A Systematic Study of Power Corrections from World Deep Inelastic Scattering Measurements.

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Abstract

By performing an analysis in moment space using high statistics DIS world data, we extract the values of both the QCD parameter $\Lambda_{\overline{MS}}^{(4)}$ up to NLO and of the power corrections to the proton structure function, $F_2$. At variance with previous analyses, the use of moments allows us to extend the kinematical range to larger values of $x$, where we find that power corrections are quantitatively more important. Our results are consistent with the $n$ dependence predicted by IR renormalon calculations. We discuss preliminary results on nuclear targets with the intent of illustrating a possible strategy to disentangle power corrections ascribed to IR renormalons from the ones generated dynamically e.g. from rescattering in the final state. The latter appear to be modified in nuclear targets.

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Abstract: By performing an analysis in moment space using high statistics DIS world data, we extract the values of both the QCD parameter $\Lambda_{\text{MS}}^{(4)}$ up to NLO and of the power corrections to the proton structure function, $F_2$. At variance with previous analyses, the use of moments allows us to extend the kinematical range to larger values of $x$, where we find that power corrections are quantitatively more important. Our results are consistent with the $n$ dependence predicted by IR renormalon calculations. We discuss preliminary results on nuclear targets with the intent of illustrating a possible strategy to disentangle power corrections ascribed to IR renormalons from the ones generated dynamically, e.g., from rescattering in the final state. The latter appear to be modified in nuclear targets.

1. QCD FITS TO MOMENTS OF $F_2$

The $Q^2$ dependence of the structure functions in Deep Inelastic Scattering (DIS) as well as in other related processes (e.g., Drell-Yan) can be described accurately within perturbative QCD (pQCD) up to NLO provided one confines calculations to the kinematical region of $Q^2 \geq 10 \text{ GeV}^2$ and Bjorken $x$: $0.1 \leq x \leq 0.7$ (corresponding to high values of the invariant mass squared: $W^2 \gg 4 \text{ GeV}^2$). At the border of this kinematical region the agreement between pQCD calculations and experiment is no longer accurate nor unambiguous because of the increasing importance of non-perturbative (np) physics. At large $x$ the agreement with the data is known to improve by including power corrections (see e.g., [4]). Aside from parton model based phenomenological interpretations, the presence of power corrections still constitutes a rather elusive problem for theory. Canonical methods such as the hard scattering factorization (HSF) or OPE (for a review see [4] and references therein), are hampered by the large and hard-to-classify number of operators. Comparison with data does not allow yet to distinguish among different higher twist contributions (see e.g., [4]). More recently the idea has been developed that a one to one correspondence can be defined between the dynamically generated higher twist terms and the ambiguities in the resummation of the asymptotic pQCD series, or renormalons ([5] and references therein). As for np methods, there seems to be indications from lattice studies that power corrections do surface though not seemingly directly related to renormalons ([6]).

A preliminary step in order to test recent developments is to explore whether, given the accuracy and kinematical coverage of present data, power corrections can be separated unambiguously and their actual size determined, from NLO and higher order terms, and from a number of other non-QCD contributions. With the aim of achieving a clear-cut answer, we started our analysis from the most well known structure function, $F_2$.

We constructed moments,

$$M_n(Q^2) = \int_0^1 dx F_2(x, Q^2)x^{n-2},$$

from the NMC, BCDMS and SLAC data sets. Differently from previous analyses, we set no lower limit on the final state invariant mass, thus extending the kinematical domain in $x$ up to $x \approx 1$ and $Q^2 \geq 2 \text{ GeV}^2$. Moments are more directly connected to OPE, they can be calculated...
in principle using non-perturbative methods and, on the practical side, they are the only way to include data at large $x$ without getting into the complications of the resonance structure.

We performed a fit of the following expression

$$M_n(Q^2) = M_n^{pQCD} + \sum_{k=1}^{n} M_n^{(2k+2)}(Q^2) \frac{1}{Q^{2k}}, \quad (2)$$

where the $Q^2$ dependence of $M_n^{pQCD} = M_n(\mu^2)C_n(Q^2, \mu^2)$, $\mu^2$ being a given scale, was considered up to NLO. Furthermore, since we are interested in the large $x$ behavior, we restricted the analysis to the Non Singlet (NS) contribution therefore avoiding ambiguities associated with the gluon distribution. The subtraction of the Singlet contribution introduces some error. However, based on current parametrizations we estimated it to be $7 - 12\%$ of the total moment for $n = 3$ and $Q^2 = 2 - 50 \text{GeV}^2$ and to be less then $1\%$ for $n = 8$. Further sources of systematic error arise from the extrapolation to regions where no data are available which constitute 11.3% and 23.5% of the whole kinematic domain contributing to $M_n$ at $n = 3$ and $n = 8$, respectively, and from Target Mass Corrections (TMC) which display an inverse power-like behavior and increase with $n$ [4]. In order to be able to compare with previous extractions we will show here results obtained in the “factorized” approximation, i.e.

