Status of Longitudinal Polarized Parton Densities and Higher Twist

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Abstract. The present status of the longitudinal polarized parton densities (PDFs) and the contribution of their first moments to the nucleon spin is discussed. Special attention is paid to the role of higher twist effects in determining the PDFs and to the polarized strange quark and gluon densities, which are still not well determined from the present data.

Keywords: QCD, spin structure functions, polarized parton densities, higher twist

PACS: 13.60.Hb, 12.38-t, 14.20.Dh

INTRODUCTION AND METHODS OF ANALYSIS

Our present knowledge about the nucleon spin structure 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. One of the important and best studied aspects of this knowledge is the determination of the longitudinal polarized parton densities in QCD and their first moments, which correspond to the spins carried by the quarks and gluons in the nucleon.

There are some peculiarities which make the QCD analysis of the data more complicated and difficult than that in the unpolarized case:

i) A half of the present polarized DIS data are at moderate \( Q^2 \) and \( W^2 \) (\( Q^2 \sim 1 - 4 \text{ GeV}^2 \), \( 4 \text{ GeV}^2 < W^2 < 10 \text{ GeV}^2 \)), or in the so-called preasymptotic region. So, in contrast to the unpolarized case, the \( 1/Q^2 \) terms (kinematic - \( \gamma^2 \) factor, target mass corrections, and dynamic - higher twist corrections to the spin structure function \( g_1 \)) have to be accounted for in the analysis in order to determine correctly the polarized PDFs.

ii) Due to the lack of charged current neutrino data, only the sum \( (\Delta q + \Delta \bar{q}) \) can be determined from inclusive DIS and information from semi-inclusive DIS (SIDIS) is needed for the flavor decomposition of the polarized sea \( (\Delta \bar{u}, \Delta \bar{d}, \Delta \bar{s}) \). Such an analysis, however, requires knowledge of the fragmentation functions which are not well known at present. Note that in the unpolarized case, SIDIS processes have never been used for a flavor separation of the parton densities.

The best manner to determine the polarized PDFs is to perform a QCD fit to the...
data on $g_1/F_1$, which can be obtained if both $A_\parallel$ and $A_\perp$ asymmetries are measured. In the case if only $A_\parallel$ is measured, the quantity $A_\parallel/D(1+\gamma^2)$ is a good approximation of $g_1/F_1$, where D is the depolarization factor and $\gamma^2 = 4M^2x^2/Q^2$. The data on the photon-nucleon asymmetry $A_1$ are not suitable for the determination of PDFs because the structure function $g_2$ is not well known in QCD and the approximation $(A_1)^{\text{theor}}(= g_1/F_1 - \gamma^2 g_2/F_1) \approx (g_1/F_1)^{\text{theor}}$ in the preasymptotic region used by some of the groups is not reasonable.

In QCD, one can split $g_1$ and $F_1$ into leading (LT) and higher twist (HT) pieces

$$g_1 = (g_1)_{\text{LT}} + (g_1)_{\text{HT}}, \quad F_1 = (F_1)_{\text{LT}} + (F_1)_{\text{HT}}.$$  \hspace{1cm} (1)

Then, approximately

$$\frac{g_1}{F_1} \approx \frac{(g_1)_{\text{LT}}}{(F_1)_{\text{LT}}} \left[ 1 + \frac{(g_1)_{\text{HT}}}{(g_1)_{\text{LT}}} - \frac{(F_1)_{\text{HT}}}{(F_1)_{\text{LT}}} \right].$$  \hspace{1cm} (2)

Note that LT pieces of $g_1$ and $F_1$ are expressed by the polarized and unpolarized PDFs, respectively.

There are mainly two methods to fit the data - taking or NOT taking into account the HT corrections to $g_1$. According to the first \[1\], the data on $g_1/F_1$ have been fitted taking into account the contribution of the first term $h(x)/Q^2$ in $(g_1)_{\text{HT}}$ and using the experimental data for the unpolarized structure function $F_1$

$$\left[ \frac{g_1(x, Q^2)}{F_1(x, Q^2)} \right]_{\text{exp}} \Leftrightarrow \frac{g_1(x, Q^2)_{\text{LT}} + h(x)/Q^2}{F_1(x, Q^2)_{\text{exp}}}. \hspace{1cm} (3)$$

According to the second approach \[2\] only the LT expression in (1) have been used in the fit to the $g_1/F_1$ data

$$\left[ \frac{g_1(x, Q^2)}{F_1(x, Q^2)} \right]_{\text{exp}} \Leftrightarrow \frac{g_1(x, Q^2)_{\text{LT}}}{F_1(x, Q^2)_{\text{LT}}}. \hspace{1cm} (4)$$

It is obvious that the two methods are equivalent in a pure DIS region where HT can be ignored. To be equivalent in the preasymptotic region requires a cancellation between the ratios $(g_1)_{\text{HT}}/(g_1)_{\text{LT}}$ and $(F_1)_{\text{HT}}/(F_1)_{\text{LT}}$ in (2). Fig. 1 (left), based on our recent results on $g_1$ \[3\] and the unpolarized results of \[4\], demonstrates the validity of this for $x \geq 0.15$, but clearly indicates that ignoring HT terms in the ratio $g_1/F_1$ below $x = 0.15$, as was done by groups using the second method or some its modifications \[5, 6\], is incorrect. Note that in this case the HT effects are absorbed in the extracted PDFs which differ from those determined in the presence of HT (see \[3\] for more details).

