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THE ROLE OF HIGHER TWISTS IN DETERMINING POLARIZED PARTON DENSITIES IN THE NUCLEON

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Different methods to extract the polarized parton densities from the world polarized DIS data are considered. The higher twist corrections $h^N(x)/Q^2$ to the spin-dependent proton and neutron g_1 structure functions are found to be nonnegligible and important in the QCD analysis of the present experimental data. Their role in determining the polarized parton densities in the framework of different approaches is discussed. The values of the quark and gluon polarizations are presented, and their dependence on the factorization scheme employed is considered.

Рассмотрены различные методы извлечения поляризованных партонных распределений из мировых данных по глубоконеупругому рассеянию лептонов. Определен вклад $h^N(x)/Q^2$ высших твистов в спинзависимую структурную функцию g_1. Этот вклад оказывается отличным от нуля, имеет различный вид для случая протонной и нейтронной мишеней и должен учитываться при определении поляризованных партонных распределений. Представлены значения кварковых и глюонных поляризаций и их зависимость от выбора схемы факторизации.

INTRODUCTION

Spurred on by the famous EMC experiment [1] at CERN in 1987, there has been a huge growth of interest in *polarized* DIS experiments which yield more refined information about the partonic structure of the nucleon; i.e., how the nucleon spin is divided up among its constituents, quarks and gluons. Many experiments have been carried out at SLAC, CERN, DESY and JLab to measure the longitudinal ($A_{\|}$) and transverse ($A_{\perp}$) asymmetries and to extract from them the photon–nucleon asymmetries $A_1(x,Q^2)$ and $A_2(x,Q^2)$ as well as the nucleon spin-dependent structure functions $g_1(x,Q^2)$ and $g_2(x,Q^2)$.

As in the unpolarized case, the main goal is to confront the QCD predictions to the experimental data and to determine the polarized parton densities. The knowledge of them will help us to make predictions for other processes like polarized hadron–hadron reactions, polarized Drell–Yan processes, etc. There is, however, an important difference between the kinematic regions of the unpolarized and polarized data sets. While in the unpolarized case we can cut the low Q^2 and W^2 data in order to eliminate the less known nonperturbative higher twist effects, it is impossible to perform such a procedure for the present data on the spin-dependent structure functions without loosing too much information. So, to extract correctly the polarized parton densities from the experimental data, special attention should be

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paid to the higher twist (powers in $1/Q^2$) corrections to the nucleon structure functions. Their role in determining the polarized parton densities in the nucleon using different approaches of QCD fits to the data is mainly discussed in this talk. It is also considered how the results are influenced by the recent JLab Hall A [2] and HERMES [3] data.

1. QCD TREATMENT OF $g_1(x, Q^2)$

In QCD the spin-structure function g_1 can be written in the following form:

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

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 $\tau \geqslant 3$. In (1) we have dropped the nucleon target label N. The HT power corrections (up to $\mathcal{O}(1/Q^2)$ terms) can be divided into two parts:

$$g_1(x, Q^2)_{\rm HT} = h(x, Q^2)/Q^2 + h^{\rm TMC}(x, Q^2)/Q^2, \tag{2}$$

where $h^{\rm TMC}(x, Q^2)$ are the calculable [4] kinematic target mass corrections and $h(x, Q^2)$ are the *dynamical* higher twist ($\tau = 3$ and $\tau = 4$) corrections to g_1, which are related to multiparton correlations in the nucleon. The latter are nonperturbative effects and cannot be calculated without using models. In (1) $g_1(x, Q^2)_{\rm LT}$ is the well known pQCD expression and in NLO it has the form

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

where $\Delta q(x, Q^2), \Delta\bar{q}(x, Q^2)$ 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; the symbol $\otimes$ denotes the usual convolution in Bjorken x space; N_f is the number of active flavors.

It is well known that at NLO and beyond, the parton densities, as well as the Wilson coefficient functions, become dependent on the renormalization (or factorization) scheme employed[1]. While in the unpolarized case the difference between the moments of the parton densities (PD) calculated in different factorization schemes

$$M_n({\rm PD})_{{\rm scheme}_1} - M_n({\rm PD})_{{\rm scheme}_2} = \mathcal{O}(\alpha_s) \tag{4}$$

is a small quantity, of order α_s, in the polarized case this difference could be large because of the gluon anomaly [5, 6]

$$\Delta G(Q^2) = \int_0^1 \Delta G(x, Q^2)dx \propto [\alpha_s(Q^2)]^{-1}. \tag{5}$$

[1]Of course, physical quantities such as the virtual photon–nucleon asymmetries $A_i(x, Q^2)$ and the polarized structure functions $g_i(x, Q^2)$ are independent of choice of the factorization convention.

