Longitudinal Polarized Parton Densities Updated

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Abstract

We have re-analyzed the world data on inclusive polarized DIS, in both NLO and LO QCD, including the new HERMES and COMPASS data. The updated NLO polarized densities are given in both the MS and JET schemes. The impact of the new data on the results is discussed.

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Since the famous European Muon Collaboration (EMC) experiment [1] at CERN in 1987, substantial efforts, both experimental and theoretical, have been devoted to understanding the partonic spin structure of the nucleon, i.e., how the nucleon spin is built up out from the intrinsic spin and orbital angular momentum of its constituents, quarks and gluons. Our present knowledge about the spin structure of the nucleon comes mainly from polarized inclusive and semi-inclusive DIS experiments at SLAC, CERN, DESY and JLab, polarized proton-proton collisions at RHIC and polarized photoproduction experiments. The determination of the longitudinal polarized parton densities in QCD is one of the important and best studied aspects of this knowledge.

In this Brief Report we present an updated version of our Set 1 and Set 2 NLO QCD polarized parton densities in both the $\overline{\text{MS}}$ and the JET (or so-called chirally invariant) [2] factorization schemes, as well as the LO ones, determined in our recent analysis [3]. Comparing to our previous analysis: i) The old HERMES proton [4] and neutron [5] data are replaced with the new HERMES proton and deuteron data [6] and ii) a complete treatment of the recent COMPASS data on the longitudinal asymmetry $A_1^d$ [7] is included. A FORTRAN package of the obtained polarized parton densities (LSS’05) will be presented at the Durham HEpdata web site to be used for practical purposes.

In QCD the spin structure function $g_1$ has the following form ($Q^2 >> \Lambda^2$):

$$g_1(x, Q^2) = g_1(x, Q^2)_{LT} + g_1(x, Q^2)_{HT},$$

where "LT" denotes the leading twist ($\tau = 2$) contribution to $g_1$, while "HT" denotes the contribution to $g_1$ arising from QCD operators of higher twist, namely $\tau \geq 3$. In Eq. (1) (the nucleon target label N is dropped)

$$g_1(x, Q^2)_{LT} = g_1(x, Q^2)_{pQCD} + h_{TMC}(x, Q^2)/Q^2 + \mathcal{O}(M^4/Q^4),$$

where $g_1(x, Q^2)_{pQCD}$ is the well known (logarithmic in $Q^2$) pQCD contribution and $h_{TMC}(x, Q^2)$ are the calculable [8] kinematic target mass corrections, which effectively belong to the LT term. In Eq. (1)

$$g_1(x, Q^2)_{HT} = h(x, Q^2)/Q^2 + \mathcal{O}(\Lambda^4/Q^4),$$

where $h(x, Q^2)$ are the dynamical higher twist ($\tau = 3$ and $\tau = 4$) corrections to $g_1$, which are related to multi-parton correlations in the nucleon. The latter are non-perturbative effects and cannot be calculated without using models.
Let us recall that the Set 1 polarized parton densities correspond to fits to \( g_1/F_1 \) and \( A_1 \approx g_1/F_1 \) data (so called '\( g_1/F_1 \)’ fits):

\[
\left[ \frac{g_1(x, Q_2^2)}{F_1(x, Q_2^2)} \right]_{\text{exp}} \Leftrightarrow \frac{g_1(x, Q_2^2)_{\text{pQCD}}}{F_1(x, Q_2^2)_{\text{pQCD}}},
\]

(4)

where for the structure functions \( g_1 \) and \( F_1 \) their leading twist NLO QCD expressions are used. (Why this method is incorrect for extracting the LO polarized PDs, is discussed in Ref. [11].) The Set 2 polarized PD correspond to fits to \( g_1/F_1 \) and \( A_1 \) data where the experimental data for the unpolarized structure function \( F_1(x, Q_2^2) \) are used

\[
\left[ \frac{g_N^N(x, Q_2^2)}{F_N^N(x, Q_2^2)} \right]_{\text{exp}} \Leftrightarrow \frac{g_N^N(x, Q_2^2)_{\text{LT}} + h_N^N(x)/Q^2}{F_N^N(x, Q_2^2)_{\text{exp}}},
\]

(5)

As usual, \( F_1 \) is replaced by its expression in terms of the usually extracted from unpolarized DIS experiments \( F_2 \) and \( R \) and phenomenological parametrizations of the experimental data for \( F_2(x, Q^2) \) [9] and the ratio \( R(x, Q^2) \) of the longitudinal to transverse \( \gamma N \) cross-sections [10] are used. Note that such a procedure is equivalent to a fit to \( g_1 \) data themselves and we will refer to these as '(\( g_1^{\text{LT}} + \text{HT} \)’ fits). In this case the HT corrections to \( g_1 \) cannot be compensated and have to be taken into account (for more details see our previous paper [3]). In (5) \( g_N^N(x, Q_2^2)_{\text{LT}} \) (\( N=p, n, d \)) is given by the leading twist expression (2) in LO/NLO approximation including the target mass corrections and \( h_N^N(x) \) are the dynamical \( \tau = 3 \) and \( \tau = 4 \) HT corrections which are extracted in a model independent way.

