Remarks on Next-to-Leading Order Analysis of Polarized Deep Inelastic Scattering Data

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Abstract

Since the $x$ dependence of the axial-anomaly effect in inclusive polarized deep inelastic scattering is fixed, the transformation from the $\overline{\text{MS}}$ scheme to different factorization schemes are not arbitrary. If the quark spin distribution is demanded to be anomaly-free so that it does not evolve with $Q^2$ and hard gluons contribute to the first moment of $g_1(x)$, then all the moments of coefficient and splitting functions are fixed by perturbative QCD for a given $\gamma_5$ prescription, contrary to the commonly used Adler-Bardeen (AB) or AB-like scheme. It is urged that, in order to correctly demonstrate the effect of factorization scheme dependence, the QCD analysis of polarized structure functions in next-to-leading order should be performed, besides the $\overline{\text{MS}}$ scheme, in the chiral-invariant factorization scheme in which the axial anomaly resides in the gluon coefficient function, instead of the less consistent and ambiguous AB scheme.
Because of the availability of the two-loop polarized splitting functions $\Delta P^{(1)}_{ij}(x)$ recently [4], it became possible to embark on a full next-to-leading order (NLO) analysis of the experimental data of polarized structure functions by taking into account the measured $x$ dependence of $Q^2$ at each $x$ bin. The NLO analyses have been performed in the $\overline{\text{MS}}$ scheme and the Adler-Bardeen (AB) scheme [2-10]. Of course, physical quantities such as the polarized structure function $g_1(x)$ are independent of choice of the factorization convention. Physically, the spin-dependent valence quark and gluon distributions should be the same in both factorization schemes. The recent analysis by the E154 Collaboration [8] has determined the first moments of parton spin densities in both schemes:

\[
\begin{align*}
(\Delta u_v)_{\overline{\text{MS}}} &= 0.69^{+0.03+0.05+0.14}_{-0.02-0.04-0.01}, \\
(\Delta d_v)_{\overline{\text{MS}}} &= -0.40^{+0.03+0.03+0.07}_{-0.04-0.03-0.00}, \\
\Delta G_{\overline{\text{MS}}} &= 1.8^{+0.6+0.4+0.1}_{-0.7-0.5-0.6}, \\
\Delta \Sigma_{\overline{\text{MS}}} &= 0.20^{+0.05+0.04+0.01}_{-0.06-0.05-0.01}, \\
(\Delta u_v)_{\text{AB}} &= 0.74^{+0.03+0.03+0.07}_{-0.02-0.03-0.01}, \\
(\Delta d_v)_{\text{AB}} &= -0.33^{+0.02+0.01+0.01}_{-0.04-0.05-0.03}, \\
\Delta G_{\text{AB}} &= 0.4^{+1.0+0.9+1.1}_{-0.7-0.6-0.1}, \\
\Delta \Sigma_{\text{AB}} &= 0.25^{+0.07+0.05+0.05}_{-0.07-0.05-0.02},
\end{align*}
\]

where errors are statistic, systematical and theoretical, and $\Delta \Sigma = \Delta u + \Delta d + \Delta s$ with

\[
\Delta q = \Delta q_v + \Delta q_s = \int_0^1 dx \Delta q(x) = \int_0^1 dx [q^\uparrow(x) + \bar{q}^\uparrow(x) - q^\downarrow(x) - \bar{q}^\downarrow(x)].
\]

We see that although the results of the fits in both $\overline{\text{MS}}$ and AB schemes are consistent within errors, the central values for $\Delta q_v$, especially for $\Delta G$, are not the same and the fits are significantly less stable in the AB scheme. This sounds somewhat annoying since if the polarized structure function is truly factorization scheme independent, then it is expected that the central values and errors of $\Delta q_v$ and $\Delta G$ in the $\overline{\text{MS}}$ and AB prescriptions should be quite similar and that $\Delta \Sigma$ obeys the relation

\[
\Delta \Sigma_{\overline{\text{MS}}} = \Delta \Sigma_{\text{AB}} - \frac{3\alpha_s}{2\pi} \Delta G_{\text{AB}}.
\]

Also, because the NLO spin-dependent splitting functions $\Delta P^{(1)}_{ij}(x)$ are originally calculated in the $\overline{\text{MS}}$ scheme, one may wonder if the polarized splitting kernels in NLO proposed in the AB scheme will render the evolution of $g_1^p(x, Q^2)$ scheme independent.

