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# A Combined Analysis of SLAC Experiments on Deep Inelastic e–p and e–d Scattering*

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## ABSTRACT

We report recent work on the extraction of $R = \sigma_L/\sigma_T$ and the structure function $F_2$ over a large kinematic range, which is based on a reanalysis of deep inelastic $e-p$ and $e-d$ scattering cross sections measured at SLAC between 1970 and 1985. All these data were corrected for radiative effects using improved versions of external and internal radiative correction procedures. The data from seven individual experiments were normalized to those from the recent high-precision SLAC experiment E140.

We find that $R_p = R_d$, as expected in QCD. The value of $R$ is higher than predicted by QCD even when target-mass effects are included. This difference indicates that additional dynamical higher-twist effects may be present.

The structure functions $F_2p$ and $F_2d$ were also extracted from the full data sets of normalized cross sections using an empirical fit to $R$. These structure functions were then compared with data from the CERN muon scattering experiments BCDMS and EMC. We find that our data are consistent with the EMC data, if the latter are multiplied by a normalization factor of 1.07. No single, uniform normalization factor can be applied to the BCDMS data that will bring them into agreement with the SLAC data in the region of overlap.

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**Introduction:** *Since* 1970 a series of deep inelastic $e-p$ and $e-d$ scattering experiments at SLAC[1,2,3,4,5,6] has steadily improved our knowledge of the proton and deuteron structure functions. The last of these, completed in 1985, was a high-statistics measurement designed to extract accurate values of the ratio $R = \sigma_L/\sigma_T$ from inelastic $e-p$, $e-d$ and $e-Fe$ cross sections.[6] As part of that experiment, an intensive effort was made to reduce systematic errors in the measured cross sections to the 1 percent level. A key to this effort was the use of much-improved procedures for calculating radiative corrections to the raw cross-section data.[7]

In the present work, completed in the past year, these improved correction procedures were applied to all SLAC deep inelastic $e-p$ and $e-d$ cross sections dating back to 1970. Such a reanalysis of this data permitted us to extract $R(x, Q^2)$ over an extended kinematic range $0.1 \leq x \leq 0.9$ and $0.64 \leq Q^2 \leq 20\ GeV^2$. An empirical fit to $R$ then allowed us to determine the structure function $F_2(x, Q^2)$ over the same range of $x$ and an even greater $Q^2$ range.

**Definitions and Kinematics:** *In* the first Born approximation, the differential cross section for scattering from a nucleon of an unpolarized charged lepton with incident energy $E$, scattering angle $\theta$ and final energy $E'$ can be written in terms of the two structure functions $F_1$ and $F_2$ as

$$\frac{d\sigma}{d\Omega dE'} = \sigma^{Mott}\left[\frac{1}{\nu}F_2(x, Q^2) + \frac{2}{M}F_1(x, Q^2)\tan^2(\frac{\theta}{2})\right] , \tag{1}$$

or, in terms of $R$ and the cross section $\sigma_T$ for absorption of transversely polarized virtual photons as

$$\frac{d\sigma}{d\Omega dE'} = \Gamma\sigma_T(x, Q^2)\left[1 + \epsilon R(x, Q^2)\right] . \tag{2}$$

where $\sigma^{Mott}$ is the Mott cross section, $M$ is the nucleon mass, $\nu = E - E'$ is the energy of the virtual photon that mediates the interaction, $Q^2 = 4EE'\sin^2(\theta/2)$ is the square of the invariant four-momentum transfer, and the Bjorken scaling variable $x = Q^2/2M\nu$ is a measure of the longitudinal momentum carried by the struck nucleon constituents. In Eq. (2) the quantity $\Gamma$ represents the flux of virtual photons exchanged between the lepton and nucleon lines, with polarization given by $\epsilon = [1 + 2(1 + \nu^2/Q^2)\tan^2(\theta/2)]^{-1}$.

**Data Analysis:** *To* extract accurate values of $F_1$ and $F_2$, or equivalently $R$ and $\sigma_T$, requires measurements of the deep inelastic cross section at a range of $\theta$ (or $\epsilon$) for given values of $(x, Q^2)$. Between 1970 and 1985 the 1.6 GeV, 8 GeV and 20 GeV spectrometers in SLAC End Station A were used to measure $e-p$ and $e-d$ cross sections at angles ranging from 4.0 to 60 degrees, with incident energies $E$ ranging up to 21.0 GeV. We have combined data from eight separate experiments done using these spectrometers, in order to cover the widest possible range of $x$, $Q^2$ and $\epsilon$.

Previous attempts to extract $R$ by combining subsets of these data1,4 were inhibited by: a) uncertainties in radiative corrections of order 5 percent; and b) uncertainties in the relative normalizations of the various experiments to one another. The present analysis is based on key advances in both categories. First, recent improvements in both internal and external radiative corrections[7] have reduced the systematic uncertainty due to them to the level of 1 percent in overall normalization and less than 1 percent in point-to-point variations. Second, we normalize all deuterium data to the recent high-precision experiment E140,[6] using a smooth global fit. A similar fit is used to normalize the hydrogen data. The statistical accuracy of these fits permits us to reduce the relative normalization uncertainties to the level of 0.7 percent.

Radiative corrections to the cross section data were calculated using the exact "internal" prescription of Akhundov, Bardin and Shumeiko[8] (ABS). An additional "external" correction (due to straggling of the electrons in the target material) was calculated with the complete formalism of Mo and Tsai[9] (MT). The internal corrections of ABS agreed to better than 1 percent with improved, exact internal calculations based on MT over a large range of SLAC kinematics. Furthermore, the external corrections have been used to correct data from slac experiment E139[5] taken with iron targets of 0.02, 0.06 and 0.12 radiation length, and the corrected cross sections agreed with one another to better than 1 percent. All experiments contributing to the present analysis used hydrogen and deuterium targets of less than 0.02 radiation length. Therefore this test of the external radiative corrections for longer targets indicates that our procedure is highly accurate for short radiation lengths.

Normalized cross sections from all experiments were binned in intervals of $x$ and $Q2$, and a bin centering correction was applied. Values of the cross section were linearly regressed versus $\epsilon$ according to Eq. (2) to extract $R(x, Q^2)$ at the center of each bin. Systematic errors in the original cross sections and in the normalization factors were propagated through the regression procedure. Each extraction of $R(x, Q^2)$ typically included data from four experiments and covered an $\epsilon$ range of 0.5. The average value of $\chi^2$ per degree of freedom for these fits is 0.92, over a total of 190 separate regressions.

