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Micro-Review of Structure Functions and Parton Distribution Functions*

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There has recently been a great deal of discussion concerning the surprising differences in the measurements of the nucleon structure function $F_2(x,Q^2)$, off of a hydrogen target, by the high statistics muoproduction experiments EMC [1] and BCDMS [2]. In this short review I will attempt to summarize the status of the experimental measurements of the structure functions and highlight any significant disagreements. At the conclusion I will comment on the status of the extraction of the parton distribution functions from these measurements.

As can be seen from Tables I and II, there are high statistics measurements of the structure function $F_2(x,Q^2)$, which reflects the sum of $q + \bar{q}$ [3], obtained by scattering both muon and neutrino beams from a wide range of targets. In addition the neutrino experiments provide a direct, although statistically less significant, measurement of $xF_3(x,Q^2)$ which reflects the contribution of the valence quarks q_v.

Table I

MUON EXPERIMENTS			
	BCDMS	BFP	EMC
Target	C and H_2	Fe	H_2 D_2 Fe
Energy	100 - 280	93, 215	120 - 280
x-range	.06 - .80	.08 - .65	.03 - .65
Q^2-range	25 - 280	5 - 220	3 - 200
* events	C: 680K	690K	Fe: 1080K
$R(x,Q^2)$	Expt.	0.0	0.0

Table II

NEUTRINO EXPERIMENTS				
	BEBC	CCFRR	CDHSW	CHARM
Target	Ne H	Fe	Fe	Marble
Energy	10 - 200	30 - 250	30 - 300	10 - 200
x-range	.025 - .80	.02 - .65	.02 - .65	.02 - .55
Q^2-range	2 - 70	1 - 200	0.2 - 200	0.2 - 100
$R(x, Q^2)$	R(QCD)	R(QCD)	R(QCD)	0.1
# Events	25K	170K	940K	160K
SU(3) symmetry	$\bar{s} = 0.25\,(\bar{u} + \bar{d})$ $c = \bar{c} = 0$		$\bar{s} = 0.2\,(\bar{u} + \bar{d})$ $c = \bar{c} = 0$	
Charm	slow rescale: m = 1.5		No correction	

Before comparing these measurements it should be noted that differences, outside of the statistical errors, are **expected** due to experimental systematic effects and to the different kinematical regions covered by experiments. The impact of this last point is shown in Fig. 1. Note that at the same value of x the average value of Q^2 can differ by as much as an order of magnitude between various experiments. Care must be taken to remove this "natural" difference before comparing measurements.

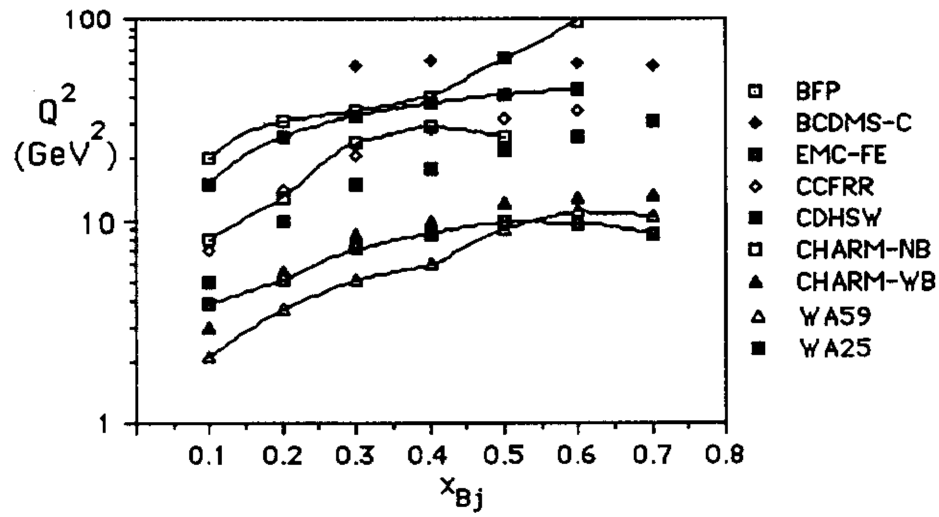


Fig. 1 The dependence of Q^2 on x_{Bj} for various experiments

$F_2(x,Q^2)$: Heavy Targets Experiments

Because of the relatively small neutrino cross section most of the high statistics neutrino experiments have used heavy target (i.e Fe) detectors. Muon experiments, on the other hand, can get sufficient statistics even with H_2 or D_2 targets. We will discuss the relation between heavy and light target results - the "EMC Effect" - shortly, but for now let's examine the ratio of the structure function $F_2(x,Q^2)$ as measured by the heavy target experiments. The black points on Fig. 2 indicate the ratio of $F_2(x,Q^2)$ as measured by two high statistics muon experiments, EMC on iron [4] and BCDMS on carbon [5].

