Measurements of Nucleon Structure Functions, $F_2(x, Q^2)$ and $xF_3(x, Q^2)$, from the CCFR Data: PQCD and the Mean-Square Charge Test

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We present measurements of nucleon structure functions, $F_2(x,Q^2)$ and $xF_3(x,Q^2)$, from the high-statistics, high-energy neutrino-iron scattering experiment at the Fermilab Tevatron. The existing high-statistics xF_3 determination by the CDHSW collaboration is compared to our data. The data presented here constitute the first corroboration of the QCD prediction of xF_3 evolution at low-x. Comparison of the neutrino determination of $F_2(x,Q^2)$ with that obtained from the charged-lepton (e or μ) scattering leads to a precise test of the mean-square charge prediction by the Quark Parton Model.

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The high energy neutrino is a unique probe for determining the nucleon structure functions which, in the standard model, are directly related to the momentum densities of the constituent quarks. The differential cross section for the ν-N charged-current process (CC), $\nu_\mu(\overline{\nu}) + N \rightarrow \mu^-(\mu^+) + X$, in terms of the Lorentz invariant structure functions F_2, $2xF_1$, and xF_3 is:

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

where G_F is the weak Fermi coupling constant, M is the nucleon mass, E_ν is the incident neutrino energy, $s = 2E_\nu M + M^2$ is the ν-N center of mass energy, Q^2 is the square of the four-momentum transfer to the nucleon, the scaling variable $y = \frac{E_{HAD}}{E_\nu}$ is the fractional energy transferred to the hadronic vertex, and $x = \frac{Q^2}{2ME_\nu y}$, the Bjorken scaling variable, is the fractional momentum carried by the struck quark.

Accurate measurements of structure functions in deep inelastic lepton experiments depend critically upon a good understanding of calibrations and energy resolutions. The CCFR detector was calibrated in two dedicated test runs, using charged particle beams of well defined momenta[1]; the calibration studies, detailed in Ref.[3], led to a systematic precision on E_{HAD} of about 1%, and on E_μ of about 0.5%.

No direct measurement of the neutrino flux was possible in the QTB. Absolute normalization of the flux, relevant for tests of the QPM sum rule predictions,[4] was chosen so that the neutrino-nucleon total cross-section equaled the world average of the isoscalar (Fe) target experiments, $\sigma^{\nu N} = (.676 \pm .014) \times 10^{-38}\, cm^2\, E_\nu(GeV)$.[5, 6]. The relative flux determination, *i.e.* the ratio of fluxes among energies and between $\overline{\nu}$ and ν_μ, relevant for measurements of scaling violation and tests of Quantum Chromodynamics (QCD) predictions, was determined directly from the neutrino data using two techniques.[6] The extraction of F_2 and xF_3 is described in Ref.[6].

We first present a comparison of our $xF_3(x, Q^2)$ measurements with those reported by the CDHSW collaboration.[7] The magnitudes of the two data agree reasonably well for all x-bins when averaged over Q^2 as shown in Fig.1. The figure presents the ratio of the CDSHW- to the CCFR-xF_3 as a function of x, for $Q^2 > 5$ GeV^2. In each x-bin data were fitted to $A + B \times log(Q^2)$ over an overlapping range of Q^2, and interpolated to the average Q^2 of the CCFR data. The figure illustrates that, within the systematic error of the overall normalization ($\approx 2.5 - 3\%$), the average x-dependence of the two xF_3 measurements are in agreement. There are, however, differences in the Q^2-dependence at fixed x between the two data sets: the logarithmic slopes of xF_3 with respect to Q^2 do not agree well, as illustrated in Fig.2. The xF_3 slope measurements constitute an important test of the QCD prediction. The CDHSW measurement did not agree well with the QCD prediction; however, the authors stated that the observed discrepancies were within their systematic uncertainties.[7] In contrast, the CCFR measurements of xF_3 shown in Fig.2 clearly corroborate the prediction of QCD in the critical small x-region.[3]

The QPM relates the measurement of F_2 in ν-N scattering to those determined from the charged lepton, e-N or μ-N, scattering. The ratio of the two is a measure of the mean-square quark charge (in units of the square of the electron charge),[4]

$$\frac{F_2^{lN}(x)}{F_2^{\nu N}(x)} = \frac{5}{18}\left(1 - \frac{3}{5}\frac{s+\bar{s}}{q+\bar{q}}\right). \qquad (2)$$