The extracted values of $R_p$ and $R_d$ were averaged over $Q^2$ at each value of $x$. As illustrated in Figure 1, the difference of these averages is consistent with zero over the full range of $x$. We obtain a global average value $R_d - R_p = 0.002 \pm 0.009(stat) \pm 0.010(syst)$. Thereafter $R_p$ and $R_d$ were taken to be equal and combined into a single value of $R(x, Q^2)$ in each bin. These combined data are presented in Figures 2a and 2b. As found in SLAC experiment E140,[6] $R_{QCD}$ does not agree with the data. Calculations of $R_{QCD}$ plus target-mass corrections[10] are in better agreement but are still lower than measured values, especially at high $x$.[11] This excess may be evidence for additional higher-twist effects[12] or diquark contributions.[13] A fit was made to the combined $R$ data using the phenomenological form

$$R^{Model} = [1 + A_1 x^{A_2}] \left[ \frac{A_3}{\log(Q^2/.04)} F^{th} + \frac{A_4}{(Q^8 + A_5^4)^{-\frac{1}{4}}} \right], \qquad (3)$$

$$F^{th} = 1 + 12\left[\frac{Q^2}{(1+Q^2)}\right]\left[\frac{0.125^2}{(x^2+0.125^2)}\right], \quad (4)$$

where $F^{th}$ is a threshold function forcing $R^{Model}$ to agree with $R_{QCD}$ at low $x$ and high $Q^2$, and the $A_i$ (25.3136, 16.4259, 0.0656, 0.4681, 1.8845) are the parameters of the fit. The $\chi^2$ for this fit, also shown in Figure 2, is 98 for 122 degrees of freedom. This $R^{Model}$ is used in the subsequent analysis to extract $F_2^p$ and $F_2^d$ from the corrected cross sections.

Values of $F_2(x, Q^2)$ have been extracted from the measured hydrogen and deuterium cross sections from all eight experiments using Eqn. (1) and $R^{Model}$. These $F_2$ values were binned in $x$ for the purpose of comparing them with other $F_2$ measurements. A bin centering correction was applied using a smooth global fit to $F_2$. This functional form of this $F_2^{Model}$ is a modification of one used previously.1 and fits the data extremely well. Within each $x$-bin the data were then "clustered" in $Q^2$, again using $F_2^{Model}$, but without an imposed binning. We have made a comparison between the new $F_2$ values and those extracted in a previous analysis[1] for both hydrogen and deuterium. Despite recent improvements in both radiative corrections (changes as large as 5% at extreme kinematic ranges) and a new determination of the 8 GeV spectrometer acceptance (a value 2% lower than previously) the new values of $F_2$ are in remarkable agreement with the old analysis. The new analysis, includes more experiments and considerably extends the available kinematic range in both $x$ and $Q^2$. The SLAC $F_2$ data now overlap in $Q^2$ with data from EMC[14] and BCDMS[15] for $x > .35$ and come close for $x > .16$.

The overall normalization uncertainty of this study is that of E140, ±2%, including ±1% from radiative corrections, $\pm 1\frac{1}{2}$% from spectrometer acceptance, plus other smaller contributions. In Figures 3 and 4 below statistical errors are plotted to the hash-mark, and the quadrature sum of statistical and point-to-point systematic errors are represented by the full error bar. Point-to-point errors additionally include: ±1% due to estimated kinematic dependence of radiative corrections; uncertainties in $RModel$ of typically .025; uncertainties in relative normalizations of the experiments; and uncertainties due to possible $E'$-dependence of spectrometer acceptance. The curve plotted in Figures 3 and 4 is $F_2^{Model}$, which has been used in the bin centering corrections.

Figures 3a-d show a comparison of the SLAC hydrogen and deuterium data with that of the EMC collaboration. The EMC data have been multiplied by a normalization constant of 1.07. Additionally, because the EMC $F_2$ values were extracted assuming $R = 0$, we apply a small correction factor to correct these values to what would be obtained using $R^{Model}$. This correction is generally negligible except at low $x$ and very high $Q^2$ where it is as large as 5%. We observe an excellent agreement between the EMC data and our results in the region of overlap for hydrogen. The data at lower values of $x$ seem consistant except at the lowest value $x = 0.08$.

Figures 4a-d show a comparison of the SLAC hydrogen and deuterium data with that of the BCDMS collaboration. Although on average normalization of the BCDMS data agree with the SLAC results, the $x$ distribution of the data does not agree with our results in the region overlap. The BCDMS data has been extracted using the assumption the $R = R_{QCD}$, which is a good representation of $R$, at their large values of $Q^2$. We have also applied a small correction to the BCDMS data such that the value of $R$ used is the same as $R^{Model}$. It appears that the BCDMS data is low compared to SLAC for $x \geq 0.55$ and is high for $x \leq 0.275$.

Previous comparison of EMC and BCDMS data[16] have indicated that the experiments disagree by +5% to +10% at low $x$ and −10% to −15% at high $x$. Global fits in both $x$ and $Q^2$ to both data sets have very large $\chi^2$ per degree of freedom.In the region of overlap, our results favor the EMC shape of the $x$ distribution, but agree more with BCDMS in overall average normalization. We are planning to also study the ratio of neutron to proton structure functions for fixed values of x as a function of $Q^2$. The combined analysis of SLAC data will be extended to the resonance region in the near future.

In conclusion, the reanalyzed SLAC data on the proton and deuteron structure function $F_2$ disagree with both CERN high energy muon experiments. In the kinmatic region of overlap, the EMC data is low in normalization by 7% compared to SLAC. The BCDMS data agrees in overall normalization, but is 5% to 10% high at small $x$ and is 10% to 15% low at large $x$. It has been suggested[17] that the source of the disagreement may be larger than anticipated systematic errors in the BCDMS data only at the lower $Q^2$ region which overlap with SLAC, because of the higher sensitivity to incident beam energy in that region. The precise results from our SLAC data now provide the best low $Q^2$ anchor for comparison with high $Q^2$ muon and neutrino scattering experiments. Some of the remaining questions at large $x$ will be resolved by data from the recently approved run for E140A, which will probably run in 1990.

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## FIGURE CAPTIONS

**Figure 1:** Results of the $R_d - R_p$ study, averaged over $Q^2$. This difference is consistent with zero for all $x$. The global average value is $R_d - R_p = 0.002 \pm 0.009(stat) \pm 0.010(syst)$. The $\chi 2$ per degree of freedom of this average is 83/86.

**Figure 2a-b:** Results for $R(x, Q^2)$ averaged over hydrogen and deuterium. Also plotted are $R_{QCD}$, $R_{QCD}$+target mass terms, and the phenomological fit $R^{Model}$. Observed values are greater than $R_{QCD}$+target mass terms and suggest the presence of dynamical higher twist contributions.

**Figures 3a-d:** A comparison of our result based on all SLAC experimental measurements of the structure function $F_2$ for hydrogen and deuterium with the data of EMC. The EMC data has been multiplied by a factor of 1.07. In the region of overlap the two data sets agree. The curve is an empirical fit to the SLAC data.

**Figures 4a-d:** A comparison of our result based on all SLAC experimental measurements of the structure function $F_2$ for hydrogen and deuterium with the data of BCDMS. The BCDMS data appears correct in overall normalization. However, in the region of overlap with SLAC, BCDMS data appears to be 5% to 10% higher at small $x$, and about 10% to 15% lower at large $x$.