Let us recall the transformation rules relating the first moments of the singlet quark density, $\Delta\Sigma(Q^2)$, and the strange sea, $(\Delta s + \Delta\bar{s})(Q^2)$, in the JET and $\overline{\mathrm{MS}}$ schemes:

$$\Delta\Sigma_{\mathrm{JET}} = \Delta\Sigma_{\overline{\mathrm{MS}}}(Q^2) + N_f \frac{\alpha_s(Q^2)}{2\pi}\Delta G(Q^2) = \Delta\Sigma_{\overline{\mathrm{MS}}}(Q^2) + \mathcal{O}(1), \quad (6)$$

$$(\Delta s + \Delta\bar{s})_{\mathrm{JET}} = (\Delta s + \Delta\bar{s})_{\overline{\mathrm{MS}}}(Q^2) + \frac{\alpha_s(Q^2)}{2\pi}\Delta G(Q^2) = (\Delta s + \Delta\bar{s})_{\overline{\mathrm{MS}}}(Q^2) + \mathcal{O}(1). \quad (7)$$

Note that ΔG is the same in the factorization schemes under consideration and that the singlet $\Delta\Sigma(Q^2)$, as well as the strange sea polarization $(\Delta s + \Delta\bar{s})(Q^2)$, are Q^2-*independent* quantities in the JET scheme.

Indeed, due to the behavior (5) of $\Delta G(Q^2)$, the difference between $\Delta\Sigma(Q^2)$, as well as Δs, calculated in the JET and $\overline{\mathrm{MS}}$ schemes could be large, of order $\mathcal{O}(1)$, if the gluon polarization $\Delta G(Q^2)$ is large in the $Q^2 \sim 1{-}10$ GeV^2 region. To illustrate how large this difference can be, we present in Fig. 1 the strange sea quark densities $x\Delta s(x)$ at $Q^2 = 1$ GeV^2 obtained in our recent analysis [7] of the world DIS data in the $\overline{\mathrm{MS}}$ and JET schemes ($\Delta s = \Delta\bar{s}$ is assumed, $\Delta G = 0.80$). As seen from Fig. 1, the difference between them is definitely large. What follows from this discussion is that the LO QCD will be a bad approximation at least for small quantities like sea quark polarizations $\Delta\bar{q}$, if the gluon polarization is large.

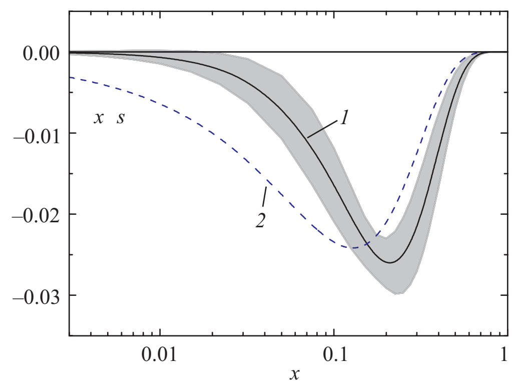

Fig. 1. Comparison between NLO polarized sea parton densities at $Q^2 = 1$ GeV^2 in the JET (*1*) and $\overline{\mathrm{MS}}$ (*2*) schemes

2. QCD FITS TO THE DATA AND THE ROLE OF HIGHER TWISTS

Up to now, two approaches have mainly been used to extract the polarized parton densities (PPD) from the world polarized DIS data. According to the first [8, 9] the leading twist LO/NLO QCD expressions for the structure functions g_1^N and F_1^N have been used in order to confront the data on $A_1(\approx g_1/F_1)$ and g_1/F_1. It was shown [9, 10] that in this case the extracted from the world data «effective» HT corrections $h^{A_1}(x)$ to A_1

$$A_1(x, Q^2) = (1+\gamma^2)\frac{g_1(x, Q^2)_{\mathrm{LT}}}{F_1(x, Q^2)_{\mathrm{LT}}} + \frac{h^{A_1}(x)}{Q^2} \quad (8)$$

are negligible and consistent with zero within the errors, $h^{A_1}(x) \approx 0$ (see Fig. 2). This result has been confirmed independently in [8]. In Fig. 2 our new results on the HT corrections to A_1 (open circles) including in the world data set [1, 11] the recent JLab/Hall A [2] and HERMES [3] data on g_1/F_1 for neutron and deuteron, respectively, are also shown. As seen from Fig. 2, due to the much more precise JLab/Hall A and HERMES new data, the HT