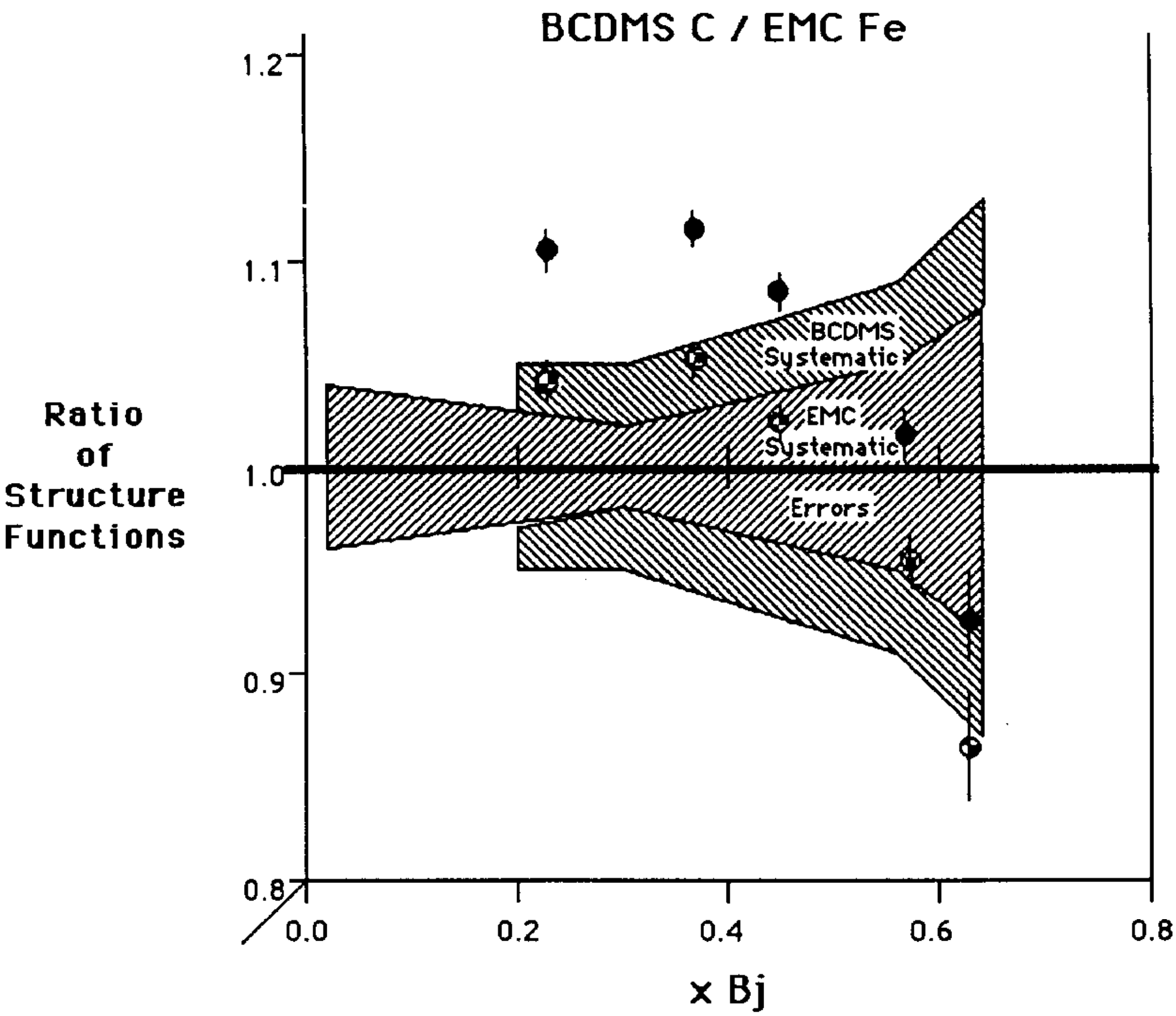
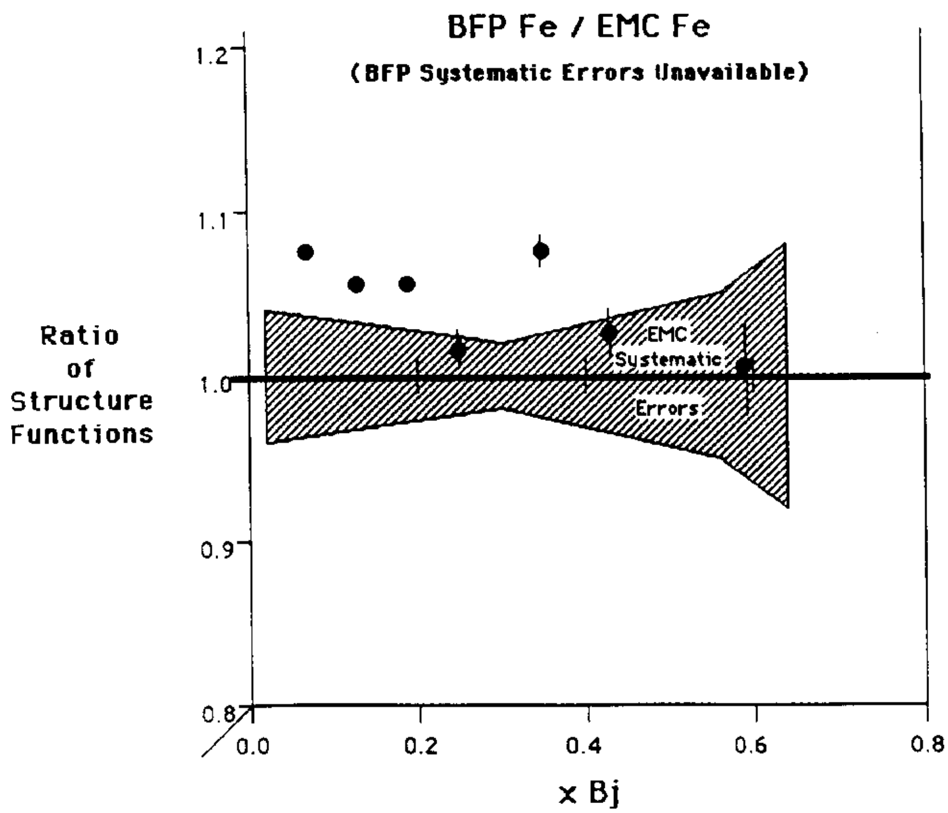
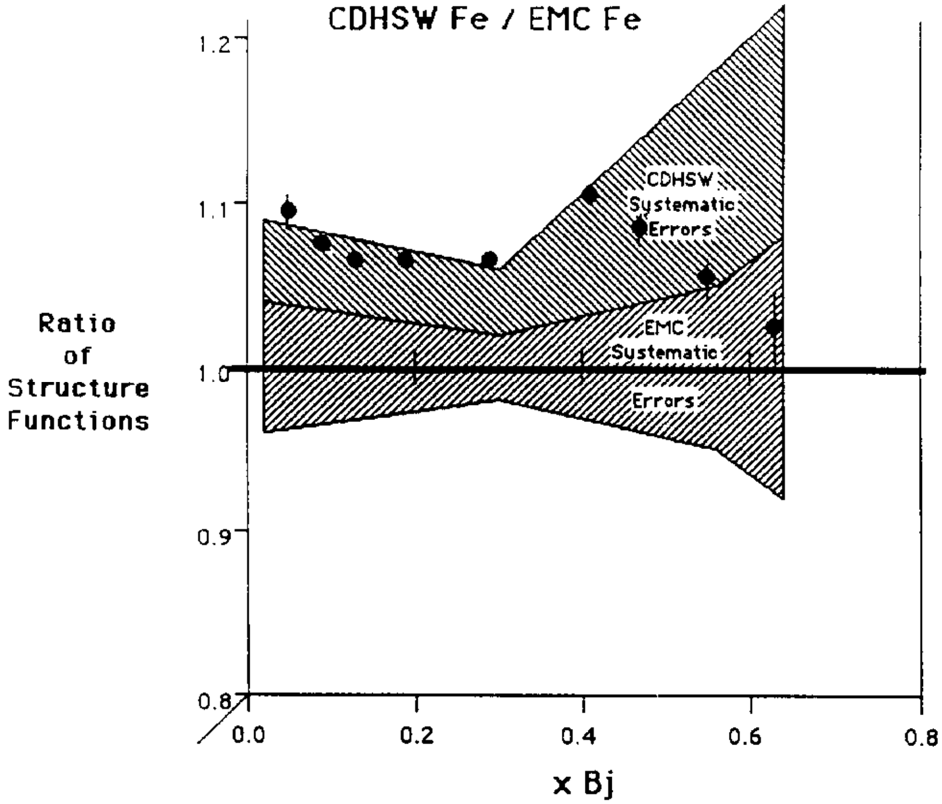


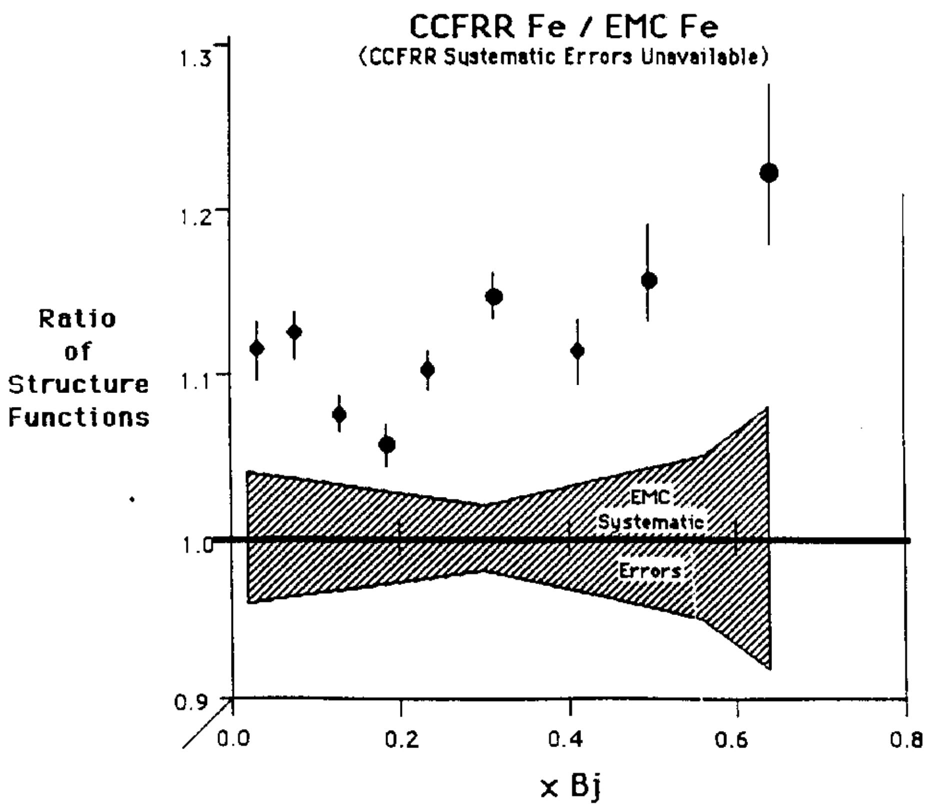
Fig. 2 The ratio of $F_2(x,Q^2)$ measured by the BCDMS carbon experiment to that measured by the EMC Fe experiment (black points). The black / white points show the effect of a 5% change in relative normalization.

The error bars on the individual points are statistical and the systematic error from each experiment is shown in the cross hatched area. There are no low x points since the high minimum Q^2 of the BCDMS carbon experiment translates to a minimum x of about 0.2. The first thing one notices is the x-dependent trend of the ratio. However, as the black/white points indicate, the significance of this trend is lost when a 5% change in the relative normalization between the two sets of data is introduced. Even though both experiments sit in the same beam at CERN, each measures the flux independently so a relative offset is certainly possible.

The following set of figures shows the ratio of $F_2(x,Q^2)$ measured by the other considered heavy target experiments BFP [6], CCFRR [7], and CDHSW [8] always with respect to EMC. When comparing neutrino to muon results, a constant 5/18 has been applied neglecting the small x contribution from sea quarks to this factor. The systematic errors for the CCFRR and BFP points are not available but are thought to be larger than the EMC systematic errors which are shown. In all cases, a shift in scale of a few percent statistically eliminates any discrepancy.




