Improved Determination of α_s From Neutrino-Nucleon Scattering

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We present an improved determination of the proton structure functions F_2 and xF_3 from the Columbia-Chicago-Fermilab-Rochester Collaboration ν-Fe deep inelastic scattering experiment. Comparisons to corrected high-statistics charged-lepton scattering results for F_2 from the NMC, E665, SLAC, and BCDMS experiments indicate good agreement for $x > 0.1$ but some discrepancy at lower x. The Q^2 evolution of both the F_2 and xF_3 structure functions yields a value of the strong coupling constant at the scale of mass of the Z boson of $\alpha_s(M_Z^2) = 0.119 \pm 0.002(\text{expt}) \pm 0.004(\text{theory})$. This is one of the most precise measurements of this quantity. [S0031-9007(97)03809-X]

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High-energy neutrinos are a unique probe for testing quantum chromodynamics (QCD) and understanding the parton properties of nucleon structure. Combinations of neutrino and antineutrino scattering data are used to determine the F_2 and xF_3 structure functions (SFs) which determine the valence, sea, and gluon parton distributions in the nucleon [1,2]. The universalities of parton distributions can also be studied by comparing neutrino and charged-lepton scattering data. Past measurements have indicated that F_2^ν differs from $F_2^{e/\mu}$ by 10%–20% in the low-x region. These differences are larger than the quoted experimental errors of the measurements and may indicate the need for modifications of the theoretical modeling to include higher-order or new physics contributions. QCD predicts the scaling violations (Q^2 dependence) of F_2 and xF_3 and, experimentally, the observed scaling violations can be tested against those predictions to determine α_s [3] or the related QCD scale parameter, Λ_{QCD}. The α_s determination from neutrino scattering has a small theoretical uncertainty since the electroweak radiative corrections, scale uncertainties, and next-to-leading order (NLO) corrections are well understood.

In this paper, we present an updated analysis of the Columbia-Chicago-Fermilab-Rochester (CCFR) Collaboration neutrino scattering data with improved estimates of quark model parameters [4] and systematic uncertainties. The α_s measurement from this analysis is one of the most precise due to the high energy and statistics of the experiment compared to previous measurements [5].

The differential cross sections for the ν-N charged-current process $\nu_\mu(\overline{\nu}_\mu) + N \to \mu^-(\mu^+) + X$, in terms of the Lorentz-invariant structure functions F_2, $2xF_1$, and xF_3 are

$$\frac{d\sigma^{\nu,\overline{\nu}}}{dx\,dy} = \frac{G_F^2 M E_\nu}{\pi}\left[\left(1 - y - \frac{Mxy}{2E_\nu}\right)F_2(x,Q^2) + \frac{y^2}{2}2xF_1(x,Q^2) \pm y\left(1 - \frac{y}{2}\right)xF_3(x,Q^2)\right], \quad (1)$$

where G_F is the weak Fermi coupling constant, M is the nucleon mass, E_ν is the incident neutrino energy, Q^2 is the square of the four-momentum transfer to the nucleon, the scaling variable $y = E_{\text{had}}/E_\nu$ is the fractional energy transferred to the hadronic vertex with E_{had} equal to the measured hadronic energy, and $x = Q^2/2ME_\nu y$, the Bjorken scaling variable, is the fractional momentum carried by the struck quark. 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 $R = \frac{\sigma_L}{\sigma_T}$ is the ratio of the cross section of longitudinally to transversely polarized W bosons. In the leading-order quark-parton model, F_2 is the singlet distribution $xq^S = x\sum(q + \overline{q})$, the sum of the momentum densities of all interacting quark constituents, and xF_3 is the nonsinglet distribution $xq^{\text{NS}} = x\sum(q - \overline{q}) = xu_V + xd_V$, the valence quark momentum density; these relations are modified by higher-order QCD corrections.

The neutrino deep inelastic scattering (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

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Collaboration. The detector, described in Refs. [6,7], consists of a target calorimeter instrumented with both scintillators and drift chambers for measuring the energy of the hadron shower E_{had} and the muon angle θ_μ, followed by a toroid spectrometer for measuring the muon momentum p_μ. There are 950 000 ν_μ events and 170 000 $\overline{\nu}_\mu$ events in the data sample after fiducial-volume cuts, geometric cuts, and kinematic cuts of $p_\mu > 15$ GeV, $\theta_\mu < 150$ mr, $E_{\mathrm{had}} > 10$ GeV, and $30 < E_\nu < 360$ GeV, to select regions of high efficiency and small systematic errors in reconstruction.

