Next-to-next-to-leading order QCD analysis of DIS structure functions

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Abstract

It is performed for the first time a next-to-next-to-leading order analysis of deep inelastic structure functions \( F_2 \) and \( F_L \) using the recently determined first moments of the non-singlet anomalous dimensions and the corresponding Wilson coefficients. From a comparison to BCDMS data we found a slight decrease in the energy scale of perturbative QCD with respect to the next-to-leading order analysis, which brings the scale closer to the value predicted from a scheme invariant approach.
The determination of the QCD coupling constant $\alpha_s$ at some energy is one of the present problems of both experimental and theoretical high energy physics. Deep inelastic lepton-nucleon scattering (DIS) has been one of the most important processes for qualitative tests of perturbative QCD and in particular for the determination of the energy scale $\Lambda$ involved in $\alpha_s$. In the last few years quite exact experimental data for DIS structure functions has been obtained (see [1], for review) over a wide range of the Bjorken variable $x$. Theoretical knowledge had been restricted to next-to-leading order (NLO) approximation (see [2] and its references) except sum rules [3] and the lower (Mellin) moment of the longitudinal structure function $F_L$ [4] which have been known with next-to-next-to-leading (NNLO) accuracy.

The purpose of this letter is to present a NNLO analysis of structure functions. The two new ingredients needed in the calculation, i.e. the anomalous dimensions at three loops and the Wilson coefficients of the quark and gluon operators at two and three loops for the transverse and longitudinal parts, respectively, were recently calculated by Larin, van Ritbergen and Vermaseren: The first ten $O(\alpha_s^2)$ moments of the $F_2$ coefficients [5], and the $n = 2, 4, 6$ and $8$ moments for the non-singlet (NS) anomalous dimension at NNLO, and also the $F_L$ coefficients at $O(\alpha_s^3)$ [7].

Some attempts have also been made in order to include the effect of higher order corrections in structure functions using the information of the NLO and the invariance on the renormalization scheme of the physical results. Here we extend one of these scheme invariant approaches with the inclusion of NNLO terms.

At three loops the Mellin moments of structure functions at two different scales $Q^2$ and $Q_0^2$ are related by

$$M_{2,n}(Q^2) = \sum_j M_{2,n}(Q_0^2) \left[ \frac{\alpha}{\alpha_0} \right]^{d_j} \left[ 1 + (\alpha - \alpha_0) \left( Q_n^{(1)j} + B_{2,n}^{(1)j} \right) \right.\right.$$

$$+ \left. (\alpha^2 - \alpha_0^2) \left( \bar{Q}_n^{(2)j} + B_{2,n}^{(2)j} + Q_n^{(1)j} B_{2,n}^{(1)j} \right) + (\alpha_0 - \alpha)\alpha_0 \left( Q_n^{(1)j} + B_{2,n}^{(1)j} \right)^2 \right]$$

The corresponding kernels into Mellin convolutions with parton distributions were calculated by van Neerven and Zijlstra [6]. Through this work we use the short notation $\alpha = \alpha_s(Q^2)/4\pi$ and $\alpha_0 = \alpha_s(Q_0^2)/4\pi$, and the standard definition for moments $M_{i,n} = \int_0^1 dx x^{n-2} F_i(x)$. For more details on the notation see ref. [2] and references therein.

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\[ M_{L,n}(Q^2) = \sum_j M^j_{L,n}(Q_0^2) \left[ \frac{\alpha}{\alpha_0} \right] d^n_{j+1} \left[ 1 + (\alpha - \alpha_0) \left( Q^{(1)j}_{L,n} + R^{(2)j}_{L,n} \right) \right. \]
\[ \left. + (\alpha^2 - \alpha_0^2) \left( \tilde{Q}^{(2)j}_{L,n} + Q^{(1)j}_{n} R^{(2)j}_{L,n} \right) + (\alpha_0 - \alpha) \alpha_0 (Q^{(1)j}_{n} + R^{(2)j}_{L,n})^2 \right], \]

where \( j \) extends to singlet and non-singlet contributions.

