ν_μ and μ scattering are in good agreement with the predictions of Next to Leading Order PDFs (using massive charm production schemes), thus resolving the long-standing discrepancy between the two sets of data.

Deep inelastic lepton-nucleon scattering experiments have been used to determine the quark distributions in the nucleon. However, the quark distributions determined

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from muon and neutrino experiments were found to be different at small values of x, because of a disagreement in the extracted structure functions. Here, we report on a measurement of differential cross sections and structure functions from CCFR ν_μ-Fe and $\overline{\nu}_\mu$-Fe data. We find that the neutrino-muon difference is resolved by extracting the ν_μ structure functions in a physics model independent way.

The sum of ν_μ and $\overline{\nu}_\mu$ differential cross sections for charged current interactions on an isoscalar target is related to the structure functions as follows:

$$F(\epsilon) \equiv \left[\frac{d^2\sigma^\nu}{dxdy} + \frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right] \frac{(1-\epsilon)\pi}{y^2 G_F^2 M E_\nu} = 2xF_1[1+\epsilon R] + \frac{y(1-y/2)}{1+(1-y)^2}\Delta xF_3.$$

Here G_F is the Fermi weak coupling constant, M is the nucleon mass, E_ν is the incident energy, the scaling variable $y = E_h/E_\nu$ is the fractional energy transferred to the hadronic vertex, E_h is the final state hadronic energy, and $\epsilon \simeq 2(1-y)/(1+(1-y)^2)$ is the polarization of the virtual W boson. The structure function $2xF_1$ is expressed in terms of F_2 by $2xF_1(x,Q^2) = F_2(x,Q^2) \times \frac{1+4M^2x^2/Q^2}{1+R(x,Q^2)}$, where Q^2 is the square of the four-momentum transfer to the nucleon, $x = Q^2/2ME_h$ (the Bjorken scaling variable) is the fractional momentum carried by the struck quark, and $R = \frac{\sigma_L}{\sigma_T}$ is the ratio of the cross-sections of longitudinally- to transversely-polarized W-bosons. The ΔxF_3 term, which in leading order $\simeq 4x(s-c)$, is not present in the μ-scattering case. In addition, in a ν_μ charged current interaction with s (or $\overline{c}$) quarks, there is a threshold suppression originating from the production of heavy c quarks in the final state. For μ-scattering, there is no suppression for scattering from s quarks, but more suppression when scattering from c quarks since there are two heavy quarks (c and $\overline{c}$) in the final state.

In previous analyses of ν_μ data, light-flavor universal physics model dependent (PMD) structure functions were extracted by applying a slow rescaling correction to correct for the charm mass suppression in the final state. In addition, the ΔxF_3 term (used as input in the extraction) was calculated from a leading order charm production model. These resulted in a physics model dependent (PMD) structure functions. In the new analysis reported here, slow rescaling corrections are not applied, and ΔxF_3 and F_2 are extracted from two parameter fits to the data. We compare the values of ΔxF_3 to various charm production models. The extracted physics model independent (PMI) values for F_2^ν are then compared with F_2^μ within the framework of NLO models for massive charm production.

The CCFR experiment collected data using the Fermilab Tevatron Quad-Triplet wide-band ν_μ and $\overline{\nu}_\mu$ beam. The raw differential cross sections per nucleon on iron are determined in bins of x, y, and E_ν ($0.01 < x < 0.65$, $0.05 < y < 0.95$, and $30 < E_\nu < 360.$ GeV). Figure 1 (a) shows typical differential cross sections at $E_\nu = 150$ GeV. Next, the raw cross sections are corrected for electroweak radiative effects, the W boson propagator, and for the 5.67% non-isoscalar excess of neutrons over protons in iron (only important at high x). Values of ΔxF_3 and F_2 are extracted from the sums of the corrected ν_μ-Fe and $\overline{\nu}_\mu$-Fe differential cross sections at different energy bins according to Eq. (1). It is challenging to fit ΔxF_3, R, and $2xF_1$ using the y distribution at a given x and Q^2 because of the strong correlation between the ΔxF_3 and R terms, unless the full range of y is covered by the data. Covering this range (especially the high y region) is hard because of the low acceptance. Therefore, we restrict the analysis to two parameter fits. Our strategy is to fit ΔxF_3 and $2xF_1$ (or equivalently F_2) for $x < 0.1$ where the ΔxF_3 contribution is relatively large, while constraining R using the $R^{\mu/e}_{world}$ QCD inspired empirical fit to all available R from electron- and μ-scattering data. The $R^{\mu/e}_{world}$ fit is also in good agreement with NMC R^{μ} data at low x, and with the most recent NNLO QCD calculations (including target mass effects) of R by Bodek and Yang

