Determination of polarized PDFs from a QCD analysis of inclusive and semi-inclusive Deep Inelastic Scattering data

Elliot Leader*
Imperial College, Prince Consort Road, London SW7 2BW, England.

Aleksander V. Sidorov†
Bogoliubov Theoretical Laboratory Joint Institute for Nuclear Research 141980 Dubna, Russia.

Dimiter B. Stamenov‡
Institute for Nuclear Research and Nuclear Energy
Bulgarian Academy of Sciences Blvd. Tsarigradsko Chaussee 72, Sofia 1784, Bulgaria

Abstract

A new combined NLO QCD analysis of the polarized inclusive and semi-inclusive DIS data is presented. In contrast to previous combined analyses, the $1/Q^2$ terms (kinematic - target mass corrections, and dynamic - higher twist corrections) in the expression for the nucleon spin structure function g_1 are taken into account. The new COMPASS data are included in the analysis. The impact of the semi-inclusive data on the polarized parton densities (PDFs) and on the higher twist corrections is discussed. The new results for the PDFs are compared to both the LSS'06 PDFs, obtained from the fit to the inclusive DIS data alone, and to those obtained from the DSSV global analysis.

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I. INTRODUCTION

Experiments on polarized inclusive deep inelastic lepton-hadron scattering (DIS), reactions of the type $l+p \rightarrow l'+X$ with both polarized lepton and hadron, because of the non-existence of neutrino data, can only, in principle yield information on the sum of quark and antiquark parton densities i.e. information on the polarized densities $\Delta u + \Delta \bar{u}$, $\Delta d + \Delta \bar{d}$, $\Delta s + \Delta \bar{s}$ and ΔG.

Information about the antiquark densities $\Delta \bar{u}$, $\Delta \bar{d}$ and the separate Δs and $\Delta \bar{s}$ strange densities thus has to be extracted from other reactions, notably polarized semi-inclusive lepton-hadron reactions (SIDIS) $l+p \rightarrow l'+h+X$, where h is a detected hadron in the final state, or from semi-inclusive hadronic scattering (SIHS) like $p+p \rightarrow h+X$, involving polarized protons, and only possible at the RHIC collider at Brookhaven National Laboratory.

QCD analyses of polarized DIS data, at next to leading order accuracy, have been carried out for some decades (for more recent analyses see [1, 2]), but it was only in 2008 that de Florian, Sassot , Strattmann and Vogelsang (DSSV), in a ground-breaking paper [3], carried out a combined analysis of polarized DIS, SIDIS and SIHS, at NLO accuracy.

The technical problems involved in going from an analysis of DIS to such a combined analysis are formidable. In this paper we extend our study of polarized DIS to a joint analysis of the world data on DIS and SIDIS reactions.

In contrast to the situation in unpolarized DIS, a large portion of the most accurate data on polarized DIS lie in a kinematical region where Target Mass Corrections (TMC) of order M^2/Q^2 (whose form is exactly known), and dynamical Higher Twist (HT) corrections of order Λ^2_{QCD}/Q^2 are important. We have thus included such terms in our description of the DIS data. However, for the SIDIS data, we do not know the analogous results at present, so do not include such terms. As it happens almost all the SIDIS data we utilize are in kinematic regions where such corrections should not be important.

Despite the fact that it has been emphasized in the literature for more than a decade that DIS data can only, in principle, yield information on the sum of quark and antiquark densities, some analyses of purely inclusive DIS continue to show results for valence densities, under what are termed *assumptions* about the sea-quark densities $\Delta \bar{u}(x)$ and $\Delta \bar{d}(x)$. It is important to realize that these are not really physical assumptions, but merely conventions. In contrast, it is important to note that although we tend to think of the strange quark density as a sea-quark density, $\Delta s(x) + \Delta \bar{s}(x)$ is fully determined by the purely inclusive DIS data. This is particularly important because of the apparent incompatibility of the polarized strange quark density obtained from DIS and from SIDIS data, as will be discussed in detail later.

In this paper we present the results of our NLO QCD analysis of polarized inclusive and semi-inclusive DIS data. Our analysis differs from DSSV in the following respects:

(i) We have included new data from the COMPASS group at CERN, which were not available in 2008.

(ii) We are more careful in handling the kinemat-

*Electronic address: e.leader@imperial.ac.uk
†Electronic address: sidorov@theor.jinr.ru
‡Electronic address: stamenov@inrne.bas.bg

ics and include target mass corrections and higher twist terms in the DIS sector of our analysis.

(iii) Our parametrization of the parton densities is similar to that of DSSV, but differs in some important aspects, as will be explained in detail in Section III.

II. QCD FRAMEWORK FOR INCLUSIVE AND SEMI-INCLUSIVE POLARIZED DIS

A. Inclusive DIS

One of the features of polarized DIS is that more than half of the present data are at moderate Q^2 and W^2 ($Q^2 \sim 1-5$ GeV^2, 4 GeV$^2 <$ W$^2 <$ 10 GeV^2), or in the so-called *preasymptotic* region. This is especially the case for the very precise experiments performed at the Jefferson Laboratory. So, in contrast to the unpolarized case this region cannot be excluded from the analysis. As was shown in [4], 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 QCD the spin structure function g_1 has the following form for $Q^2 >> \Lambda^2$ (the nucleon target label N is not shown) :

$$g_1(x,Q^2) = g_1(x,Q^2)_{\rm LT} + g_1(x,Q^2)_{\rm HT}\ , \qquad (1)$$

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 $\tau \geq 3$.

