PROGRESS IN THE DETERMINATION OF POLARIZED PDFs AND HIGHER TWIST

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Abstract

The impact of the recent very precise CLAS and COMPASS $g_1/F_1$ data on polarized parton densities and higher twist effects is discussed. It is demonstrated that the low $Q^2$ CLAS data improve essentially our knowledge of higher twist corrections to the spin structure function $g_1$, while the large $Q^2$ COMPASS data influence mainly the strange quark and gluon polarizations. It is also shown that the uncertainties in the determination of the polarized parton densities are significantly reduced. We find also that the present inclusive DIS data cannot rule out a negative polarized and changing in sign gluon densities. The present status of the proton spin sum rule is discussed.

1 Introduction

One of the features of polarized DIS is that a lot of the present data are in the preasymptotic region ($Q^2 \sim 1-5 \text{ GeV}^2$, $4 \text{ GeV}^2 < W^2 < 10 \text{ GeV}^2$). This is especially the case for the experiments performed at the Jefferson Laboratory. As was shown in [1], to confront correctly the QCD predictions to the experimental data including the preasymptotic region, the non-perturbative higher twist (powers in $1/Q^2$) corrections to the nucleon spin structure functions have to be taken into account too.

In this talk we discuss the impact of the recent very precise CLAS [2] and COMPASS [3] inclusive polarized DIS data on the determination of both the longitudinal polarized parton densities (PDFs) in the nucleon and the higher twist (HT) effects. These experiments give important information about the nucleon structure in quite different kinematic regions. While the CLAS data entirely belong to the preasymptotic region and as one can expect they should mainly influence the higher twist effects, the COMPASS data on the spin asymmetry $A_1^d$ are large $Q^2$ data and they should affect mainly the polarized parton densities. In addition, due to COMPASS measurements we have for the first time accurate data at small $x$ ($0.004 < x < 0.015$), which allow to determine the behavior of the PDFs at small $x$ region and therefore to calculate more precisely the first moment of the nucleon spin structure $g_1$. 
2 NLO QCD analysis of the data

The method used to extract simultaneously the polarized parton densities and higher twist corrections to the spin-dependent nucleon structure function $g_1$ is described in [1]. According to this method, the $g_1/F_1$ and $A_1(\approx g_1/F_1)$ data have been fitted using the experimental data for the unpolarized structure function $F_1(x,Q^2)$

$$\frac{g_1(x,Q^2)}{F_1(x,Q^2)}_{\text{exp}} \Leftrightarrow \frac{g_1(x,Q^2)_{\text{LT}} + h(x)/Q^2}{F_1(x,Q^2)_{\text{exp}}}.$$ (1)

As usual, $F_1$ is replaced by its expression in terms of the usually extracted from unpolarized DIS experiments $F_2$ and $R$ and the phenomenological parametrizations of the experimental data for $F_2(x,Q^2)$ [4] and the ratio $R(x,Q^2)$ of the longitudinal to transverse $\gamma N$ cross-sections [5] are used. Note that such a procedure is equivalent to a fit to $(g_1)_{\text{exp}}$, but it is more precise than the fit to the $g_1$ data themselves actually presented by the experimental groups because here the $g_1$ data are extracted in the same way for all of the data sets.

In Eq. (1) "LT" denotes the leading twist contribution to $g_1$

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

where $g_1(x,Q^2)_{\text{pQCD}}$ is the well known (logarithmic in $Q^2$) NLO pQCD contribution

$$g_1(x,Q^2)_{\text{pQCD}} = \frac{1}{2} \sum_q e_q^2 \frac{((\Delta q + \Delta \bar{q}) \otimes (1 + \frac{\alpha_s(Q^2)}{2\pi} \delta C_q) + \frac{\alpha_s(Q^2)}{2\pi} \Delta G \otimes \frac{\delta C_G}{N_f}},$$ (3)

