PHYSICAL REVIEW D **91,** 054017 (2015)

New analysis concerning the strange quark polarization puzzle

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

Alexander 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, Boulevard Tsarigradsko Chaussee 72, Sofia 1784, Bulgaria

(Received 16 October 2014; published 11 March 2015)

The fact that analyses of *semi-inclusive* deep inelastic scattering suggest that the polarized strange quark density $\Delta s(x) + \Delta\bar{s}(x)$ is positive in the measured region of Bjorken x, whereas all analyses of *inclusive* deep inelastic scattering yield significantly negative values of this quantity, is known as the "strange quark polarization puzzle." We have analyzed the world data on inclusive deep inelastic scattering, including the COMPASS 2010 proton data on the spin asymmetries, and for the first time, the new extremely precise JLab CLAS data on the proton and deuteron spin structure functions. Despite allowing, in our parametrization, for a possible sign change, our results confirm that the inclusive data yield significantly negative values for the polarized strange quark density.

DOI: 10.1103/PhysRevD.91.054017 PACS numbers: 13.60.Hb, 12.38.-t, 14.20.Dh

I. INTRODUCTION

In the absence of neutrino reactions on a polarized target, the inclusive polarized deep inelastic lepton-hadron reactions determine only the sum of quark and antiquark polarized parton density functions (PDFs), $\Delta q(x) + \Delta\bar{q}(x)$, and provide no information at all about the individual polarized quark and antiquark densities. All analyses of the polarized *inclusive* DIS data have produced results for the polarized strange quark density function, $\Delta s(x) + \Delta\bar{s}(x)$, which are significantly *negative* for all values of x (see for instance [1,2]), in contradiction to the positive values obtained from combined analyses of inclusive and semi-inclusive deep inelastic scattering data [3,4] using de Florian, Sassot, Stratmann (DSS) fragmentation functions (FFs) [5]. This problem is known as the strange quark polarization puzzle. It was shown [6], however, that the polarized strange quark density is very sensitive to the kaon fragmentation functions, and if the set of Hirai-Kumano-Nagai-Sudoh (HKNS) fragmentation functions [7] is used, the polarized strange quark density obtained from the combined analysis turns out to be negative and well consistent with values obtained from the pure deep inelastic scattering analyses. Since it has turned out that neither the HKNS nor the DSS FFs are consistent with the recent HERMES data on pion and kaon *multiplicities* [8], one can conclude now that the values for the polarized strange quark density $\Delta s(x) + \Delta\bar{s}(x)$ determined from the combined analyses [3,4] and [6] of the inclusive and semi-inclusive DIS data, cannot be correct. On the other hand, a disadvantage of the QCD analyses of the pure inclusive polarized DIS data is that in all of them simple input parametrizations for the polarized strange quark density, which do not permit a sign change of the density, have been used. Note that the value of the first moment of the polarized strange quark density must be negative. This follows from the experimental values for $\Delta\Sigma$, the spin carried by all the quarks, and for $a_8 = 3F - D$, where a_8 is the eighth component of the axial Cabibbo current, with constants F and D determined from hyperon β decays. Thus if $\Delta s(x) + \Delta\bar{s}(x)$ is positive for medium values of x, it has to be negative at small values of x, implying that there should be a sign change. The previous simple input parametrizations were used because the data did not allow a reasonable determination of the parameters responsible for the sign change [9]. The situation has now changed.

In this paper we present a next-to-leading order (NLO) QCD analysis of the polarized inclusive DIS data including in the world data set the recent very precise JLAB CLAS data on the proton and deuteron spin structure functions [10]. The aim of our analysis is to answer the question if it is possible, in the presence of the new CLAS data, to determine the polarized strange quark density $\Delta s(x, Q^2) + \Delta\bar{s}(x, Q^2)$ using a more general input parametrization which allows for a sign change. Compared with our last fit to inclusive DIS data [1], the following changes are made:

(i) We use now more general input parametrizations for the sum of quark and antiquark polarized PDFs $\Delta q(x) + \Delta\bar{q}(x)$ instead of the valence and sea quark