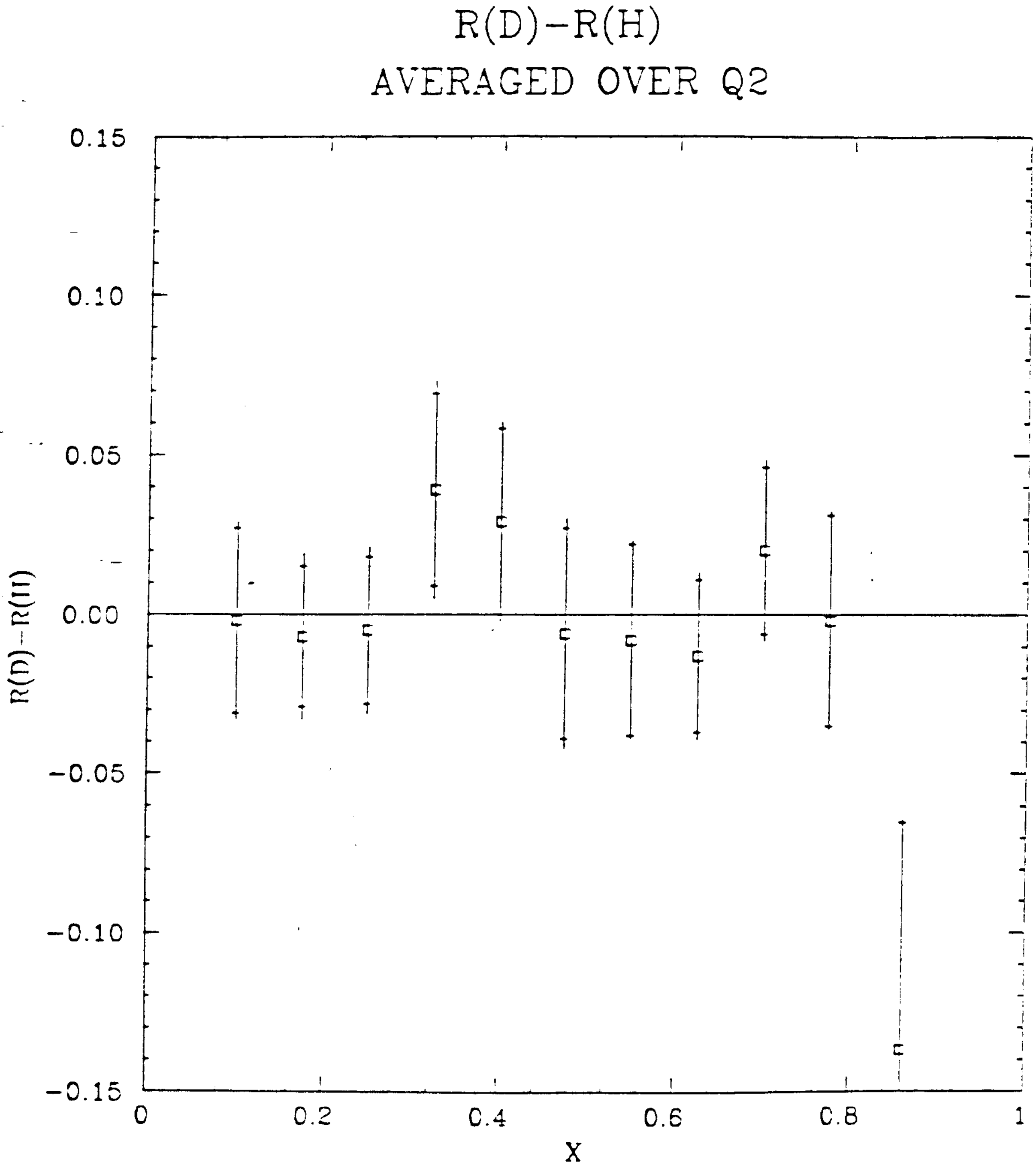


FIGURE 1.
AVERAGE OVER ALL (x,Q2) = .002 +/- .009 +/- .010.
X2/df = 83/86.

# $R(x,Q^2)$
# H–D AVERAGE
# LOW X

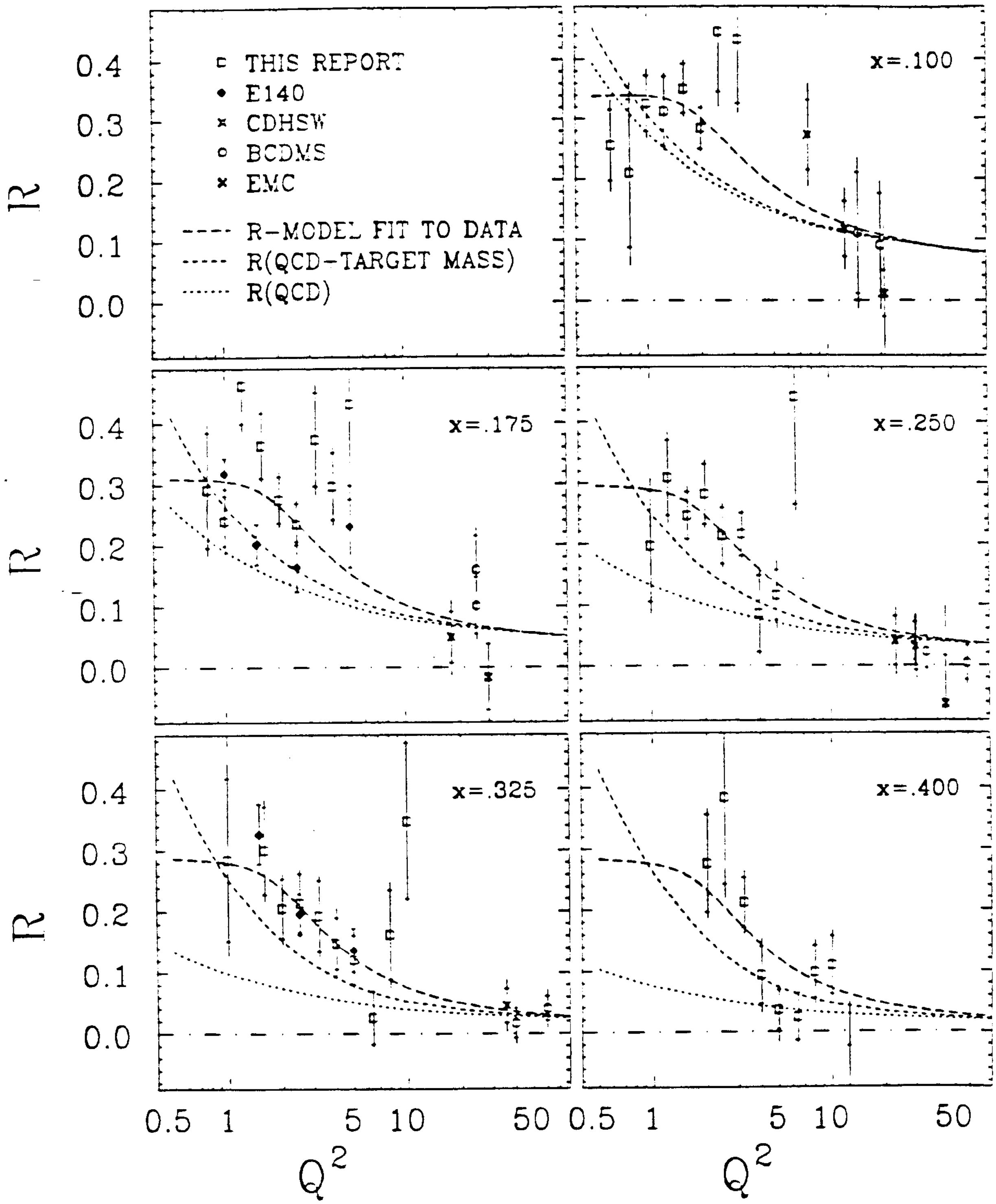


FIGURE 2A.