and $h^{\text{TMC}}(x,Q^2)$ are the calculable kinematic target mass corrections [6], which effectively belong to the LT term. In Eq. (3), $\Delta q(x,Q^2)$, $\Delta \bar{q}(x,Q^2)$ and $\Delta G(x,Q^2)$ are quark, antiquark and gluon polarized densities in the proton, which evolve in $Q^2$ according to the spin-dependent NLO DGLAP equations. $\delta C(x)_{q,G}$ are the NLO spin-dependent Wilson coefficient functions and the symbol $\otimes$ denotes the usual convolution in Bjorken $x$ space. $N_f$ is the number of active flavors ($N_f = 3$ in our analysis). $h(x)/Q^2$ in Eq. (1) corresponds to the first term in the $(\Lambda^2_{QCD}/Q^2)^n$ expansion of higher twist contribution to $g_1$. Its logarithmic $Q^2$ dependence, which is not known in QCD, is neglected. Compared to the principal $1/Q^2$ dependence it is expected to be small and the accuracy of the present data does not allow its determination. Therefore, the extracted from the data values of $h(x)$ correspond to the mean $Q^2$ for each $x$-bean.

Let us discuss now how inclusion of the CLAS EG1 proton and deuteron $g_1/F_1$ data [2] and the new COMPASS data on $A_1^d$ [3] influence our previous results [7] on polarized PDFs and higher twist obtained from the NLO QCD fit to the world data [8], before the CLAS and the latest COMPASS data were available.

3 Impact of the new data on polarized PDFs and HT

The new CLAS EG1/p, d data on $g_1/F_1$ (633 experimental points) [2] and the recent COMPASS data on the longitudinal asymmetry $A_1^d$ (15 experimental points) [3] are at very different kinematic regions. While the CLAS data are high-precision data at low
$Q^2: \{x \sim 0.1 - 0.6, \ Q^2 \sim 1 - 5 \text{ GeV}^2, \ W > 2 \text{ GeV}\}$, the COMPASS data are mainly at large $Q^2: \{0.0046 \leq x \leq 0.57, \ Q^2 \sim 1 - 55 \text{ GeV}^2\}$ and the only precise data covering the low $x$ region. Therefore, they will play a different role in the improvement of the determination of the polarized PDFs and higher twist effects. The new PDFs and HT and their uncertainties will be compared with those of LSS’05 determined from our previous analysis of the world data [8] available before the CLAS EG1/p, d and COMPASS’06 data have appeared.

As the CLAS data are mainly low $Q^2$ data where the role of HT becomes important, they should help to fix better the higher twist effects. Indeed, due to the CLAS data, the determination of HT corrections to the proton and neutron spin structure functions, $h^p(x)$ and $h^n(x)$, is significantly improved in the CLAS $x$ region, compared to the values of HT obtained from our LSS’05 analysis [7] in which a NLO(\overline{\text{MS}}) QCD approximation for $g_1(x, Q^2)_{LT}$ was used. This effect is illustrated in Fig. 1. One can conclude now that the HT corrections for the proton target are definitely different from zero and negative in the $x$ region: 0.1-0.4. Also, including the CLAS data in the analysis, the HT corrections for the neutron target are better determined in the $x$ region: 0.2-0.4. Note that $h^n(x)$ at $x \sim 0.5$ was already fixed very precisely from the JLab Hall A data on the ratio $g_1^{(n)}/F_1^{(n)}$. We have found that the impact of the COMPASS’06 data on the values of higher twist corrections and their uncertainties is negligible. The only exception are the central values of HT at small $x$ for both the proton and the neutron targets which are slightly lower than the old ones. Note that this is the only region where the COMPASS DIS events are at small $Q^2$: 1-4 GeV$^2$.

The effect of the new data on the polarized PDFs and their uncertainties is demonstrated in Figures 2 and 3, respectively. The central values of both the $(\Delta u + \Delta \bar{u})$ and $(\Delta d + \Delta \bar{d})$ parton densities do not change in the experimental region (the corresponding LSS’06 curves can not be distinguished from those of LSS’05). As one can see from Fig. 2 the new data influence only the polarized gluon and strange quark sea densities (while the magnitude of strange sea decreases at $x < 0.1$, the gluon density increases at $x > 0.1$). As expected, the central values of the polarized PD 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 $g_1$ in Eq. (1). So, the change of the central values of the polarized gluon and strange quark sea densities is entirely due to the new COMPASS data. On the contrary, the accuracy of the determination of polarized PDFs is essentially improved due to the CLAS data (the dashed curves in Fig. 3). This improvement is a consequence of the much better determination of higher twist contributions to the spin structure function $g_1$, as discussed above. The impact of COMPASS data on the uncertainties for the PDFs is also shown in Fig. 3 (the solid curves). As seen, they help to improve in addition the accuracy of the
Figure 2. Effect of new data on the NLO($\overline{\text{MS}}$) polarized parton densities.