CDHSW Fe / EMC Fe
Ratio of Structure Functions
CDHSW Systematic Errors
EMC Systematic Errors
1.2
1.1
1.0
0.9
0.8
0.0
0.2
0.4
0.6
0.8
x Bj


CCFRR Fe / EMC Fe
(CCFRR Systematic Errors Unavailable)
Ratio of Structure Functions
EMC Systematic Errors
1.3
1.2
1.1
1.0
0.9
0.0
0.2
0.4
0.6
0.8
x Bj

Before leaving the heavy target experiments there is one very new result from the Fermilab-MIT-MSU neutrino collaboration (E594) which tests whether the quark distributions as seen by the neutral current and the charged current are the same. The following figure shows the valence quark distribution (Fig. 4a) as determined from the FMM neutral current data [9] as compared to the distribution determined by the CCFRR, CDHSW and CHARM [10] charged current data. Fig. 4b shows a similar comparison for the sea quark distribution. There is excellent agreement in both cases.

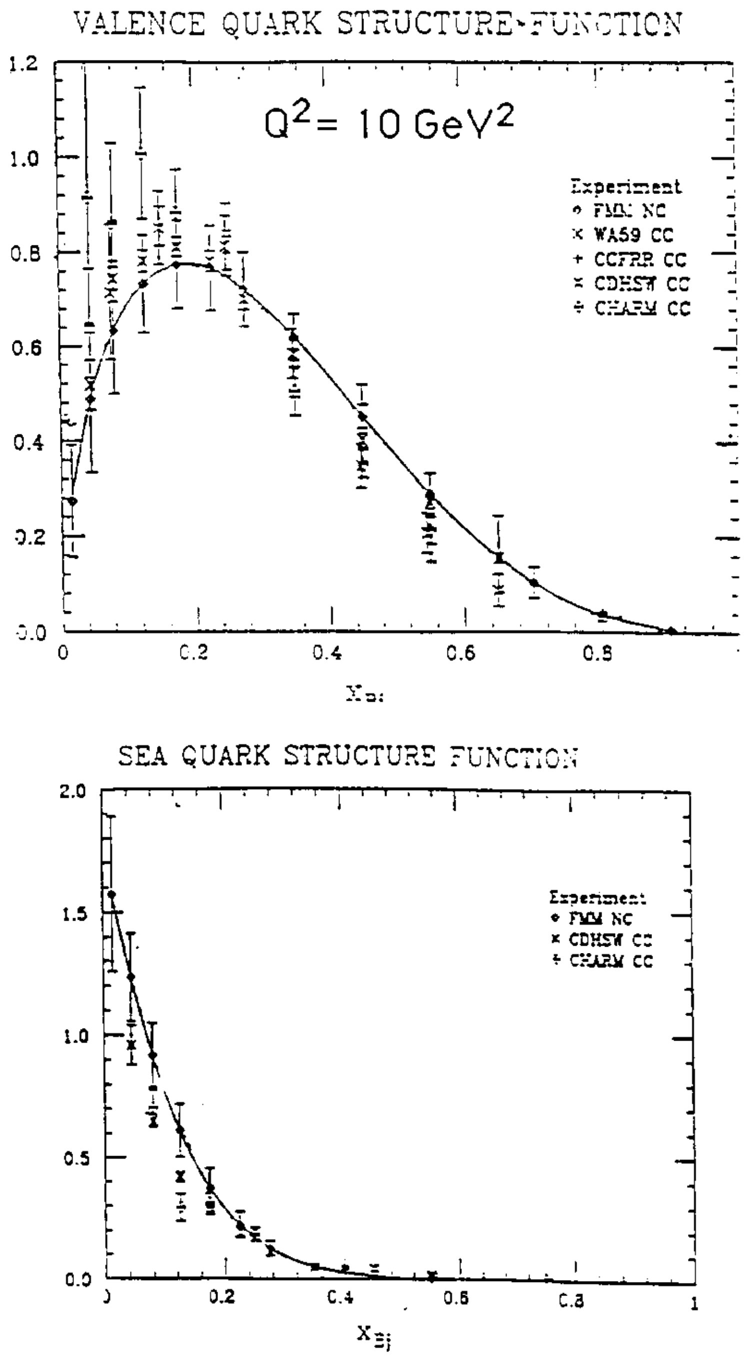


Fig. 4 Comparison of NC to CC valence and sea quark distributions

$F_2(x,Q^2)$: Hydrogen Data

Fig. 5 shows the ratio of $F_2(x,Q^2)$ as measured by the two muon experiments BCDMS and EMC using a hydrogen target in both cases. There is an x-dependent trend similar to the BCDMS-EMC heavy target comparison shown earlier. However, in this case, no shift in relative normalization can eliminate the differences. There is a statistically significant difference between these results of the two muon experiments. The curve drawn is an

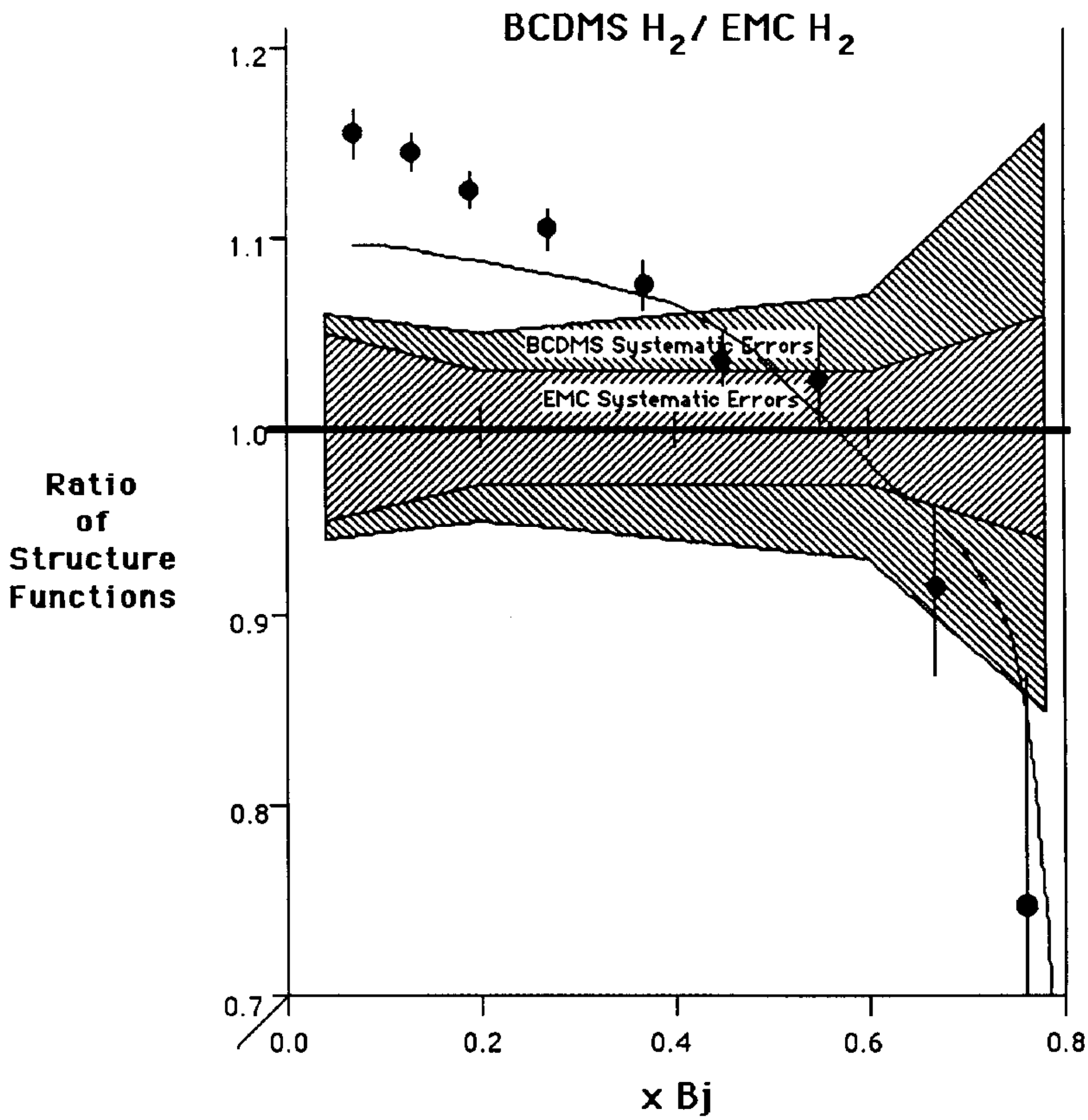


Fig. 5 The ratio of the BCDMS and EMC hydrogen exposures. Refer to the text for an explanation of the curve.

attempt by R. Mount [11] to simulate the ratio by assuming a 10% relative normalization error **and** that the BCDMS scattered muon energy was wrong by 0.5 GeV + 0.6% E_μ. Even these extreme assumptions cannot force an agreement between these two high statistics experiments.