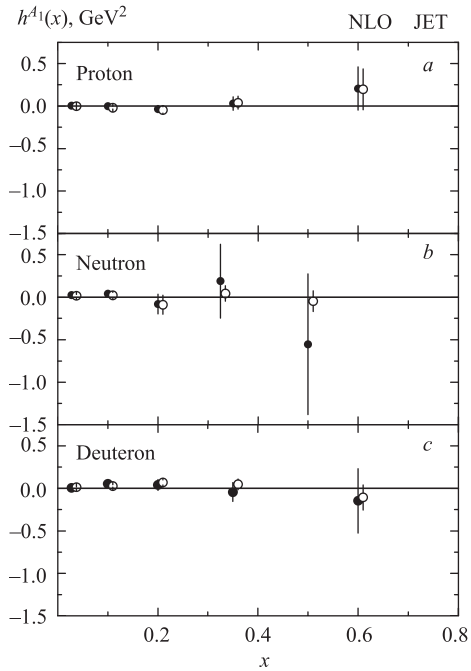

Fig. 2. Effective higher twist contribution $h^{A_1}(x)$ to the spin asymmetry $A_1^N(x, Q^2)$ extracted from the data. • — world data; ○ — world data + JLab/Hall A + HERMES/d (prel.)

corrections $h^{A_1}(x)$ to A_1 for the neutron and deuteron targets are much better determined now at large x and better consistent with zero in this kinematic region.

What follows from these results is that the higher twist corrections to g_1 and F_1 compensate each other in the ratio g_1/F_1 and the PPD extracted this way are less sensitive to higher twist effects.

According to the second approach [12, 13], g_1/F_1 and A_1 data have been fitted using phenomenological parametrizations of the experimental data for the unpolarized structure function $F_2(x, Q^2)$ and the ratio $R(x, Q^2)$ of F_2 and F_1 (F_1 has been replaced by the usually extracted from unpolarized DIS experiments F_2 and R). Note that such a procedure is equivalent to a fit to $(g_1)_{\rm exp}$, but it is more precise than the fit to the g_1 data themselves actually presented by the experimental groups. The point is that most of the experimental data on g_1 have been extracted from the A_1 and g_1/F_1 data using the additional assumption that the ratio g_1/F_1 does not depend on Q^2. Also, different experimental groups have used *different* parametrizations for F_2 and R.

If the second approach is applied to the data, the «effective higher twist» contribution $h^{A_1}(x)/Q^2$ to $A_1(g_1/F_1)$ is found [8] to be sizeable and important in the fit (the HT corrections to g_1 cannot be compensated because the HT corrections to $F_1(F_2$ and $R)$ are absorbed by the phenomenological parametrizations of the data on F_2 and R). Therefore, to extract correctly the polarized parton densities from the g_1 data, the HT corrections to g_1 have to be taken into account. Note that a QCD fit to the data in this case, keeping in $g_1(x, Q^2)_{\rm QCD}$

only the leading-twist expression (as was done in [12,13]), leads to some «effective» parton densities which involve in themselves the HT effects and, therefore, are not quite correct.