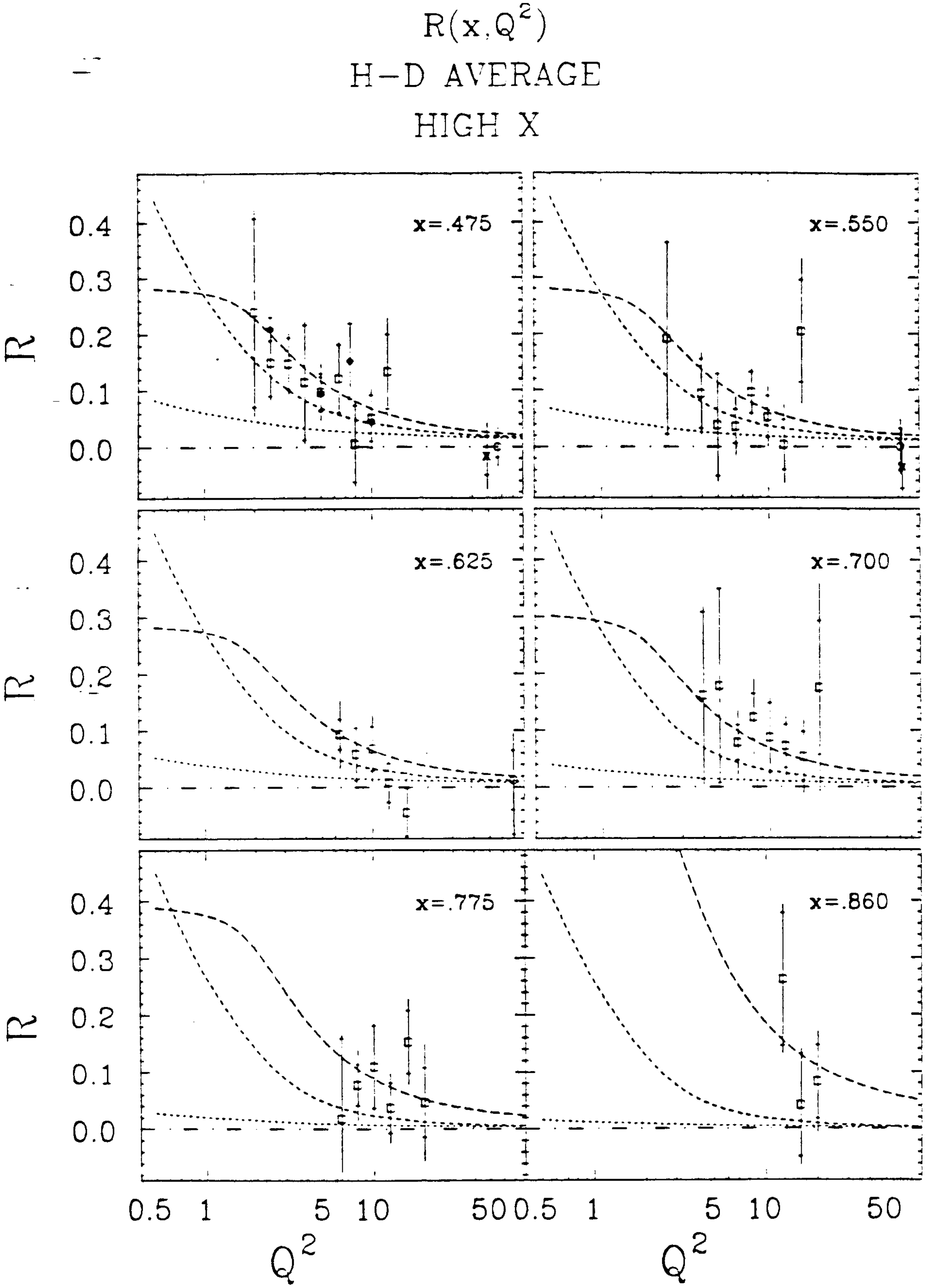
R(x,Q^2)
H-D AVERAGE
HIGH X
x=.475
x=.550
x=.625
x=.700
x=.775
x=.860
R
0.4
0.3
0.2
0.1
0.0
Q^2
0.5
1
5
10
50

FIGURE 2B.

F$_2$
SLAC+EMC
HYDROGEN
LOW X

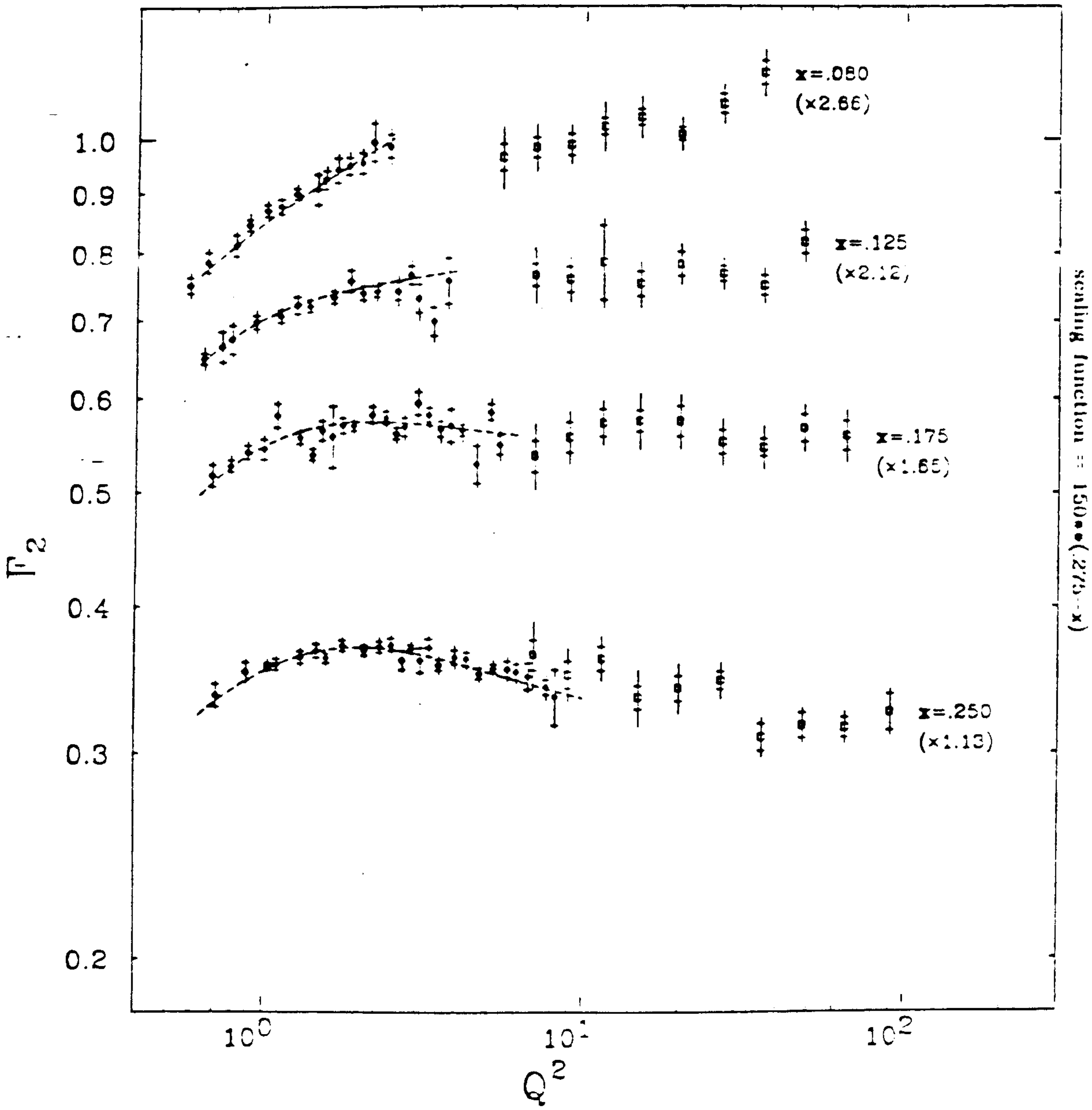


FIGURE 3A.
EMC DATA NORMALIZED BY 1.070.
CURVE DRAWN IS BEST FIT TO SLAC DATA.