Status of the "EMC Effect"

The most recent results, supporting the observation of an x-dependent discrepancy between $F_2(x,Q^2)$ when measured on iron as compared to deuterium, come from SLAC E140 [12] and EMC' [13]. These new results are plotted together with earlier results in Fig. 6. They confirm the important characteristics that the ratio is below 1 at very low x rises above 1 around $x \approx 0.15$ and then steadily decreases until $x \approx 0.7$.

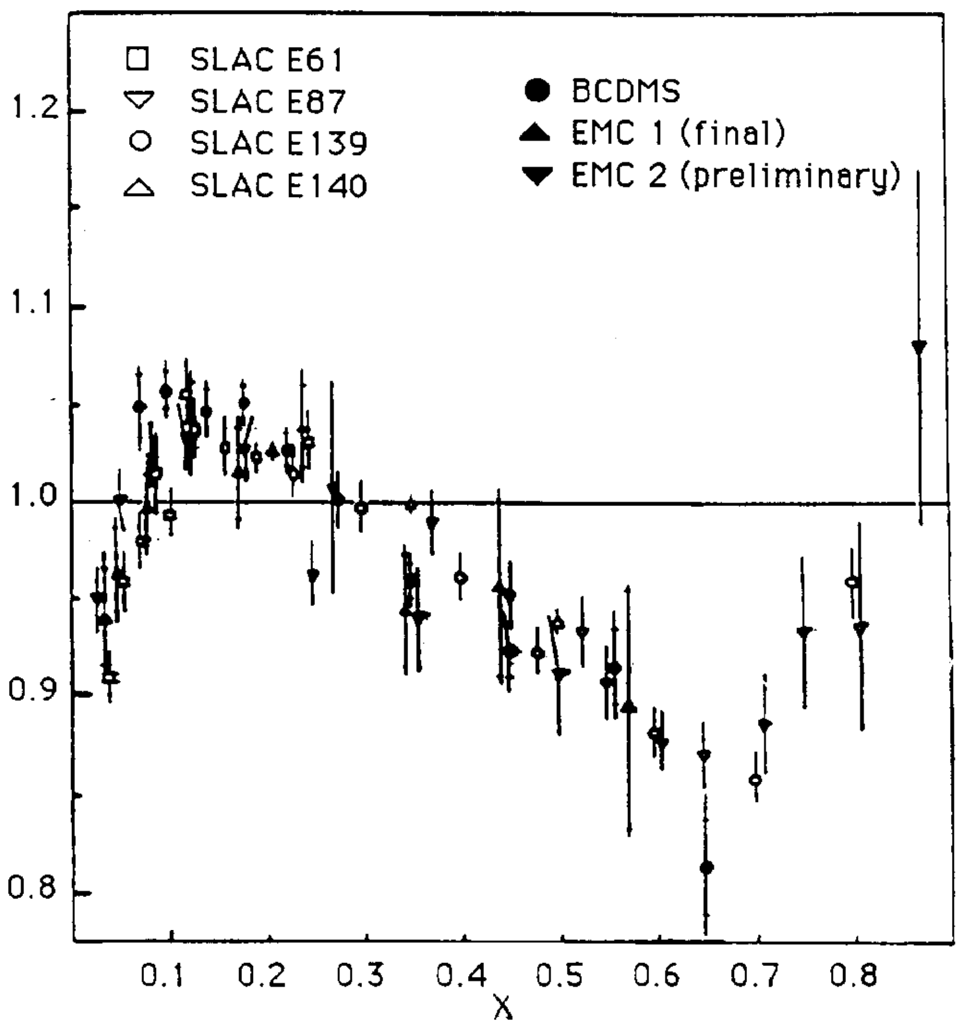


Fig. 6 A summary of recent measurements of the ratio of $F_2(x,Q^2)$ as measured with Fe or C compared to deuterium measurements.

There have been many attempts to explain this effect. One recent model by Berger and Qiu [14] has model predictions, shown in Fig. 7, for x > 0.1 and the assumption of shadowing to describe x < 0.1. A recent quark cluster model by Lassila [15] claims to be able to predict the entire x range without additional input. Reference to other models can be found in [14] and [15].

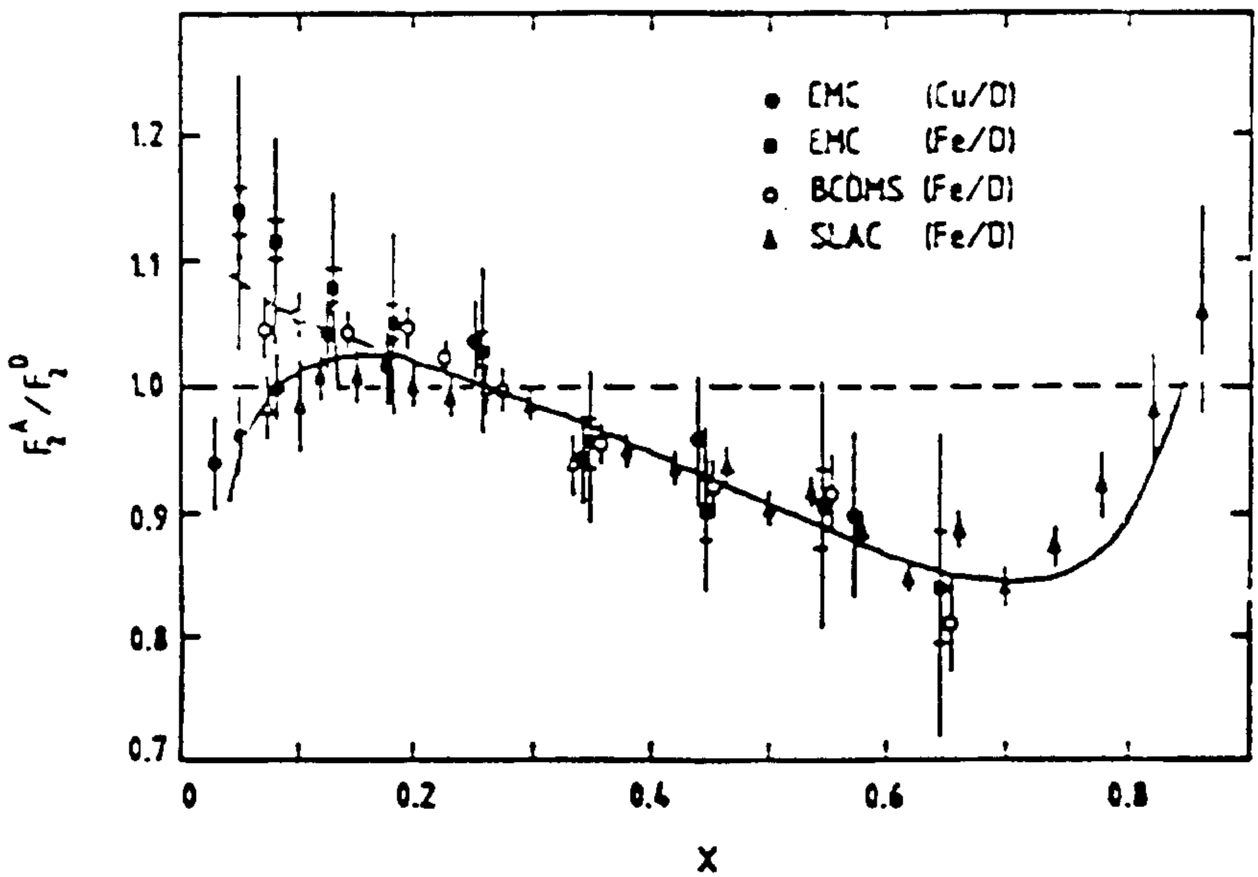


Fig. 7 The prediction of the model of Berger and Qiu compared to the most recent measurements of the EMC Effect.

The experimental evidence for a possible new attribute of the EMC effect was recently summarized by F. Taylor [16] who fit current data to the hypothesis that the EMC effect has a Q^2 dependence given by

$$\frac{d\,(F_2^{Fe} / F_2^{D_2})}{d\,(\ln Q^2)} = (0.077 \pm 0.023 \pm .047) - (0.25 \pm 0.09 \pm 0.14)\, x_{Bj}$$

(± statistical ± systematic). The data and fit are shown in Fig. 8.

