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Shares of sea and valence quarks in the proton spin puzzle

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The first moments of the polarized valence PDFs truncated to the wide Bjorken x region $0.004 < x < 0.7$ are directly (without any fitting procedure) extracted in NLO QCD from the combined semi-inclusive DIS data of COMPASS and HERMES. Applying the proposed original procedure to these results we estimate the contributions of light sea quarks to the proton spin, which occur just zero within the errors.

The first moments of polarized parton distribution functions (PDFs), which directly compose the nucleon spin together with the orbital parton momenta, are of crucial importance for solution of the proton spin puzzle, attracting great both theoretical and experimental efforts during many years. Nowadays, there is a huge growth of interest to the semi-inclusive DIS (SIDIS) experiments with longitudinally polarized beam and target such as SMC [1], HERMES [2], COMPASS [3] (see, for instance, [4] for review). It is of importance that namely SIDIS-experiments allow us to find the sea and valence contributions to the nucleon spin in separation. In this short letter we focus on this important task. To this end we apply the new method of the polarized SIDIS-data QCD analysis elaborated in [5, 6, 7] (see also [4] for more details). First, we will extract the valence contributions to the proton spin (first moments of the polarized valence PDFs) from the combined SIDIS-data on pion production of COMPASS- and HERMES-collaborations. Then, using these results, sum rules and well known purely inclusive data on Γ_{1d} we will estimate the sea contributions to the spin of proton.

The procedure of direct extraction in NLO QCD of n-th moments of the valence PDFs from the measured difference asymmetries is described in Refs. [5, 7, 4] in detail. The key equations allowing to find from the data on the difference asymmetries $A_{p,d}^{\pi^+-\pi^-}$ the n-th moments $\Delta_n^{'}q \equiv \int_a^b dx\, x^{n-1}q(x)$ of valence PDFs truncated to the accessible for measurement x region (a,b) look as

$$\Delta_n^{'}u_V \simeq \frac{1}{5}\frac{\mathcal{A}_p^{(n)}+\mathcal{A}_d^{(n)}}{L_{(n)1}-L_{(n)2}};\ \Delta_n^{'}d_V \simeq \frac{1}{5}\frac{4\mathcal{A}_d^{(n)}-\mathcal{A}_p^{(n)}}{L_{(n)1}-L_{(n)2}}, \quad (1)$$

where all notations are almost the same as in Ref. [7] (see (9)–(16) in [7]). The only difference is that we rewrite equation for the quantities $\mathcal{A}_{p,d}^{(n)}$ entering (1) in more convenient form[2)] (compare with (16) in [7]):

$$\begin{aligned}\mathcal{A}_p^{(n)} = &\sum_{i=1}^{N_{\text{bins}}} A_p^{\pi^+-\pi^-}(\langle x_i\rangle)\Big|_Z \times \\ &\times \int_{x_{i-1}}^{x_i} dx x^{n-1}(1+R)^{-1}(4u_V-d_V)(x) \times \\ &\times \int_Z^1 dz_h \left[1+\otimes\frac{\alpha_s}{2\pi}C_{qq}^2\otimes\right](D_1-D_2),\end{aligned} \quad (2)$$

and analogously for $\mathcal{A}_d^{(n)}$ with the replacements $(1+R)^{-1} \to (1+R)^{-1}(1-1.5\,\omega_D)^{-1}$ and $(4u_V-d_V) \to (u_V+d_V)$. In our calculations we use NLO-parametrization AKK08 [9] for fragmentation functions, NLO-parametrization GJR08 [10] for unpolarized PDFs and parametrization for $R=\sigma_L/\sigma_T$ from [11]. Polarized ΔC_{qq} and unpolarized C_{qq}^1, C_{qq}^L ($C_{qq}^2 = C_{qq}^1 + C_{qq}^L$, see (2)) Wilson coefficients are taken from [12].