The functions \( d^n_{j}, Q^{(1)j}_{n}, \) and \( \tilde{Q}^{(2)j}_{n} \) are related to the one-loop, two-loop [9] and three-loop [7] anomalous dimensions \((\gamma^{(i)})\), \( i = 0, 1, 2 \). In the non-singlet case one has

\[
\begin{align*}
    d^n_{NS} &= \frac{\gamma^{(0)n}_{NS}}{2\beta_0}, \\
    Q^{(1)NS}_{n} &= \frac{\gamma^{(1)n}_{NS}}{2\beta_0} - \frac{\gamma^{(0)n}_{NS} \beta_1}{2\beta_0^2}, \\
    \tilde{Q}^{(2)NS}_{n} &= \frac{Q^{(2)NS}_{n} + (Q^{(1)NS}_{n})^2}{2}, \\
    Q^{(2)NS}_{n} &= \frac{\gamma^{(2)n}_{NS}}{2\beta_0} - \frac{\beta_1}{\beta_0} Q^{(1)NS}_{n} - \frac{\beta_2 \gamma^{(0)n}_{NS}}{2\beta_0^2}.
\end{align*}
\]

The quantities \( B^{(1)j}_{k,n} \) and \( B^{(2)j}_{L,n} \) are the NLO (NNLO) Wilson coefficients of \( F_2 \) and \( F_L \) respectively. References for the two-loop coefficients can be found for example in [3], while the new three-loop results are in [7]. In eq. (2) \( R^{(i)NS}_{L,n} = B^{(i)NS}_{L,n} / B^{(1)NS}_{L,n} \) for \( i = 2, 3 \). \( \beta_i \) are the coefficients of the renormalization group beta function. For the scheme dependent \( \beta_2 \) we use the \( \overline{MS} \) expression given in ref. [8].

In eq. (3) the moments \( M_2(Q_0^2) \) and \( M_L(Q_0^2) \) are related at NLO by

\[
M^j_{L,n}(Q_0^2) = M^j_{2,n}(Q_0^2) \alpha_0 B^{(1)j}_{L,n} \left[ 1 + \alpha_0 [R^{(2)j}_{L,n} - B^{(1)j}_{2,n}] \right. \]
\[ \left. + \alpha_0^2 [R^{(3)j}_{L,n} - B^{(2)j}_{2,n} - B^{(1)j}_{2,n} (R^{(2)j}_{L,n} - B^{(1)j}_{2,n})] \right], \]

and the three-loop coupling constant is obtained by solving the transcendental equation

\[
\beta_0 \ln \frac{Q^2}{\Lambda^2} = \frac{1}{\alpha} + \frac{\beta_1}{\beta_0} \ln(\beta_0 \alpha) + \left( \frac{\beta_2}{\beta_0} - \frac{\beta_2^2}{\beta_0^2} \right) \alpha, \]

The only piece unknown in the perturbative calculation is the moment of \( F_2 \) at some energy scale \( Q_0 \). In the non-singlet case it is parametrized by

\[
M_{2,n}(Q_0^2) = \int_0^1 dx x^{n-2} \left[ A x^\alpha (1 - x)^\beta (1 + \gamma x) \right],
\]
where \( A, \alpha, \beta \) and \( \gamma \), in addition to the energy scale \( \Lambda \), have to be obtained from fits to experimental data.

The expressions for the moments \( M_{2,n}(Q^2) \) and \( M_{L,n}(Q^2) \) in the scheme-invariant (SI) approach can be found in [4], where the equations for the SI coupling constants \( a_{k,n}^{(i)} \), for \( i=1 \) (NLO), were also given. At three loops they obey the following equations:

\[
\beta_0 \ln \frac{Q^2}{\Lambda^2_{MS}} - r_{k,n}^{(1)} = \frac{1}{a_{k,n}^{(1)}} + \frac{\beta_1}{\beta_0} \ln(\beta_0 a_{k,n}^{(2)}) + \left( \frac{\tilde{\beta}_2}{\beta_0} - \frac{\beta^2_1}{\beta^2_0} \right) a_{k,n}^{(2)}, \tag{6}
\]

where

\[
\tilde{\beta}_2 = \beta_2 - r_{k,n}^{(1)} \beta_1 + \beta_0 (r_{k,n}^{(2)} \beta_0 - (r_{k,n}^{(1)})^2), \tag{7}
\]