Here the small x-dependent correction in parentheses is due to the asymmetry of the strange and charm sea of the nucleon. The F_2^{lN} data were multiplied by (18/5) times the strange sea correction, and plotted in Fig.3. The comparison of the CCFR-Fe data (solid circle) to those of SLAC-'D' (diamond),[8] BCDMS-'D' (square),[9] EMC-Fe (cross),[10] and CDHSW-Fe (fuzzy cross),[7] is shown (Fig.3) in a few illustrative x-bins as a function of Q^2. For this comparison, the deuterium data were further corrected for the difference between the light and heavy nuclei using the measured ratio $F_2(Fe)/F_2(D)$ as a function of x.[8] This correction spanned a range from +4% at $x = 0.12$, to -4% at $x = 0.4$, to -12% at $x = 0.6$.

Figure 3 shows good agreement between the SLAC and the CCFR measurements of F_2. These are the first measurements showing substantial overlap with the precise low-Q^2 SLAC data. At higher Q^2, the CCFR data are in good agreement with those of BCDMS-'D', and BCDMS-C data;[9] however, the latter exist only in the limited range $0.25 \leq x \leq 0.80$, and for clarity are not shown in Fig.3. The EMC-Fe data tend to be systematically lower in magnitude by about 7%; and display steeper dependence on Q^2 at low x than those of CCFR.

The CDHSW data in the range $0.1 \leq x \leq 0.275$, tend to lie lower than those from this experiment — the disagreement being primarily in the low-Q^2 range of the x-bins. Although the extracted $F_2(x, Q^2)$ depend upon model dependent corrections which are not precisely the same in the two experiments, it should be noted that the corrections in the discrepant x-bins in Fig.3 are no larger than ±2-4%. The origin of this x- and Q^2 dependent disagreement is not understood. The two data sets show better agreement for $x \leq 0.1$ and $x \geq 0.35$.

The mean-square charge test, or the comparison of the CCFR F_2 with those of the muon scattering experiments, is summarized in Fig.4. Data from each μ experiment are corrected using Eq.2, and the muon-to-neutrino F_2 ratio is formed in each x-bin averaged over the overlapping Q^2 range with $Q^2 > 5$ GeV^2. The resulting ratios are plotted as a function of x in Fig.4. It should be noted that the CCFR data span a larger range of any other single experiment shown in the figure. Systematic errors due to calibration and relative normalization are shown in the figure but absolute normalization errors are not shown. The BCDMS/CCFR ratios are in good agreement with the expected mean square charge. The EMC-

Fe/CCFR ratios are systematically lower by about 7% than the prediction, but are reasonably constant as a function of x; although, due to the averaging over Q^2 the slope-discrepancy would be obscured. The EMC-'D'/CCFR ratios show similar characteristics and are not shown for clarity in Fig.4.[10] The results of the mean-square charge test are contained in Table 1. The conclusions of this test do not change for a relaxed (> 1 GeV^2), or a more stringent (> 20 GeV^2) Q^2-cut.

In conclusion, we have presented precision measurements of the nucleon structure functions F_2 and xF_3 spanning a large range of Q^2. The absolute level of the xF_3 data agree with that of CDHSW data; however, the Q^2-dependences disagree. This discrepancy is also seen in F_2 — the CDHSW data show a steeper Q^2 dependence in the range $0.1 \leq x \leq 0.35$. The CCFR F_2 data are in good agreement with quark charges when compared with the SLAC-'D', the BCDMS-'D' and C data, but show a disagreement of about 7% when compared to the EMC-Fe.

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Table 1: **The Mean-Square Charge Test with $Q^2 > 5$ GeV^2:** The average ratio, as in Eq.2, for μ- to the CCFR ν-data is presented. The ratio is evaluated in the Q^2 range overlapping with that of the CCFR data. The Q^2-range spanned by the CCFR data is a superset of all the μ-experiments. The estimated systematic error in the absolute normalization of the CCFR data (the denominator) is 2.5%.