Both COMPASS [13, 14] and HERMES [2] collaborations published the data only on asymmetries $A_{p,d}^{\pi^\pm}$, while the published data on the pion difference asymmetries $A_{p,d}^{\pi^+-\pi^-}$ are still absent. That is why the special procedure was applied in [7] to construct asymmetries $A_{p,d}^{\pi^+-\pi^-}$ from the HERMES-data on pion production, and we repeat here this procedure for the COMPASS-data. Namely, in each i-th bin the pion difference asymmetries can be rewritten as

$$A^{\pi^+-\pi^-}(x_i)=\frac{R_i^{+/-}}{R_i^{+/-}-1}A^{\pi^+}(x_i)-\frac{1}{R_i^{+/-}-1}A^{\pi^-}(x_i), \quad (3)$$

where the quantity $R_i^{+/-}$ is the ratio of unpolarized cross-sections for π^+ and π^- production: $R_i^{+/-} = \sigma_{\text{unpol}}^{\pi^+}(x_i)/\sigma_{\text{unpol}}^{\pi^-}(x_i) = N_i^{\pi^+}/N_i^{\pi^-}$. As it was ar-

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[2)]This form allows to explicitly account for the corrections due to the factor $R=\sigma_L/\sigma_T$ and the deuteron D-state contribution $\omega_D = 0.05 \pm 0.01$ (see, for example, discussion around (10) in [8] and references therein).

gued in Ref. [7] this relative quantity is very well reproduced by the the LEPTO generator of unpolarized events [15], which gives a good description of the fragmentation processes. So, we again use here the LEPTO-generator for this purpose.

Let us now discuss the question of Q^2 dependence of asymmetries and its influence on the final results. The point is that both DIS- and SIDIS-asymmetries very weakly depend on Q^2 (see, for instance, Fig. 5 in Ref. [16]), so that the approximation

$$A(x_i, Q_i^2) \simeq A(x_i, Q_0^2) \quad (4)$$

is commonly used (see, for example, Refs. [1, 2, 14]) for analysis of the DIS- and SIDIS-asymmetries. Nevertheless, for more comprehensive analysis, it is useful to account for the corrections caused by the weak Q^2 dependence of the difference asymmetries, i.e., to estimate the shifts

$$\delta_i A_{p,d}^{\pi^+-\pi^-} = A_{p,d}^{\pi^+-\pi^-}(x_i, Q_0^2) - A_{p,d}^{\pi^+-\pi^-}(x_i, Q_i^2) \quad (5)$$

in the difference asymmetries and their influence on the moments of the valence PDFs. To this end we first approximate r.h.s of (5) by the respective difference of "theoretical" asymmetries, calculated with substitution of two new parameterizations [17, 8] on polarized PDFs (elaborated with application of both DIS and SIDIS data) to the theoretical expressions for the difference asymmetries in NLO QCD (see the respective equations in [5, 7]). Then we average[3)] the results on $\delta_i A_{p,d}^{\pi^+-\pi^-}$ obtained with two applied parametrizations. Adding the calculated in this way $\delta_i A_{p,d}^{\pi^+-\pi^-}$ to the initial experimental asymmetries $A_{p,d}^{\pi^+-\pi^-}(x_i, Q_i^2)$, we estimate the evolved from Q_i^2 to Q_0^2 asymmetries $A_{p,d}^{\pi^+-\pi^-}(x_i, Q_0^2)|_{\text{evolved}}$. Using the obtained in such a way[4)] evolved asymmetries we extract the respective corrected moments of the valence PDFs $\Delta'_n q_V|_{\text{corrected}}$. After that we compare the corrected moments $\Delta'_n q_V|_{\text{corrected}}$ with the respective moments $\Delta'_n q_V$, obtained within the approximation (4), and calculate the respective shifts $\delta(\Delta'_n q_V) = \Delta'_n q_V|_{\text{corrected}} - \Delta'_n q_V$ as well as the relative quantities $\delta(\Delta'_n q_V)/\Delta'_n q_V$. Of importance is the optimal choice of the common for evolved asymmetries scale Q_0^2, allowing as much as possible to reduce shifts in the results due to evolution. Our experience shows that for combined analysis of COMPASS- and HERMES-data (see below) the optimal choice is close to $Q_0^2 = 10\,\text{GeV}^2$.