In order to calculate the SF in Eq. (1) from the number of observed ν_μ and $\overline{\nu}_\mu$ events, it is necessary to determine the ν_μ and $\overline{\nu}_\mu$ flux. No direct measurement of the absolute flux was possible in the QTB. The absolute normalization of the ν_μ flux was fixed to the constraint that the neutrino-nucleon total cross section equaled the world average of the isoscalar-corrected Fe target experiments, $\sigma^{\nu\mathrm{Fe}}/E_\nu = (0.677 \pm 0.014) \times 10^{-38}\ \mathrm{cm}^2/\mathrm{GeV}$ [8,9]. The relative flux determination, i.e., the ratio of the flux between different energies and between ν_μ and $\overline{\nu}_\mu$, was determined from the low-E_{had} events using a technique described in Refs. [8,10,11]. The cross sections, multiplied by the flux, are compared to the observed number of ν-N and $\overline{\nu}$-N events in an x and Q^2 bin to extract $F_2(x, Q^2)$ and $xF_3(x, Q^2)$.

SFs extracted from the CCFR data have been previously presented [12]. In the earlier analysis, the muon and hadron energy calibrations were determined using a Monte Carlo technique in an attempt to reduce the dominant source of systematic error in the analysis, the relative calibration between the muon and hadron energies. Our subsequent analysis determined that the control of systematic errors for this technique was insufficient to justify its continued use. This paper presents a reextraction of the SFs that uses the calibrations directly determined from the test beam data collected during the course of the experiment [6,7], which results in a net change of +2.1% in the relative calibration and an increase in the corresponding systematic error to 1.4%. Other changes in the SF extraction include more complete radiative corrections [13], and the value of R now used in the extraction comes from a global fit to the world's measurements [14]. In addition, the estimates of the experimental and theoretical systematic errors in the analysis are improved [10]. The structure functions are corrected for radiative effects [13], the nonisoscalarity of the Fe target, the charm-production threshold [15,16], and the mass of the W-boson propagator. The SFs with statistical errors, along with the QCD fits described below, are shown in Fig. 1 [17].

The structure function F_2 from ν DIS on iron can be compared to F_2 from e and μ 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 $F_2^{\ell D}$ to $F_2^{\ell\mathrm{Fe}}$. This correction was made by parametrizing the $F_2^{\ell N}/F_2^{\ell D}$ data from SLAC and NMC [18]. F_2 from