Experiment	Ratio	Stat. Error	Syst. Error	Normalization Error
BCDMS-C	1.018	±0.002	±0.012	±0.03
BCDMS-'D'	1.000	±0.002	±0.012	±0.03
EMC-Fe	0.921	±0.002	±0.023	±0.05

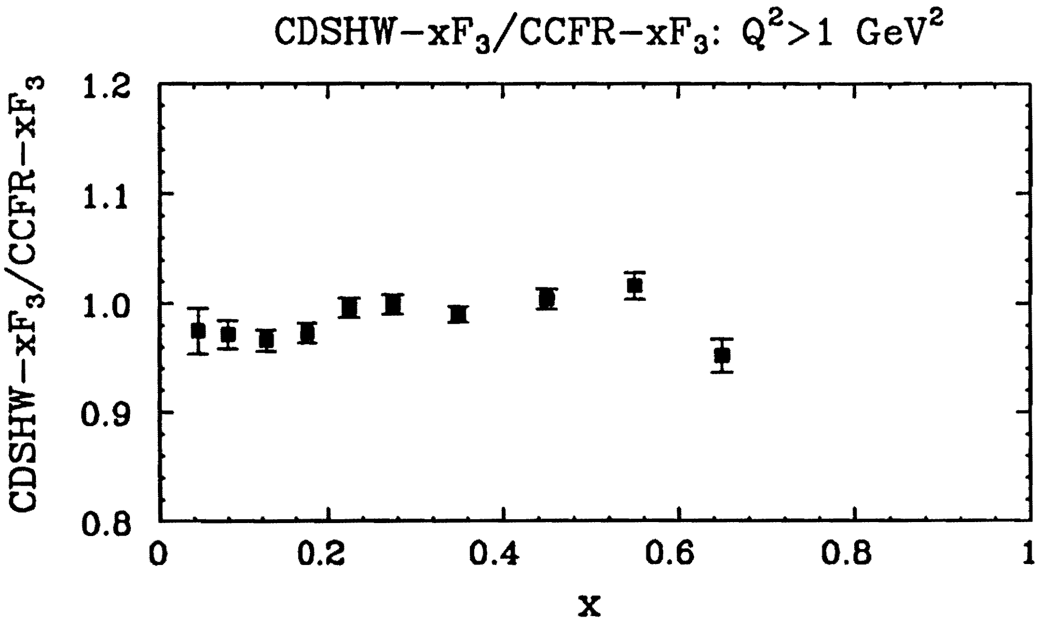