**POLARIZED PARTON DENSITIES AND HIGHER TWIST**

Let us start our discussion with the impact of the COMPASS \[6\] and CLAS \[7\] inclusive DIS data on the *longitudinal* polarized PDFs and higher twist effects. The precise
FIGURE 1. Comparison of HT terms in $g_1$ and $F_1$ (left). HT effects for protons and neutrons (right).

FIGURE 2. Impact of CLAS and COMPASS data on the uncertainties for NLO$(\overline{\text{MS}})$ polarized PDFs.

CLAS data on $g_1^p/F_1^p$ and $g_1^d/F_1^d$ are data at low $Q^2(1−4\ GeV^2)$ while COMPASS has presented data on $A_1^d$ mainly at large $Q^2$ and very small $x$ (0.004 $\leq x \leq$ 0.02), the only precise data at such small $x$. Compared to the HT values obtained in the LSS’05 analysis [8], the uncertainties in the HT values at each $x$ in the CLAS region ($x \sim 0.1–0.6$) are significantly reduced by the CLAS data, as seen in Fig. 1 (right). As expected, the central values of the polarized PDFs are practically not affected by the CLAS data. This is a consequence of the fact that at low $Q^2$ the deviation from logarithmic in $Q^2$ pQCD behaviour of $g_1$ is accounted for by the higher twist term in $g_1$. The accuracy of the determination of polarized PDFs, however, is essentially improved. This improvement is illustrated in Fig. 2 (red curves). It is a consequence of the much better determination
of higher twist contribution in $g_1$, as discussed above. The impact of COMPASS data on the PDFs uncertainties is also shown in Fig. 2 (the blue curves). As seen, they help to improve in addition the accuracy of the determination of the gluon and strange sea quark polarized densities at $x < 0.2$ and $x < 0.1$, respectively. Another important effect of COMPASS data (see [3] and slides of Stamenov’s talk at this Symposium [9]) is that $\Delta s(x)$ and respectively, $\Delta \Sigma(x)$, are less negative at $x$ smaller than 0.1.

The present inclusive DIS data cannot distinguish between positive, negative and sign-changing $\Delta G(x)$ (see Fig. 3 (left)). In all the cases the magnitude of $\Delta G$ is small: $|\Delta G| < 0.4$ and the corresponding polarized quark densities are very close to each other. COMPASS analysis finds also a negative $\Delta G(x)$, but has some peculiarities which suggest it is not physical. Also, we have found that if in the input gluon parametrization a term $(1 + \gamma x)$ is added, where $\gamma$ is a free parameter to be determined from the fit to the data, a negative $\Delta G$ solution is impossible. So, although the negative $\Delta G$ cannot be formally ruled out by the data, it seems to be not reasonable.

A primary goal of the RHIC spin program is to determine the gluon polarization. There are two sources of information: $p + \bar{p} \rightarrow \pi^0(\pi^+/-) + X, \ p + \bar{p} \rightarrow jet + X$. We will mention here the combined QCD analysis of the inclusive DIS and RHIC $\pi^0$-production data [10] which has been recently performed by AAC [11]. Two solutions for $\Delta G(x)$, positive and node, have been found with values for the first moments at $Q^2 = 1 GeV^2$: $\Delta G = 0.40 +/- 0.28$ and $-0.12 +/- 1.78$, respectively. Note that for the node $\Delta G(x)$ solution the positivity condition $\Delta G(x) \leq G(x)$ is broken for $x \geq 0.4$, which makes it questionable. For more details about the possibilities of the RHIC data to constrain the gluon polarization $\Delta G$ see the talks presented by STAR and PHENIX Collaborations at this Symposium [9]. The main conclusion is that the magnitude of $\Delta G$ is smaller than 0.4, but the present RHIC data cannot determine the form of the gluon density $\Delta G(x)$.

In Fig. 3(right) we compare the polarized gluon densities obtained by different QCD analyses (divided by the MRST'02 version of the unpolarized gluon density $G(x)$) with directly measured values of $\Delta G(x)/G(x)$ at $\mu^2 = 3 GeV^2$. One can see from Fig. 3(right) that the most precise values of $\Delta G/G$, the COMPASS ones [12], are well consistent with
most of the polarized gluon densities determined in the recent QCD analysis, and one conclude that the present high \( p_t \) measurements cannot distinguish between the different scenarios for \( \Delta G(x) \).