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

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

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

and $h^{\rm TMC}(x,Q^2)$ are the exactly calculable kinematic target mass corrections [5], which, being purely kinematic, 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, anti-quark 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). In addition to the LT contribution, the dynamical higher twist effects

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

must be taken into account at low Q^2. The latter are non-perturbative effects and cannot be calculated in a model independent way. That is why we prefer to extract them directly from the experimental data. The method used to extract simultaneously the polarized parton densities and higher twist corrections to g_1 from data on g_1/F_1 and $A_1(\approx g_1/F_1)$, is described in [4]. Accordingly the g_1/F_1 data have been fitted using the experimental data for the unpolarized structure function $F_1(x,Q^2)$

$$\left[\frac{g_1(x,Q^2)}{F_1(x,Q^2)}\right]_{exp} \Leftrightarrow \frac{g_1(x,Q^2)_{\rm LT} + h(x)/Q^2}{F_1(x,Q^2)_{exp}}\ . \qquad (5)$$

As usual, F_1 is replaced by its expression in terms of the usually extracted from unpolarized DIS experiments F_2 and R. As in our previous analyses, the phenomenological parametrizations of the experimental data for $F_2(x,Q^2)$ [6] and the ratio $R(x,Q^2)$ of the longitudinal to transverse γN cross-sections [7] are used. Note that such a procedure is equivalent to a fit to $(g_1)_{exp}$, 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. Note also, that in our analysis the logarithmic Q^2 dependence of $h(x,Q^2)$ in Eq. (5), 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.

B. Semi-inclusive DIS

As in the inclusive DIS case, the measured double spin asymmetries A_{1N}^h for the polarized semi-inclusive deep inelastic scattering, $\vec{l}+\vec{N} \to l+h+X$, where in addition to the scattered lepton, hadron h is also detected, can be presented by the ratio of the spin structure functions g_{1N}^h and g_{2N}^h, and the unpolarized structure function F_{1N}^h

$$A_{1N}^h(x,z,Q^2) = \frac{g_{1N}^h(x,z,Q^2) - \gamma^2 g_{2N}^h(x,z,Q^2)}{F_{1N}^h(x,z,Q^2)}, \qquad (6)$$

where x is the Bjorken variable, $z = (p_h.p_N)/(p_N.q)$ is the fractional energy of the hadrons in the c.m.s. frame of the nucleon and the virtual photon, and q is the usual notation for the photon four-momentum ($-q^2 = Q^2$). In (6) the index N is used for the different targets and in what follows it will be suppressed. Note also that in (6) the contribution of the spin structure function g_2^h to the asymmetry A_1^h can be neglected by two reasons. First, although g_2^h is not measured yet, it is expected to be small as in the inclusive DIS case. And second, the g_2^h term is multiplied by a factor $\gamma^2 = 4M^2x^2/Q^2$ which in the kinematic region of the present SIDIS experiments is negligible.

For the time being it is not known how to account for the HT and TMC corrections in SIDIS processes. Fortunately, they should be less important due to the kinematic region and the accuracy of the present SIDIS data. So, in our QCD analysis we will use the approximate equation

$$A_{1N}^h(x,z,Q^2) = \frac{g_{1N}^h(x,z,Q^2)_{NLO}}{F_{1N}^h(x,z,Q^2)_{NLO}}, \tag{7}$$

In NLO QCD the structure functions g_1^h and F_1^h have the following forms

$$\begin{aligned} 2g_1^h(x,z,Q^2) &= \sum_{q,\bar{q}}^{n_f} e_q^2 \Bigg\{ \Delta q(x,Q^2) D_q^h(z,Q^2) \\ &+ \frac{\alpha_s(Q^2)}{2\pi} \Big[\Delta q \otimes \Delta C_{qq}^{(1)} \otimes D_q^h \\ &+ \Delta q \otimes \Delta C_{gq}^{(1)} \otimes D_g^h \\ &+ \Delta g \otimes \Delta C_{qg}^{(1)} \otimes D_q^h \Big] (x,z,Q^2) \Bigg\}, \end{aligned} \tag{8}$$

$$\begin{aligned} 2F_1^h(x,z,Q^2) &= \sum_{q,\bar{q}}^{n_f} e_q^2 \Bigg\{ q(x,Q^2) D_q^h(z,Q^2) \\ &+ \frac{\alpha_s(Q^2)}{2\pi} \Big[q \otimes C_{qq}^{(1)} \otimes D_q^h \\ &+ q \otimes C_{gq}^{(1)} \otimes D_g^h \\ &+ g \otimes C_{qg}^{(1)} \otimes D_q^h \Big] (x,z,Q^2) \Bigg\}. \end{aligned} \tag{9}$$

In Eqs. (8) and (9) $\Delta C_{ij}^{(1)}(x,z)$ and $C_{ij}^{(1)}(x,z)$ are the NLO partonic coefficient functions in the $\overline{\rm MS}$ scheme collected in [8]. $D_{q,\bar{q}}^h$, D_g^h are the fragmentation functions for quarks, anti-quarks and gluons, and n_f is the number of active flavors ($n_f = 3$ in our present analysis).

C. Method of analysis

In our previous analyses of the inclusive DIS data the inverse Mellin transformation method has been used to calculate the spin structure function $g_1(x,Q^2)$ from its moments. The *double* Mellin transform technique was developed by Stratmann and Vogelsang and first applied in the NLO QCD analysis of SIDIS data [9]. We have used it to calculate the structure functions $g_1^h(x,Q^2)$ and $F_1^h(x,Q^2)$ from their moments. The expressions for the moments of the coefficient functions $\Delta C_{ij}^{(1)}(x,z)$ and $C_{ij}^{(1)}(x,z)$ needed in these calculations can been found in [9]. For the unpolarized parton densities we use the NLO MRST'02 PDFs [10], and for the fragmentation functions, the NLO DSS set [11] for pions, kaons and unindentified hadrons.

Compared with our previous fits to the inclusive DIS data only (for example, see [2]) we use now a more general parametrization for the input NLO polarized parton densities at $Q_0^2 = 1\ GeV^2$. It has the form for $(\Delta u + \Delta\bar{u})$ and $(\Delta d + \Delta\bar{d})$

$$\begin{aligned} x(\Delta u + \Delta\bar{u})(x,Q_0^2) &= A_{u+\bar{u}} x^{\alpha_{u+\bar{u}}} (1-x)^{\beta_{u+\bar{u}}} \\ & \quad (1 + \epsilon_{u+\bar{u}}\sqrt{x} + \gamma_{u+\bar{u}} x), \\ x(\Delta d + \Delta\bar{d})(x,Q_0^2) &= A_{d+\bar{d}} x^{\alpha_{d+\bar{d}}} (1-x)^{\beta_{d+\bar{d}}} \\ & \quad (1 + \epsilon_{d+\bar{d}}\sqrt{x} + \gamma_{d+\bar{d}} x), \end{aligned} \tag{10}$$