Figure 3. Impact of GLAS and COMPASS data on the uncertainties for NLO($\overline{\text{MS}}$) polarized PDFs.
Figure 4. Expected uncertainties for NLO(\overline{\text{MS}}) polarized PDFs after including the data set to be collected with CLAS12 experiment including statistical and systematic errors.

determination of the gluon and strange sea quark polarized densities at small \( x \): \( x < 0.2 \) for the gluons and \( x < 0.1 \) for the strange sea.

An essential further improvement (the dashed lines in Fig. 4) can be achieved after including in the analysis the data set to be collected with CLAS12 experiment [9] planned to be performed using a 12 GeV electron beam at Jefferson Laboratory, USA.

At the end of this Section we would like to mention that all results on the PDFs presented here have been obtained when 5 \( x \)-bins have been used to extract the HT values. Due to the good accuracy of the CLAS data, one can split the measured \( x \) region of the world data set into 7 bins instead of 5, as used up to now, and therefore, can determine more precisely the \( x \)-dependence of the HT corrections to \( g_1 \). The numerical results of the best fit to the data using 7 \( x \)-bins are presented in [10]. It is important to emphasize that the central values for the PDFs(5 bins) and PDFs(7 bins) excepting the gluons are very close to each other. However, the uncertainties for the PDFs(5 bins) are smaller than those for PDFs(7 bins), especially for \( \Delta s(x) \) and \( \Delta G(x) \). That is why we prefer to present here the PDFs and there uncertainties corresponding to 5 bins in \( x \) using for the HT values.

4 The sign of the gluon polarization

We have observed also that the present inclusive DIS data cannot rule out the solutions with negative and changing in sign gluon polarizations (see Fig 5a). The shape of the negative gluon density differs from that of positive one. In all the cases the magnitude of \( \Delta G \) (the first moment of the gluon density) is small: \( |\Delta G| \leq 0.4 \) and the corresponding
polarized quark densities \((\Delta u + \Delta \bar{u})\) and \((\Delta d + \Delta \bar{d})\) are very close to each other. The corresponding strange sea densities are shown in Fig. 5b. Note, however, that the uncertainties for PDFs corresponding to the solution with \(\Delta G < 0\) are larger than those in the case of \(\Delta G > 0\) (for more details see [10]). In Fig. 6 the ratio \(\Delta G(x)/G(x)\) calculated for the different \(\Delta G(x)\) obtained in our analysis and using \(G(x)_{\text{MRST'}02}\) [11] for the unpolarized gluon density, is compared to the existing direct measurements of \(\Delta G(x)/G(x)\). The error band correspond to statistic and systematic errors of \(\Delta G(x)\). The most precise value for \(\Delta G/G\), the COMPASS one, is well consistent with any of the polarized gluon densities determined in our analysis. One can see from Fig. 6 that in order to choose between gluons with positive and negative polarization direct measurements of \(\Delta G(x)\) at large \(x\): \(x > 0.3\) are needed.

5 The proton spin sum rule and spin puzzle

Using the values for the singlet and gluon polarizations \(\Delta \Sigma(Q^2)\) and \(\Delta G(Q^2)\) at \(Q^2 = 1 \text{ GeV}^2\) obtained in our analysis (\(\overline{\text{MS}}\) scheme): \(\Delta \Sigma = 0.207 \pm 0.039\) and \(\Delta G = 0.237 \pm 0.153\) we have found the following value for the spin of the proton at \(Q^2 = 1 \text{ GeV}^2\):

\[
S_z = \frac{1}{2} = \frac{1}{2} \Delta \Sigma(Q^2) + \Delta G(Q^2) + L_z(Q^2) = 0.34 \pm 0.15 + L_z(Q^2). \tag{4}
\]

So, in order to satisfy the proton spin sum rule (4) the sum of the quark and gluon orbital angular momentum \(L_z = L_z^q + L_z^g\) should be different from zero and positive. Note that the quark orbital momentum \(L_z^q\) will be determined soon from the data using the forward extrapolation of the generalized paron densities (GPD).