In this short Letter, we wish to emphasize that since the $x$ dependence of the axial-anomaly effect in the quark spin distribution or in the gluon coefficient function, depending on the chosen factorization scheme, is fixed, the transformation of coefficient and splitting functions from the $\overline{\text{MS}}$ scheme to the improved parton model scheme in which the spin-dependent quark distribution does not evolve with $Q^2$ and hard gluons make contributions to
the first moment of $g_1^p(x)$, is also determined. As a consequence, we urge that a NLO analysis of $g_1(x, Q^2)$ data should be performed in the so-called chiral-invariant factorization scheme to be introduced below in order to see if $g_1(x, Q^2)$, $\Delta q_v(x, Q^2)$, $\Delta G(x, Q^2)$ are really scheme independent. Although none of the material presented in this Letter is new, a clarification on this issue is fundamentally important for the QCD analysis of polarized structure functions in NLO.

Including QCD corrections to NLO, the generic expression for the polarized proton structure function has the form

$$g_1^p(x, Q^2) = \frac{1}{2} \sum e_q^2 \left[ \Delta C_q(x, \alpha_s) \otimes \Delta q(x, Q^2) + \Delta C_G(x, \alpha_s) \otimes \Delta G(x, Q^2) \right]$$

$$= \frac{1}{2} \sum e_q^2 \left[ \Delta q^{(0)}(x, Q^2) + \Delta q^{(1)}(x, Q^2) + \Delta q_s^G(x, Q^2) + \Delta C_q^{(1)}(x, \alpha_s) \otimes \Delta q^{(0)}(x, Q^2) + \Delta C_G^{(1)}(x, \alpha_s) \otimes \Delta G(x, Q^2) + \cdots \right],$$

where uses of $\Delta C_q^{(0)}(x) = \delta(1 - x)$ and $\Delta C_G^{(0)}(x) = 0$ have been made, $\otimes$ denotes the convolution

$$f(x) \otimes g(x) = \int_x^1 \frac{dy}{y} f\left(\frac{x}{y}\right) g(y),$$

and $\Delta C_q$, $\Delta C_G$ are short-distance quark and gluon coefficient functions, respectively. More specifically, $\Delta C_G^{(1)}$ arises from the hard part of the polarized photon-gluon cross section, while $\Delta C_q^{(1)}$ from the short-distance part of the photon-quark cross section. Contrary to the coefficient functions, $\Delta q_s^G(x)$ and $\Delta q^{(1)}(x)$ come from the soft part of polarized photon-gluon and photon-quark scatterings. Explicitly, they are given by

$$\Delta q^{(1)}(x, Q^2) = \Delta \phi_q^{(1)}(x) \otimes \Delta q^{(0)}(x, Q^2), \quad \Delta q_s^G(x, Q^2) = \Delta \phi_{q/G}^{(1)}(x) \otimes \Delta G(x, Q^2),$$

where $\Delta \phi_{j/i}(x)$ is the polarized distribution of parton $j$ in parton $i$. Diagrammatically, $\Delta \phi_q^{(1)}$ and $\Delta \phi_{q/G}^{(1)}$ are depicted in Fig. 1 (see e.g. [11]).

Since $\Delta \phi^{(1)}$ is ultravioletly divergent, it is clear that, just like the case of unpolarized deep inelastic scattering (DIS), the coefficient functions $\Delta C_q$ and $\Delta C_G$ depend on how the parton spin distributions $\Delta \phi_{j/i}$ are defined, or how the ultraviolet regulator is specified on $\Delta \phi^{(1)}$. That is, the ambiguities in defining $\Delta \phi_{q/q}^{(1)}$ and $\Delta \phi_{q/G}^{(1)}$ are reflected on the ambiguities in extracting $\Delta C_q^{(1)}$ and $\Delta C_G^{(1)}$. Consequently, the decomposition of the photon-gluon and photon-quark cross sections into the hard and soft parts depends on the choice of the factorization scheme and the factorization scale $\mu$ [for simplicity, we have set $\mu^2 = Q^2$ in Eq. (4)].
Of course, the physical quantity $g_1^p(x)$ is independent of the factorization prescription (for a review on the issue of factorization, see [12]).