Figure Captions

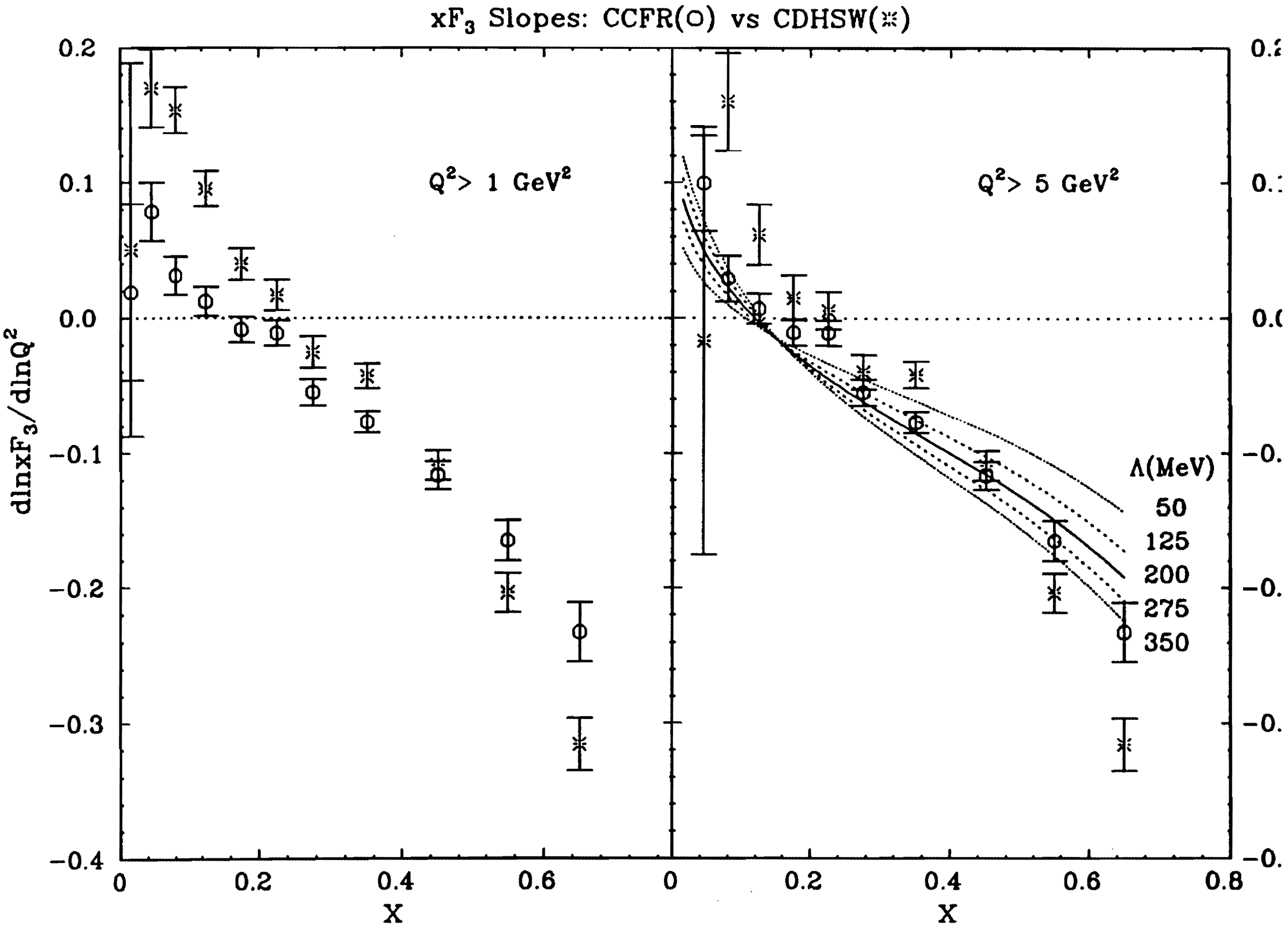
Figure 1: The ratio, CDHSW-xF$_3$/CCFR-xF$_3$, with $Q^2 > 1$ GeV^2, as a function of x with statistical errors only.