and

\[
\begin{align*}
\beta_0 \ln \frac{Q^2}{\Lambda^2_{MS}} - r_{2,n}^{(1)} &= \frac{Q_n^{(1)} + B_{2,n}}{d_j^n}, \\
\beta_0 \ln \frac{Q^2}{\Lambda^2_{MS}} - r_{L,n}^{(1)} &= \frac{Q_n^{(1)} + R_{2,n}}{d_j^n + 1}, \\
\beta_0 \ln \frac{Q^2}{\Lambda^2_{MS}} - r_{2,n}^{(2)} &= \frac{Q_n^{(1)} + B_{2,n} + Q_n^{(1)} B_{2,n}}{d_j^n} - \frac{d_j^n - 1}{2} (r_{2,n}^{(1)})^2, \\
\beta_0 \ln \frac{Q^2}{\Lambda^2_{MS}} - r_{L,n}^{(2)} &= \frac{Q_n^{(1)} + R_{2,n} + Q_n^{(1)} R_{2,n}}{d_j^n + 1} - \frac{d_j^n}{2} (r_{L,n}^{(1)})^2.
\end{align*}
\]  

In the two-loop approximation the couplings \( a_{k,n}^{(1)} \) obey similar equations to eq. (6) but without the term linear in \( a_{k,n}^{(1)} \).

With the statistic of present experiments it has been shown that structure functions \( (F) \) can be reliably reconstructed from their moments with the help of orthogonal Jacobi polynomials \( \Theta_{k}^{\alpha\beta}(x) \) (see [13] and references therein)

\[
F(x, Q^2) \sim x^\alpha (1-x)^\beta \sum_{k=0}^{N_{max}} a_k(Q^2) \Theta_{k}^{\alpha\beta}(x), \tag{9}
\]
where the coefficients $a_k$ are connected to the moments of $F$ through

$$a_k(Q^2) = \sum_{j=0}^{k} C_j^{(k)}(\alpha, \beta) M_{j+2}(Q^2).$$ 

(10)

This method has been used as a simple and fast alternative (in computer consuming time) to solve the evolution equations, but here it is specially useful because only the moments are known instead of the explicit analytical result in $x$.

Notice that for the non-singlet anomalous dimensions and $F_L$ Wilson coefficients only the first four even moments have been calculated (see above) while the polynomial reconstruction requires also the odd ones and at least 8 in total in order to get an accurate result [14]. We solve this problem by obtaining the values for $n = 3, 5$ and 7 from smooth interpolation (see fig. 1). This interpolation is based on theoretical investigations (see [15, 16]) where it was showed that the $n$-dependent functions in the Wilson coefficients and anomalous dimensions can be transformed to polygamma-functions (and some others associated to it) which are continuous in its arguments. Thus, the analytical extension from even values of the argument to odd ones (see [15]) and moreover to non integer ones (see [16]) can be done without any problem.

The three-loops anomalous dimension can also be extrapolated to $n > 8$ if one assumes that the behavior observed for the first eight moments, which is similar to the two-loop anomalous dimension (see fig. 2), remains at higher $n$. In that case one can use the relation

$$\gamma_{NS}^{(2)m} = \gamma_{NS}^{(1)n} \gamma_{NS}^{(2)2} \gamma_{NS}^{(1)2}$$

(11)

to extend the calculation to higher $n$ (dashed line in fig. 1).

There is not, however, an analogous relation to extrapolate the Wilson coefficients, of which we only know the values at $n=2,...,10$ for $F_2$ and $n = 2, ..., 8$ for $F_L$. Thus the sum in eq. (9) was restricted to $N_{max}=6$, i.e. moments from $n=2$ to $n=8$.

The inclusion of target mass (TM) corrections is not possible at NNLO, because one would need to know the moments for $n > 8$ (see eq. (23) from [2]). Also, we did not consider TM effects in the rest of the analysis in order to make a meaningful comparison between the results.
We have performed a series of non-singlet fits to $F_2$ BCDMS deuterium [1] and proton [2] data, and also to SLAC reanalyzed $R = F_L/2xF_1$ data from deuterium [10]. Structure functions were calculated at LO, NLO, NNLO and in both scheme invariant, NLO (SI-N) and NNLO (SI-NN), approaches for comparison [4]. Throughout this work we have considered $n_f = 4$ in the theoretical expressions, and the reference point in eq. (5) was fixed to $Q_0^2 = 50 \text{ GeV}^2$.