and

$$\begin{aligned} x\Delta\bar{u}(x,Q_0^2) &= A_{\bar{u}} x^{\alpha_{\bar{u}}} (1-x)^{\beta_{\bar{u}}} (1 + \gamma_{\bar{u}} x), \\ x\Delta\bar{d}(x,Q_0^2) &= A_{\bar{d}} x^{\alpha_{\bar{d}}} (1-x)^{\beta_{\bar{d}}} (1 + \gamma_{\bar{d}} x), \\ x\Delta\bar{s}(x,Q_0^2) &= A_{\bar{s}} x^{\alpha_{\bar{s}}} (1-x)^{\beta_{\bar{s}}} (1 + \gamma_{\bar{s}} x), \\ x\Delta G(x,Q_0^2) &= A_G x^{\alpha_G} (1-x)^{\beta_G} (1 + \gamma_G x), \end{aligned} \tag{11}$$

for the polarized sea quarks $\Delta\bar{q}$ and the gluon parton densities. Since the accuracy of the present SIDIS data is not enough to distinguish Δs from $\Delta\bar{s}$, we assume the relation $\Delta s(x) = \Delta\bar{s}(x)$.

As usual, the set of free parameters $\{a_i\}$ in (10) and (11) is reduced by the well known sum rules

$$a_3 = g_A = \mathrm{F} + \mathrm{D} = 1.269 \pm 0.003, \quad [12] \tag{12}$$

$$a_8 = 3\mathrm{F} - \mathrm{D} = 0.585 \pm 0.025, \quad [13] \tag{13}$$

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

$$a_3 = (\Delta u + \Delta\bar{u})(Q^2) - (\Delta d + \Delta\bar{d})(Q^2), \tag{14}$$

$$\begin{aligned} a_8 &= (\Delta u + \Delta\bar{u})(Q^2) + (\Delta d + \Delta\bar{d})(Q^2) \\ & \quad -2(\Delta s + \Delta\bar{s})(Q^2). \end{aligned} \tag{15}$$

The sum rule (12) reflects isospin SU(2) symmetry, whereas (13) is a consequence of the $SU(3)_f$ flavor symmetry treatment of the hyperon β-decays. So, using the constraints (12) and (13) the parameters $A_{\bar{u}}$ and $A_{\bar{d}}$ in (10) can be determined as functions of the another parameters connected with $(\Delta u + \Delta\bar{u})$, $(\Delta d + \Delta\bar{d})$ and $\Delta\bar{s}$. In addition, we assume that the parameters $\alpha_{u+\bar{u}}$ and $\alpha_{d+\bar{d}}$ which control the small x behavior of $(\Delta u + \Delta\bar{u})$ and $(\Delta d + \Delta\bar{d})$ are equal to those of $\Delta\bar{u}$ and $\Delta\bar{d}$, respectively, which is reasonable as sea quarks likely dominate in this region.

The large x behavior of the polarized sea quarks and gluon densities is mainly determined from the positivity constraints

$$|\Delta f_i(x,Q_0^2)| \le f_i(x,Q_0^2), \quad |\Delta \bar{f}_i(x,Q_0^2)| \le \bar{f}_i(x,Q_0^2). \quad (16)$$

The constraints (16) are the consequence of a probabilistic interpretation of the parton densities in the naive parton model, which is still valid in LO QCD. Beyond LO the parton densities are not physical quantities and the positivity constraints on the polarized parton densities are more complicated. They follow from the positivity condition for the polarized lepton-hadron cross-sections $\Delta\sigma_i$ in terms of the unpolarized ones ($|\Delta\sigma_i| \le \sigma_i$) and include also the Wilson coefficient functions. It was shown [14], however, that for all practical purposes it is enough, at the present stage, to consider LO positivity bounds for LO as well as for NLO parton densities, since NLO corrections are only relevant at the level of accuracy of a few percent.

For the unpolarized NLO parton densities on the RHS of (16) we are using the MRST'02 parton densities [10]. In order to guarantee fulfilling of positivity condition we assume the following equation for the parameters β_i which control the large x behavior of the polarized sea quarks and gluons

$$\beta_{\bar{q}} = \beta_G = \beta_{sea(MRST02)} = 7.276. \quad (17)$$

The rest of parameters $\{a_i\} = \{A_i, \alpha_i, \beta_i, \epsilon_i, \gamma_i\}$, as well as the unknown higher twist corrections $h^N(x)$ to g_1^N in (5) have been determined from a simultaneous fit to the DIS and SIDIS data. For the determination of HT the measured x region has been split into 5 bins and to any x-bin two parameters $h_i^{(p)}$ and $h_i^{(n)}$ have been attached [4]. For a deuteron target the relation $h_i^{(d)} = 0.925(h_i^{(p)} + h_i^{(n)})/2$ has been used. So, to the set of parameters $\{a_i\}$ connected with the input polarized PDFs (10, 11), 10 parameters for the HT corrections, $h_i^{(p)}$ and $h_i^{(n)}$, $(i = 1, 2, .., 5)$, have been added.

In the polarized DIS and SIDIS processes the Q^2 range and the accuracy of the data are much smaller than that in the unpolarized case. That is why, in all calculations we have used a fixed value of the NLO QCD parameter $\Lambda_{\overline{\rm MS}}(n_f = 4) = 311$ MeV, which corresponds to $\alpha_s(M_z^2) = 0.1197$, as obtained by the MRST NLO QCD analysis [10] of the world unpolarized data. The value of $\Lambda_{\overline{\rm MS}}$ above is slightly changed from that of MRST02 because the scale dependence of the strong running coupling $\alpha_s(Q^2)$ is calculated using the so-called "Denominator" representation [15]

$$\frac{\alpha_s(Q^2)}{4\pi} = \frac{1}{\beta_0 ln(Q^2/\Lambda^2_{\overline{\rm MS}}) + \frac{\beta_1}{\beta_0} ln\{ln(Q^2/\Lambda^2_{\overline{\rm MS}}) + \frac{\beta_1}{\beta_0^2}\}}, \quad (18)$$

which is a more precise iterative solution of its renormalization group equation at NLO accuracy. In (18) $\beta_0 = 11 - 2n_f/3$, $\beta_1 = 102 - 38n_f/3$ and $\Lambda_{\overline{\rm MS}}(n_f = 3, 4, 5) = 366,\ 311,\ 224$ MeV. The number of active flavors n_f in $\alpha_s(Q^2)$ was fixed by the number of quarks with $m_q^2 \le Q^2$ taking $m_c = 1.43\ GeV$ and $m_b = 4.3\ GeV$.