$F_2$

SLAC+EMC

HYDROGEN

HIGH X

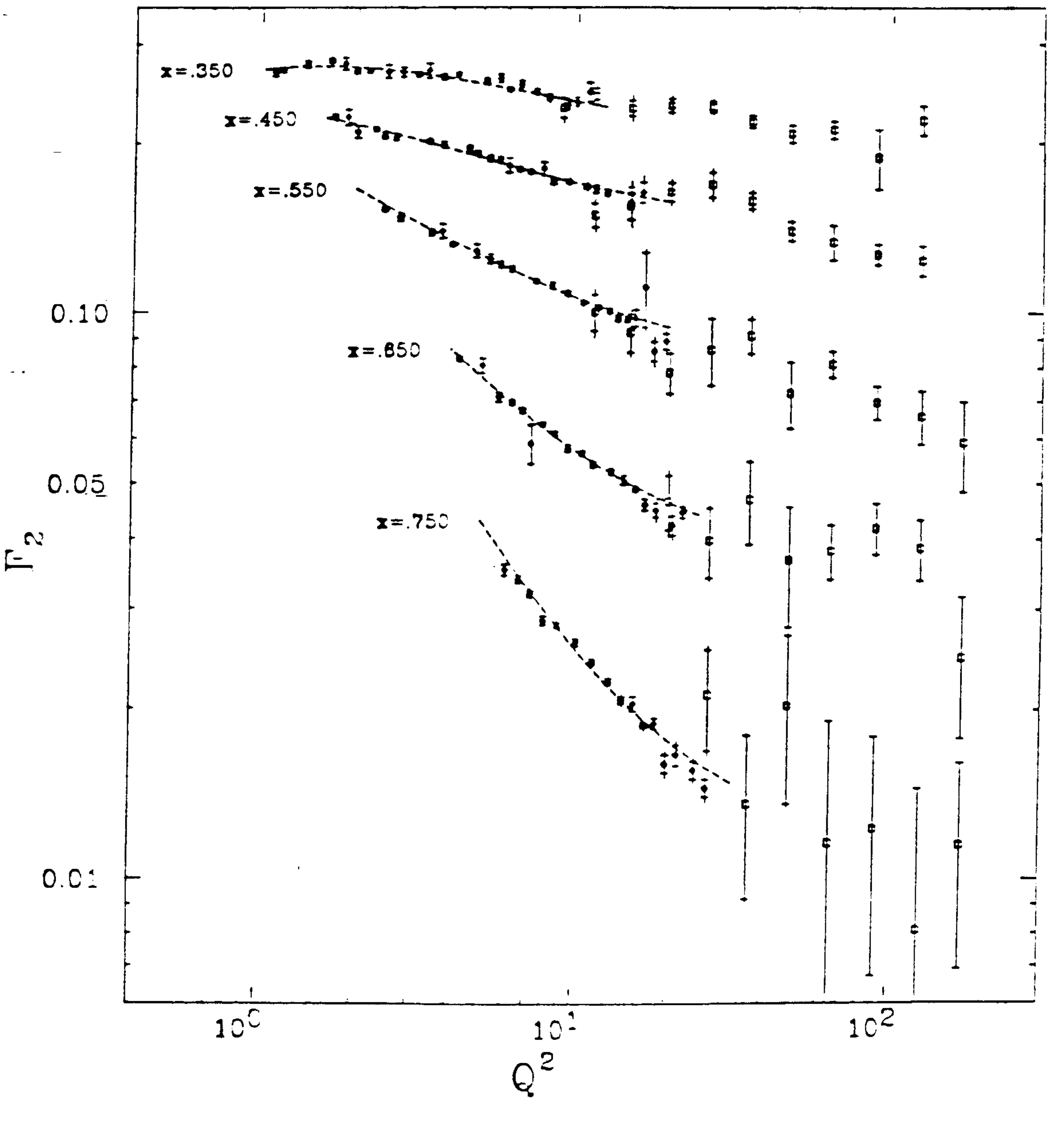


FIGURE 3B.

EMC DATA NORMALIZED BY 1.070.

CURVE DRAWN IS BEST FIT TO SLAC DATA.