$$M_n(Q^2) = M_n^{pQCD} \left(1 + a_n^{(1)} \frac{\tau^2}{Q^2} + a_n^{(2)} \frac{\gamma^4}{Q^4}\right), \quad (3)$$

corresponding to $M_n^{(i)} = a_n^{(i)}\tau^2$ etc., where the $n$ dependence of the power corrections is included in the functions $a_n^{(i)}$, $i = 1, 2$; $\tau^2$ and $\gamma^4$ are the parameters to be determined by the fit, besides the pQCD ones; no $Q^2$ dependence is assumed for $M_n^{(4)}$. Power corrections of order higher than $O(1/Q^3)$ are found to be negligible for $Q^2 \geq 2 \text{GeV}^2$. In order to compare with similar recent extractions [4], we set in Eqs. (2) and (3): $\gamma^4 = 0$, and $\tau^2 = M_n^{(4)}(Q^2)/nM_n^{pQCD}(Q^2)$. Our results can be also anti-Mellin transformed to reconstruct $F_2(x, Q^2)$, by using the properties of the Mellin transforms. Since the $n$ dependence found in different models is rather simple, no polynomial technique was found to be necessary at this level.

| Collaboration          | Range in $Q^2 \text{ GeV}^2$ | $\Lambda^{(4)}_{\overline{MS}} \text{ MeV}$ | $\tau^2 \text{ GeV}^2$ |
|-----------------------|-------------------------------|-----------------------------------------------|------------------------|
| Before 1980 [1]       | 1.9 − 85                      | 300 $\leftrightarrow$ 1000                   | −0.1 $\leftrightarrow$ 0.25 |
| NMC [1]               | 0.5 − 260                     | 250                                           | 0.18 ± 0.12            |
| NMC+BCDMS+SLAC [2]    | 0.5 − 260                     | 263 ± 42 ± 55                                 | 0.09 ± 0.04            |
| CCFR [11]             | 5 − 199.5                     | 371 ± 31                                      | 0.24 ± 0.1             |
| BEBC-WA59 [12]        | $Q^2 < 64$                    | 110$^{+50}_{-45}$                             | −0.16 ± 0.05           |
| This paper $\gamma^4 = 0$ | 5 − 260                      | 241 ± 36                                      | 0.21 ± 0.09            |
| This paper $\gamma^4 \neq 0$ | 2 − 260                      | 250                                           | 0.25 ± 0.20            |

2. DISCUSSION OF RESULTS

Our results for the parameters $\Lambda^{(4)}_{\overline{MS}}$ and $\tau^2$ are given in Table 1 and compared with the ones obtained in previous extractions. Since recent analyses used directly $F_2(x, Q^2)$, giving $x$-dependent power correction coefficients, $C_{HT}(x)$, we calculated the values of $\tau^2$ shown in the Table by performing Mellin transforms of $C_{HT}(x)$, times the corresponding pQCD structure functions parametrizations. The form $a_n^{(i)} = n$, transforming into $C_{HT}(x) \approx 1/(1 - x)$ at large $x$ was used consistently.

The first line of Table 1 was included in order to show the highly enhanced accuracy provided by the NMC, BCDMS and SLAC set of data where it is now possible to perform a more careful extraction of power corrections. An anti-correlation clearly emerges from our fits between the parameters of pQCD, e.g. $\Lambda$, and the coefficients of the power corrections. We studied this correlation;
details of our study are presented in [8]. Here it suffices to say that it originates from a region in \( Q^2 (5 \leq Q^2 \leq 20 \text{ GeV}^2) \) where neither the LO, simply logarithmic pQCD behavior, nor the pure power correction terms are dominant, whereas a mixture of higher order and \( 1/Q^2 \) terms are simultaneously present.