Keeping in mind the above discussion, we have analyzed the world data [1,11] on inclusive polarized DIS taking into account the higher twist corrections to the nucleon structure function $g_1^N(x,Q^2)$. In our fit to the data we have used the following expressions for g_1/F_1 and A_1:

$$\begin{aligned}\left[\frac{g_1^N(x,Q^2)}{F_1^N(x,Q^2)}\right]_{\rm exp} &\Leftrightarrow \frac{g_1^N(x,Q^2)_{\rm LT}+h^N(x)/Q^2}{F_2^N(x,Q^2)_{\rm exp}}2x\frac{[1+R(x,Q^2)_{\rm exp}]}{(1+\gamma^2)}\ ,\\ A_1^N(x,Q^2)_{\rm exp} &\Leftrightarrow \frac{g_1^N(x,Q^2)_{\rm LT}+h^N(x)/Q^2}{F_2^N(x,Q^2)_{\rm exp}}2x[1+R(x,Q^2)_{\rm exp}],\end{aligned} \qquad (9)$$

where $g_1^N(x,Q^2)_{\rm LT}$ is given by the leading twist expression (3) including the target mass corrections ($N = p,n,d$). The dynamical HT corrections $h^N(x)$ in (9) are included and extracted in a *model-independent way*. In our analysis their Q^2-dependence is neglected. It is small and the accuracy of the present data does not allow one to determine it. For the unpolarized structure functions $F_2^N(x,Q^2)_{\rm exp}$ and $R(x,Q^2)_{\rm exp}$ we have used the NMC parametrization [14] and the SLAC parametrization $\rm R_{1998}$ [15], respectively. The details of our analysis are given in [7].

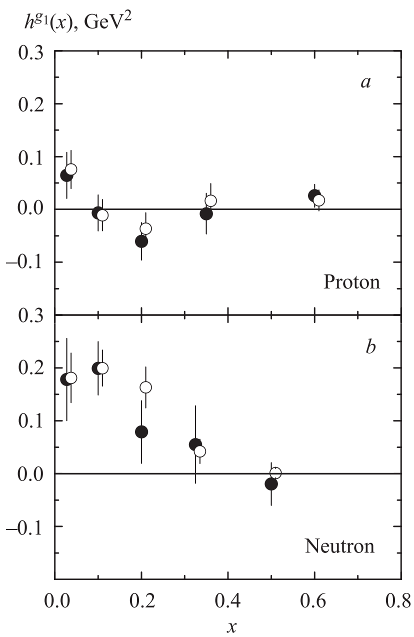

Fig. 3. Higher twist corrections to the proton (*a*) and neutron (*b*) g_1 structure functions extracted from the data on g_1 in the NLO QCD approximation for $g_1(x,Q^2)_{\rm LT}$. • — world data; ○ — world data + JLab/Hall A + HERMES/d (prel.)

We have found that the fit to the data is significantly improved when the higher twist corrections to g_1 are included in the analysis, especially in the LO QCD case. We have also found that the size of the HT corrections to g_1 is *not* negligible and their shape depends on the target (see Fig. 3). In Fig. 3 our new results on the HT corrections to g_1 (open circles), including in the world data set the recent JLab/Hall A [2] and HERMES [3] data, are also presented. As seen from Fig. 3, the higher twist corrections to the neutron spin structure functions in the large x region are much better determined now. It was also shown (see Fig. 4) that the NLO QCD polarized PD($g_1^{\rm LT}$+HT) determined from the data on g_1, including higher twist effects, are in good agreement with the polarized PD($g_1^{\rm NLO}/F_1^{\rm NLO}$) found earlier from our analysis [9] of the data on g_1/F_1 and A_1 using for the structure functions g_1 and F_1 only their *leading*-twist expressions in NLO QCD. This observation confirms once more that the higher twist corrections to g_1/F_1 and A_1 are negligible, so that in the analysis of g_1/F_1 and A_1 data it is enough to account only for the leading twist of the structure functions g_1 and F_1. On the other hand, in fits to the g_1 data themselves the higher twist contribution to g_1 must be taken into account. The latter is especially important for the LO QCD analysis of the inclusive and semi-inclusive DIS data.