As in our previous analyses [3, 12], for the input LO and NLO polarized parton densities at \( Q_0^2 \) = 1 GeV\(^2\) we have adopted a simple parametrization

\[
\begin{align*}
x \Delta u_v(x, Q_0^2) &= \eta_u A_u x^{a_u} u_v(x, Q_0^2), \\
x \Delta d_v(x, Q_0^2) &= \eta_d A_d x^{a_d} d_v(x, Q_0^2), \\
x \Delta s(x, Q_0^2) &= \eta_s A_s x^{a_s} s(x, Q_0^2), \\
x \Delta G(x, Q_0^2) &= \eta_g A_g x^{a_g} G(x, Q_0^2),
\end{align*}
\]

(6)

where on the RHS of (6) we have used the MRST98 (central gluon) [13] and MRST99 (central gluon) [14] parametrizations for the LO and NLO(MS) unpolarized densities, respectively. The normalization factors \( A_i \) in (6) are fixed such that \( \eta_i \) are the first moments of the polarized densities. To fit better the data in LO QCD, an additional factor \((1+\gamma_v x)\) on the RHS is used for the valence quarks. Bearing in mind that the light quark sea densities \( \Delta \bar{u} \) and \( \Delta \bar{d} \) cannot, in principle, be determined from the present
inclusive data (in the absence of polararized charged current neutrino experiments) we have adopted the convention of a flavor symmetric sea

$$\Delta u_{\text{sea}} = \Delta \bar{u} = \Delta d_{\text{sea}} = \Delta \bar{d} = \Delta s = \Delta \bar{s}. \quad (7)$$

Note that this convention affects the results for the valence parton densities, but not the results for the strange sea quark a gluon densities.

The first moments of the valence quark densities $\eta_u$ and $\eta_d$ are constrained by the sum rules

$$a_3 = g_A = F + D = 1.2670 \pm 0.0035 \quad [15], \quad (8)$$

$$a_8 = 3F - D = 0.585 \pm 0.025 \quad [16], \quad (9)$$

where $a_3$ and $a_8$ are non-singlet combinations of the first moments of the polarized parton densities corresponding to 3rd and 8th components of the axial vector Cabibbo current

$$a_3 = (\Delta u + \Delta \bar{u})(Q^2) - (\Delta d + \Delta \bar{d})(Q^2), \quad (10)$$

$$a_8 = (\Delta u + \Delta \bar{u})(Q^2) + (\Delta d + \Delta \bar{d})(Q^2) - 2(\Delta s + \Delta \bar{s})(Q^2). \quad (11)$$

As in [3], we have used the MRST02(NLO) unpolarized parton densities [17] to constrain via positivity our Set 1 and Set 2 polarized PD in both $\overline{\text{MS}}$ and JET schemes.

The numerical results of our fits to the world data [1, 6, 7, 18] on $g_1/F_1$ and $A_1$ are presented in Tables I and II. The data used (190 experimental points) cover the following kinematic region \( \{0.005 \leq x \leq 0.75, \ 1 < Q^2 \leq 58 \ GeV^2\} \). The total (statistical and systematic) errors are taken into account. The systematic errors are added quadratically. It is seen from the Tables I and II that the values of $\chi^2/DF(\overline{\text{MS}})$ and $\chi^2/DF(\text{JET})$ coincide almost exactly for the ‘$g_1/F_1$’ as well as for the ($g_1^{LT} + \text{HT}$) fits, which is a good indication of the stability of the analysis regardless of the scheme used. Analytic formulae for the input parton densities and higher twist contributions are given in the Appendix.

Let us note the main features of our new results:

i) The new Set 1 and Set 2 polarized PD are close to those determined in our recent analysis [3]. However, due to more accurate HERMES/d and COMPASS (small $x$ region) data the polarized PD are better determined now (see the errors in the Tables 1 and 2 in [3] and this paper).

ii) Compared to our previous results [11, 12] we obtain now smaller values for the gluon polarization (the first moment of $\Delta G(x, Q^2)$), which leads to a smaller difference between the values of the strange quark polarization (the first moment of $\Delta s(x, Q^2)$)
determined in the \( \overline{\text{MS}} \) and the JET schemes, respectively. As a consequence, the difference between the quark helicity \( \Delta \Sigma \) determined in these two schemes is also smaller. This fact has been already observed in our recent analysis [3].

