SLAC-PUB-2907
April 1982
(T/E)

POSSIBLE EVIDENCE FOR SUBSTANTIAL NON-PERTURBATIVE QUANTUM-CHROMODYNAMIC EFFECTS*

R. Michael Barnett
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94305

ABSTRACT

A search for non-perturbative effects in the structure functions of deep-inelastic scattering reveals substantial effects which could be due to important physical phenomena or to systematic errors in the experiments. In either case the measurements of α_s and Λ are seriously jeopardized. $F_2(\mu N)$, $F_2(\nu N)$ and $xF_3(\nu N)$ are examined.

(Submitted to Physical Review Letters)

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*Work supported by the Department of Energy under contract DE-AC03-76SF00515.

It is clear that Quantum Chromodynamics (QCD) calculated as a perturbative expansion in the strong coupling constant, α_s, is in approximate agreement with a variety of data.[1] However, for some time now, consideration has also been given to the possibility that there may be measurable non-perturbative corrections (higher-twist terms) which fall as inverse powers of Q^2 or W^2 (the hadronic-mass squared).[2] These terms may reflect diquark scattering, $k_\perp$ effects, etc. More recently it has been suggested by Gupta and Quinn[3] that there may be other non-perturbative corrections which do not vanish as powers of Q^2. If such terms were large, they would create problems for results based on perturbative calculations, and could invalidate (or modify) measurements of the strong coupling constant.

In either case it is worthwhile to examine data to search for evidence of deviation from perturbative predictions. In particular in deep-inelastic scattering one might consider whether there is an extraneous W^2 dependence evident in the data. This might be reflected by a W^2 dependence in the value of the strong coupling parameter Λ ($\alpha_s \approx 12\pi/(25 \log Q^2/\Lambda^2)$). To check this I have examined three data sets using different cuts on W^2. These data are for the structure functions F_2 from the European Muon Collaboration (EMC)[4] and the CERN-Dortmund-Heidelberg-Saclay collaboration (CDHS)[5] and for xF_3 from CDHS.[5] I have used the QCD evolution equations to fit all data simultaneously. Where I have shown second-order results, the $\overline{MS}$ scheme was used. In all cases I have considered only data with $W^2 > 10$ GeV^2 in order to eliminate any "trivial" mass dependences. Some data sets lack the statistical power to allow examination of distinct W^2 bins. So I begin by showing in Fig. 1 the data[6] for the strong coupling parameter Λ for two different W^2 cuts: $W^2 > 10$ GeV^2 and $W^2 > 20$ GeV^2. One sees a clear trend toward lower Λ

at higher W^2, which is independent of the minimum Q^2 cut. This is, of course, contrary to the predictions of perturbative QCD. As a check to be sure that this trend does not reflect a simple inadequacy of leading-order calculations, I have, for xF_3, shown that the results are not substantially affected by going to second-order or by use of V^2-evolution.[7]

For the F_2 data sets it is possible to divide the data into two W^2 bins as shown in Fig. 2. Now the conflict of the data with perturbative QCD appears more clearly (although one still doesn't know if the problem is in the theory or in the data). I have shown the results with different x-cuts (the results are similar with no x-cuts). The x-cuts are necessary because we expect perturbative QCD to fail at low x, and the gluon distribution is particularly poorly determined at small x. The shape of the gluon distribution has a major impact on Λ determinations[8] (especially at small x), and I have required that the gluon distribution be identical for the fits in the two W^2 bins. If one divides the data into two x-bins ($0.1 < x < 0.4$ and $0.4 < x < 0.7$) instead of W^2 bins, one obtains similar results which is not completely surprising since W^2 and x are not independent ($W^2 \equiv Q^2(1-x)/x + m^2$). In x-bins the results are more sensitive to the choice of gluon distribution.

One might ask if these results could be due to intrinsic charm[9] or other hadronic thresholds. The answer is no. Such thresholds would enhance the W^2 dependence. As a test I incorporated intrinsic charm and found that it has a relatively small effect increasing the discrepancy. Clearly leptonic thresholds are an unlikely source of this problem. Use of the ξ-scaling variable[10] and inclusion of Q^2 dependence in the β function have little impact also.