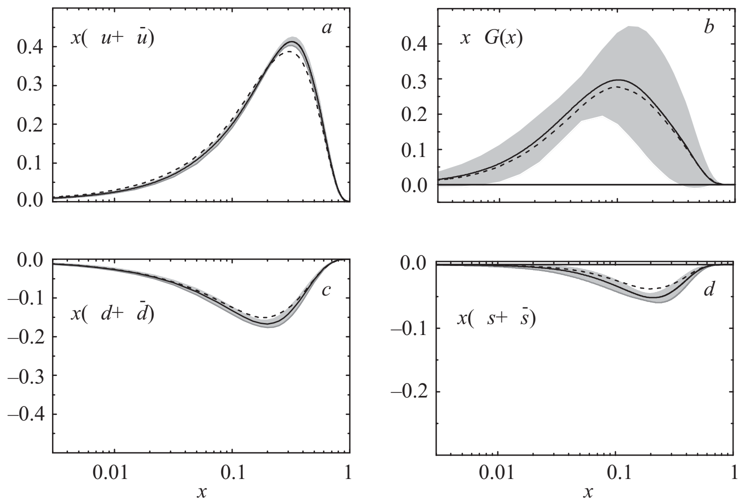

Fig. 4. NLO (JET) polarized parton densities PD($g_1^{\rm NLO}+{\rm HT}$) (solid curves) together with error bands compared to PD($g_1^{\rm NLO}/F_1^{\rm NLO}$) (dashed curves) at $Q^2=1$ GeV^2. The error bands represent the total errors

Let us now turn to the quark and gluon polarizations (the first moments of the polarized parton densities) obtained using (9). Note that in the absence of polarized charge current neutrino data, only the sum of quark and antiquark polarized parton densities (correspondingly the sum of their first moments) can be extracted from the present inclusive data. The results are presented for $Q^2=1$ GeV^2 in the JET scheme:

$$\begin{aligned}(\Delta u+\Delta\bar{u})(Q^2) &= \ \ 0.84\ \pm\ 0.03, \qquad (\Delta d+\Delta\bar{d})(Q^2)\ =\ -0.43\ \pm\ 0.04,\\ (\Delta s+\Delta\bar{s}) &= -0.09\ \pm\ 0.03, \qquad \Delta\Sigma\ =\ 0.32\ \pm\ 0.06,\\ \Delta G(Q^2) &= \ \ 0.80\ \pm\ 0.48.\end{aligned} \tag{10}$$

They are consistent with the quark and gluon polarizations obtained in our previous analysis [9] of the data on g_1/F_1 and A_1 using for the structure functions g_1 and F_1 only their *leading*-twist expressions in NLO QCD.

Note that in the JET scheme the singlet $\Delta\Sigma(Q^2)$, as well as the strange sea polarization $(\Delta s+\Delta\bar{s})(Q^2)$, are *$Q^2$-independent* quantities. Then, in this scheme it is meaningful to directly interpret $\Delta\Sigma$ as the contribution of the quark spins to the nucleon spin and to compare its value obtained from DIS region with the predictions of the different (constituent, chiral, etc.) quark models at low Q^2. Our value of $\Delta\Sigma_{\rm JET}=0.32\pm0.06$ is still far from the value 0.6 of $\Delta\Sigma$ in small-Q^2 region predicted in relativistic constituent quark models [16]. Note, however, that the value of $\Delta\Sigma$ is expected to be smaller than 0.6 if the nonperturbative vacuum spin effects will be taken into account [17]. So, there is a good chance to nicely explain the proton spin puzzle due to the gluon anomaly.

We present also the values for the singlet and strange sea polarizations obtained in the $\overline{\rm MS}$ scheme at the same Q^2, $Q^2=1$ GeV^2:

$$(\Delta s+\Delta\bar{s})(Q^2)_{\overline{\rm MS}}=-0.15\ \pm\ 0.05, \quad a_0(Q^2)=\Delta\Sigma(Q^2)_{\overline{\rm MS}}=0.14\ \pm\ 0.07. \tag{11}$$

Here $a_0(Q^2)$ is the axial charge, which depends on Q^2 and in the $\overline{\mathrm{MS}}$ scheme is equal to $\Delta\Sigma(Q^2)_{\overline{\mathrm{MS}}}$. The small value of the axial charge has been first found by the EMC experiment [1] and triggered a big discussion about the so-called «proton spin crisis». One can see from (10) and (11), however, that the difference between the values of strange sea polarizations, as well as of $\Delta\Sigma(Q^2)$, obtained in the JET and $\overline{\mathrm{MS}}$ schemes is large (it is because of the large and positive gluon polarization).

Using our results in the JET scheme on $\Delta\Sigma$ and the gluon polarization ΔG we obtain for the nucleon spin helicity sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G(Q^2) + L_z(Q^2) = \frac{1}{2}\ 0.32 + 0.80 + L_z = 0.96 + L_z, \tag{12}$$

so that the orbital angular momentum $L_z(Q^2)$ should be *negative* at $Q^2 = 1$ GeV^2. As $\Delta\Sigma$ does not depend on Q^2 in the JET scheme and $\Delta G(Q^2)$ increases with Q^2, $L_z(Q^2)$ should become more negative at Q^2 larger than 1 GeV^2.