\( iii \) The shape of both the polarized strange quark and gluon densities is rather different from that of LSS’01 [12] (see Fig. 1). This is mainly due to the different positivity bounds imposed on the polarized PD in the LSS’01 and LSS’05 fits. The impact of positivity constrains on polarized PD has been discussed in detail in [3].

\( iv \) The effect of the new data on the higher twist corrections to the proton and neutron spin structure functions, \( h^p(x) \) and \( h^n(x) \), is negligible (see Fig. 2). The new values are in good agreement with the old ones although there is a tendency for the central values for the proton target to be slightly higher than the old ones. For the neutron target the only difference is that the new value of \( h^n(x) \) at \( x \approx 0.2 \) is considerably higher than the old one and definitely different from zero.

Finally, let us illustrate how important the higher twist corrections are for the description of the data. In Fig. 3 we compare the new very accurate HERMES deuteron data on the ratio \( g_1/F_1 \) at measured \( x \) and \( Q^2 \) with the theoretical curves for \( g_1 \) obtained by: i) the best fit to the data using only the LT term in Eq. 5 (dotted curve) and ii) the best fit to the data taking into account in (5) the HT corrections too (solid curve). The dashed curve corresponds to the LT term when the HT corrections are accounted for. As expected, the role of HT corrections is significant in the small \( x \) region where

Figure 1: Comparison between our two sets of NLO(\( \overline{\text{MS}} \)) polarized parton densities, LSS’01 and LSS’05(Set 1), at \( Q^2 = 4 \ GeV^2 \).
the values of $Q^2$ are relatively small: $Q^2 \approx 1.2 - 2.5 \text{ GeV}^2$.

![NLO MS](image)

Figure 2: Effect of the new data on the higher twist values.

![g/F1](image)

Figure 3: The effect of higher twist corrections (see the text).

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Appendix

A. Input Parton densities

For practical purposes we present here explicitly our Set 1 and Set 2 of polarized parton densities at $Q^2 = 1$ GeV$^2$. The polarized valence quark densities correspond to the convention of a SU(3) flavour symmetric sea.

LSS’05 (Set 1) - NLO(\overline{\text{MS}}) PD($g_1/F_1$):
\begin{align*}
x\Delta u_v(x) &= 0.4604 x^{0.6240} (1 - x)^{3.428} (1 + 2.179 x^{1/2} + 14.57 x) , \\
x\Delta d_v(x) &= -0.02408 x^{0.3680} (1 - x)^{3.864} (1 + 35.47 x^{1/2} + 28.97 x) , \\
x\Delta s(x) &= -0.02226 x^{0.3546} (1 - x)^{7.449} (1 + 3.656 x^{1/2} + 19.50 x) , \\
x\Delta G(x) &= 641.0 x^{3.341} (1 - x)^{6.879} (1 - 3.147 x^{1/2} + 3.148 x) . \quad (A.1)
\end{align*}

LSS’05 (Set 1) - NLO(JET) PD($g_1/F_1$):
\begin{align*}
x\Delta u_v(x) &= 0.4589 x^{0.6224} (1 - x)^{3.428} (1 + 2.179 x^{1/2} + 14.57 x) , \\
x\Delta d_v(x) &= -0.02490 x^{0.3813} (1 - x)^{3.864} (1 + 35.47 x^{1/2} + 28.97 x) , \\
x\Delta s(x) &= -0.01577 x^{0.3127} (1 - x)^{6.449} (1 + 3.656 x^{1/2} + 19.50 x) , \\
x\Delta G(x) &= 923.6 x^{4.138} (1 - x)^{6.879} (1 - 3.147 x^{1/2} + 3.148 x) . \quad (A.2)
\end{align*}

LSS’05 (Set 2) - LO PD($g_1 + \text{HT}$):
\begin{align*}
x\Delta u_v(x) &= 0.1760 x^{0.3012} (1 - x)^{3.177} (1 + 1.610 x)(1 - 0.4085 x^{1/2} + 17.60 x) , \\
x\Delta d_v(x) &= -0.00765 x^{0.1535} (1 - x)^{3.398} (1 + 3.797 x)(1 + 37.25 x^{1/2} + 31.14 x) , \\
x\Delta s(x) &= -0.04660 x^{0.3542} (1 - x)^{8.653} (1 - 0.9052 x^{1/2} + 11.53 x) , \\
x\Delta G(x) &= 303.6 x^{3.188} (1 - x)^{6.879} (1 - 3.147 x^{1/2} + 3.148 x) . \quad (A.3)
\end{align*}