In the analysis of $R$ we have fitted simultaneously $F_2$ in order to fix as much as possible the scale $\Lambda$ with the help of the more precise BCDMS data.

The analysis has been restricted to data with $Q^2 > 5 \text{ GeV}^2$ to avoid the kinematic region where higher twist effects could affect $F_2$ because they are not under theoretical control. In $R$ this cut excludes the region affected by corrections of order $1/Q^4$ or higher. Also we analyze the region $x > 0.35$ where the influence of gluons can be neglected and the non-singlet evolution is justified. In addition, it has been used $F_2$ data with $y > 0.16$, being $y$ the fraction of energy in the laboratory system transferred to the nucleus, in order to exclude a region of large systematic errors. In practice it produces a different $Q^2$ cut for each $x$ bin which excludes even more the region (high $x$ and low $Q^2$) where power corrections could affect.

Table 1 summarizes the results obtained. In the fits to only $F_2$ we find that there is a small difference between $\chi^2$ obtained from different theoretical predictions, which shows that data does not discriminate between them. However, in the analysis of the more precise proton data, the LO fit gives the worst agreement.

There are also differences in the central value of $\Lambda$ of the fits. The scale obtained in the SI-N analysis, even though within the errors, is significantly smaller than the NLO result (12 % for deuterium and 9 % for proton). This decreasing was already observed in earlier similar analyses (see for example ref. [2] and references therein) and interpreted as the result of the influence of higher order corrections which are better taken into account by the scheme invariant treatment [4]. Now, one can test this supposition by comparing the

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3 The results at LO, NLO and SI-N for deuterium here are different from those in a similar analysis in reference [2] due to the inclusion of target mass corrections in [2]. We have also checked that the using of a higher $N_{\text{max}}$ in eq. (9), when it is possible, does not affect significantly the results.  

4 We do not clarify the concrete SI procedure here. This may be Stevenson’s PMS [22], Grunberg’s EC method [23] and other procedures (see for example [4, 24] and its
results from the analysis NNLO and SI-N. One can see in table 1 that the value of $\Lambda$ at NNLO is lower than at NLO even though the decreasing is not so pronounced as it is in the SI-N case. We think however that it shows the trend predicted by SI-N. This behavior has also been observed in another independent analysis [20].

We have also fitted $F_2$ in the SI-NN case. In this case equations (4) above and also eq. (16) and (17) in [2] have been used in the calculation. The results presented in table 1 show that there is no appreciable variation in $\Lambda$ with respect to the standard NNLO approximation.

For the combined fits to $F_2$ and $R$ (without twist corrections) the situation is unfortunately more complicated. Some of the predictions are fitting better $R$ than $F_2$, giving higher $\Lambda$ values that can not be compared. Notice for example the poor partial fit to $F_2$ in the SI-N analysis. However, if target mass corrections are included in $R$, one gets a very good fit to $F_2$ (see for example [2]). It shows that these corrections, which are very large in $R$ [2, 21], are essential for a meaningful combined analysis.

Comparing the results obtained from the NLO and NNLO analyses, one can also notice, as in the fits to only $F_2$, a small decreasing in $\Lambda$ in the NNLO case.

In the SI-NN fits we were not able to converge to a reasonable value of $\chi^2$. This could be due to large $\alpha^3$ corrections in $F_L$, or again an effect due to the absence of TM corrections. Also it is possible that the use of $N_{max} = 6$ to reconstruct $F_L$ from the moments is not sufficient in this case. This point will be clarify when $\alpha^3$ correction to $F_L$ are known at larger values of $n$.

Finally, trying to improve the agreement with $R$ data we have included twist-4 corrections in the calculation of $F_L$. That contribution has been simply parametrized by [17]

$$M_{L,n}^{\text{twist-4}}(Q^2) = 8\frac{\kappa^2}{Q^2}M_{2,n}(Q^2),$$

where the energy scale $\kappa$ is the only unknown parameter which has to be determined from data.

In all cases we found a significant improvement of the agreement with $R$ data. The scale $\kappa$ is higher than in previous analysis [2] because in the present work it contains part of the effect due to target mass corrections, references), which seems to lead to similar conclusions (see [18, 19]).