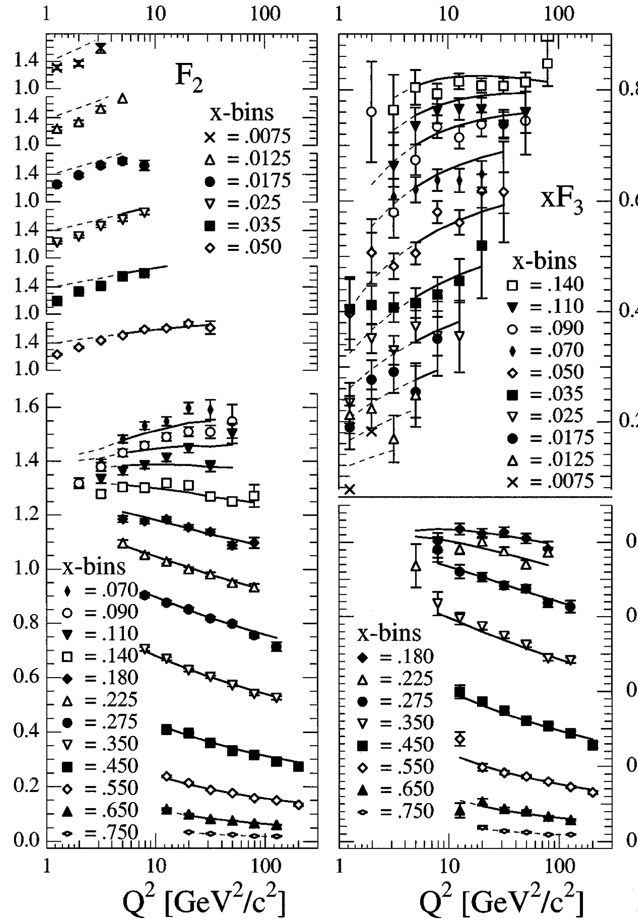

FIG. 1. The F_2 and xF_3 data (statistical errors) and the best QCD fit (solid line). Cuts of $Q^2 > 5\ \mathrm{GeV}^2$, $W^2 > 10\ \mathrm{GeV}^2$, and $x < 0.7$ were applied for the NLO-QCD fit which include target mass corrections. The dashed line extrapolates the QCD fit into the data regions excluded by the cuts. Deviations of the data from the extrapolated fit are partly due to nonperturbative effects.

electromagnetic interactions couples to the constituent quarks with the square of the quark electric charge. Thus a second correction is necessary:

$$\frac{F_2^\ell}{F_2^\nu} = \frac{5}{18}\left(1 - \frac{3}{5}\,\frac{(s + \overline{s} - c - \overline{c})}{(q + \overline{q})}\right). \tag{2}$$

This formula is exact to all orders in QCD in the DIS renormalization scheme, so for the purposes of this comparison the charged-lepton structure functions were corrected according to Eq. (2) with quark distributions given by CTEQ4D [2], which parametrizes the parton densities in the DIS scheme. 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 structure functions from NMC, E665, SLAC, and BCDMS [19,20] for selected x bins are shown in Fig. 2. There is a 15% discrepancy between the NMC charged lepton F_2 and the CCFR neutrino F_2 at $x = 0.0125$. As the value of x increases, the discrepancy decreases, until there is agreement between CCFR and the charged-lepton experiments above $x = 0.1$.

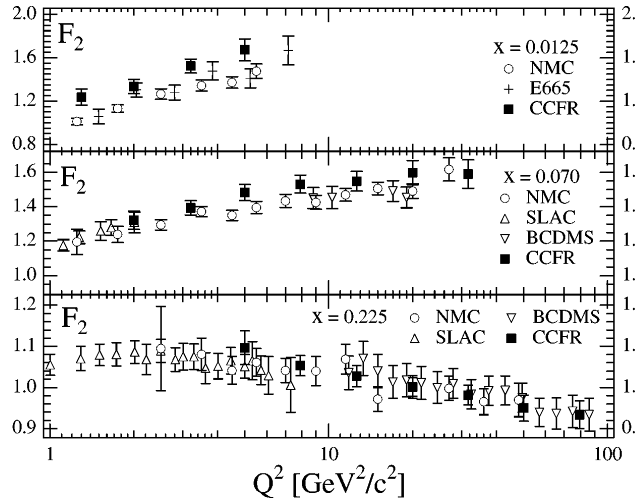

FIG. 2. F_2 from CCFR ν-Fe DIS compared to F_2 from eD and μD DIS. Errors bars are the statistical and systematic errors added in quadrature. The charged-lepton data have been corrected to an isoscalar Fe target, and for quark-charge effects in the DIS scheme which is valid to all orders (see text). The NMC data plotted were extracted with the same R as used in the CCFR analysis [19].

The discrepancy between CCFR and NMC at low x is outside the experimental systematic errors quoted by the groups and several suggestions for an explanation have been put forward. One suggestion [21], 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 [22]. Other suggestions are that the strange sea may have a different distribution than the normally assumed form [23], or that the heavy nuclear target correction may be different between neutrinos and charged leptons. More experimental data will be necessary to resolve this issue.

According to perturbative QCD (PQCD), the Q^2 dependence of the quark momentum densities is described by "evolution equations" [3]. The evolution of the nonsinglet distribution does not depend on assumptions about the gluons, but the singlet distribution coevolves with the gluon distribution. The previous CCFR analysis [12] compared only the SF to the nonsinglet evolution. This analysis takes advantage of the ability of neutrino DIS to measure both F_2 and xF_3, and simultaneously evolves the nonsinglet, singlet, and gluon distributions for a more precise determination of Λ_{QCD}.