Let us finally discuss the so called "spin puzzle" - the discrepancy between the values of the singlet polarization \(\Delta \Sigma\): 0.2-0.3 in the DIS region and 0.6 at low \(Q^2 (Q^2 \sim \Lambda_{\text{QCD}}^2)\) (see Fig. 7a). For better understanding of the situation it is useful to use the JET factorization scheme [12], in which \(\Delta \Sigma(Q^2)\) does not depend on \(Q^2\). Then, in this scheme it is meaningful to directly interpret the singlet polarization \(\Delta \Sigma\) as the contribution of the quark spins to the nucleon spin and to compare its values obtained in the DIS and low \(Q^2\) regions. The value of \(\Delta \Sigma_{\text{JET}}\) obtained in our LSS’06 analysis of the DIS data is

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**Figure 5.** Strange quark sea densities \(x\Delta s(x)\) corresponding to the fits with \(\Delta G > 0, \Delta G < 0\) and changing in sign \(x\Delta G\).
0.26 ± 0.08.

On the other hand the well known value of 0.6 for
\( \Delta \Sigma(Q^2 \sim \Lambda^2_{QCD}) = \Delta u_v + \Delta d_v + \Delta q_{\text{sea}} \) is predicted in the relativistic constituent quark model (CQM) [13]. However, this model does NOT account for the vacuum (quark sea) polarization. It was qualitatively shown in the instanton models [14, 15] that due to the non-perturbative vacuum spin effects the contribution of the sea quark polarization to \( \Delta \Sigma \) is negative. So, the value of \( \Delta \Sigma \) in the non-perturbative region \( (Q^2 \sim \Lambda^2_{QCD}) \) is really smaller than 0.6. Also, it was found from a combined analysis of forward scattering parity-violating elastic \( \vec{e}p \) asymmetry data from G0 and HAPPEx experiments at JLab, and elastic \( \nu p \) and \( \bar{\nu} p \) scattering data from Experiment 734 at BNL, that the strange axial form factor \( G_A^S(Q^2) \), which is strongly related with \( \Delta s \) \( (G_A^S(Q^2 = 0) = \Delta s) \), is negative in the region \( 0.4 < Q^2 < 1 \text{ GeV}^2 \) [16] (see Fig. 7b), i.e there is a strong indication that the strange quark contribution to \( \Delta \Sigma \) at low \( Q^2 \) is negative. In conclusion, we are very close to the solution of the so called ”spin puzzle”.

**Conclusion**

We have studied the impact of the CLAS and latest COMPASS data on the polarized parton densities and higher twist contributions. It was demonstrated that the inclusion of the low \( Q^2 \) CLAS data in the NLO QCD analysis of the world DIS data improves essentially our knowledge of HT corrections to \( g_1 \) and does not affect the central values of PDFs, while the large \( Q^2 \) COMPASS data influence mainly the strange quark and gluon polarizations, but practically do not change the HT corrections. The uncertainties in the

![Figure 6](image6.png)

**Figure 6.** Comparison between the experimental data and NLO(MS) curves for the gluon polarization \( \Delta G(x)/G(x) \) at \( Q^2 = 3 \text{ GeV}^2 \) corresponding to \( \Delta G > 0 \), \( \Delta G < 0 \) and an oscillating-in-sign \( x \Delta G \).

![Figure 7](image7.png)

**Figure 7.** A possible explanation of the nucleon’s spin puzzle (a). Results of analysis for the strange axial form factor of the proton (b).
determination of polarized parton densities is significantly reduced due to both of the data sets. These results strongly support the QCD framework, in which the leading twist pQCD contribution is supplemented by higher twist terms of $O(\Lambda_{QCD}^2/Q^2)$.

Finally, one of the important messages coming from this analysis is that it is impossible to describe the very precise CLAS data if the HT corrections are not taken into account. Note that if the low $Q^2$ data are not too accurate, it would be possible to describe them using only the leading twist term in $g_1$ (logarithmic in $Q^2$), i.e. to mimic the power in $Q^2$ dependence of $g_1$ with a logarithmic one (using different forms for the input PDFs and/or more free parameters associated with them) which was done in the analyses of another groups before the CLAS data were available.

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