6
The value of \( \Lambda \) from the NNLO analysis is lower than the NLO result, as in the others cases analyzed above, and equal to the SI-NN result. For the scale \( \kappa \), this behavior is obtained only in the proton case.

In conclusion, it has been performed for the first time a NNLO analysis of \( F_2 \) and \( R \) data. We found a slight decrease of \( \Lambda \) when the NNLO expression for the moments is used, which brings the result closer to scheme invariant predictions. This behavior is also in agreement with similar analyses of \( R \)-ratio in \( e^+e^- \) annihilation, the \( \tau \)-lepton decay rate (see [18]) and the Gross-Llewellyn Smith sum rule in [19].

Acknowledgements

One of the authors (G.P.) acknowledges the financial support from the ‘Comision Interministerial de Ciencia y Tecnología’, Spain. Another of the author (A.V.K.) is grateful to A.L.Kataev, S.A.Larin and T. van Ritbergen for useful discussions. The authors are also grateful to S.A.Larin for the information about the preprint [7].

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Figure captions

1. Three-loop coefficient of the non-singlet anomalous dimension in the $\overline{MS}$ renormalization scheme.

2. One, two and three-loop coefficients of the non-singlet anomalous dimension in the $\overline{MS}$ renormalization scheme normalized to the value of the first moment $n = 2$.

Table captions

1. Results of non-singlet fits to $F_2$ proton $^{11}$ and deuterium $^{12}$ data from BCDMS, and to $R$ data from SLAC $^{10}$. Errors given are statistical.
| Deuterium | $\Lambda_{\overline{MS}}$ (MeV) | $\kappa$ (MeV) | $\chi^2(F_2)/\text{dof}$ | $\chi^2(R)/\text{dof}$ |
|-----------|-------------------------------|---------------|--------------------------|--------------------------|
| $F_2$     | LO 182 ± 32                   | 63.5/65       |                          |                          |
|           | NLO 182 ± 30                  | 62.7/65       |                          |                          |
|           | SI(N) 159 ± 25                | 62.4/65       |                          |                          |
|           | NNLO 168 ± 27                 | 62.5/65       |                          |                          |
|           | SI(NN) 164 ± 26               | 62.4/65       |                          |                          |
| $F_2$ and $R$ | LO 223 ± 35                 | 65.1/65       | 91.5/43                  |                          |
|           | NLO 235 ± 34                  | 65.5/65       | 90.9/43                  |                          |
|           | SI(N) 238 ± 28                | 70.8/65       | 66.3/43                  |                          |
|           | NNLO 218 ± 27                 | 65.5/65       | 79.9/43                  |                          |
| $F_2$ and $R$ (Including twist-4) | LO 181 ± 31             | 63.5/65       | 41.4/43                  |                          |
|           | NLO 180 ± 29                  | 62.7/65       | 41.5/43                  |                          |
|           | SI(N) 157 ± 25                | 62.4/65       | 41.4/43                  |                          |
|           | NNLO 159 ± 21                 | 62.8/65       | 44.6/43                  |                          |
| Proton    |                              |               |                          |                          |
| $F_2$     | LO 171 ± 27                   | 51.2/60       |                          |                          |
|           | NLO 175 ± 26                  | 47.6/60       |                          |                          |
|           | SI(N) 159 ± 23                | 46.0/60       |                          |                          |
|           | NNLO 168 ± 25                 | 46.4/60       |                          |                          |
|           | SI(NN) 169 ± 25               | 45.8/60       |                          |                          |
| $F_2$ and $R$ | LO 200 ± 30               | 52.8/60       | 92.3/43                  |                          |
|           | NLO 222 ± 29                  | 50.0/60       | 82.8/43                  |                          |
|           | SI(N) 231 ± 25                | 54.5/60       | 59.2/43                  |                          |
|           | NNLO 209 ± 23                 | 48.8/60       | 79.7/43                  |                          |
| $F_2$ and $R$ (Including twist-4) | LO 168 ± 27            | 52.0/60       | 43.0/43                  |                          |
|           | NLO 175 ± 26                  | 48.2/60       | 43.5/43                  |                          |
|           | SI(N) 158 ± 23                | 46.6/60       | 42.7/43                  |                          |
|           | NNLO 158 ± 22                 | 46.5/60       | 47.8/43                  |                          |
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