Systematic uncertainties in the structure function extraction were investigated, leading to correlated errors for each of the data points in Fig. 1. The largest sources of systematic error in the determination of Λ_{QCD} are the muon and hadron absolute energy calibrations. The error in the energy calibration was measured to be 1% for p_μ [7], and 1% for E_{had} for the E744 and E770 data separately [6]. Another major source of systematic error is the error in the value of $\sigma^{\overline{\nu}}/\sigma^{\nu}$, the ratio of the total $\overline{\nu}$ to ν cross section. The value chosen was the world average of ν-Fe DIS experiments, including this one [9,10], $\sigma^{\overline{\nu}}/\sigma^{\nu} = 0.499 \pm 0.007$. Other sources of systematic error were investigated, including systematic errors in the flux extraction and variations in the physics model used in the Monte Carlo, but the effects of these other sources were small [10]. To determine the uncertainty for each source, the structure functions F_2 and xF_3 are extracted with the given systematic quantity changed by one error unit up and down, where an "error unit" is the best estimate of the systematic error prior to the fit described below. The difference of these modified structure functions and the standard ones gives the point-to-point correlated systematic errors in F_2 and xF_3 for each (x, Q^2) bin. Complete tables of errors can be found in Refs. [10,17].

For the PQCD analysis of the structure functions, we performed a χ^2 fit which minimizes the difference between a theoretical prediction and the measured values of F_2 and xF_3 in each (x, Q^2) bin. The theoretical prediction is obtained using the Duke and Owens NLO QCD evolution program [10,24]. The prediction incorporates a parametrization of the parton distributions for the singlet, nonsinglet, and gluon distributions at a reference value $Q_0^2 = 5$ GeV as shown in Table I and includes Λ_{NLO} as a fit parameter. The prediction is compared to the structure function data using a χ^2 that includes the statistical errors (including the $\Delta F_2 \Delta xF_3$ correlations) and the correlated systematic uncertainties. The systematic errors are included by introducing a parameter $\delta(k)$ for each systematic uncertainty. This parameter controls the amount of systematic deviation added to the structure function and is also included in the χ^2 function [Eq. (4)]. For this procedure, we define the structure-function vector $\vec{F} = (F_2 \; xF_3)^T$ and the structure-function statistical error matrix $\hat{V} = (\sigma_{ij})$ for $i, j = \{F_2, xF_3\}$. Then the χ^2 for a global fit is given by

$$\vec{F}^{\mathrm{diff}} = \vec{F}^{\mathrm{data}} - \vec{F}^{\mathrm{theory}} + \sum_k \delta(k)(\vec{F}^k - \vec{F}^{\mathrm{data}}), \quad (3)$$

$$\chi^2 = (\vec{F}^{\mathrm{diff}})^T \hat{V}^{-1} (\vec{F}^{\mathrm{diff}}) + \sum_k \delta(k)^2, \quad (4)$$

TABLE I. Results of the global systematic fit to the CCFR data. The parton distributions at $Q_0^2 = 5\ \mathrm{GeV}^2$ are parametrized by $xq^{\mathrm{NS}}(x) = A_{\mathrm{NS}} x^{\eta_1}(1-x)^{\eta_2}$, $xq^S(x) = xq^{\mathrm{NS}}(x) + A_s(1-x)^{\eta_s}$, $xG(x) = A_G(1-x)^{\eta_G}$. $\delta(k)$ is the fractional shift for the best value of systematic quantity k as determined by the fit. Only the most important sources of systematic error are shown. $\delta(C_{\mathrm{had}}^{744})$ is the shift for the E744 hadron energy calibration, $\delta(C_{\mathrm{had}}^{770})$ is the shift for the E770 hadron energy calibration, $\delta(C_\mu)$ is the shift for the muon energy calibration, and $\delta(\sigma^{\overline{\nu}}/\sigma^{\nu})$ is the shift for the ratio of the total $\overline{\nu}$ to ν cross section. The χ^2 of the fit is 158 for 164 degrees of freedom.

Parameter	Fit results	Parameter	Fit results
$\Lambda_{\overline{MS}}$	337 ± 28 MeV	A_G	2.22 ± 0.34
η_1	0.805 ± 0.009	η_G	4.65 ± 0.68
η_2	3.94 ± 0.03	$\delta(C_{\mathrm{had}}^{744})$	0.95 ± 0.42
A_{NS}	8.60 ± 0.18	$\delta(C_{\mathrm{had}}^{770})$	0.28 ± 0.27
A_S	1.47 ± 0.04	$\delta(C_\mu)$	0.21 ± 0.18
η_S	7.67 ± 0.13	$\delta(\sigma^{\overline{\nu}}/\sigma^{\nu})$	0.04 ± 0.50

where $\vec{F}^{\text{data}}$ are the measured values as shown in Fig. 1, $\vec{F}^{\text{theory}}$ are the predictions from the evolution program that depend on fit parameters including $\Lambda_{\overline{MS}}$, and $\vec{F}^k$ are the structure functions measured with the kth systematic uncertainty changed by one standard error.