We perform the combined analysis of COMPASS [14, 13] and HERMES [2] data on pion production with both proton and deuteron targets. COMPASS-collaboration published their data on $A_{p,d}^{\pi^\pm}$ in the Bjorken x ranges $0.004 < x < 0.7$ and $0.004 < x < 0.3$ for proton and deuteron targets, respectively, while the HERMES-data on $A_{p,d}^{\pi^\pm}$ were presented in the range $0.023 < x < 0.6$ for both targets. Thus, inclusion of HERMES-data in the analysis is especially important because COMPASS deuteron data on pion production are still absent in the region $0.3 < x < 0.7$. Besides, application of the combined data allows us to increase the available statistics, and, thereby, to decrease the errors.

The statistical addition of asymmetries $A_{p,d}^{\pi^\pm}$ and their errors is performed in accordance with the standard formulas

$$A_N^h|_{\text{averaged}} = \\ = \frac{A_N^h|_{\text{exp1}}/(\delta A_N^h|_{\text{exp1}})^2 + A_N^h|_{\text{exp2}}/(\delta A_N^h|_{\text{exp2}})^2}{1/(\delta A_N^h|_{\text{exp1}})^2 + 1/(\delta A_N^h|_{\text{exp2}})^2}, \quad (6)$$

$$(\delta A_N^h|_{\text{averaged}})^2 = \frac{1}{1/(\delta A_N^h|_{\text{exp1}})^2 + 1/(\delta A_N^h|_{\text{exp2}})^2}. \quad (7)$$

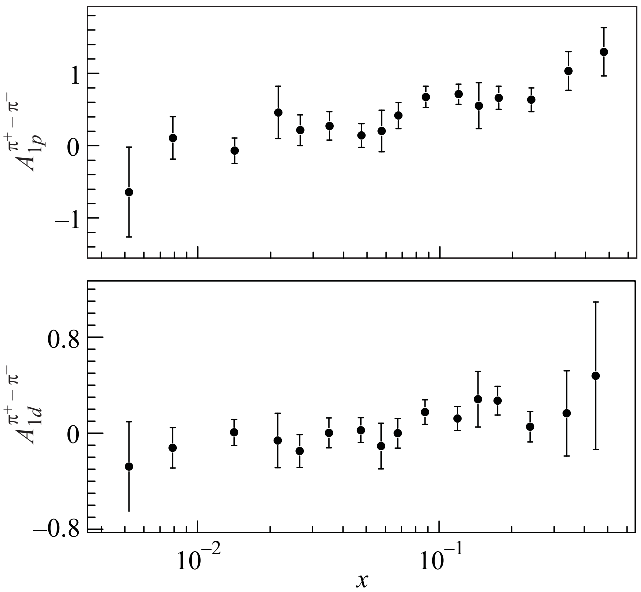
At the same time one can apply (6), (7) directly only for coinciding x bins of different experiments. To solve the problem with the different binnings we apply the procedure similar to one used by SMC-collaboration (see section VD in Ref. [18]) for the combined analysis of structure function g_1 and its first moment, applying the data of experiments with the essentially different x-binnings. The results on the difference asymmetries and their errors obtained in such a way are presented in figure. The respective results on the moments of polarized valence PDFs are presented in Table 1. In this table we present the results obtained both with and without corrections due to weak Q^2-dependence of asymmetries. One can see that the difference is not too significant (the relative corrections $\delta(\Delta'_n q_V)/\Delta'_n q_V$ take the small values).

Thus, we estimated in NLO QCD the contributions of valence quarks (first moments of polarized valence PDFs) to the nucleon spin. Let us now estimate the respective contributions of light sea quarks.