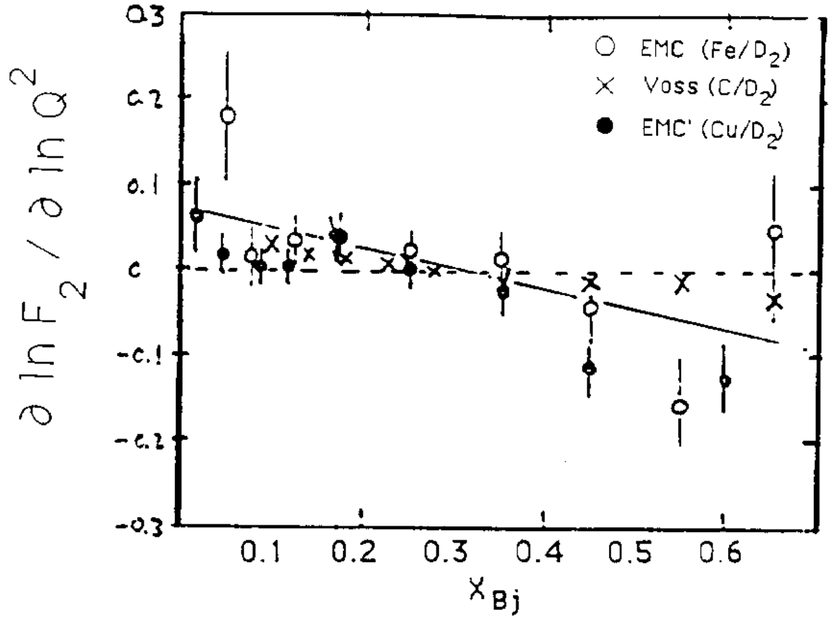


Fig. 8 The Q^2 dependence of the EMC effect using the data from SLAC experiment E139, EMC, and BCDMS experiments.

The Longitudinal Structure Function

There have been numerous experiments attempting to measure the ratio - $R(x,Q^2)$ - of the longitudinal to transverse structure functions. An indication of the accuracy of the current measurements is shown in Fig. 9.

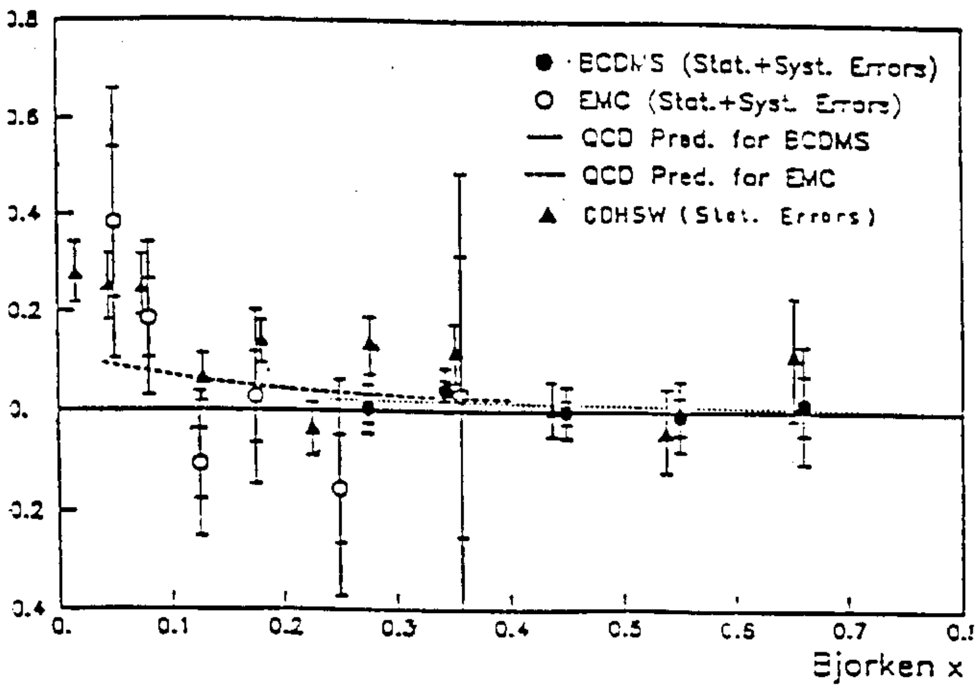


Fig. 9 R(x) as measured by CDHSW, EMC, and BCDMS

The most recent effort by SLAC experiment E140 has demonstrated the importance of (kinematical) higher twist contributions to the interpretation of this ratio. As shown in Fig. 10, the bare Twist 2 QCD prediction lies significantly below the E140 data points. With the addition of target mass corrections, the prediction is consistent with the data.

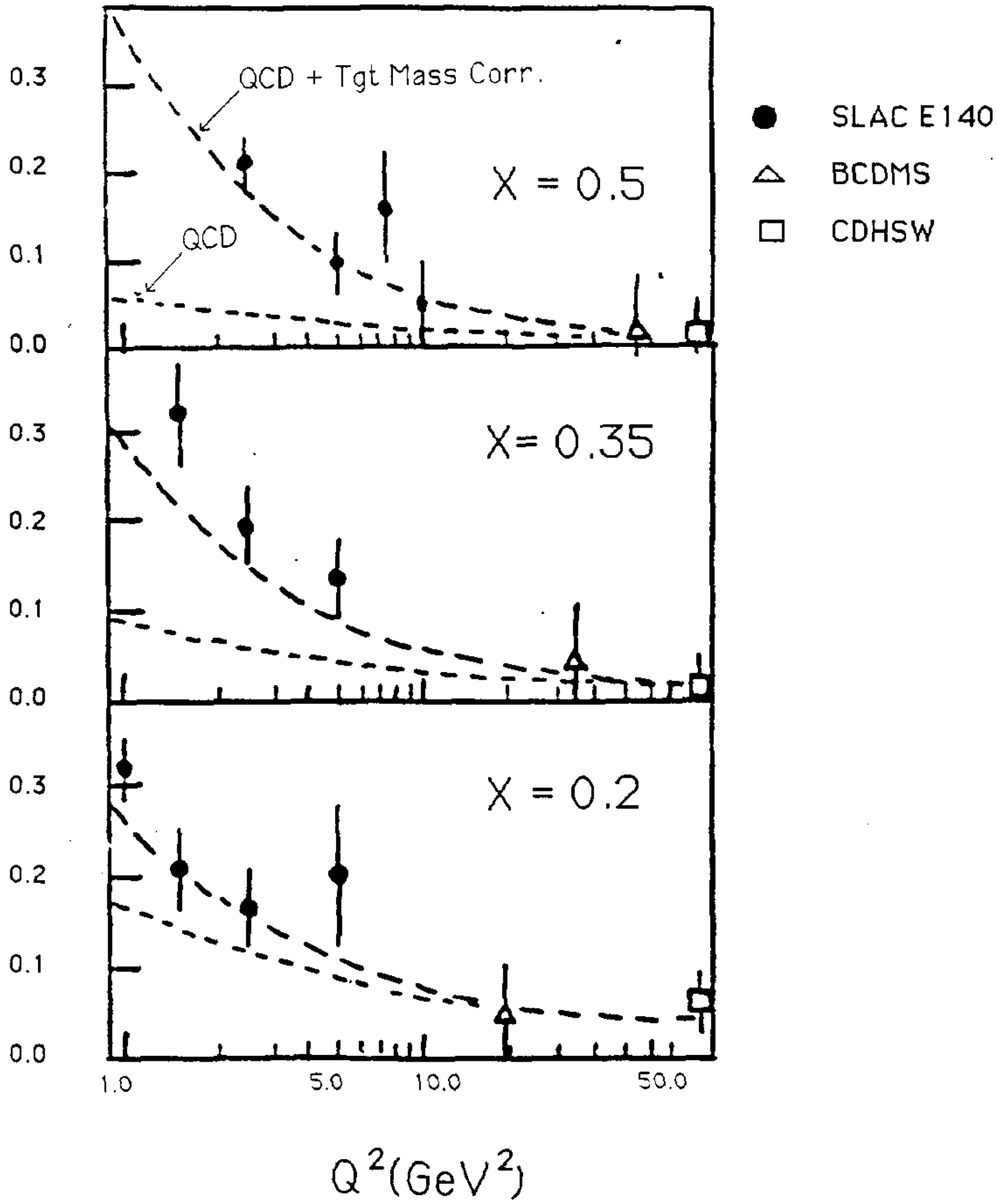


Fig. 10 The measured values of R from E140, CDHSW and BCDMS as compared to the QCD predictions with and without target mass correction.

QCD Interpretation of the Structure Function Data

That there is an x and Q^2 dependence to F_2 is clearly demonstrated in Fig. 11 which compares all high statistics results.