However, the situation for the polarized DIS case is more complicated: In addition to all the ambiguities that spin-averaged parton distributions have, the parton spin densities are subject to two extra ambiguities, namely, the axial anomaly and the definition of $\gamma_5$ in $n$ dimension [11]. It is well known that the polarized triangle diagram for $\Delta \phi^{(1)}_{q/G}$ (see Fig. 1) has an axial anomaly. There are two extreme ultraviolet regulators of interest. One of them, which we refer to as the chiral-invariant (CI) factorization scheme, respects chiral symmetry and gauge invariance but not the axial anomaly. This corresponds to a direct brute-force cutoff $\sim \mu$ on the $k_\perp$ integration in the triangle diagram (i.e. $k_\perp^2 \lesssim \mu^2$) with $k_\perp$ being the quark transverse momentum perpendicular to the virtual photon direction. Since the gluonic anomaly is manifested at $k_\perp^2 \rightarrow \infty$, it is evident that the spin-dependent quark distribution [i.e. $\Delta q^{(1)}(x)$] in the CI factorization scheme is anomaly-free. Note that this is the $k_\perp$-factorization scheme employed in the usual improved parton model [13].

The other ultraviolet cutoff on the triangle diagram of Fig. 1, as employed in the approach of the operator product expansion (OPE), is chosen to satisfy gauge symmetry and the gluonic anomaly. As a result, chiral symmetry is broken in this gauge-invariant (GI) factorization scheme and a sea polarization is perturbatively induced from hard gluons via the anomaly. This perturbative mechanism for sea quark polarization is independent of the light quark masses. A straightforward calculation gives [14, 12]

$$\Delta \phi^{(1)}_{q/G}(x)_{\text{GI}} = \Delta \phi^{(1)}_{q/G}(x)_{\text{CI}} - \frac{\alpha_s}{\pi}(1 - x),$$

where the term $\frac{\alpha_s}{\pi}(1 - x)$ originates from the QCD anomaly arising from the region where $k_\perp^2 \rightarrow \infty$. Two remarks are in order. First, this term was erroneously claimed in some early literature [12, 3] to be a soft term coming from $k_\perp^2 \sim m_q^2$ (see below). Second, although the

Figure 1: Diagrams for the quark spin distributions inside the parton: $\Delta \phi^{(1)}_{q/q}$ and $\Delta \phi^{(1)}_{q/G}$.
quark spin distribution inside the gluon $\Delta q_{q/G}^{(1)}(x)$ cannot be reliably calculated by perturbative QCD, its difference in GI and CI schemes is trustworthy in QCD. Since the polarized valence quark distributions are $k_{\perp}$-factorization scheme independent, the total quark spin distributions in GI and CI schemes are related via Eq. (6) \[10\]

\[
\Delta q(x, Q^2)_{\text{GI}} = \Delta q(x, Q^2)_{\text{CI}} - \frac{\alpha_s(Q^2)}{\pi} (1 - x) \otimes \Delta G(x, Q^2). \tag{8}
\]

For a derivation of this important result based on a different approach, namely, the nonlocal light-ray operator technique, see Müller and Teryaev \[17\]. The $x$ dependence of the anomaly effect is thus fixed.

The axial anomaly in the box diagram for polarized photon-gluon scattering also occurs at $k_{\perp}^2 \to \infty$, more precisely, at $k_{\perp}^2 = [(1 - x)/4x]Q^2$ with $x \to 0$. It is natural to expect that the axial anomaly resides in the gluon coefficient function $\Delta C_{G}^{(1)}$ in the CI scheme, whereas its effect in the GI scheme is shifted to the quark spin density. Since $\Delta C_{G}^{(1)}(x)$ is the hard part of the polarized photon-gluon cross section, which is sometimes denoted by $g_{1}^{G}(x)$, the polarized structure function of the gluon target, we have

\[
\Delta C_{G}^{(1)}(x) = g_{1}^{G}(x) - \Delta q_{q/G}^{(1)}(x). \tag{9}
\]