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

TABLE I. Data used in our 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 [12]	DIS(p)	10	4.2
SMC [13]	DIS(p)	12	4.8
SMC [13]	DIS(d)	12	17.8
COMPASS [11]	DIS(p)	15	11.1
COMPASS [14]	DIS(d)	15	9.2
SLAC/E142 [15]	DIS(n)	8	6.7
SLAC/E143 [16]	DIS(p)	28	15.6
SLAC/E143 [16]	DIS(d)	28	39.7
SLAC/E154 [17]	DIS(n)	11	2.0
SLAC/E155 [18]	DIS(p)	24	24.9
SLAC/E155 [19]	DIS(d)	24	16.6
HERMES [20]	DIS(p)	9	5.1
HERMES [20]	DIS(d)	9	5.9
JLab-Hall A [21]	DIS(n)	3	0.2
CLAS'06 [22]	DIS(p)	151	122.3
CLAS'06 [22]	DIS(d)	482	430.0
CLAS'14 [10]	DIS(p)	32	17.6
CLAS'14 [10]	DIS(d)	29	6.8
TOTAL		902	740.6

densities. In particular, for the polarized strange quark density, allowance is made for a sign change of the density.

(ii) We do not make any assumptions about the polarized light sea quark densities $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$ which have been used in all previous analyses, because as was stressed above only the sums $\Delta q(x,Q^2)+\Delta\bar{q}(x,Q^2)$ can be extracted from the data, and the assumptions made cannot be tested. Note here that in contrast to the light sea quark densities, the strange quark density $(\Delta s+\Delta\bar{s})(x,Q^2)$ can be well determined from the inclusive data if they are sufficiently precise.

In addition, the COMPASS proton data on the spin asymmetries [11], which were not available at the time of our last analysis of the inclusive DIS data [1], have also been included.

II. RESULTS OF ANALYSIS

In this section we will present and discuss the results of our new NLO QCD fit to the present world data on polarized inclusive DIS adding to the old data set ([12–22]), used in our previous analysis [1], the COMPASS proton data [11] and the new CLAS data [10]. The data used (902 experimental points) cover the following kinematic region: $\{0.005 \le x \le 0.75, 1 < Q^2 \le 62\ \text{GeV}^2\}$. Note that for the CLAS data, a cut $W > 2$ GeV was imposed in order to exclude the resonance region.

The method used is the same as in our previous QCD analysis of the inclusive DIS data (see [1] and the references therein). The main difference, as was mentioned in the Introduction, is that we use now input parametrizations at $Q_0^2 = 1\ \text{GeV}^2$ for the sum of quark and antiquark polarized parton densities instead of the valence and sea quark densities, which in addition are more general,

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

and do *not* use any assumptions about the light sea quark densities $\Delta\bar{u}$ and $\Delta\bar{d}$. In (1) the notation $q_+ = q+\bar{q}$ is used for $q = u, d, s$.

As usual, the set of free parameters in (1) is reduced by the well-known sum rules [23,24],

$$a_3 = g_A = \text{F}+\text{D} = 1.269 \pm 0.003, \tag{2}$$

$$a_8 = 3\text{F}-\text{D} = 0.585 \pm 0.025, \tag{3}$$

where a_3 and a_8 are nonsinglet combinations of the first moments of the polarized parton densities corresponding to the third and eighth components of the axial vector Cabibbo current,

$$\begin{aligned} a_3 &= (\Delta u+\Delta\bar{u})(Q^2)-(\Delta d+\Delta\bar{d})(Q^2), \\ a_8 &= (\Delta u+\Delta\bar{u})(Q^2)+(\Delta d+\Delta\bar{d})(Q^2) \end{aligned} \tag{4}$$

$$-2(\Delta s+\Delta\bar{s})(Q^2). \tag{5}$$

The sum rule (2) reflects isospin SU(2) symmetry, whereas (3) is a consequence of the $SU(3)_f$ flavor symmetry treatment of the hyperon β decays. So, using

TABLE II. The parameters of the NLO input polarized PDFs at $Q^2 = 1\ \text{GeV}^2$ obtained from the best fit to the data. The errors shown are total (statistical and systematic). The parameters marked by (*) are fixed.