The advantage of the analytic expression (18) for α_s is that: first, it reproduces with a very good accuracy the numerical solution of the renormalization group equation needed at small Q^2, down to $Q^2 = 1\ GeV^2$, and second, for $Q^2 > 4\ GeV^2$ it practically coincides with the behavior of α_s corresponding to its usual $1/ln(Q^2/\Lambda^2_{\overline{\rm MS}})$-expansion at NLO [12].

III. RESULTS OF ANALYSIS

The numerical results of our global NLO QCD fit to the world inclusive [16–27] and semi-inclusive [25, 28–30] DIS data are presented in Tables I and II. The data used (841 experimental points for DIS and 202 experimental points for SIDIS) cover the following kinematic regions: $\{0.005 \le x \le 0.75,\ \ 1 < Q^2 \le 62\ GeV^2\}$ for DIS and $\{0.005 \le x \le 0.48,\ \ 1 < Q^2 \le 60\ GeV^2\}$ for SIDIS processes. The statistical and systematic errors are added in quadrature.

In Table I the data sets, both for inclusive and semi-inclusive DIS, used in our analysis are listed and the corresponding values of χ^2 obtained from the best fit to the data are presented. As seen from Table I, a good description of the data is achieved for both the inclusive (χ^2_{NrP}=0.85) and semi-inclusive (χ^2_{NrP}=0.90) processes (NrP is the number of corresponding experimantal points). The total value of χ^2_{DF} is 0.88. The quality of the fit to the data is demonstrated in Fig. 1 for some of the SIDIS asymmetries obtained by the HERMES and COMPASS Collaborations.

The values of the parameters attached to the input polarized PDFs obtained from the best fit to the data are presented in Table II. The errors correspond to $\Delta\chi^2 = 1$. Note also that only the experimental errors (statistical and systematic) are taken into account in their calculation. It was impossible to determine from the fit the parameters $\epsilon_{d+\bar{d}}$ and $\gamma_{\bar{d}}$ in Eqs. (10) and (11), respectively, so they were eliminated i.e. put equal to zero. Note that the central value of $\gamma_{\bar{d}}$ obtained from the fits was always positive. So that its elimination does not change the negative behaviour of $x\Delta\bar{d}(x)$ for any x in the measured region.

A. The role of semi-inclusive DIS data in determining the polarized sea quark densities

Let us discuss the impact of semi-inclusive DIS data on the polarized PDFs. Due to SIDIS data a flavor decomposition of the polarized sea is achieved and the light anti-quark polarized densities $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ are determined without any additional assumptions. While $\Delta\bar{d}(x)$ is negative for any x in the measured x region, $\Delta\bar{u}(x)$ is a positive, passes zero around $x = 0.2$ and becomes negative for large x. Sign-changing solutions are also found for the polarized strange sea $\Delta\bar{s}(x)$ and gluon $\Delta G(x)$ densities. The sign-changing behavior for

TABLE I: Data used in our global NLO QCD analysis, the individual χ^2 for each set and the total χ^2 of the fit

experiment	process	N_{data}	χ^2
EMC [16]	DIS(p)	10	4.2
SMC [17]	DIS(p)	12	5.5
SMC [17]	DIS(d)	12	18.0
COMPASS [18]	DIS(p)	15	12.0
COMPASS [19]	DIS(d)	15	8.4
SLAC/E142 [20]	DIS(n)	8	5.8
SLAC/E143 [21]	DIS(p)	28	17.8
SLAC/E143 [21]	DIS(d)	28	39.9
SLAC/E154 [22]	DIS(n)	11	2.6
SLAC/E155 [23]	DIS(p)	24	25.5
SLAC/E155 [24]	DIS(d)	24	16.5
HERMES [25]	DIS(p)	9	5.4
HERMES [25]	DIS(d)	9	6.8
JLab-Hall A [26]	DIS(n)	3	0.3
CLAS [27]	DIS(p)	151	119.9
CLAS [27]	DIS(d)	482	427.9
SMC [28]	SIDIS(p,h^+)	12	18.1
SMC [28]	SIDIS(p,h^-)	12	11.2
SMC [28]	SIDIS(d,h^+)	12	9.4
SMC [28]	SIDIS(d,h^-)	12	13.8
HERMES [25]	SIDIS(p,h^+)	9	5.9
HERMES [25]	SIDIS(p,h^-)	9	5.3
HERMES [25]	SIDIS(d,h^+)	9	10.5
HERMES [25]	SIDIS(d,h^-)	9	4.8
HERMES [25]	SIDIS(p,π^+)	9	9.9
HERMES [25]	SIDIS(p,π^-)	9	5.1
HERMES [25]	SIDIS(d,π^+)	9	8.6
HERMES [25]	SIDIS(d,π^-)	9	19.8
HERMES [25]	SIDIS(d,K^+)	9	6.7
HERMES [25]	SIDIS(d,K^-)	9	5.6
COMPASS [29]	SIDIS(d,h^+)	12	7.6
COMPASS [29]	SIDIS(d,h^-)	12	10.9
COMPASS [30]	SIDIS(d,π^+)	10	2.6
COMPASS [30]	SIDIS(d,π^-)	10	4.5
COMPASS [30]	SIDIS(d,K^+)	10	7.8
COMPASS [30]	SIDIS(d,K^-)	10	13.7
TOTAL:		1043	898.6

$\Delta G(x)$ is not surprising since it was already found from the analysis of the inclusive DIS data alone [2]. On the other hand, on the basis of results from all published analyses of inclusive DIS, we consider the sign-changing solution for $\Delta\bar{s}(x)$ quite puzzling. The central values of the sea quark and gluon polarized densities together with their error bands are presented and compared to those of DSSV (dashed curves) in Fig. 2. The main difference between the LSS and DSSV sets is in the strange sea quark density $\Delta\bar{s}(x)$. Although the first moments are almost equal (-0.054 and -0.055 at $Q^2 = 1\ GeV^2$ for LSS and DSSV, respectively), our $\Delta\bar{s}(x)$ is less negative for $x < 0.03$ and less positive for $x > 0.03$. Note that DSSV have used an additional constraint $\alpha_{\bar{s}} = \alpha_{\bar{d}}$ for the parameters $\alpha_{\bar{s}}$ and $\alpha_{\bar{d}}$ which means a similar small x behavior for the sea quark densities $\Delta\bar{s}(x)$ and$\Delta\bar{d}(x)$. We do not think this assumption is reasonable. The central values of our gluon density and its first moment are rather different from those of DSSV, however they coincide within the errors which are still large in the measured x region.