F2
SLAC+EMC
DEUTERIUM
LOW X

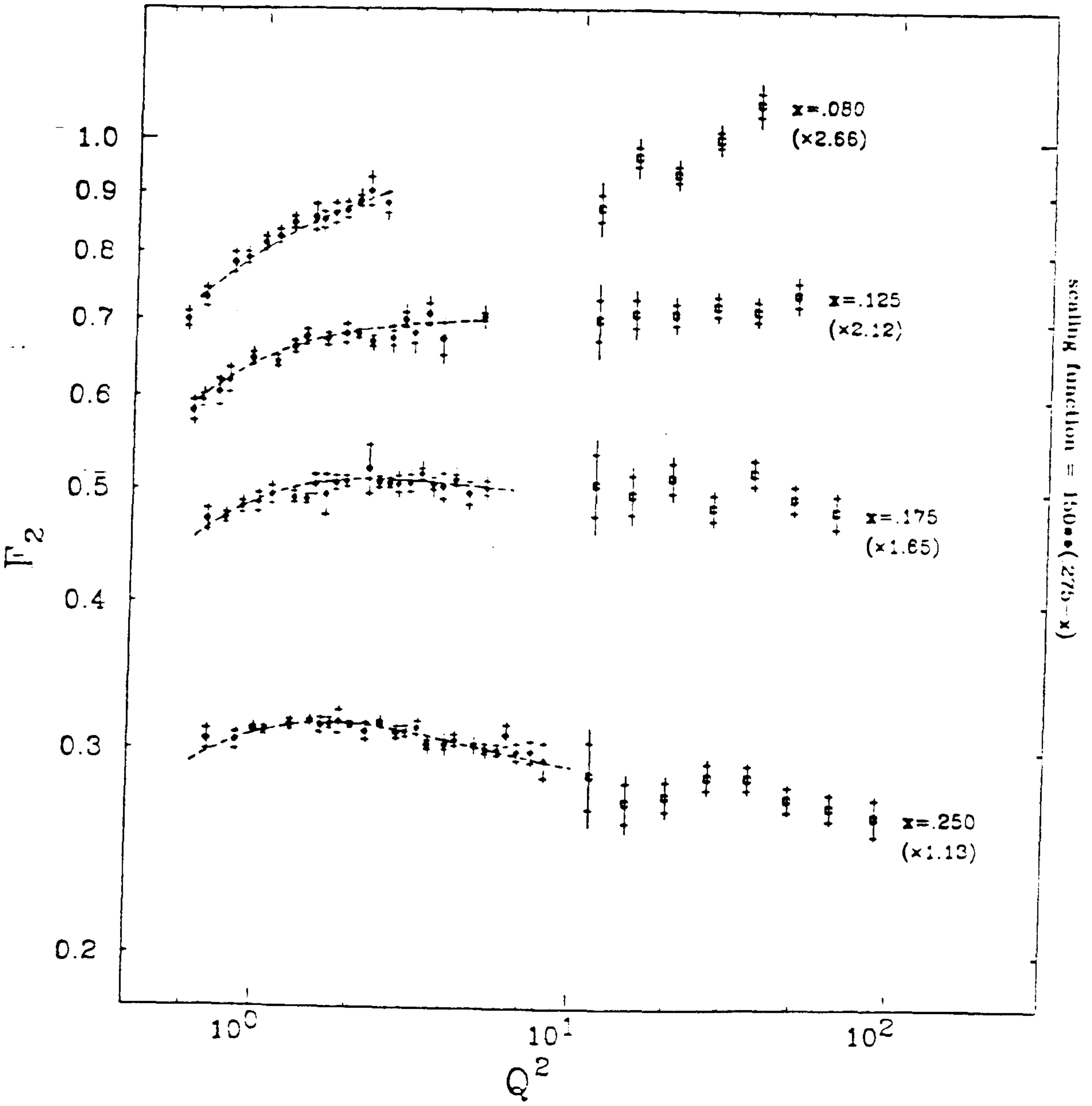


FIGURE 3C.
EMC DATA NORMALIZED BY 1.070.
CURVE DRAWN IS BEST FIT TO SLAC DATA.

$F_2$
SLAC+EMC
DEUTERIUM
HIGH X

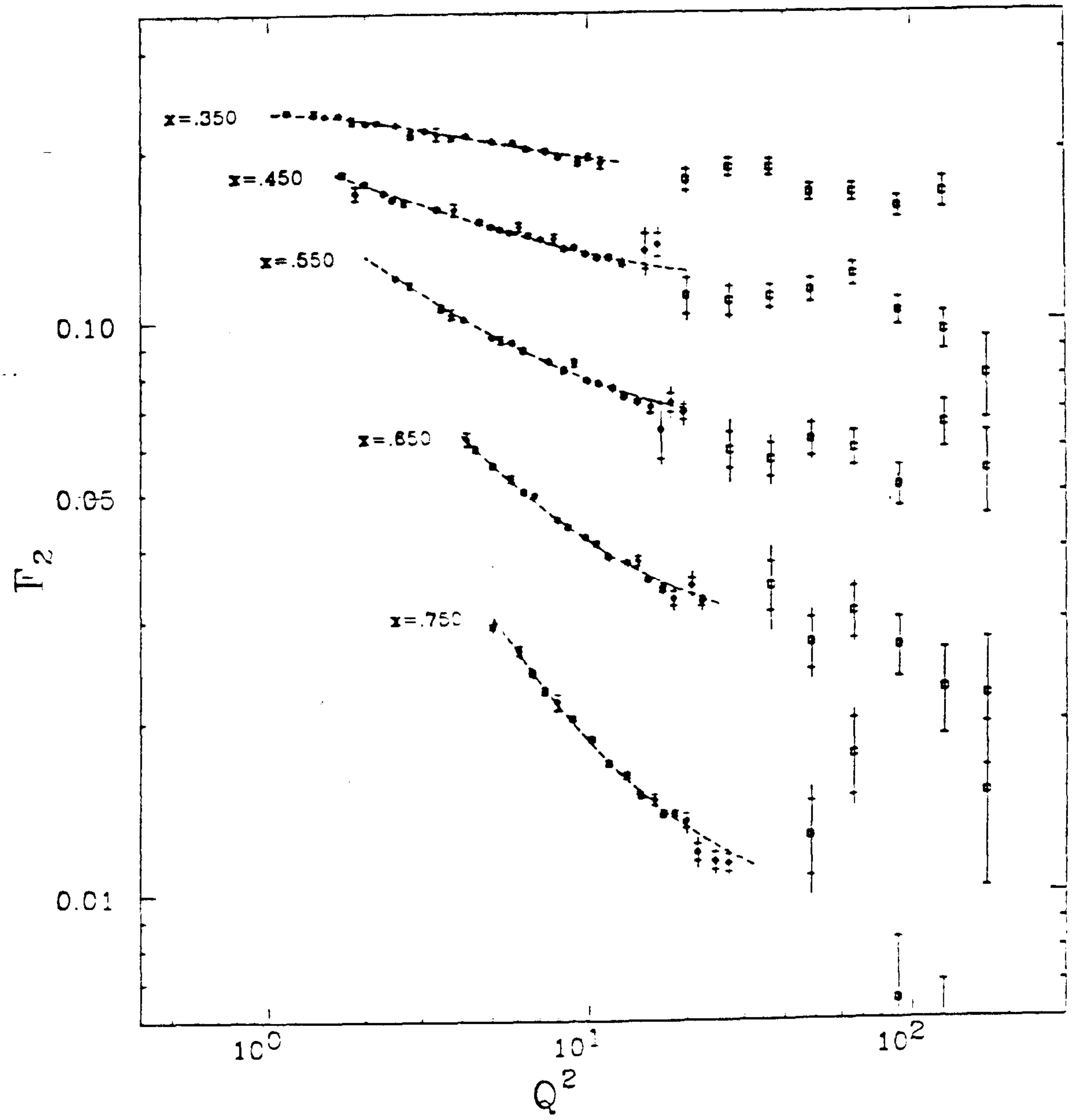


FIGURE 3D.
EMC DATA NORMALIZED BY 1.070.
CURVE DRAWN IS BEST FIT TO SLAC DATA.