It follows from Eqs. (7) and (9) that

\[
\Delta C_{G}^{(1)}(x)_{\text{GI}} = \Delta C_{G}^{(1)}(x)_{\text{CI}} + \frac{\alpha_s}{\pi} (1 - x). \tag{10}
\]

It has been argued that the GI scheme is pathologic and inappropriate \[8\] based on the observation that a direct calculation of $g_{1}^{G}(x)$ using the mass regulator, for example, for the infrared divergence gives

\[
g_{1}^{G}(x) = \frac{\alpha_s}{2\pi} (2x - 1) \left( \ln \frac{Q^2}{m^2} + \ln \frac{1 - x}{x} - 1 \right) + \frac{\alpha_s}{\pi} (1 - x), \tag{11}
\]

where the last term in Eq. (11) is an effect of chiral symmetry breaking and it arises from the soft region $k_{\perp}^2 \sim m^2$. By comparing (10) with (11), it appears that $\Delta C_{G}^{(1)}(x)_{\text{GI}}$, which is “hard” by definition, contains an unwanted “soft” term. This is actually not the case. Choosing a chiral-invariant cutoff on the $k_{\perp}$-integration, a perturbative QCD evaluation yields (see \[12\] for a review on the detail of derivation)

\[
\Delta C_{G}^{(1)}(x)_{\text{CI}} = \frac{\alpha_s}{2\pi} \left[ (2x - 1)(\ln \frac{1 - x}{x} - 1) \right]. \tag{12}
\]
The $\frac{a_s}{\pi}(1-x)$ term disappears in $\Delta C_G^{(1)}(x)_{\text{CI}}$, as it should be, but it emerges again in the GI scheme due to the axial anomaly [see Eq. (10) or (7)] and this time reappears in the hard region. That is, the gluon coefficient $\Delta C_G^{(1)}(x)_{\text{GI}}$ is genuinely hard.

It is easily seen that the first moments of $\Delta C_G(x)$, $\sum_q \Delta q(x)$ and $g_1^p(x)$ are given by

$$\int_0^1 dx \Delta C_G^{(1)}(x)_{\text{GI}} = 0, \quad \int_0^1 dx \Delta C_G^{(1)}(x)_{\text{CI}} = -\frac{a_s}{2\pi}, \quad (13)$$

$$\Delta \Sigma_{\text{GI}}(Q^2) = \Delta \Sigma_{\text{CI}}(Q^2) - \frac{n_f a_s(Q^2)}{2\pi} \Delta G(Q^2), \quad (14)$$

and

$$\Gamma_1^p \equiv \int_0^1 g_1^p(x, Q^2) dx = \frac{1}{2} \sum e_q^2 \left( \Delta q_{\text{CI}}(Q^2) - \frac{a_s(Q^2)}{2\pi} \Delta G(Q^2) \right)$$

$$= \frac{1}{2} \sum e_q^2 \Delta q_{\text{GI}}(Q^2), \quad (15)$$

where $\Delta G \equiv \int_0^1 \Delta G(x) dx$, and we have neglected contributions to $g_1^p$ from $\Delta \phi_{1/q}$ and $\Delta C^{(1)}_q$. Note that $\Delta \Sigma_{\text{GI}}(Q^2)$ is equivalent to the singlet axial charge $\langle p, s | J_5^\mu | p, s \rangle$. The well-known results (12-14) indicate that $\Gamma_1^p$ receives anomalous gluon contributions in the CI factorization scheme (e.g. the improved parton model), whereas hard gluons do not play any role in $\Gamma_1^p$ in the GI scheme such as the OPE approach. From (14) it is evident that the sea quark or anomalous gluon interpretation for the suppression of $\Gamma_1^p$ observed experimentally is simply a matter of convention [18]. From Eqs. (8) and (14) we see that $\Delta q^G(x) + \Delta C^{(1)}_q(x) \otimes \Delta G(x)$ and hence $g_1^p(x)$ is independent of the choice of the $k_\perp$-factorization scheme, as it should be. We would like to stress that physically, the GI and CI $k_\perp$-factorization schemes are exactly on the same footing, though philosophically one may argue that it is more natural to have $\Delta C_G$ include all short-distance contributions.