The idea of the procedure for investigation of the sea contributions to the nucleon spin in NLO QCD is based on the proper application of $SU_f(2)$ (Bjorken sum rule) and $SU_f(3)$ sum rules

3) Notice that the shifts in asymmetries as well as in the final results on the moments of valence PDFs obtained with both applied parameterizations differ very insignificantly from each other.

4) Notice that the considered procedure of the asymmetry evolution is quite similar to the procedure used by SMC for the $\Gamma_{1p(d)}$ reconstruction (see Section VB in Ref. [18]).



Pion difference asymmetries $A_{1p}^{\pi^+-\pi^-}$ and $A_{1d}^{\pi^+-\pi^-}$ at $Q^2 = 10\,\mathrm{GeV}^2$, constructed with (3) from the COMPASS and HERMES data on $A_{p,d}^{\pi^\pm}$

Table 1

Four first moments of polarized valence PDFs truncated to the region $0.004 < x < 0.7$ are presented at $Q^2 = 10\,\mathbf{GeV}^2$. The moments are obtained as a result of NLO QCD analysis of the combined data on $A_{p,d}^{\pi^+-\pi^-}$, constructed with (3) from the COMPASS- and HERMES-data on $A_{p,d}^{\pi^\pm}$. Rome numbers I and II correspond to the moments uncorrected and corrected due to evolution, respectively. Besides, the relative corrections $\delta_r(\Delta'_n q_V) \equiv \delta(\Delta'_n q_V)/\Delta'_n q_V$ for moments caused by evolution are presented here

$\Delta'_n u_V$			
n	I	II	$\delta_r(\Delta'_n u_V)$, %
1	0.712 ± 0.078	0.660 ± 0.078	-4.3
2	0.166 ± 0.023	0.168 ± 0.023	0.8
3	0.055 ± 0.010	0.056 ± 0.010	1.4
4	0.022 ± 0.005	0.022 ± 0.005	1.6
$\Delta'_n d_V$			
n	I	II	$\delta_r(\Delta'_n d_V)$, %
1	-0.414 ± 0.149	-0.427 ± 0.149	3.0
2	-0.087 ± 0.053	-0.089 ± 0.053	2.5
3	-0.027 ± 0.023	-0.028 ± 0.023	2.8
4	-0.010 ± 0.011	-0.011 ± 0.011	3.3

$$a_3 \equiv (\Delta_1 u + \Delta_1 \bar{u}) - (\Delta_1 d + \Delta_1 \bar{d}) = \left|\frac{g_A}{g_V}\right| = \\ = F + D = 1.2670 \pm 0.0035, \quad (8)$$

$$a_8 \equiv \Delta_1 u + \Delta_1 \bar{u} + \Delta_1 d + \Delta_1 \bar{d} - 2(\Delta_1 s + \Delta_1 \bar{s}) = \\ = 3F - D = 0.585 \pm 0.025. \quad (9)$$

Bjorken sum rule (8) rewritten in terms of the valence and sea distributions produces quite good approximation [19, 5] (see Ref. [4] for review)

$$\Delta_1 \bar{u} - \Delta_1 \bar{d} \simeq \frac{1}{2}\left|\frac{g_A}{g_V}\right| - \frac{1}{2}\left(\Delta'_1 u_V - \Delta'_1 d_V\right) \quad (10)$$

for the difference of *full* (not truncated!) moments $\Delta_1 \bar{u}$ and $\Delta_1 \bar{d}$ even in the case of rather narrow HERMES x-range, while for the wide COMPASS x-range we deal with this approximation works very well – see the respective numerical tests in Ref. [5]. The point is that since the valence distributions (contrary to sea ones) gather far from the low boundary $x = 0$, the omitted in r.h.s. of (10) term $\int_0^a dx\,(\Delta u_V - \Delta d_V)$ is small even for HERMES low x boundary $a = 0.023$, and becomes really negligible for COMPASS $a = 0.004$ we deal with here. In turn, another omitted term $\int_{0.7}^1 dx\,(\Delta u_V - \Delta d_V)$ in r.h.s of (10) is also negligible since all quark PDFs just die out at so high x values.