$F_2$
SLAC+BCDMS
HYDROGEN
LOW X

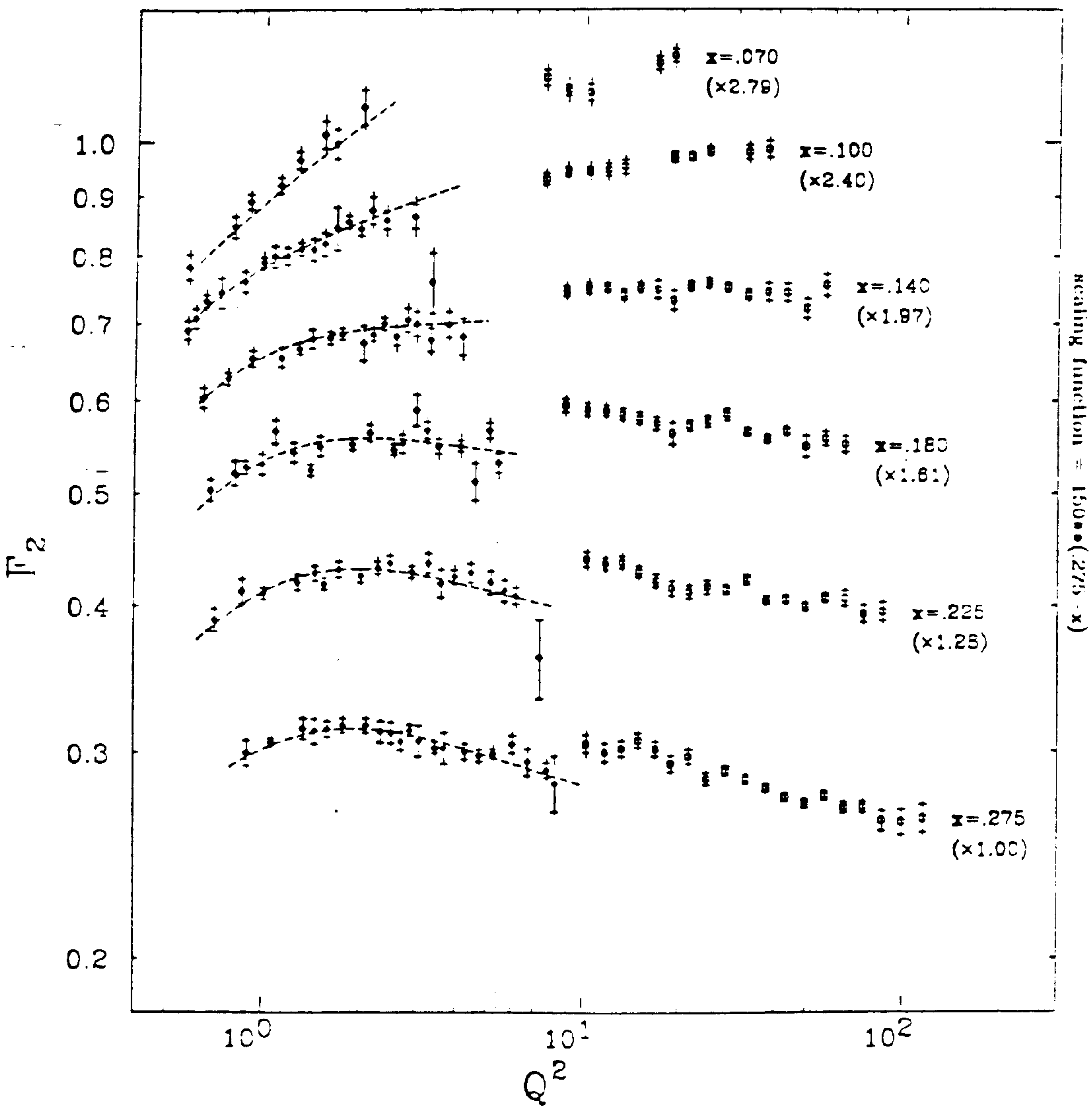


FIGURE 4A.
BCDMS DATA NORMALIZED BY 1.000.
CURVE DRAWN IS BEST FIT TO SLAC DATA.

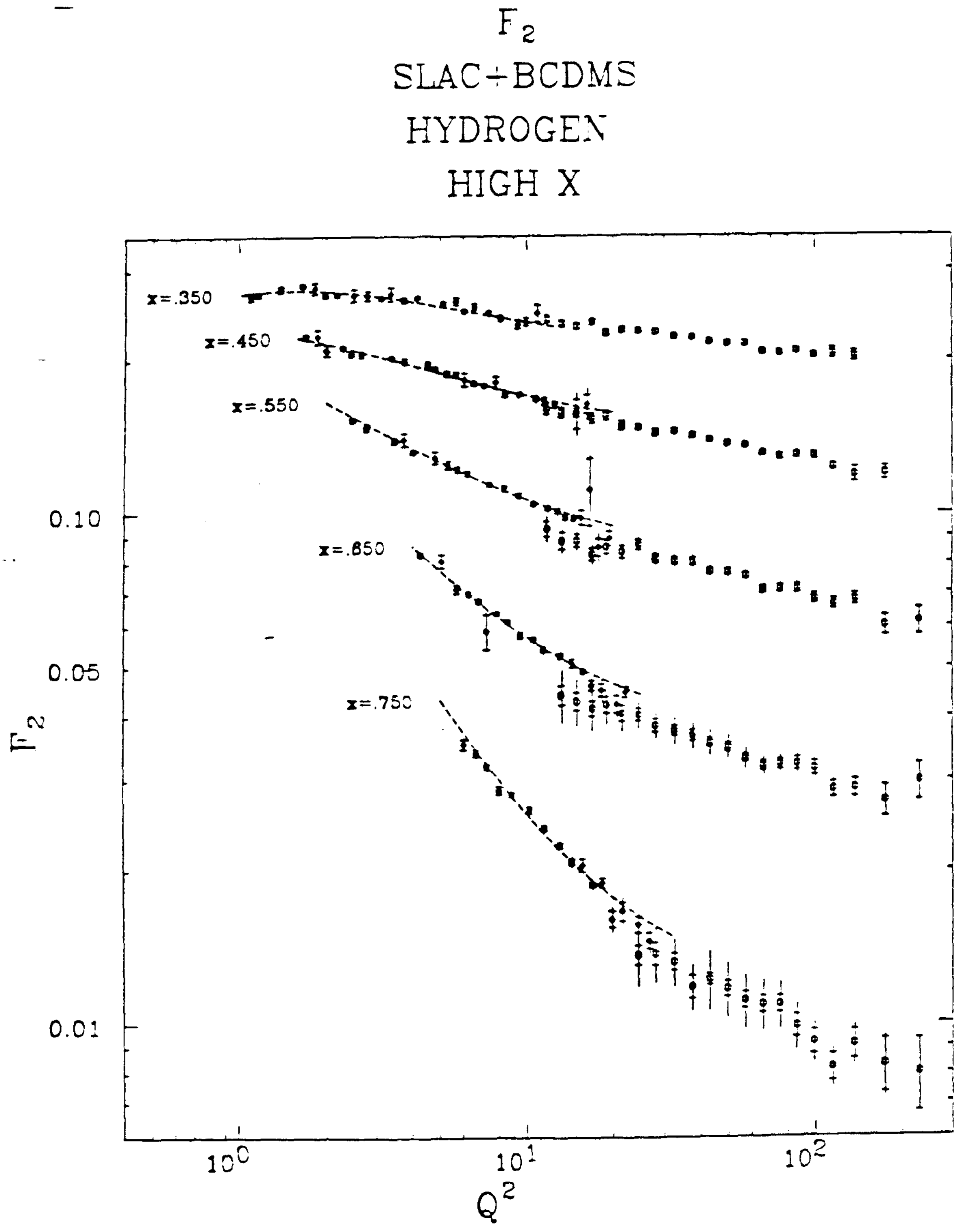


FIGURE 4B.
BCDMS DATA NORMALIZED BY 1.000.
CURVE DRAWN IS BEST FIT TO SLAC DATA.