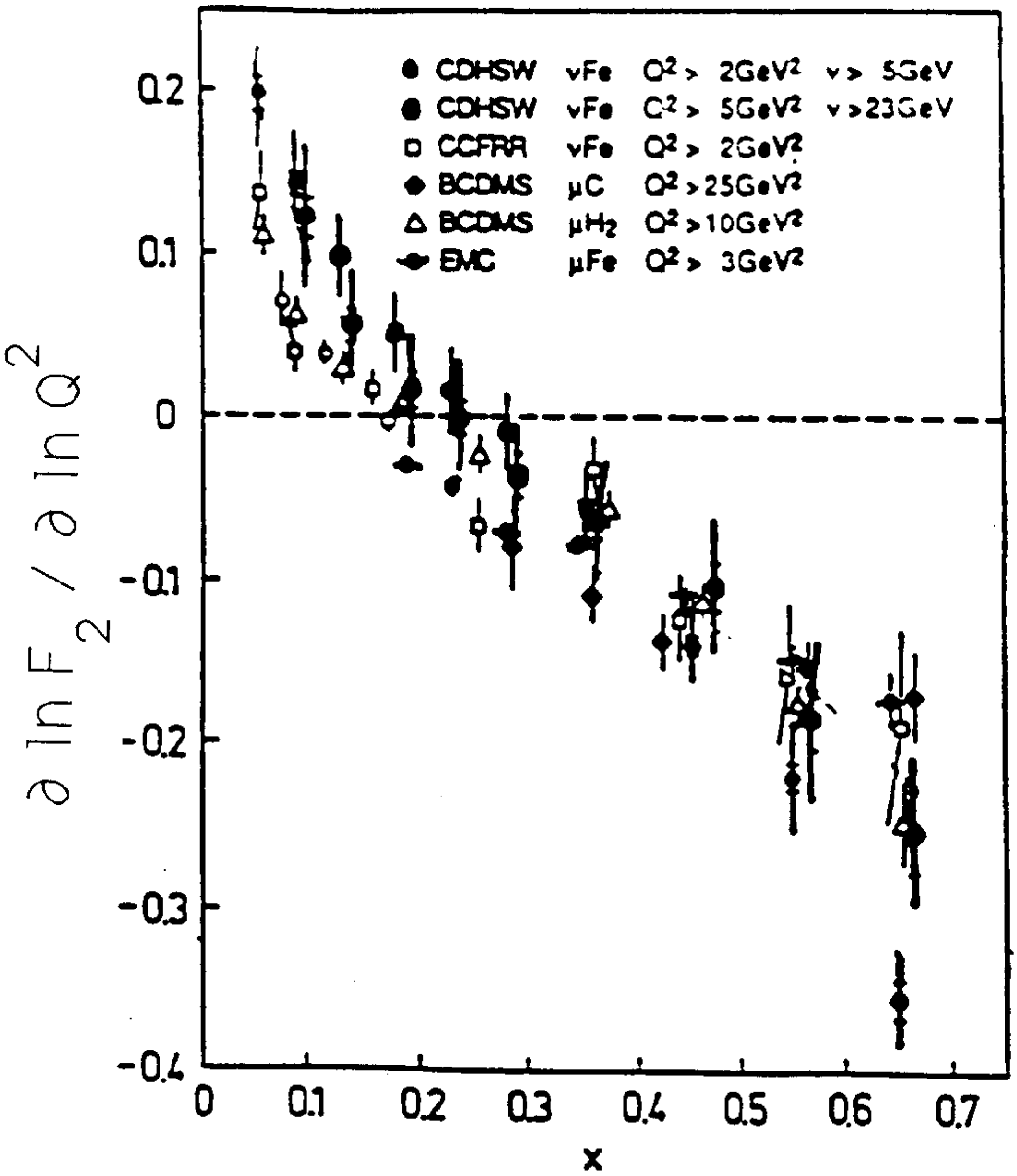


Fig. 11 d (ln F_2) / d (ln Q^2) as a function of x for the major high statistics experiments.

However, the quantitative interpretation of this x - Q^2 dependence in terms of QCD is not as straightforward. For example, Fig. 12 shows the measured slopes of F_2 by EMC and CDHSW and the **best** fit from next-to-leading order QCD. The fit is obviously atrocious! It has been pointed out [17] that as the minimum Q^2 of the data is raised, the quality and the stability of the fit improve dramatically.

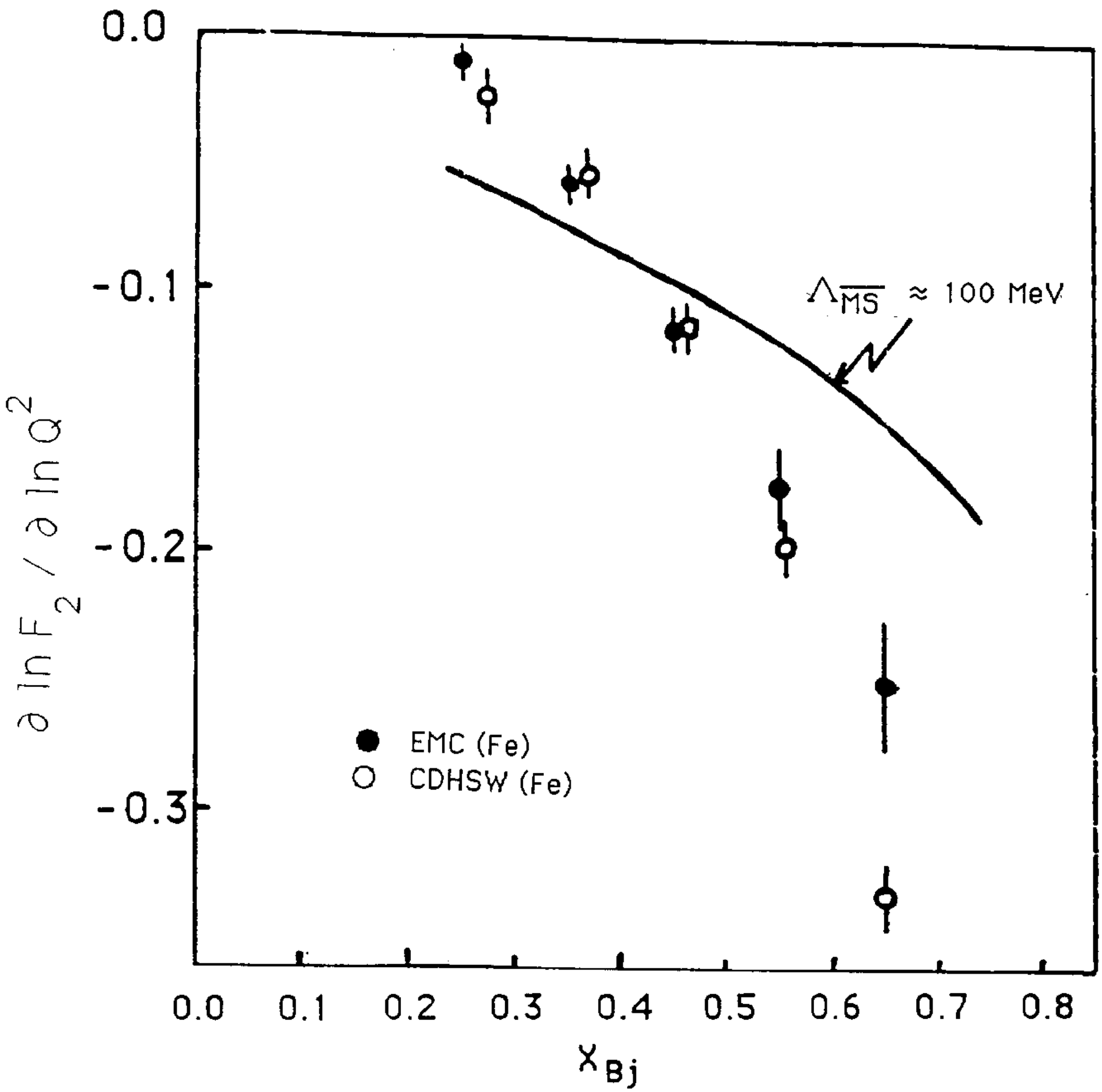


Fig. 12 F_2 measured on Iron targets by EMC and CDHSW compared to the best QCD fit.