For $x < 0.1$, R in neutrino scattering is expected to be somewhat larger than R for muon scattering because of the production of massive charm quarks in the final state. A correction for this difference is applied to $R^{\mu/e}_{world}$ using a leading order slow rescaling model to obtain an effective R for neutrino scattering, R^{ν}_{eff}. The difference between $R^{\mu/e}_{world}$ and R^{ν}_{eff} is used as a systematic error. Because of the positive correlation between R and ΔxF_3, the extracted values of F_2 are rather insensitive to the input R. If a large input R is used, a larger value of xF_3 is extracted from the y distribution, thus yielding the same value of F_2. In contrast, the extracted values of ΔxF_3 are sensitive to the assumed value of R, which is reflected in a larger systematic error. The values of ΔxF_3 are sensitive to the energy dependence of the neutrino flux ($\sim y$ dependence), but are insensitive to the absolute normalization. The uncertainty on the flux shape is estimated by using the constraint that F_2 and xF_3 should be flat over y (or E_ν) for each x and Q^2 bin.

Because of the limited statistics, we use large bins in Q^2 in the extraction of ΔxF_3 with bin centering corrections from the NLO Thorne & Roberts Variable Flavor Scheme (TR-VFS) calculation with the MRST PDFs. Figure 1 (b) shows the extracted values of ΔxF_3 as a function of x, including both statistical and systematic errors, compared to various theoretical methods for modeling heavy charm productions within a QCD framework. The three-flavor Fixed Flavor Scheme (FFS) assumes that there is no intrinsic charm in the nucleon, and all scattering from c quarks occurs via the gluon-fusion diagram. The concept behind the Variable Flavor Scheme (VFS) proposed by ACOT is that at low scale, μ, one uses the three-flavor FFS scheme, and above some scale, one changes to a four-flavor calculation and an intrinsic charm sea (which is evolved from zero) is introduced. The concept in the RT-VFS scheme is that it starts with the three-flavor FFS scheme at a low scale, becomes the four-flavor VFS scheme at high scale, and interpolates smoothly between the two regions. Shown are the predictions from the TR-VFS scheme (as corrected after DIS-2000 and implemented with MRST PDFs), with their suggested scale $\mu = Q$, and the predictions of the other two NLO calculations, ACOT-VFS (implemented with CTEQ4HQ and the recent ACOT suggested scale $\mu = m_c$ for $Q < m_c$, and $\mu^2 = {m_c}^2 + cQ^2(1 - {m_c}^2/Q^2)^n$ for $Q < m_c$ with $c = 0.5$ and $n = 2$), and the FFS (implemented with the GRV94 PDFs and GRV94 recommended scale $\mu = 2m_c$). Also shown are the predictions from $\Delta xF_3 \simeq 4Ks(x, Q^2)$ from a leading order model (LO(CCFR)) Buras-Gaemers type fit to the CCFR dimuon data (here

K is a slow rescaling correction). Figure 1 (b) (right) also shows the sensitivity to the choice of scale. The data do not favor the ACOT-VFS(CTEQ4HQ) predictions if implemented with an earlier suggested scale of $\mu = 2Pt_{max}$. With reasonable choices of scale, all the theoretical models yield similar results. However, at low Q^2 our ΔxF_3 data are higher than all the theortical models. The difference between data and theory may be due to an underestimate of the strange sea (or gluon distribution) at low Q^2, or from missing NNLO terms.