We dealt with this problem by extracting \( \Lambda \) using only data at \( Q^2 \geq 30 \text{ GeV}^2 \) and by including lower values of \( Q^2 \) stepwise in the fit, at the fixed value of \( \Lambda \). The value of \( \Lambda \) we found is consistent with 250 MeV i.e. the value previously found in [1,2]. The results presented in Table 1 are therefore clear-cut in predicting that, for similar values of \( \Lambda \), we find a contribution from power corrections which is about twice as large as in the previous QCD analysis. We seem however to find a contradiction with the analysis using neutrino data in that these show both a larger value of \( \Lambda \) and a slightly enhanced value of \( \tau^2 \). By including the \( O(1/Q^4) \) term and by using our approach of lowering the \( Q^2 \) threshold from above, we found out that \( \gamma^4 = 0 \) within error bars until one reaches the value of \( Q^2_{\text{min}} = 5 \text{ GeV}^2 \). Finally, \( \tau^2 \) and \( \gamma^4 \) are also anti-correlated. By including in the fit both parameters, \( \tau^2 \) and \( \gamma^4 \) with the lowest allowed threshold, \( Q^2_{\text{min}} = 2 \text{ GeV}^2 \), we are able to fit the data with negative values of \( \gamma^4 \) and \( \tau^2 \approx 0.25 \text{ GeV}^2 \), i.e. consistent with the value obtained at a higher threshold. We would like to point out however that due to the anti-correlation between the two parameters, by performing a general fit to the data regardless of \( Q^2 \) “thresholds”, large positive values of \( \gamma^4 \) and small values of \( \tau^2 \) can be also found [4]: such results are to be interpreted as a manifestation of the anti-correlation between parameters.

With a firm understanding of the different \( Q^2 \) dependent contributions at intermediate and low \( Q^2 \), one can subsequently investigate the renormalon hypothesis. We present here results of our study of the \( n \)-dependence of the coefficient of the \( 1/Q^2 \) term, \( a_n^{(1)} \tau^2 \), in Eq.(3). In Figure 1 we repeated our fits using the forms: \( a_n^{(1)} = n \), \( a_n^{(1)} = n \tau^2 \), corresponding to the dominance of two-quark and four-quark higher twist diagrams, respectively, in e.g. HSF models and we compared them to fits using the \( n \)-dependence predicted by renormalon calculations (for details see references [9] and [10] in [5]). Since in all predictions the \( n \)-dependent term is factored out from an unknown constant term, one can discriminate “models” based on the “flatness” of the \( n \) behavior extracted from the data. From Figure 1 one can see that the renormalon model gives clearly a better interpretation than the widely used assumption, \( a_n^{(1)} = n \).

3. CONCLUSIONS AND FUTURE DEVELOPMENTS

Our initial study of power corrections in DIS is meant to be an exploratory one centered around two points: we first addressed the question of whether there is at all a direct and clear evidence of power corrections in the data, and if their actual magnitude can be extracted; we then moved on to a phenomenological study of their nature, namely whether they can be associated to long distance features of pQCD (renormalon models) or if other dynamical mechanisms pertinent to DIS only, such as final state rescatterings should be taken into account. Our main conclusions on the first part are that indeed power corrections

![Figure 1](image-url). The value of \( \tau^2 \) vs. \( n \) extracted according to different models for the \( n \)-dependent coefficient \( a_n^{(1)} \) as explained in the text.
can be separated out from present data by using an approach in which different portions of the $Q^2$ domain (proceeding from high to low $Q^2$ values) are analyzed separately. The magnitude of the $O(1/Q^2)$ coefficient is $\tau^2 \approx 0.2 \text{GeV}^2$, which will need to be systematically compared with power corrections extracted from other reactions in further investigations, to test the presence of a universal scale. An important outcome of our study is also that, within the present accuracy and kinematical coverage of the data, meaningful results should be presented including the correlation between the different parameters of the fit. Our extractions seem to be consistent with renormalon calculations.

More detailed knowledge on the nature of power corrections can be sought in principle by using nuclear targets. By assuming the validity of IA, i.e. by disregarding nucleon rescattering effects, one obtains a factorization of the $A$ and $Q^2$ dependences of the moments [14]

$$M^A_n(Q^2) = M^A_n M^N_n(Q^2), \quad (4)$$

Deviations from such a factorization would correspond to a breakdown of IA and they would therefore signal the presence of rescattering effects. As shown in [14] present data on nuclear targets are not accurate enough to observe any feature in the ratio of moments and they support the IA hypothesis. More detailed studies, together with higher accuracy nuclear DIS data might be able to reveal an underlying structure [8]. At present, by adopting the factorized form, Eq. (4), we can extract the value of $\tau^2$ for a nucleon. Results are presented in Figure 2 and compared with the proton values. From the Figure we can see that the proton and nucleon results are consistent with one another, i.e. no difference is seen in the neutron contribution.

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