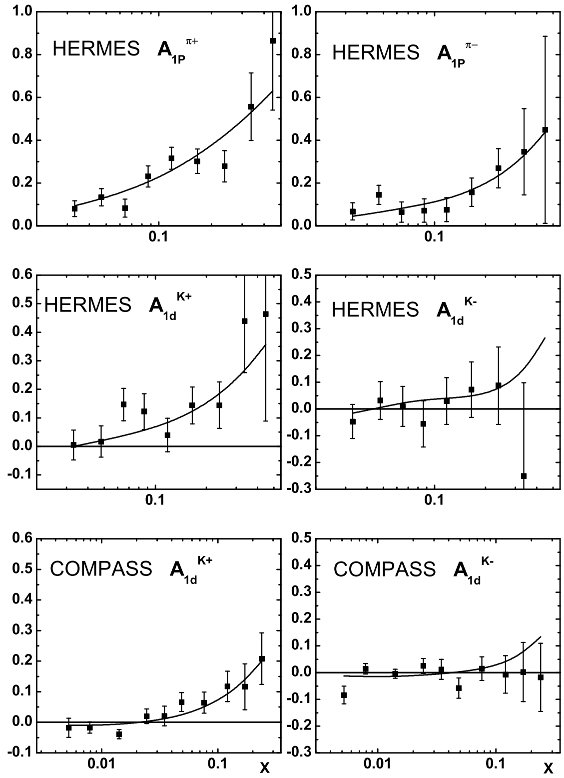

FIG. 1: Comparison of our NLO QCD results for the SIDIS asymmetries with the data at measured x and Q^2.

In Fig. 2 our LSS'06 PDFs (dotted curves) [2] obtained from the NLO QCD analysis of the world inclusive DIS data are presented too. While the light anti-quark polarized densities $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ cannot be, in principle, determined from polarized inclusive DIS data, the sum $(\Delta s + \Delta\bar{s})(x, Q^2)$ *is* well determined and all the NLO QCD analyses yield for this sum a *negative* value for any x in the measured region (for example, see Refs. [1, 2, 31]). In these analyses, however, a term like $(1 + \gamma x)$, which would permit a sign-change, was not included in the input parametrization of $(\Delta s + \Delta\bar{s})(x, Q_0^2)/2$ [32]. We therefore re-analysed the world polarized inclusive DIS data using such a term in the input strange sea quark density

$$(\Delta s + \Delta\bar{s})(x, Q_0^2)/2 = Ax^{\alpha}(1 - x)^{\beta}(1 + \gamma x). \qquad (19)$$

Our preliminary results confirm the previous ones, namely, that $(\Delta s + \Delta\bar{s})(x, Q^2)/2$ is negative in the measured (x, Q^2) region. So, the behaviour of the polarized strange quark density remains controversial. Note that in the presence of SIDIS data Δs and $\Delta\bar{s}$ can, in principle, be separately determined, as was done recently

TABLE II: The parameters of the NLO($\overline{\rm MS}$) input polarized PDFs at $Q^2 = 1$ GeV^2 obtained from the best fit to the data. The parameters marked by (*) are fixed.

flavor	A	α	β	ϵ	γ
$u+\bar{u}$	1.097*	0.782 ± 0.165	3.335 ± 0.154	-1.779 ± 0.896	10.20 ± 5.61
$d+\bar{d}$	-0.394*	0.547 ± 0.118	4.056 ± 0.543	0	6.758 ± 5.366
$\bar{u}$	0.334 ± 0.174	0.782 ± 0.165	7.267*	0	-5.136 ± 2.414
$\bar{d}$	-0.133 ± 0.075	0.547 ± 0.118	7.267*	0	0
$\bar{s}$	-0.00352 ± 0.00194	0.0458 ± 0.0206	7.267*	0	-39.02 ± 29.62
G	-68.23 ± 65.79	1.975 ± 0.459	7.267*	0	-3.536 ± 1.089

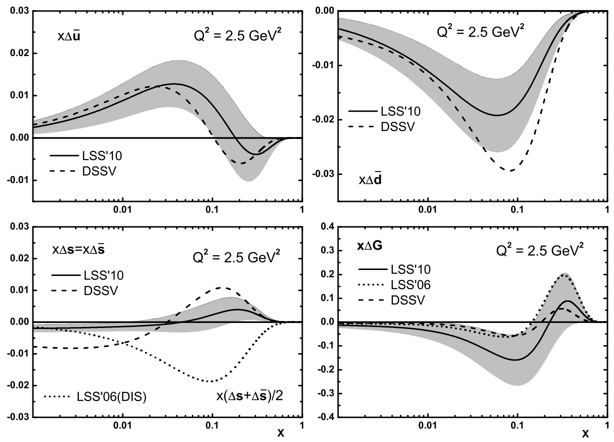

FIG. 2: Our NLO sea quarks and gluon polarized PDFs at $Q^2 = 2.5\ GeV^2$ in the $\overline{\rm MS}$ scheme. For comparison the DSSV PDFs [3] are also presented.