As discussed above, values of F_2 (PMI) for $x < 0.1$ are extracted from two parameter fits to the y distributions. In the $x > 0.1$ region, the contribution from ΔxF_3 is small and the extracted values of F_2 are insensitive to ΔxF_3. Therefore, we extract values of F_2 with an input value of R and with ΔxF_3 constrained to the TR-VFS(MRST) predictions. As in the case of the two parameter fits for $x < 0.1$, no corrections for slow rescaling are applied. Fig. 2 (a) shows our F_2 (PMI) measurements divided by the predictions from the TR-VFS(MRST) theory. Also shown are F_2^μ and F_2^e from the NMC divided by the theory predictions. In the calculation of the QCD TR-VFS(MRST) predictions, we have also included corrections for nuclear effects, target mass and higher twist corrections at low values of Q^2. As seen in Fig. 2, both the CCFR and NMC structure functions are in good agreement with the TR-VFS(MRST) predictions, and therefore in good agreement with each other. A comparison using the ACOT-VFS(CTEQ4HQ) predictions yields similar results.

In the previous analysis of the CCFR data, the extracted values of F_2 (PMD) at the lowest $x = 0.015$ and Q^2 bin were up to 20% higher than both the NMC data and the predictions of the light-flavor MRSR2 PDFs. (see figure 2 (b)). About half of the difference originates from having used a leading order model for ΔxF_3 versus using our new measurement. The other half originates from having used the leading order slow rescaling corrections, instead of using a NLO massive charm production model, and from improved modeling of the low Q^2 PDFs (which changes the radiative corrections and the overall absolute normalization to the total neutrino cross sections).

In conclusion, the F_2 (PMI) values measured in neutrino-iron and muon-deuterium scattering show good agreement with with the predictions of Next to Leading Order PDFs (using massive charm production schemes), thus resolving the long-standing discrepancy between the two sets of data. The first measurements of ΔxF_3 are higher than current theoretical predictions.