It seems clear that present day data cannot distinguish between the three scenarios for \( \Delta G(x) \). A clean distinction would be possible in the Electron-Ion Collider [13] where very precise measurements of \( g_1^p(x,Q^2) \) at very small \( x \) (\( x \geq 0.00075 \)) could be performed. Fig. 4 shows \( g_1^p(x,Q^2) \), calculated using the LSS’06 PDFs corresponding to positive and negative \( \Delta G(x) \). There is a dramatic difference at small \( x \).

Very recently the DSSV group has presented results on polarized PDFs [14] obtained from the first global analysis of the polarized DIS, SIDIS and RHIC polarized pp scattering data. Due to the SIDIS data a flavor decomposition of the polarized sea is achieved. This analysis yields changing in sign \( \Delta \bar{s}(x,Q^2) \): positive for \( x > 0.03 \) and negative for small \( x \) (see Fig. 5). Its first moment is negative (fixed in practice by the SU(3) symmetric value of \( a_8 \)) and almost identical with that obtained in the inclusive DIS analysis. It was shown in the talk by R. Windmolders at this Symposium [9] that the determination of \( \Delta \bar{s}(x) \) from SIDIS strongly depends on the fragmentation functions (FFs) and that for such an unexpected behavior of \( \Delta \bar{s}(x) \) the new FFs [15] are crucial. So, the model independent extraction of FFs is very important. The NLO(\( \overline{\text{MS}} \)) PDFs determined from analyses of different sets of data: LSS’06 (inclusive DIS data), AAC’08 (inclusive DIS and RHIC \( \pi^0 \)-production data), DSSV (DIS, SIDIS and RHIC data) are compared in Fig. 5. Note that in the LSS analysis the HT corrections have been taken into account while AAC’08 and DSSV have used the second method described above (without account for HT terms). Although the first moments are almost identical, the quark densities themselves are different, especially \( \Delta \bar{s}(x) \). Note that all analyses of the inclusive DIS data yield \( \Delta \bar{s}(x) \) negative. So, the DSSV result on \( \Delta \bar{s}(x) \) is a big challenge for our understanding of spin properties of the nucleon. We would like to emphasize also that the very accurate DIS data in the preasymptotic region require a more precise confrontation of QCD to the data, as was already mentioned in the Introduction. Otherwise, the results on PDFs will differ. A comment on an incorrect confrontation of QCD to the inclusive DIS data in the DSSV analysis is presented in Stamenov’s talk [9] at this Meeting.

**FIGURE 4.** \( g_1^p \) at different \( Q^2 \) calculated using the LSS’06 PDFs corresponding to \( \Delta G > 0 \) and \( \Delta G < 0 \).
Let us finally discuss the present status of the proton spin sum rule. Using the values for $\Delta \Sigma(Q^2)$ and $\Delta G(Q^2)$ at $Q^2 = 4 \text{ GeV}^2$ obtained in LSS’06 analysis\cite{3} one can find for the spin of the proton (the numbers in brackets correspond to node $\Delta G$):

$$S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma(Q^2) + \Delta G(Q^2) + L_z(Q^2) = 0.55(0.15) \pm 0.25(0.49) + L_z(Q^2). \tag{5}$$

Although the central values of parton contribution are very different in the two cases, in view of the big uncertainty in (5) coming mainly from the gluons, one cannot make a definite conclusion about the quark-gluon contribution in the spin of the nucleon.

**REFERENCES**

1. E. Leader, A.V. Sidorov, and D.B. Stamenov, Phys. Rev. D 67, 074017 (2003).
2. M. Glück, E. Reya, M. Stratmann, and W. Vogelsang, Phys. Rev. D 63, 094005 (2001).
3. E. Leader, A.V. Sidorov, and D.B. Stamenov, Phys. Rev. D 75, 074027 (2007).
4. S.I. Alekhi, Phys. Rev. D 68, 014002 (2003).
5. J. Blumlein, H. Bottcher, Nucl. Phys. B 636, 225 (2002); AAC, M. Hirai et al., Phys. Rev. D 69, 054021 (2004).
6. V.Y. Alexakhin et al. (COMPASS Collaboration), Phys. Lett. B 647, 8 (2007).
7. K.V. Dharmwardane et al. (CLAS Collaboration), Phys. Lett. B 641, 11 (2006).
8. E. Leader, A.V. Sidorov, and D.B. Stamenov, Phys. Rev. D 73, 034023 (2006).
9. Parallel Longitudinal Spin Session, http://spreadsheets.google.com/pub?key=pqhuBYtsrrUuuVad8k4TSA
10. A. Adare et al. (PHENIX Collaboration), Phys. Rev. D 76, 051106 (2007).
11. M. Hirai and S. Kumano, arXiv:0808.0413 [hep-ph].
12. See the talk presented by K.Kurek at this Symposium.
13. EIC Collaboration, http://web.mit.edu/eicc/Documentation.html.
14. D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. 101, 072001 (2008).
15. D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. D 75, 114010 (2007); D 76, 074033 (2007).