by the COMPASS Collaboration, where it was shown [33] that there is no significant difference between $\Delta s(x)$ and $\Delta\bar{s}(x)$ in the x-range covered by their inclusive and semi-inclusive DIS data. This result was obtained in the LO QCD approximation, with the additional assumption that the SIDIS asymmetries are Q^2-independent. We checked the latter assumption using in the calculations of the asymmetries our NLO PDFs, and found it not quite correct. Also, the errors of the extracted values of the difference $x(\Delta s(x) - \Delta\bar{s}(x))$ are rather too large to allow us to conclude that the assumption $\Delta s(x) = \Delta\bar{s}(x)$ used in our's and the DSSV analyses is correct. So, if it is not correct, it might possibly be the cause that $(\Delta s + \Delta\bar{s})(x, Q^2)/2$ densities obtained from the analyses of inclusive DIS data and combined inclusive and semi-inclusive DIS data sets, respectively, are in contradiction. However, at first glance, it looks a if the difference between Δs and $\Delta\bar{s}$ would have to be quite significant and might contradict the COMPASS results. Perhaps a more important issue is the sensitivity of the results to the form of the fragmentation functions. An analysis by the COMPASS group [30] demonstrated that the determination of $\Delta\bar{s}(x)$ strongly depends on the set of the fragmentation functions used in the analysis and that the DSS FFs are crucially responsible for the unexpected behavior of $\Delta\bar{s}(x)$ obtained from the combined analysis. The study of the sensitivity of $\Delta\bar{s}(x)$ on the FFs used in the analysis is one of the key points we plan to investigate in the future.

In Fig. 3 we present our results for the polarized $\Delta u(x)$ and $\Delta d(x)$ densities at $Q^2 = 2.5\ GeV^2$, which are consistent with those obtained by DSSV (dashed curves). As expected, the SIDIS data do not influence essentially the sums $(\Delta u(x) + \Delta\bar{u}(x))$ and $(\Delta d(x) + \Delta\bar{d}(x))$ already well determined from the analysis of the inclusive DIS data. This fact is illustrated in Fig. 3 where our results from the combined analysis are compared with our LSS'06 PDFs.

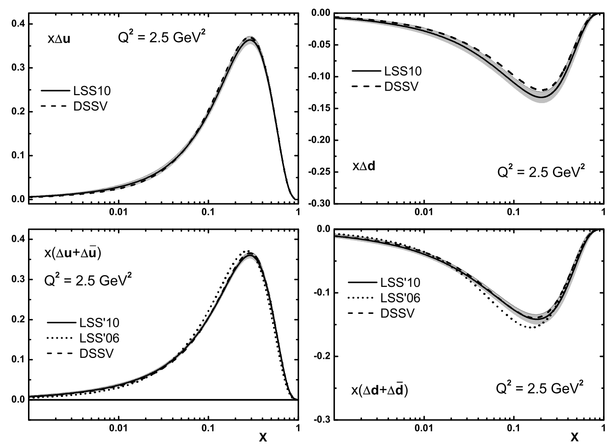

FIG. 3: Our results for Δu, Δd, $(\Delta u + \Delta\bar{u})$ and $(\Delta d + \Delta\bar{d})$ polarized parton densities at NLO approximation. DSSV [3] as well as LSS'06 [2] results for the corresponding densities are presented too.

B. High twist effects

As mentioned in Section II(A), in contrast to other combined analyses of the inclusive and semi-inclusive DIS data, we take into account the target mass and higher twist corrections in a the DIS sector. The values of the

TABLE III: The values of higher twist corrections extracted from the data in a model independent way.

x_i	$h^p(x_i)$ $[GeV^2]$	x_i	$h^n(x_i)$ $[GeV^2]$
0.028	-0.048 ± 0.037	0.028	0.093 ± 0.051
0.100	-0.084 ± 0.016	0.100	0.041 ± 0.036
0.200	-0.053 ± 0.012	0.200	0.000 ± 0.027
0.350	-0.045 ± 0.011	0.325	0.022 ± 0.018
0.600	-0.012 ± 0.014	0.500	0.017 ± 0.015

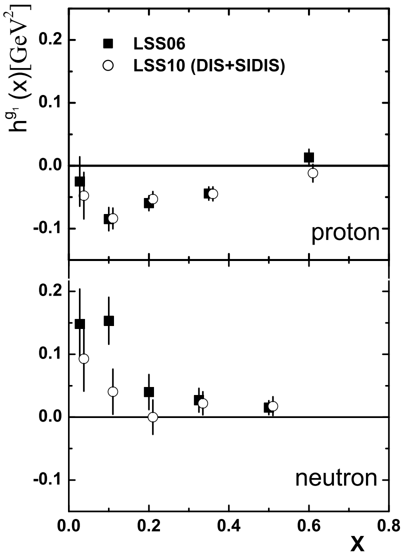

FIG. 4: Comparison between HT values corresponding to the fits of inclusive DIS [2] and combined inclusive and SIDIS data set (this analysis).

HT corrections to g_1 extracted from the data in this analysis are presented in Table III and illustrated in Fig.4.

Compared to the HT(LSS'06) corrections obtained in our analysis of the inclusive DIS data alone [2] the values of the HT corrections for the proton target are practically not changed, while the central values of HT corrections for the neutron target are smaller in the region $x < 0.2$, but in agreement with $\mathrm{HT}^{(n)}$(LSS'06) within the errors, excepting the x region around $x = 0.1$ We consider the tendency of the $\mathrm{HT}^{(n)}$ corrections to be smaller in the region $x < 0.2$ to be a result of the new behavior of $\Delta s(x)$ i.e. positive for $x > 0.03$. The positive contribution in g_1^n from $\Delta s(x)$ should be compensated by a less positive $\mathrm{HT}^{(n)}$ contribution in this region. Since the biggest difference between the values of $\Delta s(x)_{(\mathrm{DIS+SIDIS})}$ and $\Delta s(x)_{\mathrm{DIS}}$ is in the region $x \sim 0.1$ (see Fig. 2) this effect is biggest in this x region. The impact of $\Delta s(x)$ on HT corrections is visible mainly for the neutron target because the contribution of $\Delta s(x)$ in g_1^n is relatively larger than that in g_1^p.