# $F_2$
# SLAC+BCDMS
# DEUTERIUM
# LOW X

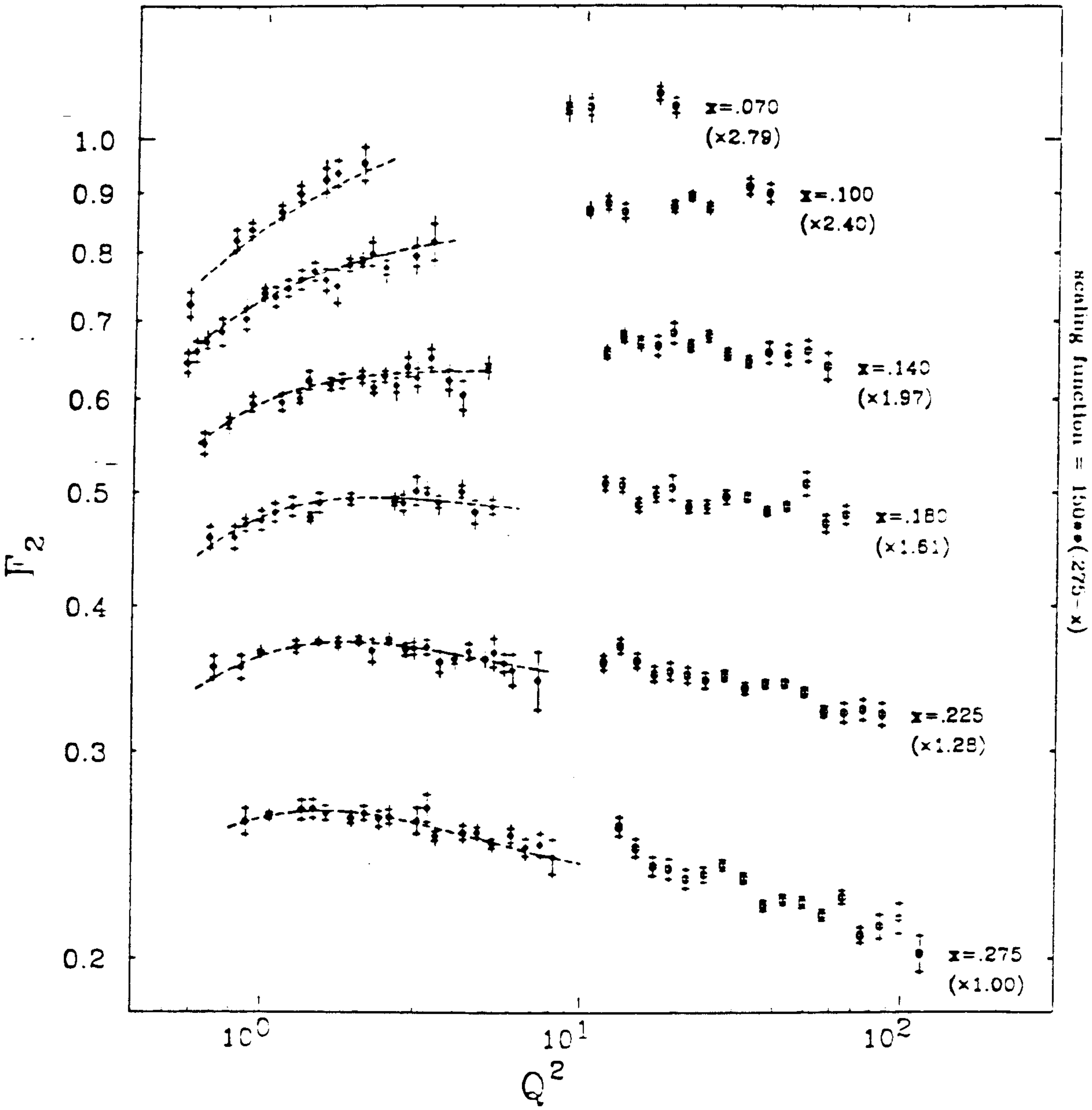


FIGURE 4C.
BCDMS DATA NORMALIZED BY 1.000.
CURVE DRAWN IS BEST FIT TO SLAC DATA.

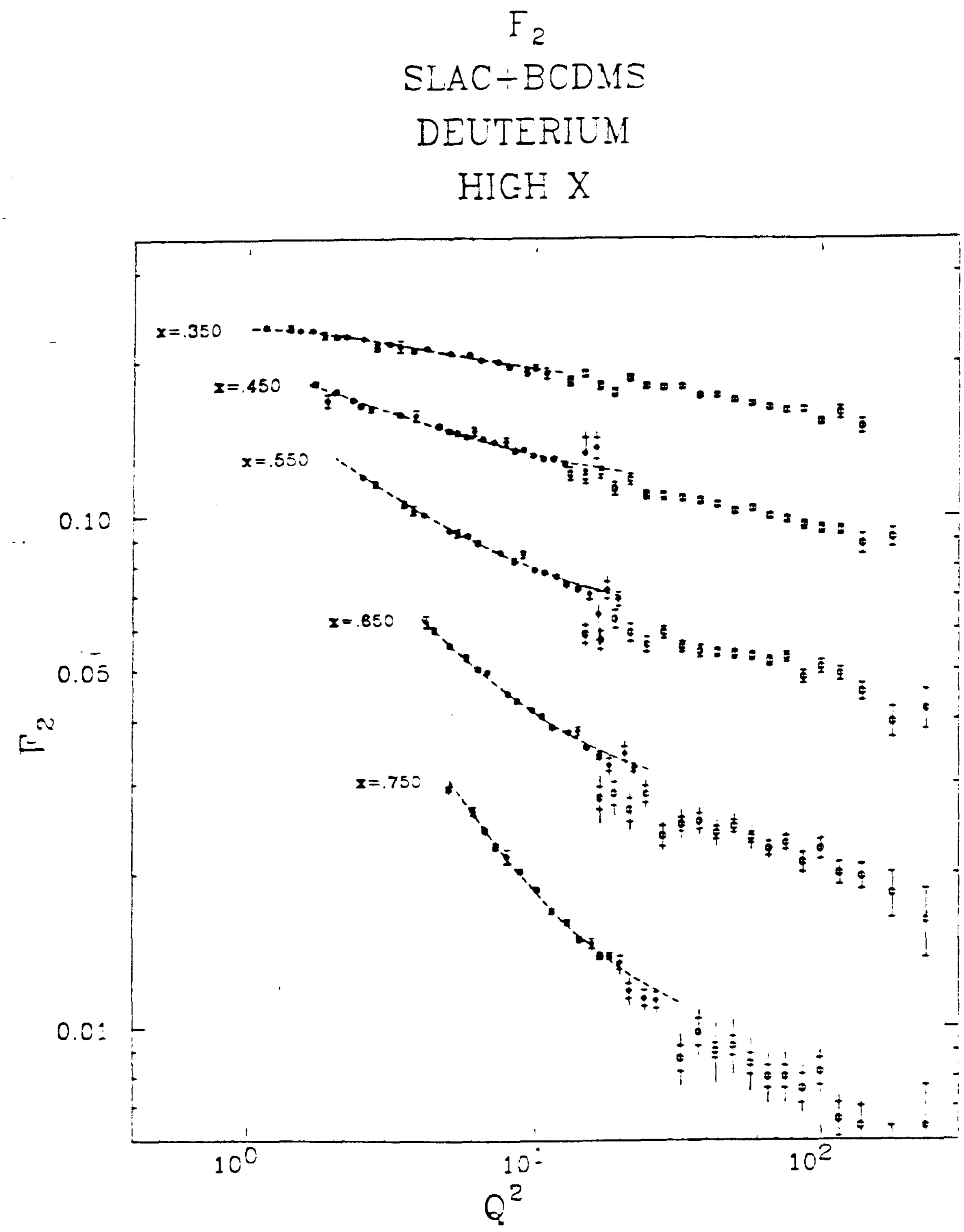


FIGURE 4D.
BCDMS DATA NORMALIZED BY 1.000.
CURVE DRAWN IS BEST FIT TO SLAC DATA.