Finally, we will briefly discuss the recent HERMES result [18] on the strange sea polarization. The HERMES collaboration at DESY, using a leading-order QCD analysis of their new data on semi-inclusive deep inelastic production of charged pions and kaons, reported a polarization for the strange quarks in the proton at $\langle Q^2\rangle = 2.5$ GeV^2, which is consistent with zero:

$$(\Delta s + \Delta\bar{s})/2 = \int_{0.023}^{0.3} \Delta s(x)dx = 0.03 \ \pm\ 0.03(\mathrm{stat.}) \ \pm\ 0.01(\mathrm{syst.}), \tag{13}$$

whereas, in all analyses of inclusive DIS [7–9, 12, 13, 19], it is found that $(\Delta s+\Delta\bar{s})(x, Q^2)$ is significantly negative. A negative value for the strange sea polarization has also been obtained in a combined analysis of inclusive and the semi-inclusive DIS data [20] presented by Navarro and Sassot [21]. (Note that in this analysis the sum rule (15) (see later) has not been used.) As an example, we present here the value of the partial moment (13) calculated for the LO polarized strange sea density obtained by Blumlein and Bottcher in their analysis [13]:

$$\text{BB LO (Set 2):} \quad (\Delta s + \Delta\bar{s})/2 = -\ 0.027 \ \pm\ 0.005(\mathrm{stat.}). \tag{14}$$

Note that in the analyses of the inclusive DIS data, additional information for the combination of the first moments of the polarized quark densities coming from the hyperon β decays is usually used:

$$a_8 = (\Delta u + \Delta\bar{u})(Q^2) + (\Delta d + \Delta\bar{d})(Q^2) - 2(\Delta s + \Delta\bar{s})(Q^2) = \\ = 3F - D = 0.585 \pm 0.025. \tag{15}$$

The value of the axial charge a_8 in (15) is a consequence of the $SU(3)$ flavor symmetry treatment of the hyperon β decays. There is some question about the accuracy of assuming $SU(3)_f$ symmetry in analyzing hyperon β decays. According to Ratcliffe [22], symmetry-breaking effects are small, of order of 10%. The recent KTeV experiment at Fermilab [23] supports this assessment. Their results of the β decay of Ξ^0, $\Xi^0 \to \Sigma^+ e\bar{\nu}$, are all consistent with exact $SU(3)_f$ symmetry. Taking into account the experimental uncertainties, one finds that $SU(3)_f$ breaking is at most of order 20%.

It was shown [24] that if the strange sea polarization is nonnegative, then $a_8 \leqslant 0.2$, which would imply a total breaking of $SU(3)_f$ flavor symmetry in hyperon β decays in contradiction with the present data. Although the HERMES result on Δs (13) is not in disagreement within two standard deviations with those obtained in the analyses of the inclusive DIS data, we have to keep in mind this circumstance. Another conclusion is that the errors in semi-inclusive DIS experiments are too large, so that we cannot constrain at present the strange sea density using the semi-inclusive DIS data alone. Also, we have to remember the observation discussed above that the LO QCD could be a bad approximation for small quantities like sea quark polarizations.

CONCLUSION

We have found that the QCD fit to the present data on the nucleon spin-structure function $g_1(x, Q^2)$ is essentially improved, especially in the LO case, when the higher twist corrections to g_1 are included in the analysis. The size of their contribution to g_1 has been extracted from the data in model-independent way and found to be nonnegligible. It was shown that in order to extract correctly the polarized parton densities from g_1 data, the higher twist corrections to g_1 have to be taken into account in the analysis. While, in the fit to g_1/F_1 and $A_1(\approx g_1/F_1)$ data it is enough to account only for the leading-twist contributions to the structure functions g_1 and F_1, because the higher twist corrections to g_1 and F_1 compensate each other in the ratio g_1/F_1. Further investigations on the role of higher twist effects in semi-inclusive DIS processes would be important for the correct determination and flavor separation of the valence and light sea quark parton densities.

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