Let us briefly discuss the values of the first moments of the higher twist corrections to the proton and neutron structure function g_1. Using the values for $h^N(x)$ from Table III we obtain for their first moments in the experimental region:

$$\bar{h}^N \equiv \int_{0.0045}^{0.75} h^N(x)dx, \qquad (N = p, n) \tag{20}$$

$\bar{h}^p = (-0.028 \pm 0.005)$ GeV^2 for the proton and $\bar{h}^n = (0.018 \pm 0.008)$ GeV^2 for the neutron target. As a result, for the non-singlet $(\bar{h}^p - \bar{h}^n)$ and the singlet $(\bar{h}^p + \bar{h}^n)$ we obtain (-0.046 ± 0.009) GeV^2 and (-0.011 ± 0.009) GeV^2, respectively. The statistical and systematic errors are added in quadrature. Note that in our notation $h = \int_0^1 h(x)dx = 4M^2(d_2 + f_2)/9$, where d_2 and f_2 are the well known quantities, connected with the matrix elements of twist 3 and twist 4 operators, respectively [34], and M is the mass of the nucleon.

Our value for the non-singlet $(\bar{h}^p - \bar{h}^n)$ is well consistent within the errors with those extracted directly from the recent analyses of the first moment of the non-singlet spin structure function $g_1^{(p-n)}(x, Q^2)$ [35, 36]. Note that our value for the non-singlet $(\bar{h}^p - \bar{h}^n)$ is also in agreement with the QCD sum rule estimates [37] as well as with the instanton model predictions [38, 39]. The values obtained for the non-singlet $(\bar{h}^p - \bar{h}^n)$ and singlet $(\bar{h}^p + \bar{h}^n)$ quantities are in qualitative agreement with the relation $|h^p + h^n| << |h^p - h^n|$ derived in the large $\mathrm{N_c}$ limit in QCD [38].

Our results on the higher twist effects are not in agreement with those obtained in [40], where the authors find no evidence for HT.

C. The sign of the gluon polarization

We have found that the combined NLO QCD analysis of the present polarized inclusive DIS and SIDIS data cannot rule out the solution with a positive gluon polarization. The values of χ^2/DF corresponding to the fits with sign-changing $x\Delta G(x, Q^2)$ and positive $x\Delta G(x, Q^2)$ are practically the same: $\chi^2/DF(\text{node } x\Delta G) = 0.883$ and $\chi^2/DF(x\Delta G > 0) = 0.888$, and the data cannot distinguish between these two solutions (see Fig. 5).

The corresponding sea quark densities are shown in Fig. 6. As seen, the sea quark densities obtained in the fits with positive and sign-changing $x\Delta G(x)$ are almost identical. Note that the extracted HT values corresponding to both fits are also effectively identical. As a result, one can conclude that including the SIDIS data in the QCD analysis does not help to constrain better the polarized gluon density.

In Fig. 7 the ratio $\Delta G(x)/G(x)$ calculated for both the sign-changing and positive solutions for $\Delta G(x)$ obtained in our NLO QCD analysis is compared with the directly measured values of $\Delta G/G$ obtained from a quasi-real photoproduction of high p_t hadron pairs [41–43], and from the open charm production [44] measurements. For

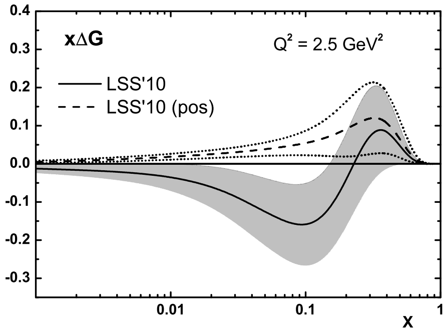

FIG. 5: Comparison between the positive and sign-changing gluon densities. The corresponding error bands are also shown.

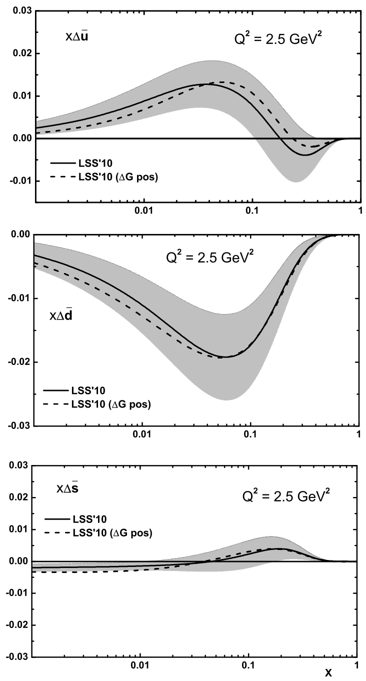

FIG. 6: Comparison between the sea quark densities corresponding to positive and changing in sign gluon densities.

the unpolarized gluon density $G(x)$ in the ratio above we have used that of the NLO MRST'02 [10]. The theoretical curves are given for $\mu^2 = 3$ GeV^2 (high p_t hadron pairs) and $\mu^2 = 13$ GeV^2 (open charm). As seen from Fig. 7, both solutions for the polarized gluon density are well consistent with the experimental values of $\Delta G/G$. It should be noted, however, that in the extraction of $\Delta G/G$ by the experiments a LO QCD treatment has been used. A NLO extraction of the measured values is needed in order for this comparison to be quite correct. In conclusion, the magnitude of the gluon density $x\Delta G(x)$ obtained from our combined NLO QCD analysis of inclusive and semi-inclusive DIS data and independently, from the photon-gluon fusion processes, is small in the region $x \simeq 0.08 - 0.2$.

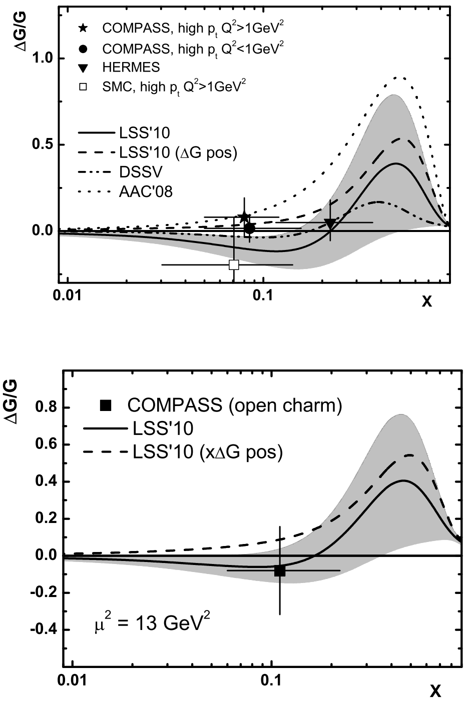

FIG. 7: Comparison between the experimental data and NLO($\overline{\text{MS}}$) curves for the ratio $\Delta G(x)/G(x)$ at $Q^2 = 3$ GeV^2 (**top** - high p_t pairs) and $Q^2 = 13$ GeV^2 (**bottom** - open charm) corresponding to positive and sign-changing $x\Delta G$. Error bars represent the total (statistical and systematic) errors. The horizontal bar on each point shows the x-range of the measurement. The NLO AAC (second Ref. in [1]) and DSSV [3] curves on $\Delta G(x)/G(x)$ are also presented.