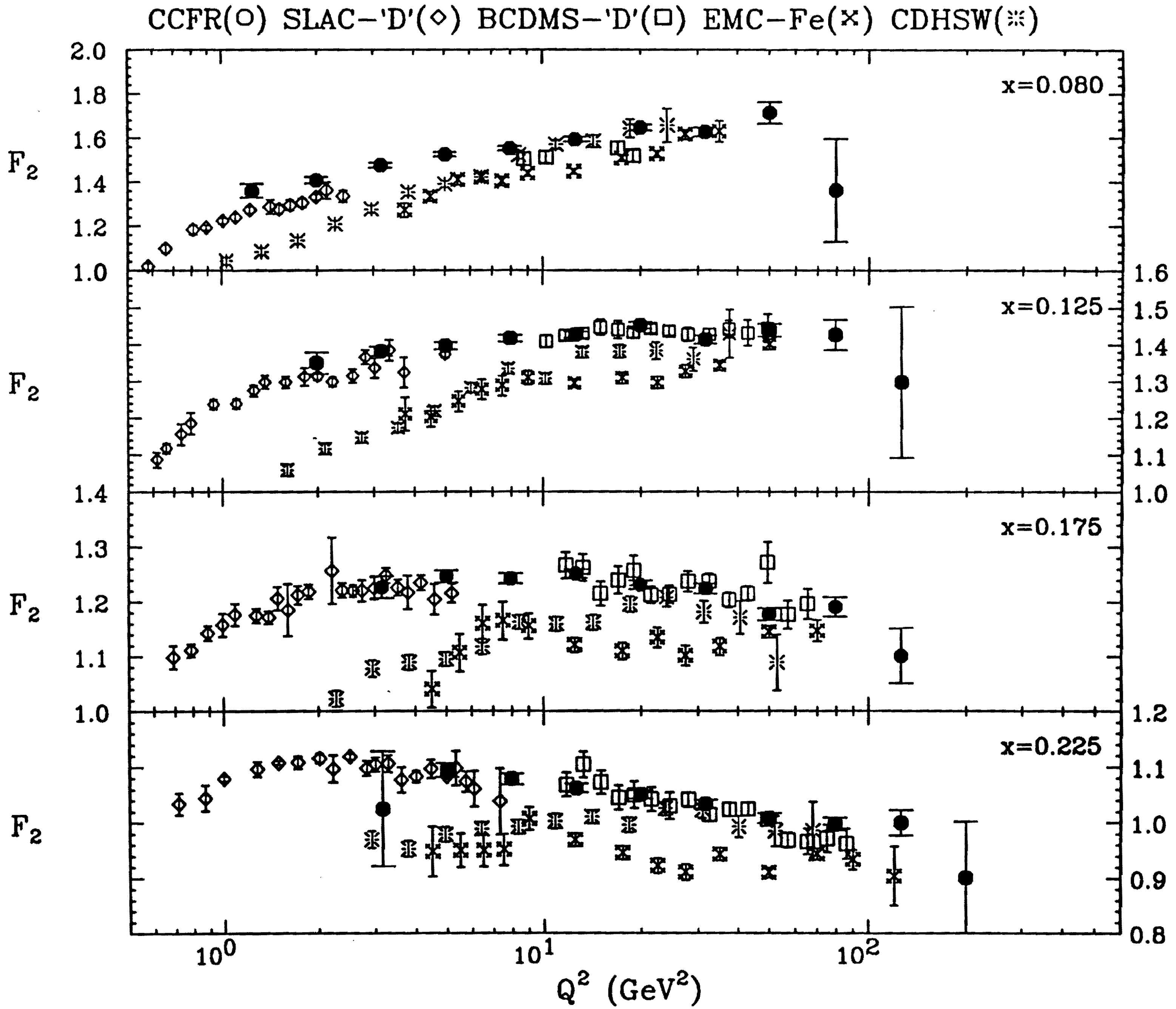
Figure 2: The logarithmic slopes of xF$_3$ for the CDHSW and CCFR data, with (a) $Q^2 > 1$ GeV^2, and (b) $Q^2 > 5$ GeV^2. Only statistical errors are shown. The curves in Fig.2b are QCD predictions for various values of $\Lambda_{\overline{MS}}$.