The $\overline{\text{MS}}$ scheme is the most common one chosen in the GI factorization convention. However, the quark coefficient function $\Delta C^{(1)}_q(x)$ in the dimensional regularization scheme is subject to another ambiguity, namely, the definition of $\gamma_5$ in $n$ dimension used to specify the ultraviolet cutoff on $\Delta \phi_{1/q}$ (see Fig. 1). For example, $\Delta C^{(1)}_q(x)$ calculated in the $\gamma_5$ prescription of ’t Hooft and Veltman, Breitenlohner and Maison (HVBM) is different from that computed in the dimension reduction scheme [11]. The result

$$\Delta C^{(1)}_q(x) = C^{(1)}_q(x) - \frac{2a_s}{3}(1 + x) \quad (16)$$

usually seen in the literature is obtained in the HVBM scheme, where $C_q(x)$ is the unpolarized quark coefficient function. Of course, the quantity $\Delta q^{(1)}(x) + \Delta C_q(x) \otimes \Delta q^{(0)}(x)$ and hence $g_1^p(x)$ is independent of the definition of $\gamma_5$ in dimensional regularization.
In order to determine the \(Q^2\) evolution of the polarized structure function \(g_1(x,Q^2)\) to NLO, it is necessary to know the two-loop splitting functions \(\Delta P_{ij}^{(1)}(x)\) in the NLO evolution equation. Since the complete results for \(\Delta P_{ij}^{(1)}(x)\) are available only in the \(\overline{\text{MS}}\) scheme, a GI factorization scheme, it is natural to ask how do we analyze the DIS data of \(g_1\) in the CI scheme? One possibility is proposed in [16] that the evolution of the parton spin distributions \(\Delta q(x,Q^2)_{\text{CI}}\) and \(\Delta G(x,Q^2)\) is first determined from the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equation, and then \(\Delta q(x,Q^2)_{\text{CI}}\) in the CI scheme is related to \(\Delta q(x,Q^2)_{\text{GI}}\) and \(\Delta G(x,Q^2)\) via Eq. (8). The other equivalent possibility, as advocated by Müller and Teryaev [17], is to make a renormalization group transformation of NLO splitting kernels and coefficient functions from the GI scheme to the CI one. In addition to the coefficient functions [cf. Eq. (10)]

\[
\Delta C_q^{(1)}(x)_{\text{CI}} = \Delta C_q^{(1)}(x)_{\text{GI}}, \quad \Delta C_G^{(1)}(x)_{\text{CI}} = \Delta C_G^{(1)}(x)_{\text{GI}} - A(x),
\]

where \(A(x) \equiv \frac{2}{\pi} (1 - x)\), the NLO splitting functions in the CI scheme can be obtained by applying Eq. (8) to the spin-dependent evolution equations:

\[
\begin{align*}
\frac{d}{dt} \Delta q_{\text{NS}}(x,t) &= \frac{\alpha_s(t)}{2\pi} \Delta P_{qq}^{\text{NS}}(x) \otimes \Delta q_{\text{NS}}(x,t), \\
\frac{d}{dt} \left( \Delta q_S(x,t) \right) &= \frac{\alpha_s(t)}{2\pi} \left( \Delta P_{qq}^S(x) 2n_f \Delta P_{qG}(x) \right) \otimes \left( \Delta q_S(x,t) \right), \\
\frac{d}{dt} \left( \Delta G(x,t) \right) &= \frac{\alpha_s(t)}{2\pi} \left( \Delta P_{qG}(x) \Delta P_{GG}(x) \right) \otimes \left( \Delta G(x,t) \right), \quad (18)
\end{align*}
\]

where \(t = \ln(Q^2/\Lambda_{\text{QCD}}^2)\), and the indices S and NS denote singlet and non-singlet parton distributions, respectively. It is straightforward to show that

\[
\begin{align*}
\Delta P_{qq}^{\text{NS}}(x)_{\text{CI}} &= \Delta P_{qq}^{\text{NS}}(x)_{\text{GI}}, \\
\Delta P_{qq}^S(x)_{\text{CI}} &= \Delta P_{qq}^S(x)_{\text{GI}} + A(x) \otimes \Delta P_{qG}(x)_{\text{GI}}, \\
\Delta P_{GG}(x)_{\text{CI}} &= \Delta P_{GG}(x)_{\text{GI}} - A(x) \otimes \Delta P_{qG}(x)_{\text{GI}}, \\
2n_f \Delta P_{qG}(x)_{\text{CI}} &= 2n_f \Delta P_{qG}(x)_{\text{GI}} - \frac{\alpha_s \beta}{4\pi} A(x) \\
&\quad - A(x) \otimes \left[ \Delta P_{qq}^S - \Delta P_{GG} + \Delta P_{qG} \otimes A \right](x)_{\text{GI}}, \quad (19)
\end{align*}
\]