When this analysis was finished, the COMPASS Collaboration reported the first data on the asymmetries $A_{1,p}^{\pi+(-)}$, $A_{1,p}^{K+(-)}$ for charged pions and kaons produced on a proton target [45]. As seen in Fig. 8, our predictions for these asymmetries are in a very good agreement with the data at measured x and Q^2.

D. The spin sum rule

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 $Q^2 = 4\ GeV^2$, the first moments of the quark singlet $\Delta\Sigma(x, Q^2)$ and gluon $\Delta G(x, Q^2)$ densities, obtained in our analysis (see Table IV) one finds for the spin of the proton:

TABLE IV: First moments of polarized PDFs at $Q^2 = 4\ GeV^2$. The corresponding DSSV values are also presented.

Fit	$\Delta\bar{s}$	ΔG	$\Delta\Sigma$
LSS10 (pos $x\Delta G$)	-0.063 ± 0.004	0.316 ± 0.190	0.207 ± 0.034
LSS10 (node $x\Delta G$)	-0.055 ± 0.006	-0.339 ± 0.458	0.254 ± 0.042
DSSV (node $x\Delta G$)	-0.056	-0.096	0.245

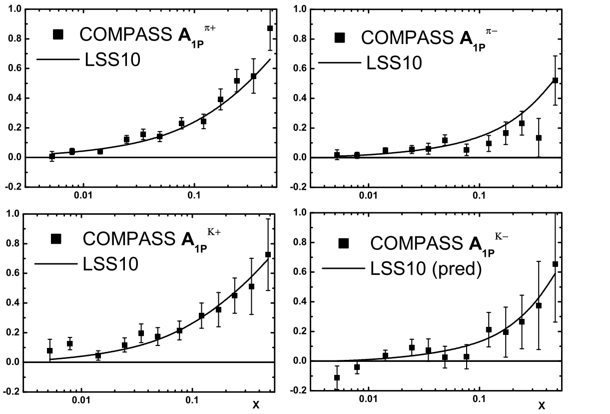

FIG. 8: Our predictions for the COMPASS asymmetries for charged pions and kaons produced on a proton target.

$$
\begin{aligned}
J_z = \frac{1}{2} &= \frac{1}{2}\Delta\Sigma(Q^2) + \Delta G(Q^2) + L_z(Q^2) \\
&= -0.21 \pm 0.46 + L_z(Q^2) \quad (\text{node } \Delta G), \\
&= \quad 0.42 \pm 0.19 + L_z(Q^2) \quad (\text{pos } \Delta G). \qquad (21)
\end{aligned}
$$

In Eq. (21) $L_z(Q^2)$ is the sum of the angular orbital momenta of the quarks and gluons. Although the central values of the quark-gluon contribution in (21) are very different in the two cases, in view of the large uncertainty coming mainly from the gluons, one cannot yet come to a definite conclusion about the contribution of the orbital angular momentum to the total spin of the proton.

IV. SUMMARY

A new combined NLO QCD analysis of the polarized inclusive and semi-inclusive DIS data is presented. In contrast to previous combined analyses, the $1/Q^2$ terms (kinematic - target mass corrections, and dynamic - higher twist corrections) to the nucleon spin structure function g_1 are taken into account. The new results for the PDFs are compared to both the LSS'06 PDFs obtained from a fit to the inclusive DIS data alone, and to those obtained from the DSSV global analysis. The role of the semi-inclusive data in determining the polarized sea quarks is discussed. Due to SIDIS data $\Delta\bar{u}(x,Q^2)$ and $\Delta\bar{d}(x,Q^2)$, as well $\Delta u(x,Q^2)$ and $\Delta d(x,Q^2)$ are determined without additional assumptions about the light sea quarks. The SIDIS data, analysed under the assumption $\Delta s(x,Q^2) = \Delta\bar{s}(x,Q^2)$, imposes a sign-changing $\Delta\bar{s}(x,Q^2)$, as in the DSSV analysis, but our values are smaller in magnitude, less negative at $x < 0.03$ and less positive for $x > 0.03$. Note that $\Delta\bar{s}(x,Q^2)_{\text{SIDIS}}$ differs essentially from the negative $\frac{1}{2}(\Delta s + \Delta\bar{s})(x,Q^2)_{\text{DIS}}$ obtained from all the QCD analyses of inclusive DIS data. As was mentioned above the behavior of $\Delta\bar{s}(x,Q^2)_{\text{SIDIS}}$ strongly depends on the fragmentation functions used in our's and the DSSV analyses. A further detailed analysis of the sensitivity of $\Delta\bar{s}(x,Q^2)$ to the FFs is needed, and any model independent constraints on FFs would help. Another possible reason for this disagreement could be the assumption $\Delta s(x,Q_0^2) = \Delta\bar{s}(x,Q_0^2)$ made in the global analyses. However, this would probably require a significant difference between Δs and $\Delta\bar{s}$. In any case, obtaining a final and unequivocal result for $\Delta\bar{s}(x)$ remains a challenge for further research on the internal spin structure of the nucleon.

We have found also that the polarized gluon density is still ambiguous, and the present polarized DIS and SIDIS data cannot distinguish between the positive and a sign-changing gluon densities $\Delta G(x)$. This ambiguity is the main reason that the quark-gluon contribution into the total spin of the proton is still not well determined.

Finally, our combined NLO QCD analysis confirm our previous results on the higher twist corrections to the nucleon spin structure function g_1^N, namely, that they are not negligible in the pre-asymptotic region and have to be accounted for in order to extract correctly the polarized PDFs.

Acknowledgments

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