If these data indicate the presence of non-perturbative effects, one should consider whether such effects can be described by conventional higher-twist terms. Since one doesn't know how such terms evolve, the standard procedure is to multiply the evolved F_2 by

$$\left[1 + \left(\frac{W_o}{W}\right)^P\right] \tag{1}$$

and then fit the data. The results for the EMC and CDHS data are quite similar, and I will concentrate on the higher statistics EMC data. If one chooses $P = 2$, one finds no improvement in the fit to the data, the Λ values of large and small W^2 remain unequal and the preferred value of W_o is equal to 0.2 GeV consistent though with zero. Similar results can be found for $P = 4$ and 8.

I made a limited search for a modified higher-twist term which would give better results. The form (analogous to Eq. (1)):

$$\left[1 - (1 - 2.5x)\left(\frac{9}{W^2}\right)^4\right] \tag{2}$$

leads to a remarkable improvement of 18 in χ^2 (117 degrees of freedom) in the EMC data. The value of $W_o = 3.0$ GeV is much larger than the value found for higher-twist terms with the standard parameterizations. This form (Eq. (2)) brings the Λ values in the two W^2 bins close to equality. The fit with and without the term of Eq. (2) differ by as much as 14% at larger x and by as much as 8% at smaller x but in the opposite direction. Whether systematic errors of this form and magnitude could exist in the data is not evident from the published papers.

Such a substantial improvement in the fit ($\Delta\chi^2 = 18$) can be interpreted as clear evidence for the presence of non-perturbative effects. However, the large magnitude of the non-perturbative term indicates that the naive form and approximations used here are inadequate to handle this problem. One must, for example, consider other higher-twist terms and consider their proper evolution.

An alternative method to look at this problem is to see if the α_s is larger than expected. A naive approach to this might be to look for power-law corrections to α_s such as:

$$\alpha_s \approx \frac{Q_o^2}{Q^2}\left(\frac{x}{0.4} - 1\right)\theta(x - 0.4) + \frac{12\pi}{25 \ \ln Q^2/\Lambda^2} \quad . \tag{3}$$

One can try making the approximation that the evolution equations such as:

$$Q^2 \frac{\partial}{\partial Q^2} xF_3\left(x,Q^2\right) = \frac{\alpha_s}{2\pi} \int_x^1 dz \ \frac{x}{z^2} \left[zF_3\left(z,Q^2\right) P_{qq}\left(\frac{x}{z}\right)\right] \tag{4}$$

are unaffected except for the correction to α_s. Here one finds a clear improvement in χ^2 ($\Delta\chi^2 \approx 16$ for EMC data) with $Q_o^2 = 10$ GeV^2, completely inconsistent with $Q_o^2 = 0$. Furthermore the Λ values in the two W^2 bins are approximately equal.

For $Q^2 = 12$ GeV^2 and $x = 0.55$, Eq. (3) corresponds to $\alpha_s \approx 0.5$. This is an alternative indication of large non-perturbative effects and may also indicate that α_s is large although Λ is small.

In summary, three different data sets appear to be in conflict with the predictions of simple perturbative QCD. In particular, perturbative QCD predicts that Λ should not be significantly dependent on W^2. It is an experimental question whether all three data sets could have a systematic error which accounts for these results. A substantial higher-twist term of a naive form can give a great improvement in the fit to the data. However, one should consider the direct impact of nonperturbative corrections on the evolution equations.

Whether the source of this conflict lies with the theory or the data, the value of Λ is quite sensitive to this problem. Λ may be smaller than present analyses indicate, but α_s may be significantly larger. And what about determinations of Λ from other processes? These too may be subject to important nonperturbative effects. I would suggest that one should, at minimum, have a mechanism (as here for the structure functions) for checking the consistency of perturbative calculations. Processes which rely on measurement of one or two numbers (such as in upsilonium decay) might be especially suspect, since we cannot use data to check for nonperturbative effects.

Much of the evidence for QCD comes from comparison of perturbative calculations with data. If these calculations are called into question, one must reconsider the evidence for QCD. I feel that further study of nonperturbative effects is necessary. And it is imperative that experimentalists make every effort to understand systematic errors in these data.