where

\[
\beta = \left( 11 - \frac{2}{3} n_f \right) + \frac{\alpha_s}{2\pi} \left( 51 - \frac{19}{3} n_f \right) + \cdots
\]

is the usual \(\beta\)-function. The above results are first obtained by Müller and Teryaev [17]. In short, Eqs. (17) and (19) provide the NLO coefficient and splitting functions necessary for the CI factorization scheme. It is easy to check that \(\Delta q_{\text{CI}} \equiv \int_0^1 dx \Delta q(x)_{\text{CI}}\) does not evolve with \(Q^2\) and that hard gluons contribute to \(\Gamma_1^p\) in an amount as shown in Eq. (14).
Several CI-like schemes were proposed in [3] in which the singlet anomalous dimension and the first moments of the gluon coefficient function are fixed to be

$$\int_0^1 dx \Delta C_G^{(1)}(x) = -\frac{\alpha_s}{2\pi}, \quad \Delta \gamma_{S,gg}^{(1)} = 0,$$

(21)

where

$$\Delta \gamma_{ij}^n = \int_0^1 \Delta P_{ij}(x)x^{n-1}dx = \Delta \gamma_{ij}^{(0),n} + \frac{\alpha_s}{2\pi} \Delta \gamma_{ij}^{(1),n} + \cdots.$$  

(22)

The remaining moments of the coefficient functions and anomalous dimensions are then constructed by modifying the counterparts in the $\overline{\text{MS}}$ scheme. Three of such schemes, namely the Adler-Bardeen (AB) scheme, the off-shell scheme, and the Altarelli-Ross scheme were considered in [3]. For example, higher moments in the AB scheme are fixed by requiring that the full scheme change from the $\overline{\text{MS}}$ scheme to the AB scheme be independent of $x$, so that the large and small $x$ behavior of the coefficient functions is unchanged. Evidently, this is in contradiction to the $(1 - x)$ behavior of the anomaly effect shown in Eq. (17); that is, though the first moments of $\Delta q(x)$ and $g_1(x)$ in the AB scheme are in agreement with the CI factorization scheme, this is no longer true for other moments. In principle, a measurement of higher moments of spin-dependent parton distributions will enable us to discern between CI and AB schemes. Since the AB scheme is not consistent with perturbative QCD for the $x$ dependence of the renormalization group transformation for coefficient and splitting functions, it is thus not pertinent to use this factorization convention to analyze the polarized structure functions in NLO.

To conclude, since the $x$ dependence of the axial-anomaly effect is fixed, the transformation of spin-dependent coefficient and splitting functions from the $\overline{\text{MS}}$ scheme to the improved parton model (or chiral-invariant) factorization scheme in which the axial anomaly is shifted to the gluon coefficient function are uniquely determined by perturbative QCD for a given $\gamma_5$ prescription, contrary to the commonly used Adler-Bardeen scheme. We thus believe that the CI scheme should be used, instead of the less consistent and ambiguous AB scheme. In order to see the factorization scheme independence of $\Delta q_v(x, Q^2)$, $\Delta G(x, Q^2)$ and $g_1(x, Q^2)$ and demonstrate the effect of scheme dependence for $\Delta q_s(x, Q^2)$, $\Delta \Sigma(x, Q^2)$, it is urged that the QCD analysis of polarized structure functions in NLO should be carried out in both $\overline{\text{MS}}$ (or any gauge-invariant) and chiral-invariant factorization schemes. The $Q^2$ evolution of parton spin distributions in the latter can be obtained by either studying the $Q^2$ evolution first in the $\overline{\text{MS}}$ scheme and then applying Eq. (8) afterwards or solving the DGLAP equation directly in the CI scheme using the splitting functions given by (13).
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