Flavor	A	α	β	ϵ	γ
$u+\bar{u}$	6.004*	1.147 ± 0.160	3.604 ± 0.160	-2.389 ± 0.443	4.207 ± 0.982
$d+\bar{d}$	−0.792*	0.690 ± 0.116	3.696 ± 0.684	0	1.760 ± 2.781
$s+\bar{s}$	-0.634 ± 0.366	0.802 ± 0.167	7.267*	0	-2.500 ± 0.162
G	-172.3 ± 133.9	2.650 ± 0.526	7.267*	0	-3.659 ± 1.018

TABLE III. The values of higher twist corrections extracted from the data in a model-independent way. $\langle x_i \rangle$ are the mean values of the x_i bins.

$\langle x_i \rangle$	$h^p(x_i)$ [GeV^2]	$\langle x_i \rangle$	$h^n(x_i)$ [GeV^2]
0.028	-0.026 ± 0.042	0.028	0.162 ± 0.056
0.100	-0.071 ± 0.018	0.100	0.115 ± 0.043
0.200	-0.045 ± 0.012	0.200	0.020 ± 0.021
0.350	-0.030 ± 0.009	0.325	0.029 ± 0.016
0.600	-0.011 ± 0.012	0.500	0.014 ± 0.014

the constraints (2) and (3), the parameters $A_{u+\bar{u}}$ and $A_{d+\bar{d}}$ in (1) can be determined as functions of the other parameters connected with $(\Delta u + \Delta\bar{u})$, $(\Delta d + \Delta\bar{d})$ and $(\Delta s + \Delta\bar{s})$.

The large x behavior of the polarized PDFs is mainly determined from the positivity constraints [4], where for the unpolarized NLO PDFs, the MRST'02 set of parton densities [25] has been used. In order to guarantee the positivity condition for the polarized strange quarks and gluons, we assume the following relation for the parameters β_i which control their large x behavior:

$$\beta_{s+\bar{s}} = \beta_G = \beta_{\mathrm{sea(MRST02)}} = 7.276. \qquad (6)$$

The rest of the parameters $\{A_i, \alpha_i, \beta_i, \epsilon_i, \gamma_i\}$, as well as the unknown higher twist corrections $h^N(x)/Q^2$ to the spin structure functions $g_1^N(x, Q^2), (N = p, n)$ have been determined simultaneously from the best fit to the DIS data. Note that the $\sqrt{x}$ term has been used only in the parametrization for the $(\Delta u + \Delta\bar{u})$ density, because the parameters ϵ_i in front of it for the other polarized densities cannot be determined from the fit and do not help to improve it. Note that the higher twist effects are nonperturbative ones and cannot be calculated in a model-independent way. That is why we prefer to extract them directly from the experimental data (for more details, see our paper [26]).

The numerical results of our NLO QCD fit to the present world data set on polarized inclusive DIS are presented in Tables I, II and III.

In Table I the data sets 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: $\chi^2/\mathrm{d.o.f.} = 0.842$ for 902 experimental points using 23 free parameters (13 for the PDFs and 10 for the higher twist corrections). The new proton and deuteron CLAS data are well consistent with the previous world data set and very well fitted: $\chi^2_{Nrp} = 0.55$ and 0.23 per point for the proton and deuteron data, respectively.

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.