The effects of target mass [16] were included in the fit. Calculations of the effects of higher-twist terms (HT) have recently become available [25] and are in agreement with the measurements of the F_2 HT [26]. However, the data in Ref. [26] were analyzed with a value of α_s smaller than our present value which would increase the measurement of HT. An analysis of HT from preliminary CCFR xF_3 data [27] indicates that the calculation of Ref. [25] yields HT that are too large. For this analysis, the values of the F_2 and xF_3 HT corrections were taken to be one-half the values from Ref. [25], with a conservative systematic error given by repeating the fit with no HT correction and with the full HT from Ref. [25].

Cuts of $Q^2 > 5\ \text{GeV}^2$ and the invariant mass squared of the hadronic system $W^2 > 10\ \text{GeV}^2$ were applied to the data to include only the perturbative region, and an $x < 0.7$ cut includes the x bins where the resolution corrections are insensitive to Fermi motion. The $E_\nu < 360$ GeV cut implies an effective limit of $Q^2 < 125\ \text{GeV}^2$. The best QCD fits to the data are shown in Fig. 1, and the results of the fit are shown in Table I. The $\delta(k)$ values from the fit are all zero within 2 standard deviations, and have errors that range from 0.12 to 0.98. The fact that these errors are all less than 1.0 indicates that the data coupled with the theory of QCD forms a more restrictive constraint on the systematic error than the variations described above.

From this fit, we obtain a measured value of $\Lambda_{\overline{MS}}$ in NLO QCD for four quark flavors of $337 \pm 28(\text{expt}) \pm 13(\text{HT})$ MeV, which yields $\alpha_s(M_Z^2) = 0.119 \pm 0.002(\text{expt}) \pm 0.001(\text{HT}) \pm 0.004(\text{scale})$, where the error due to the renormalization and factorization scales comes from Ref. [26]. The fit also yields a measurement of the gluon distribution $xG(x, Q_0^2 = 5\ \text{GeV}^2) = (2.22 \pm 0.34) \times (1 - x)^{4.65\pm0.68}$ in the region $0.04 < x < 0.70$, which is consistent with gluon distributions given in Refs. [1,2]. A fit to only the xF_3 data, which is not coupled to the gluon distribution, gives $\Lambda_{\overline{MS}} = 381 \pm 53(\text{expt}) \pm 17(\text{HT})$ MeV, which is consistent with the result of the combined F_2 and xF_3 fit but has larger errors because effectively only half the data are used. If the systematic uncertainties are not allowed to vary in the F_2 and xF_3 fit and all effects of systematic uncertainties are added in quadrature, the value of $\Lambda_{\overline{MS}}$ is found to be $381 \pm 23(\text{stat}) \pm 58(\text{syst})$ MeV.

This result is higher than our previous measurement [12], $\alpha_s(M_Z^2) = 0.111 \pm 0.002(\text{stat}) \pm 0.003(\text{syst})$, mainly due to effects of the new energy calibrations. The current measurement is also larger than the muon DIS result by the SLAC/BCDMS Collaboration [26], $\alpha_s(M_Z^2) = 0.113 \pm 0.003(\text{expt}) \pm 0.004(\text{theory})$; note that this theoretical error and the CCFR theory error are from the same calculation. The low-x discrepancy in F_2 between CCFR and NMC has a negligible effect on the α_s measurement, which is derived mainly from the high-x data.

In summary, a comparison of F_2 from ν DIS to that from charged-lepton DIS shows good agreement above $x = 0.1$ but a difference at smaller x that grows to 15% at $x \approx 0.01$. We have presented a new, high-precision measurement of $\Lambda_{\overline{MS}} = 337 \pm 28$ MeV from a fit to the simultaneous Q^2 evolution of F_2 and xF_3. This corresponds to a value of $\alpha_s(M_Z^2) = 0.119 \pm 0.002(\text{expt}) \pm 0.004(\text{theory})$ and is the most precise DIS measurement of this quantity.

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