It was only with the recently published BCDMS carbon data ($Q^2 > 20$ GeV^2) that a full agreement with QCD predictions was attained. The QCD analysis of the BCDMS carbon and hydrogen results are shown in Fig. 13. They yield a consistent value of slightly over 200 MeV for $\Lambda_{\overline{MS}}$. This value was obtained by two different methods; one taking only the high x (>0.25) data and performing a non-singlet fit, while the other fit used the data from the entire x range and simultaneously fit to the Gluon distribution with the following result,

$$x\,G(x, Q_0^2) = A\,(\eta + 1)\,(1 - x)^{\eta}\,, \quad Q_0^2 = 5\ \text{GeV}^2,\ \eta = 10 \pm 3$$

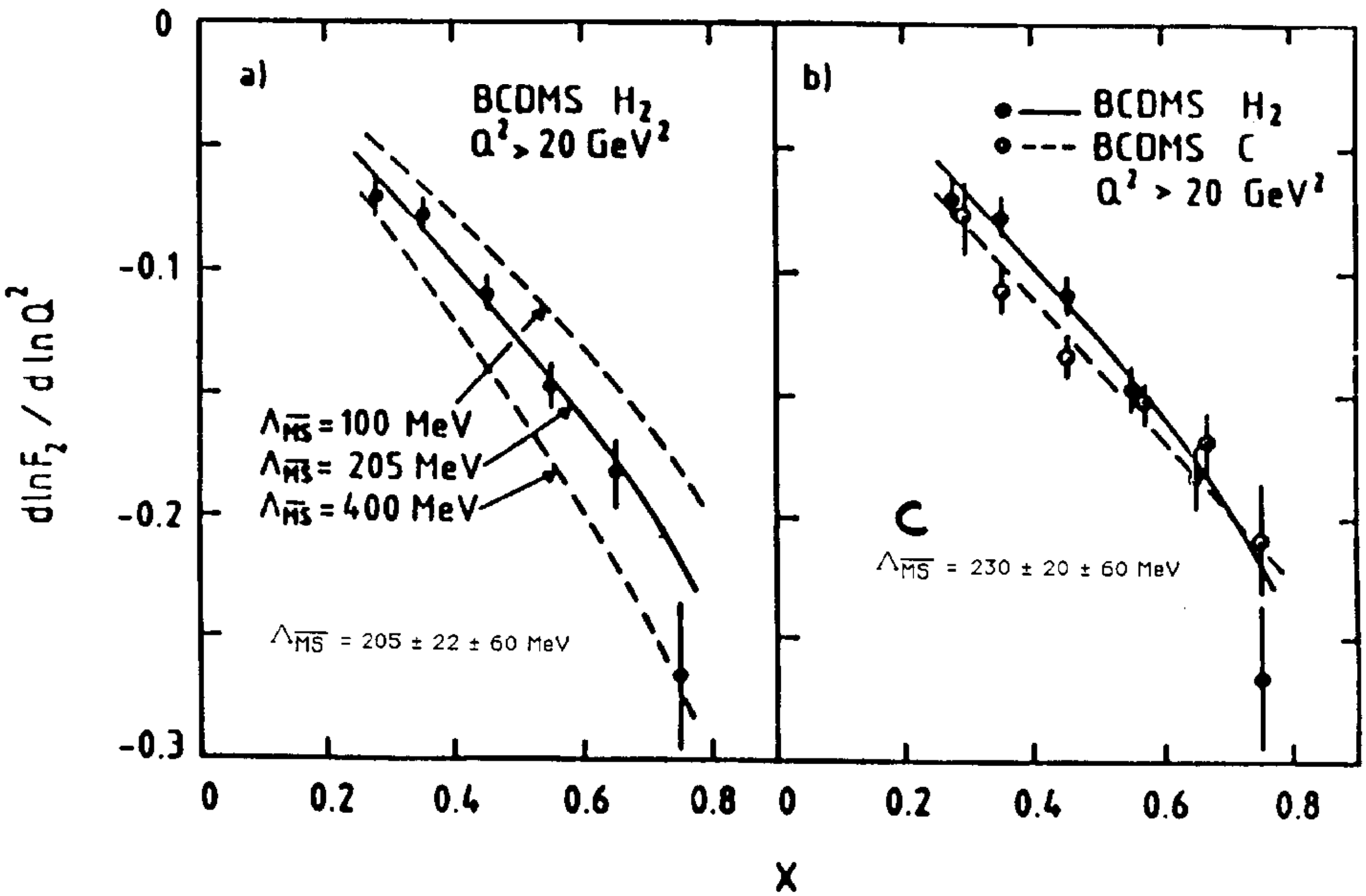


Fig. 13 The QCD analysis of BCDMS Hydrogen and Carbon Data

As mentioned, the agreement between measurement and QCD predictions can be improved by raising the minimum Q^2 of the data considered for the analysis. Another way of reconciling the data and predictions, according to F. Taylor, is to apply the Q^2 dependence of the EMC effect as formulated in an earlier section. Using the relation,

$$\frac{\partial \ln F_2^{Fe}}{\partial \ln Q^2} = \frac{\partial \ln F_2^{D_2}}{\partial \ln Q^2} + \frac{\partial \ln R^{Fe/D_2}}{\partial \ln Q^2}$$

the QCD fit to the EMC data is improved as shown in Fig. 14. A similar improvement was found for the BFP fit.

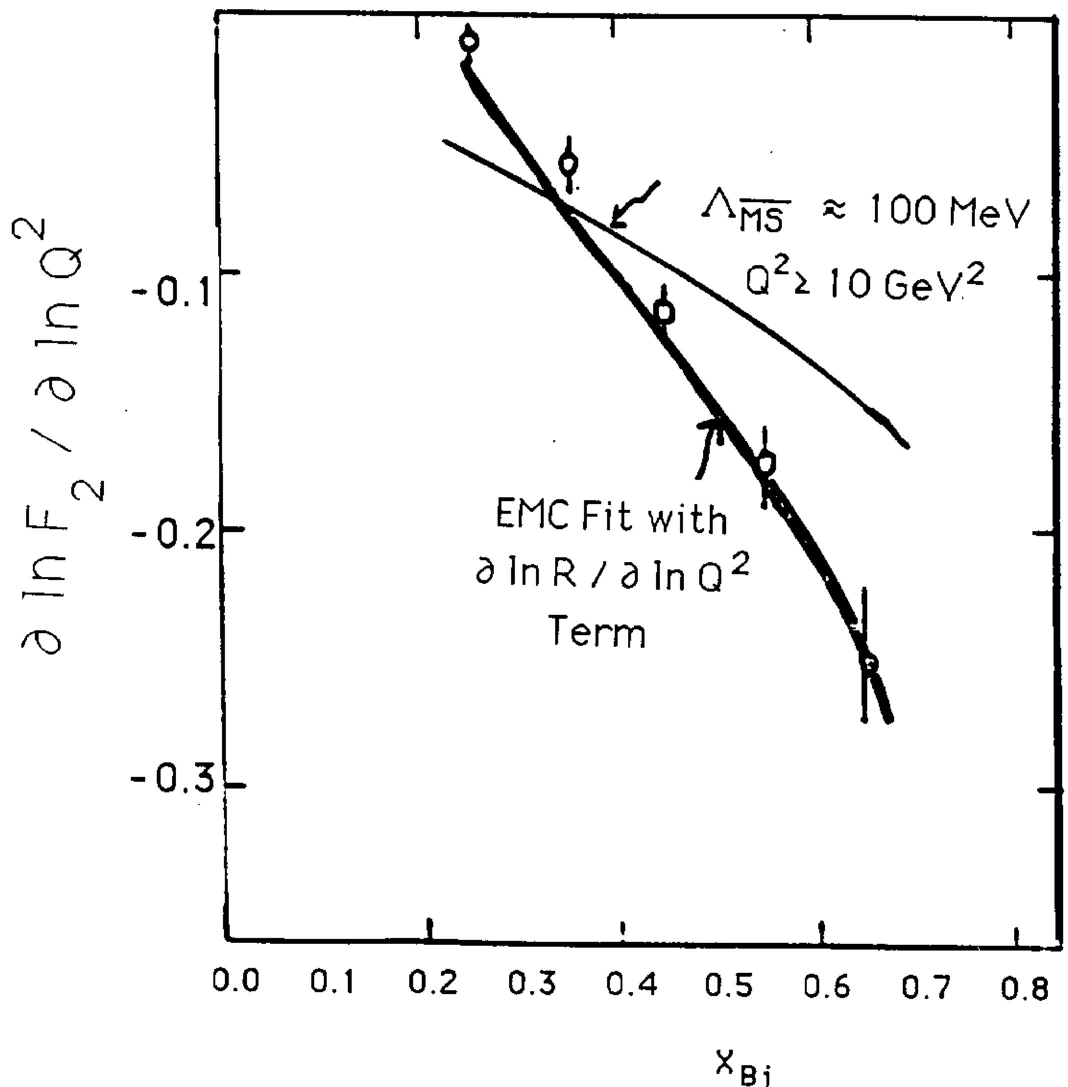


Fig. 14 QCD fits to the EMC Fe data with and without the Q^2 dependent EMC effect term - $\partial \ln R / \partial \ln Q^2$.

Determining the Parton Distribution Functions

One of the main goals of measuring the structure functions is the determination of the parton x distributions $q_i(x, Q^2)$. This is accomplished by assuming a form for the parton x dependence at a given Q^2 and using a QCD evolution program based on the Altarelli-Parisi equation to evolve the function to a Q^2 where there is a measured data point. The form of the distribution is changed until the best fit to all the measured points is obtained. The commonly used sets of parton distribution functions (PDF's) can be divided into two groups; leading order distributions such as those of references [18], [19] and [20] which were published prior to 1985, and PDF's determined using the next-to-leading expansion such as those of references [21] and [22]. Unfortunately, ALL of the above attempts to determine the PDF's ignored one or more of the following important features; EMC effect, experimental systematic errors, correlated errors, error migration, large statistics experiments. A new systematic effort is now underway which will attempt to include most of the above missing considerations as indicated in the following schematic representation of the fits.