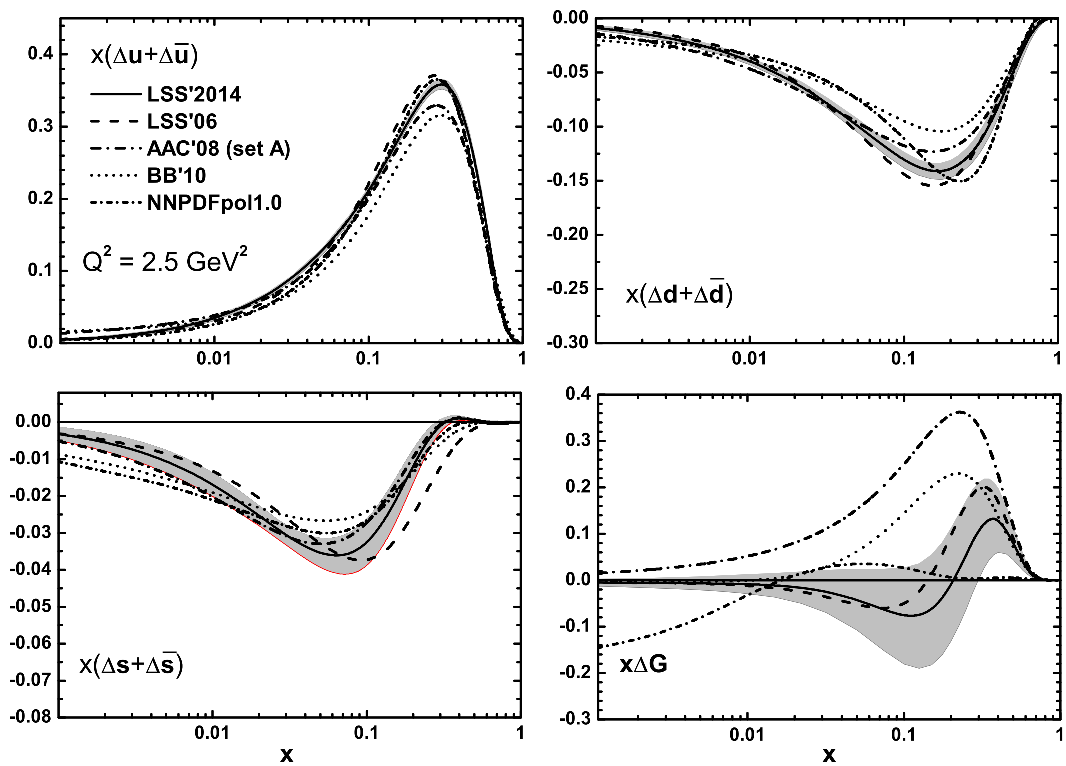

FIG. 1 (color online). Our NLO polarized PDFs compared to those of LSS'06, AAC'08, BB'10 and NNPDFpol1.0.

As seen from Table II, the parameters connected with the polarized strange quark density are well determined. Taking into account the value of the parameter $\gamma_{s+\bar{s}}$, one sees that the strange quark density is *negative* for small values of x and changes sign in the region $0.3 < x < 0.4$ (the precise point depending on the value of Q^2). Beyond this crossover point, it is exceedingly small, compatible with zero (see Fig. 1).

The extracted polarized NLO PDFs are plotted in Fig. 1 for $Q^2 = 2.5\ \mathrm{GeV}^2$ and compared to those obtained in our previous analysis [1]. In Fig. 1 the AAC'08(set A), BB'10 and NNPDFpol1.0 polarized PDFs obtained from NLO QCD analyses of the inclusive DIS data alone (respectively, the second, third and fourth Refs. in [2]) are presented too. As seen from Fig. 1, our new polarized parton densities (LSS'14 PDFs) are well consistent with our LSS'06 PDFs (dashed curves). The extracted strange quark density remains significantly negative even though the parametrization allowed a sign change as a function of x [27].

We have found that the present polarized inclusive DIS data still cannot rule out the solution with a positive gluon polarization. The values of χ^2/d.o.f. corresponding to the fits with sign-changing and positive $x\Delta G(x, Q^2)$ are practically the same, $\chi^2/\mathrm{d.o.f.}(\mathrm{node}\, x\Delta G) = 0.882$ and $\chi^2/\mathrm{d.o.f.}(x\Delta G > 0) = 0.883$, and the data cannot distinguish between these two solutions [see Fig. 2 (top)]. The corresponding strange sea quark densities are shown in Fig. 2 (bottom). As seen, the strange sea quark densities obtained in the fits with sign-changing or positive gluons are almost identical. The corresponding $\Delta u + \Delta\bar{u}$ and $\Delta d + \Delta\bar{d}$ parton densities are not presented because they cannot be distinguished from those corresponding to the changing in sign gluon density.