LSS’05 (Set 2) - NLO(\overline{\text{MS}}) PD($g_1 + \text{HT}$):
\begin{align*}
x\Delta u_v(x) &= 0.5041 x^{0.6689} (1 - x)^{3.428} (1 + 2.179 x^{1/2} + 14.57 x) , \\
x\Delta d_v(x) &= -0.02847 x^{0.4364} (1 - x)^{3.864} (1 + 35.47 x^{1/2} + 28.97 x) , \\
x\Delta s(x) &= -0.02759 x^{0.3740} (1 - x)^{7.449} (1 + 3.656 x^{1/2} + 19.50 x) , \\
x\Delta G(x) &= 303.6 x^{3.188} (1 - x)^{6.879} (1 - 3.147 x^{1/2} + 3.148 x) . \quad (A.4)
\end{align*}
LSS’05 (Set 2) - NLO(JET) PD($g_1 + HT$):

\[
\begin{align*}
  x\Delta u_v(x) &= 0.4991 x^{0.6639} (1 - x)^{3.428} (1 + 2.179 x^{1/2} + 14.57 x), \\
  x\Delta d_v(x) &= -0.02693 x^{0.4133} (1 - x)^{3.864} (1 + 35.47 x^{1/2} + 28.97 x), \\
  x\Delta s(x) &= -0.02434 x^{0.3837} (1 - x)^{7.649} (1 + 3.656 x^{1/2} + 19.50 x), \\
  x\Delta G(x) &= 736.1 x^{3.678} (1 - x)^{6.879} (1 - 3.147 x^{1/2} + 3.148 x). \quad \text{(A.5)}
\end{align*}
\]

B. Higher twist corrections

We present here the best fit parametrizations of the extracted values of higher twist corrections to $g_1$ for the proton and neutron targets (see Table 2) which are valid in the experimental $x$ region: $0.005 \leq x \leq 0.75$ .

**Fit $[g_1(x, Q^2)_{\{LO+TMC\}} + h(x)/Q^2]$**:

\[
\begin{align*}
  h^p(x) &= 0.0223 - \frac{0.2186}{\sqrt{\pi/2}} \exp\left[-2((x - 0.1905)/0.1761)^2\right] \\
  h^n(x) &= 0.0362 + \frac{0.2428}{\sqrt{\pi/2}} \exp\left[-2((x - 0.0267)/0.1768)^2\right] \quad \text{(B.1)}
\end{align*}
\]

**Fit $[g_1(x, Q^2)_{\{NLO(MS)+TMC\}} + h(x)/Q^2]$**:

\[
\begin{align*}
  h^p(x) &= 0.0360 - \frac{0.1706}{\sqrt{\pi/2}} \exp\left[-2((x - 0.2030)/0.1736)^2\right] \\
  h^n(x) &= 0.0176 + \frac{0.2313}{\sqrt{\pi/2}} \exp\left[-2((x - 0.0723)/0.1748)^2\right] \quad \text{(B.2)}
\end{align*}
\]

**Fit $[g_1(x, Q^2)_{\{NLO(JET)+TMC\}} + h(x)/Q^2]$**:

\[
\begin{align*}
  h^p(x) &= 0.0373 - \frac{0.1629}{\sqrt{\pi/2}} \exp\left[-2((x - 0.2046)/0.1700)^2\right] \\
  h^n(x) &= 0.0137 + \frac{0.2519}{\sqrt{\pi/2}} \exp\left[-2((x - 0.0676)/0.1812)^2\right] \quad \text{(B.3)}
\end{align*}
\]
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TABLE I. The parameters of the Set 1 NLO input polarized PD at $Q^2 = 1 \text{ GeV}^2$ as obtained from the best "$g_1/F_1$" fits to the world data in the $\overline{\text{MS}}$ and JET schemes. The errors shown are total (statistical and systematic). The parameters marked by (*) are fixed by the sum rules (8) and (9).