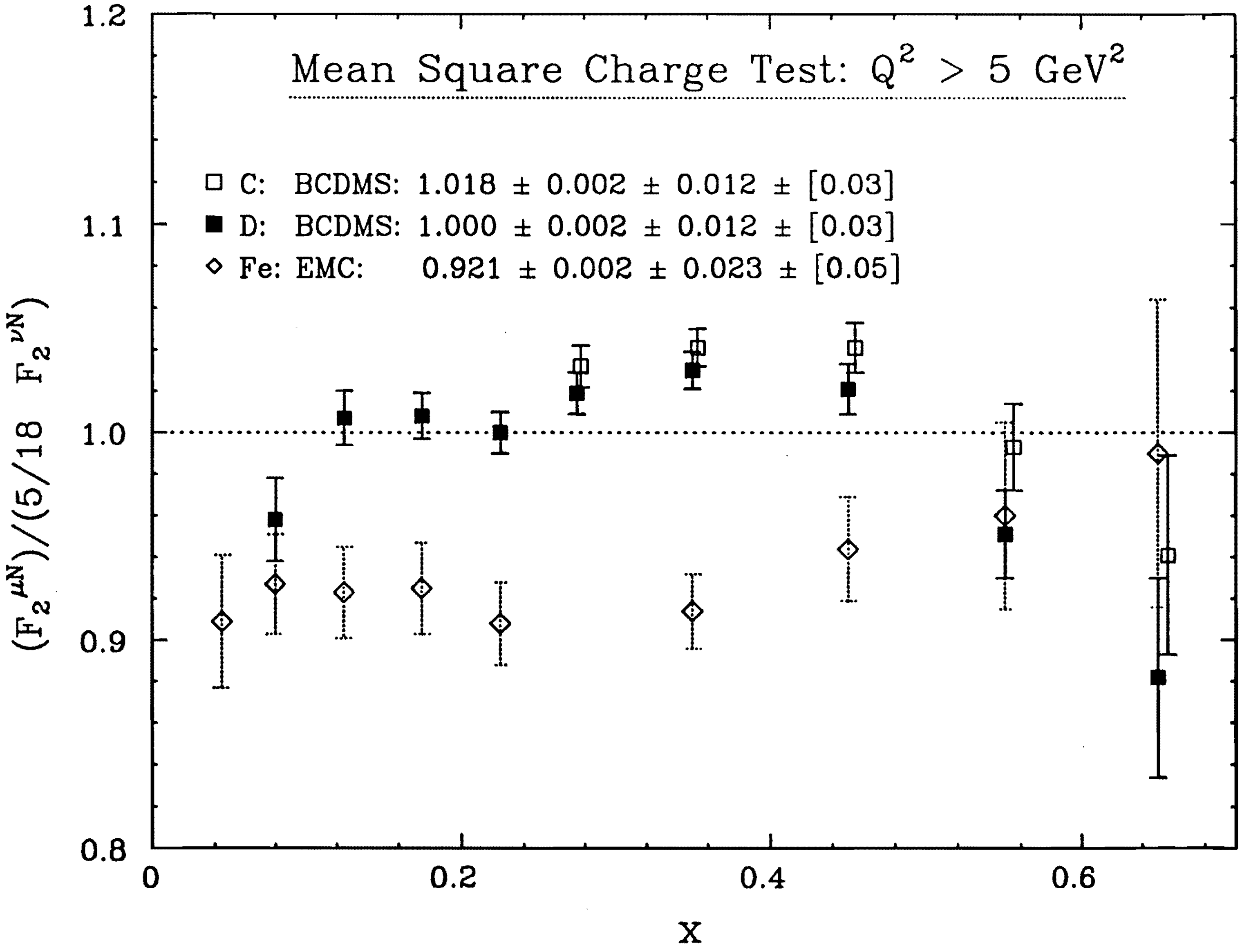
Figure 3: A comparison of $F_2(x, Q^2)$ as a function of Q^2, as measured by the CCFR, SLAC-'D', BCDMS-'D', EMC-Fe, and CDHSW-Fe in a few illustrative x-bins with statistical errors only. The deuterium data have been corrected for the EMC-effect using the Fe/D measurement of SLAC. No arbitrary normalization factor is used.

Figure 4: The mean-square charge test with $Q^2 > 5$ GeV^2: The ratio in Eq.2 is shown as a function of x. Systematic errors due to miscalibration and relative normalization of the various experiments dominate the test. The x-independent absolute normalization error is not shown, but is enumerated in Table 1. The BCDMS-C data are shown with x-bins shifted by +1% for clarity.


CDSHW−xF$_3$/CCFR−xF$_3$: Q^2>1 GeV^2
CDSHW−xF$_3$/CCFR−xF$_3$
1.2
1.1
1.0
0.9
0.8
0
0.2
0.4
0.6
0.8
1
x


xF_3 Slopes: CCFR(○) vs CDHSW(※)
$d\ln xF_3/d\ln Q^2$
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
$Q^2 > 1$ GeV^2
$Q^2 > 5$ GeV^2
Λ(MeV)
50
125
200
275
350
0
0.2
0.4
0.6
0.8
X
X


CCFR(○) SLAC-'D'(◇) BCDMS-'D'(□) EMC-Fe(×) CDHSW(⁑)
x=0.080
x=0.125
x=0.175
x=0.225
F$_2$
F$_2$
F$_2$
F$_2$
2.0
1.8
1.6
1.4
1.2
1.0
1.6
1.5
1.4
1.3
1.2
1.1
1.0
1.4
1.3
1.2
1.1
1.0
1.2
1.1
1.0
0.9
0.8
10^0
10^1
10^2
Q^2 (GeV^2)


Mean Square Charge Test: $Q^2 > 5$ GeV^2
□ C: BCDMS: 1.018 ± 0.002 ± 0.012 ± [0.03]
■ D: BCDMS: 1.000 ± 0.002 ± 0.012 ± [0.03]
◇ Fe: EMC: 0.921 ± 0.002 ± 0.023 ± [0.05]
$(F_2^{\mu N})/(5/18\ F_2^{\nu N})$
1.2
1.1
1.0
0.9
0.8
0
0.2
0.4
0.6
X