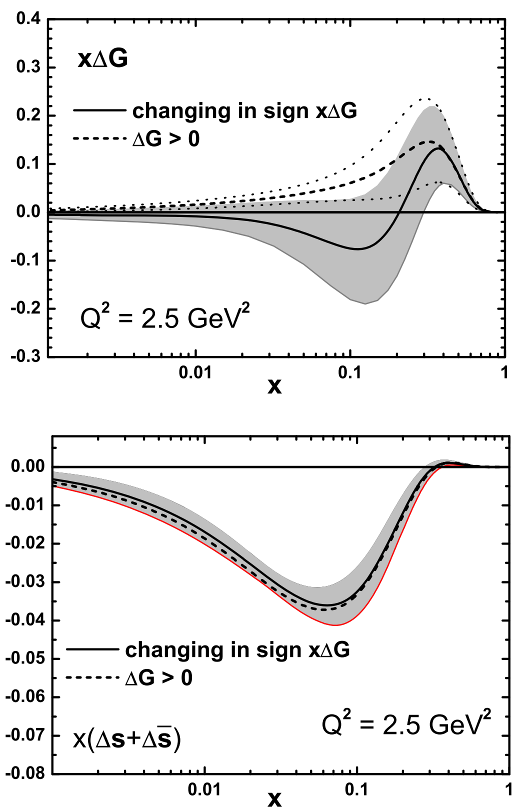

FIG. 2 (color online). Comparison between positive and sign-changing gluon densities. The dotted curves mark the error band for positive gluons (top). The corresponding strange quark densities are also shown (bottom).

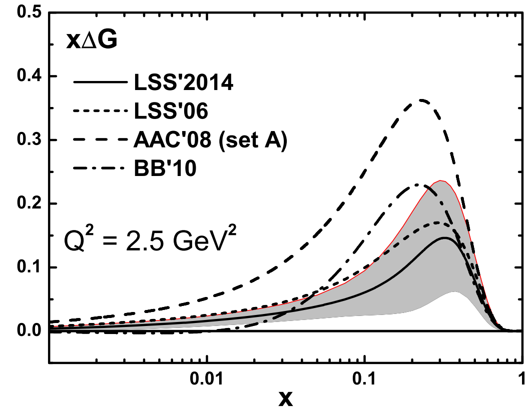

FIG. 3 (color online). Our positive solution for $x\Delta G$ compared to LSS'06, AAC'08 and BB'10 polarized gluon densities.

In Fig. 3 our positive gluon density is compared to that obtained in our previous analysis [1] when the recent CLAS data were not available. As seen, the two gluon densities are in good agreement. In Fig. 3 the gluon densities obtained by AAC and BB groups are also plotted.

As was mentioned above, we take into account the higher twist corrections $h^N(x_i)/Q^2$ to the spin structure functions in our fits to DIS data, where $h^N(x_i)$ are free parameters. The values of the HT corrections $h^p(x_i)$ and $h^n(x_i)$ for the proton and neutron targets extracted from the data in this analysis are presented in Table III. For the deuteron target the relation $h^d(x_i) = 0.925[h^p(x_i) + h^n(x_i)]/2$ have been used, where 0.925 is the value of the polarization factor D.

III. CONCLUSION

We have stressed that, in principle, the inclusive DIS data uniquely determine the polarized strange quark density. Our new analysis of the inclusive world data, including for the first time the extremely accurate JLab CLAS data on the proton and deuteron spin structure functions and the recently published COMPASS proton data, despite allowing in the parametrization for a possible sign change, has confirmed the previous claim, namely, that the inclusive data yield significantly negative values for the polarized strange quark density. The fundamental difference between the SIDIS and DIS analysis is the necessity in SIDIS to use information on the fragmentation functions, which are largely determined from multiplicity measurements. In an earlier study [6] we showed that the polarized strange quark density extracted from SIDIS data was extremely sensitive to the input fragmentation functions. Thus, we believe that the present disagreement between the SIDIS and DIS polarized strange quark densities very likely results from a lack of correctness of the fragmentation functions utilized and that the results from the inclusive analyses are correct.

ACKNOWLEDGMENTS

One of us (D. S.) is grateful to M. Hirai and S. Kumano for providing us with their AAC'08 PDFs, as well as for the useful discussion. We thank also J. Rojo and E. Nocera for providing us with the NNPDFs. This research was supported by the JINR-Bulgaria Collaborative Grant and by the Russian Foundation for Basic Research (RFBR) Grants No. 12-02-00613, No. 13-02-01005 and No. 14-01-00647.