| Fit   | $g_1^{\text{NLO}}/F_1^{\text{NLO}}(\overline{\text{MS}})$ | $g_1^{\text{NLO}}/F_1^{\text{NLO}}(\text{JET})$ |
|-------|----------------------------------------------------------|--------------------------------------------------|
| DF    | 190 - 6                                                  | 190 - 6                                          |
| $\chi^2$ | 166.2                                                  | 168.3                                             |
| $\chi^2$/DF | 0.903                                                  | 0.915                                             |
| $\eta_u$ | 0.926*                                                  | 0.926*                                            |
| $a_u$ | 0.207 ± 0.018                                           | 0.206 ± 0.018                                     |
| $\eta_d$ | - 0.341*                                               | -0.341*                                           |
| $a_d$ | 0.098 ± 0.059                                           | 0.111 ± 0.059                                     |
| $\eta_s$ | - 0.061 ± 0.007                                         | - 0.051 ± 0.008                                   |
| $a_s$ | 0.637 ± 0.082                                           | 0.595 ± 0.101                                     |
| $\eta_g$ | 0.307 ± 0.175                                          | 0.171 ± 0.166                                     |
| $a_g$ | 2.372 ± 0.691                                           | 3.169 ± 1.323                                     |
TABLE II. The parameters of the Set 2 of LO, NLO(\overline{MS}) and NLO(JET) input polarized PD at $Q^2 = 1 \ GeV^2$ as obtained from the best $(g_1 + \text{HT})$ fits to the world data. The errors shown are total (statistical and systematic). The parameters marked by (*) are fixed. Note that the TMC are included in $(g_1)^{LT}$.

| Fit  | $(g_1)_{LO}^{LT} + h(x)/Q^2$ | $(g_1)_{NLO(\overline{MS})}^{LT} + h(x)/Q^2$ | $(g_1)_{NLO(JET)}^{LT} + h(x)/Q^2$ |
|------|-----------------------------|---------------------------------|---------------------------------|
| DF   | 190 - 16                     | 190 - 16                        | 190 - 16                        |
| $\chi^2$ | 156.1                      | 154.5                           | 154.4                           |
| $\chi^2$/DF | 0.897                      | 0.888                           | 0.887                           |
| $\eta_u$ | 0.926*                     | 0.926*                          | 0.926*                          |
| $a_u$    | 0.000 ± 0.010               | 0.252 ± 0.037                   | 0.247 ± 0.038                   |
| $\gamma_u$ | 1.610 ± 0.301             | 0*                              | 0*                              |
| $\eta_d$ | -0.341*                    | -0.341*                         | -0.341*                         |
| $a_d$    | 0.000 ± 0.062               | 0.166 ± 0.124                   | 0.143 ± 0.149                   |
| $\gamma_d$ | 3.797 ± 1.736             | 0*                              | 0*                              |
| $\eta_s$ | -0.068 ± 0.006             | -0.070 ± 0.008                  | -0.060 ± 0.012                  |
| $a_s$    | 0.544 ± 0.058               | 0.656 ± 0.069                   | 0.666 ± 0.114                   |
| $\eta_g$ | 0.179*                     | 0.179 ± 0.267                   | 0.231 ± 0.283                   |
| $a_g$    | 2.218*                     | 2.218 ± 1.650                   | 2.709 ± 1.567                   |

$h^p(x_i) \ [GeV^2]$

| $x_i$ | h$^p(x_i)$ [GeV$^2$] | h$^n(x_i)$ [GeV$^2$] |
|-------|-----------------------|-----------------------|
| 0.028 | -0.010 ± 0.042        | 0.018 ± 0.047         | 0.021 ± 0.043                   |
| 0.100 | -0.078 ± 0.034        | -0.031 ± 0.032        | -0.023 ± 0.034                   |
| 0.200 | -0.151 ± 0.038        | -0.100 ± 0.040        | -0.093 ± 0.043                   |
| 0.350 | -0.011 ± 0.044        | 0.004 ± 0.046         | 0.007 ± 0.046                   |
| 0.600 | 0.022 ± 0.021         | 0.036 ± 0.020         | 0.037 ± 0.021                   |

$h^n(x_i) \ [GeV^2]$

| $x_i$ | h$^n(x_i)$ [GeV$^2$] | h$^n(x_i)$ [GeV$^2$] |
|-------|-----------------------|-----------------------|
| 0.028 | 0.230 ± 0.061         | 0.182 ± 0.065         | 0.195 ± 0.063                   |
| 0.100 | 0.174 ± 0.040         | 0.196 ± 0.038         | 0.203 ± 0.038                   |
| 0.200 | 0.064 ± 0.054         | 0.081 ± 0.061         | 0.078 ± 0.065                   |
| 0.325 | 0.038 ± 0.026         | 0.025 ± 0.029         | 0.023 ± 0.031                   |
| 0.500 | 0.036 ± 0.014         | 0.014 ± 0.013         | 0.013 ± 0.015                   |