I would like to acknowledge valuable discussions with S. Gupta, H. Quinn, D. Schlatter, L. Trentadue and other colleagues at SLAC. This work was supported by the Department of Energy under contract DE-AC03-76SF00515.

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6. In each data set I tested to see if individual data points with very bad χ^2 were responsible for aspects of the results reported here. Such points never seems to be important. Other aspects of my treatment of these data are described in Ref. 8.

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FIGURE CAPTIONS

Fig. 1. The values of Λ extracted from the CDHS data[5] for F_2 and xF_3 and the EMC data[4] for F_2. A variety of different cuts were used on the data. For F_2 the leading-order evolution equations were used. For xF_3 three cases were compared: leading order, next-to-leading-order and evolution with the V^2 variable of Ref. 7.

Fig. 2. The values of Λ extracted from the EMC data[4] and the CDHS data[5] for F_2. The data are divided into two distinct W^2 bins. Low x data are excluded by various x cuts. The gluon distribution is determined by fitting data to all W^2 (above 10 GeV^2), and then is fixed for the Λ extractions in W^2 bins. The leading-order evolution equations were used. For EMC $Q^2 > 4\ GeV^2$ and for CDHS $Q^2 > 2\ GeV^2$ were used.

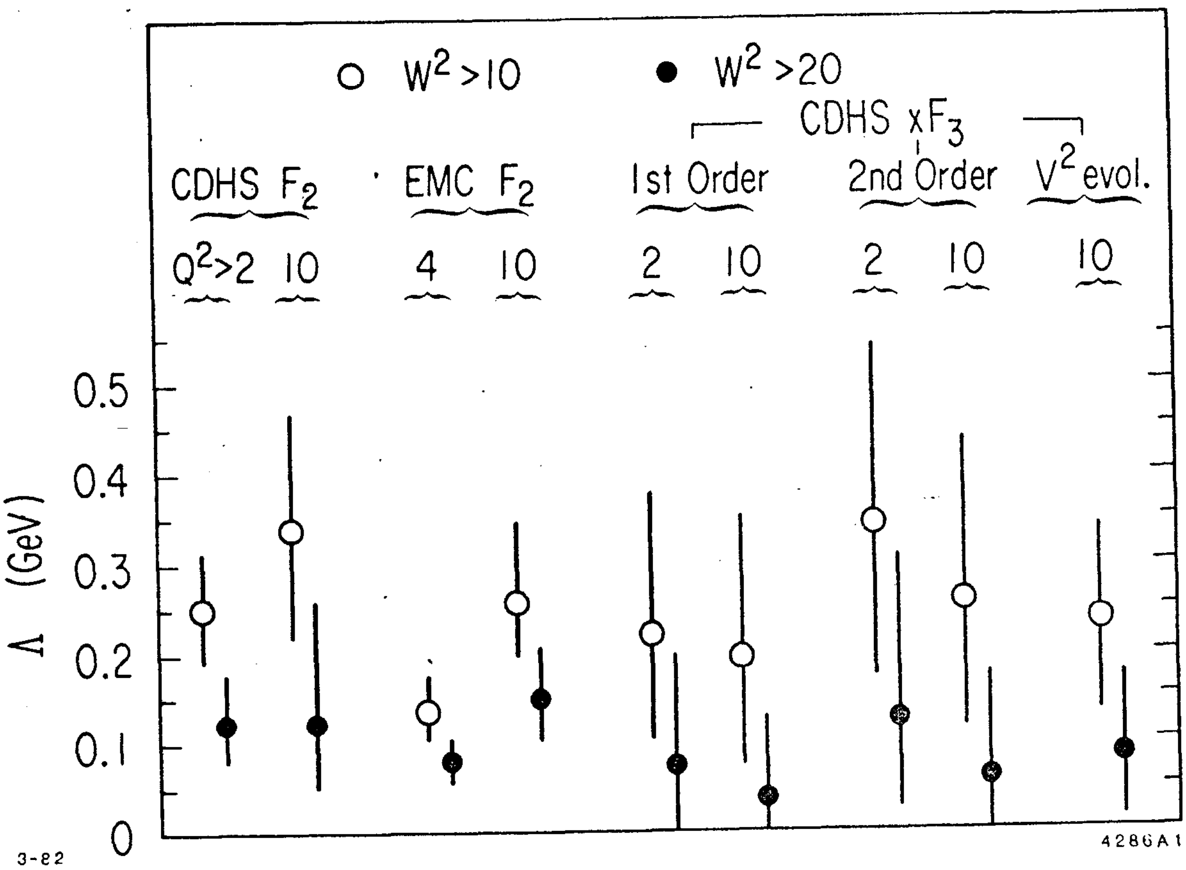
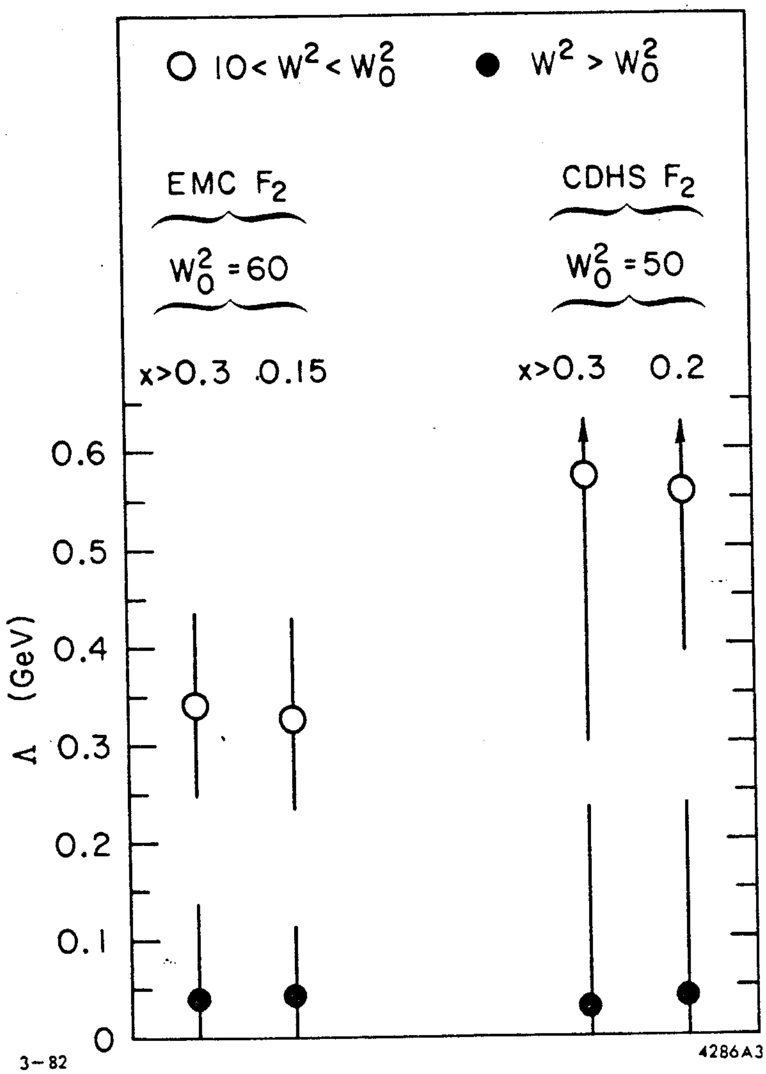

○ $W^2 > 10$
● $W^2 > 20$
CDHS xF_3
CDHS F_2
EMC F_2
1st Order
2nd Order
V^2 evol.
$Q^2 > 2$
10
4
10
2
10
2
10
10
0.5
0.4
0.3
0.2
0.1
0
Λ (GeV)
3-82
4286A1

Fig. 1



○ 10 < W² < W₀²
● W² > W₀²
EMC F₂
W₀² = 60
x>0.3
0.15
CDHS F₂
W₀² = 50
x>0.3
0.2
Λ (GeV)
0.6
0.5
0.4
0.3
0.2
0.1
0
3-82
4286A3

Fig. 2