Table 2

Sums and differences of the first moments of polarized sea PDFs, as well as the moments themselves, obtained in NLO QCD at $Q^2 = 10\,\mathbf{GeV}^2$ within the approximations (10) and (12). The truncated first moments of valence PDFs are taken from Table 1. Rome numbers I and II correspond to the moments uncorrected and corrected due to evolution, respectively

	I	II
$\Delta_1 \bar{u}$	0.068 ± 0.092	0.094 ± 0.092
$\Delta_1 \bar{d}$	-0.002 ± 0.112	0.004 ± 0.112
$\Delta_1 \bar{u} + \Delta_1 \bar{d}$	0.066 ± 0.087	0.099 ± 0.087
$\Delta_1 \bar{u} - \Delta_1 \bar{d}$	0.071 ± 0.084	0.090 ± 0.084

On the other hand, to estimate the sum of *full* moments of sea PDFs in NLO QCD we use the sum rule (9) and purely inclusive DIS data on the first moment Γ_1^d of deuteron structure function g_{1d} (measured with high precision). To this end we apply the NLO QCD expression for $\Gamma_1^N \equiv (1 - 1.5\,\omega_D)^{-1}\Gamma_1^d$:

$$\Gamma_1^N \equiv (1 - 1.5\,\omega_D)^{-1}\Gamma_1^d = \frac{1}{2}(\Gamma_1^p + \Gamma_1^n) = \\ = \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right)\left[\frac{1}{36}a_8 + \frac{1}{9}\Delta_1\Sigma(Q^2)\right], \quad (11)$$

which produces very good approximation for $\Delta_1 \bar{u} + \Delta_1 \bar{d}$ in NLO QCD:

$$\Delta_1 \bar{u} + \Delta_1 \bar{d} \simeq \\ \simeq \left[3\,(1 + \alpha_s/\pi)\,\Gamma_1^N + \frac{1}{12}a_8\right] - \frac{1}{2}(\Delta'_1 u_V + \Delta'_1 d_V), \quad (12)$$

where we again omitted the small contributions of valence PDFs $\int_0^{0.004} dx\,(\Delta u_V + \Delta d_V)$ and $\int_{0.7}^1 dx\,(\Delta u_V + \Delta d_V)$. We use in (12) the numerical value of Γ_1^N taken from the COMPASS paper [20]: $\Gamma_1^N = 0.051 \pm 0.003 \pm \pm 0.006$.

The obtained with (10), (12) results on sums and differences of the first moments of sea PDFs, as well as on the moments themselves in separation are presented in Table 2. Looking at this table one can draw an unexpected conclusion: the sea contributions to the proton spin appear in zero[5)] within the errors.

In summary, the first moments of the polarized valence PDFs truncated to the wide Bjorken x region $0.004 < x < 0.7$ are directly (without any fitting procedure) extracted in NLO QCD from the data of COMPASS and HERMES on pion production. Then, using these results and well known purely inclusive data on Γ_{1d} we estimate within the proposed original procedure the sea contributions to the spin of proton, which, surprisingly, occur just zero within the errors. Certainly, this conclusion should be considered as still preliminary, since the results on sea contributions are obtained for the restricted Bjorken x region. Nevertheless, its degree of reliability is high enough due to the discussed above advantage of approximations (10), (12) to the full moments, which become especially good for the wide COMPASS x region we deal with. Having in mind the surprisingly small [17, 8] values of $\Delta_1 G$ and $\Delta_1 s$ it seems that we now became still more close to the "classical" quantum-mechanical picture of the proton spin puzzle, where only valence quarks and their orbital moments are responsible for the nucleon spin.

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[5)] Certainly, because of evolution the first moments of sea PDFs still can deviate from zero at values of Q^2 distinct from considered here $Q^2 = 10\,\mathrm{GeV}^2$. However, in the wide range of Q^2 really available to experiment they are still negligible.

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