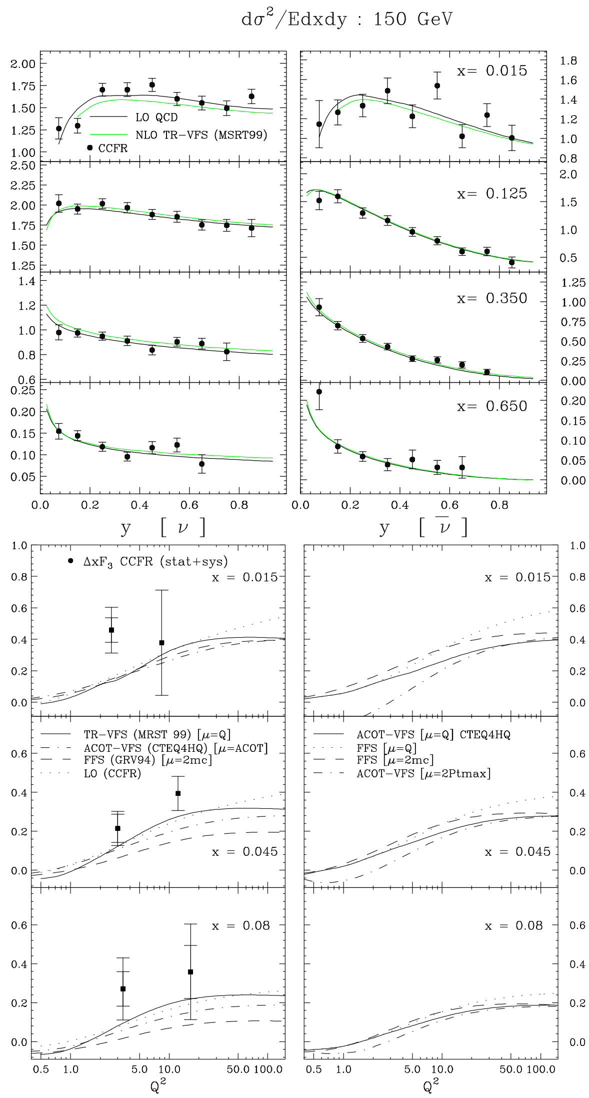

FIGURE 1. (a) Typical raw differential cross sections at $E_\nu = 150$ GeV (both statistical and systematic errors are included). (b) $\Delta x F_3$ data as a function of x compared with various schemes for massive charm production: RT-VFS(MRST), ACOT-VFS(CTEQ4HQ), FFS(GRV94), and LO(CCFR), a leading order model with a slow rescaling correction (left); Also shown is the sensitivity of the theoretical calculations to the choice of scale (right).

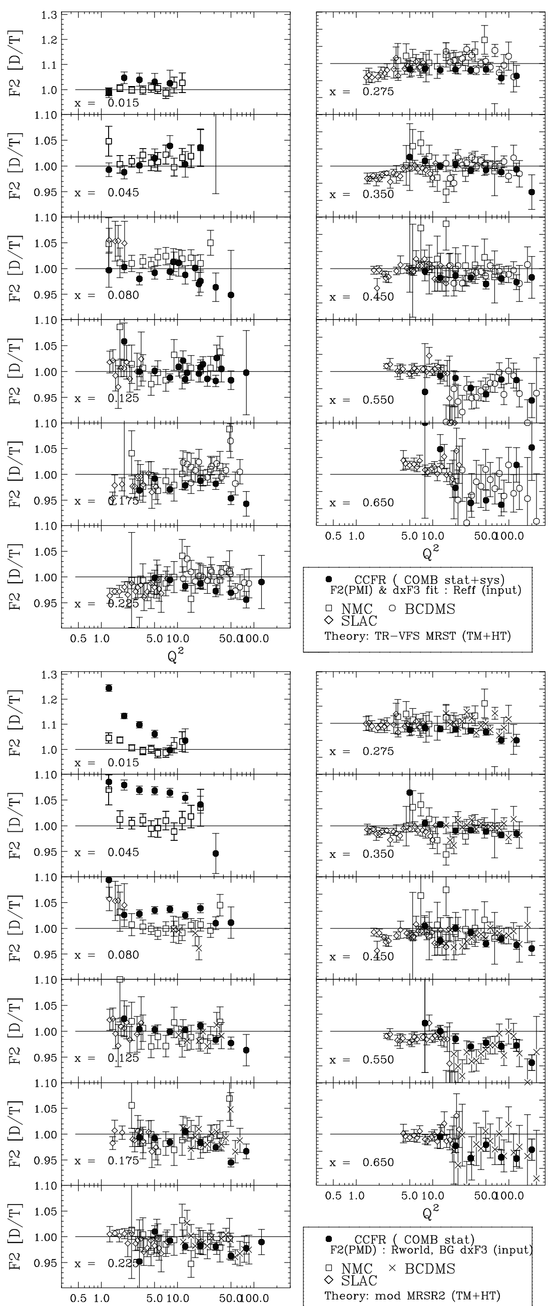

FIGURE 2. (a) Left side: The ratio (data/theory) of the F_2^ν (PMI) data divided by the predictions of TR-VFS(MRST) (with target mass and higher twist corrections). Both statistical and systematic errors are included. Also shown are the ratios of the F_2^μ (NMC) and F_2^e (SLAC) to the TR-VFS(MRST) predictions. (b) Right side: The ratio (data/theory) of the previous F_2^ν (PMD) data (and also F_2^μ (NMC) and F_2^e (SLAC)) divided by the predictions of the MRSR2 light-flavor PDFs (with target mass and higher twist corrections).