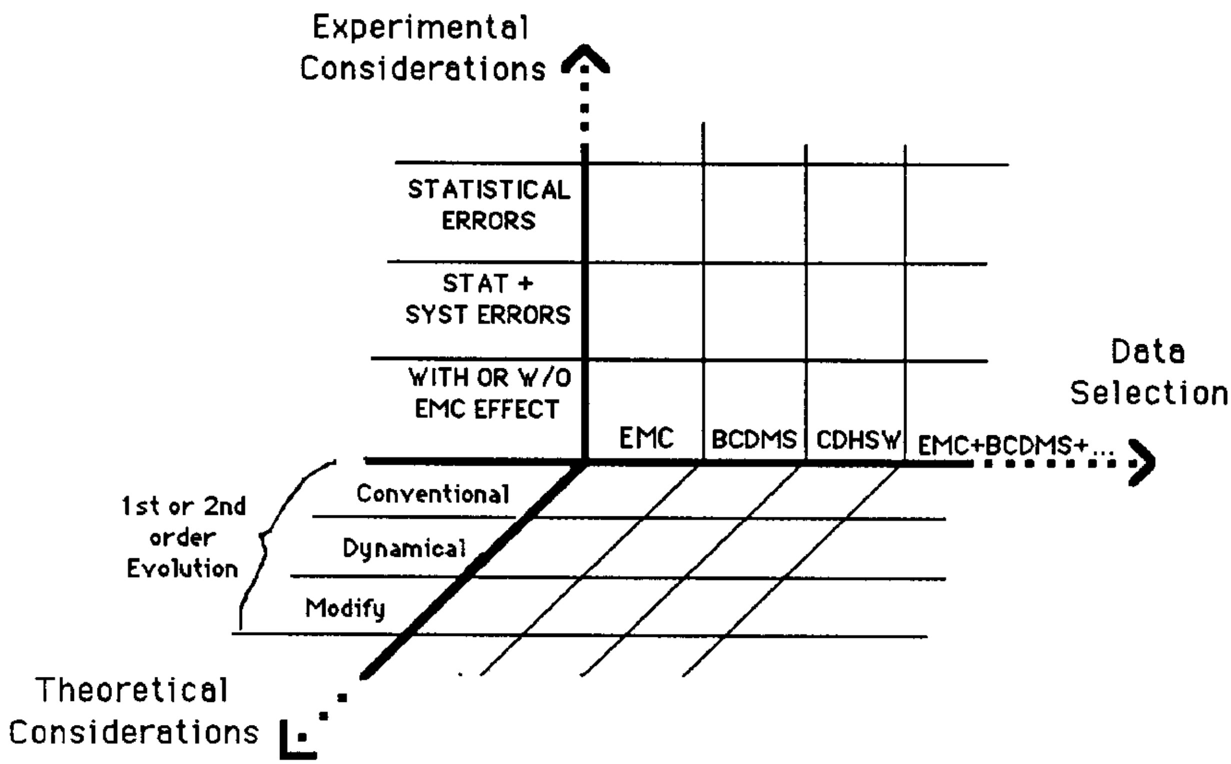


Fig. 15 An indication of the various fit combinations being attempted by the authors of reference [24].

It uses the Tung [23] QCD evolution program and is based on the H_2 data of EMC and BCDMS as well as the heavy target data of EMC, BCDMS and CDHSW. All of the data sets mentioned include systematic errors. The first results of this ongoing work is now available as a Snowmass '88 contribution [24]. A sample fit to all the data sets mentioned above is shown below. It yields a χ^2 / d.o.f. of 1.06 and uses all data with Q^2 > 20 GeV^2 (428 data points) with both statistical and systematic errors (added in quadrature) included in the fit.

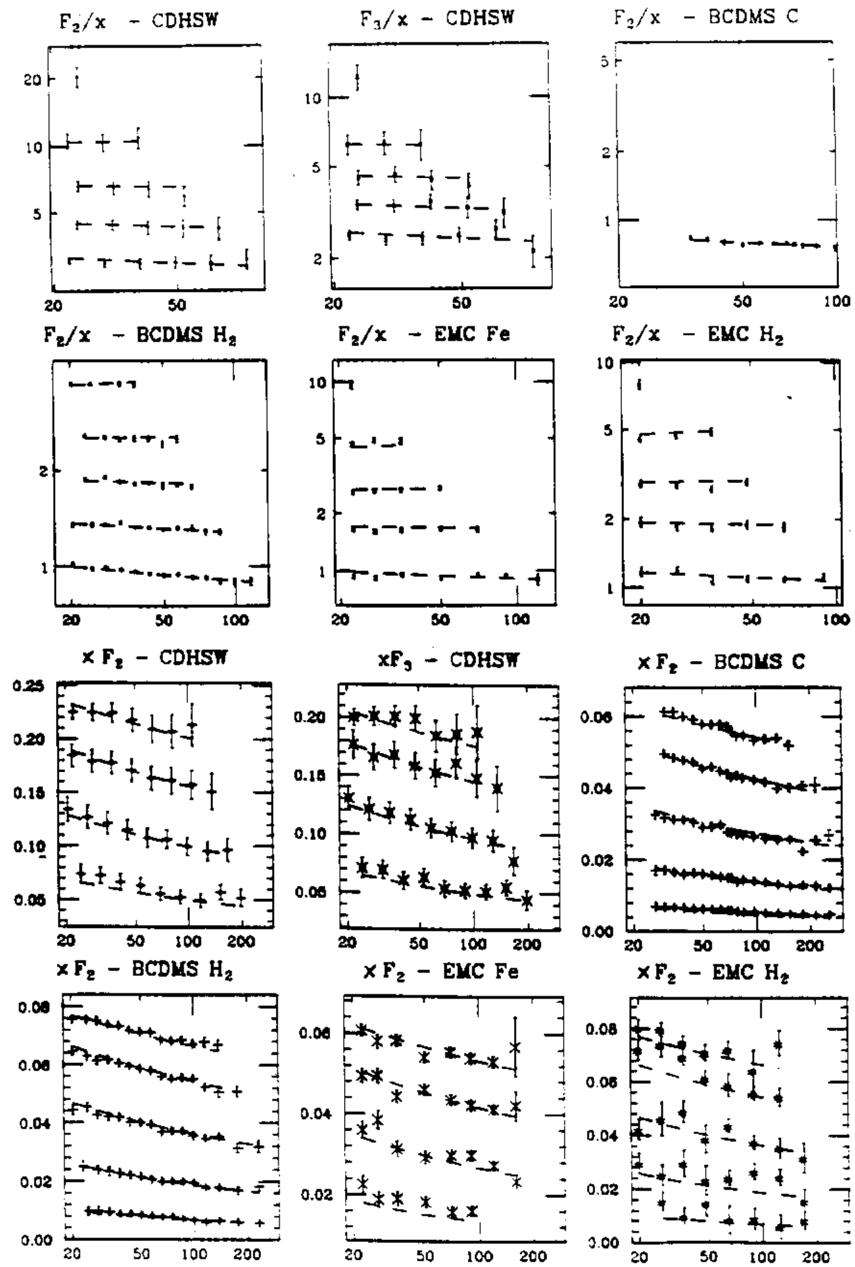


Fig. 16 A typical fit from reference [24] for data with Q^2 > 20 GeV^2. The fit yields a χ^2 / d.o.f. of 1.06 and a value of $\Lambda_{\overline{MS}}$ ≈ 350 MeV

SUMMARY

1. Measurements of $F_2(x,Q^2)$ using iron targets with muons and neutrinos are consistent.

2. There is a discrepancy between the published $F_2(x,Q^2)$ results as measured with iron as compared to those measured off carbon.

3. There is also an apparent discrepancy between the hydrogen results of EMC and BCDMS.

Are the discrepancies reported in 2. and 3. still significant if:
a) the same Q^2 cut is applied to all data
b) the same value of R is used for all analysis
c) systematic errors are included in the comparison.

4. Nucleon structure is independent of the nature of the intermediate vector boson probe. In particular, the neutral current sees the same valence and sea quark distribution as the charged current.

5. Both shadowing and anti-shadowing are now established features of the EMC effect.

6. Most models can still not explain the behavior of the ratio of $F_2(x,Q^2)$ over the entire x range.

7. Does the ratio $R(F_2^A / F_2^D)$ itself exhibit a Q^2 dependence?

8. There is still an extreme need for an accurate measurement of the longitudinal structure function.

9. The iron data do **not** agree with QCD; however, beware of Q^2 cut.

10. Carbon data non-singlet analysis agrees with QCD.

11. The hydrogen data from both EMC and BCDMS agrees with QCD

12. The world average of $\Lambda_{\overline{MS}}$ is (215 ± 15 ± 50) MeV

±stat. ± syst.

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