[1] E. Leader, A. V. Sidorov, and D. B. Stamenov, Phys. Rev. D **75**, 074027 (2007).
[2] V. Y. Alexakhin *et al.* (COMPASS Collaboration), Phys. Lett. B **647**, 8 (2007); M. Hirai and S. Kumano (Asymmetry Analysis Collaboration), Nucl. Phys. **B813**, 106 (2009); J. Blumlein and H. Böttcher, Nucl. Phys. **B841**, 205 (2010); R. Ball *et al.* (NNPDF Collaboration), Nucl. Phys. **B874**, 36 (2013); P. Jimenez-Delgado, A. Accardi, and W. Melnitchouk, Phys. Rev. D **89**, 034025 (2014).
[3] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Phys. Rev. D **80**, 034030 (2009).
[4] E. Leader, A. V. Sidorov, and D. B. Stamenov, Phys. Rev. D **82**, 114018 (2010).
[5] D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. D **75**, 114010 (2007); **76**, 074033 (2007).
[6] E. Leader, A. V. Sidorov, and D. B. Stamenov, Phys. Rev. D **84**, 014002 (2011).
[7] M. Hirai, S. Kumano, T.-H. Nagai, and K. Sudoh, Phys. Rev. D **75**, 094009 (2007).
[8] A. Airapetain *et al.* (HERMES Collaboration), Phys. Rev. D **87**, 074029 (2013).
[9] Note that the AAC group (see second Ref. in [2] and references therein) has used a very peculiar parametrization for the strange quark density in their pure inclusive DIS analyses which, in principle, permits the change of the sign, but one of the parameters responsible for the sign change is fixed by hand.
[10] Y. Prok *et al.* (CLAS Collaboration), Phys. Rev. C **90**, 025212 (2014).
[11] M. G. Alekseev *et al.* (COMPASS Collaboration), Phys. Lett. B **690**, 466 (2010).
[12] J. Ashman *et al.* (EMC Collaboration), Phys. Lett. B **206**, 364 (1988); Nucl. Phys. **B328**, 1 (1989).
[13] B. Adeva *et al.* (SMC Collaboration), Phys. Rev. D **58**, 112001 (1998).
[14] V. Yu. Alexakhin *et al.* (COMPASS Collaboration), Phys. Lett. B **647**, 8 (2007).
[15] P. L. Anthony *et al.* (SLAC E142 Collaboration), Phys. Rev. D **54**, 6620 (1996).
[16] K. Abe *et al.* (SLAC E143 Collaboration), Phys. Rev. D **58**, 112003 (1998).
[17] K. Abe *et al.* (SLAC/E154 Collaboration), Phys. Rev. Lett. **79**, 26 (1997).
[18] P. L. Anthony *et al.* (SLAC E155 Collaboration), Phys. Lett. B **493**, 19 (2000).
[19] P. L. Anthony *et al.* (SLAC E155 Collaboration), Phys. Lett. B **463**, 339 (1999).
[20] A. Airapetian *et al.* (HERMES Collaboration), Phys. Rev. D **71**, 012003 (2005).
[21] X. Zheng *et al.* (JLab/Hall A Collaboration), Phys. Rev. Lett. **92**, 012004 (2004); Phys. Rev. C **70**, 065207 (2004).
[22] K. V. Dharmwardane *et al.* (CLAS Collaboration), Phys. Lett. B **641**, 11 (2006).
[23] C. Amsler *et al.* (Particle Data Group), Phys. Lett. B **667**, 1 (2008).
[24] Asymmetry Analysis Collaboration, Y. Goto *et al.*, Phys. Rev. D **62**, 034017 (2000).
[25] A. D. Martin, R. G. Roberts, W. J. Stirling, and R. S. Thorne, Eur. Phys. J. C **28**, 455 (2003).
[26] E. Leader, A. V. Sidorov, and D. B. Stamenov, Phys. Rev. D **67**, 074017 (2003).
[27] Note that this property of the polarized strange quark density holds also if for the nonsinglet axial charge a_8 in Eq. (3), instead of its SU(3) symmetric value 0.585, the value 0.46 is used. This value corresponds to the maximal reduction of a_8 presented in the literature and is the value predicted in one of the models on SU(3)-breaking effects for a_8 [28]. The key point is that the shape of the strange quark density is the same; however, its magnitude is approximately halved. Details of the analysis on the sensitivity of polarized parton densities to variation of the value of the axial charge a_8 from its SU(3) symmetric value will be presented in a forthcoming paper.
[28] S. D. Bass and A. W. Thomas, Phys. Lett. B **684**, 216 (2010).