A NEW DETERMINATION OF POLARIZED PARTON DENSITIES IN THE NUCLEON

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(Received March 4, 2003)

In order to determine polarized parton distributions we have made a new NLO QCD fit (in $\overline{\mathrm{MS}}$ renormalization scheme) using all experimental data on spin asymmetries measured in the deep inelastic scattering on different nucleon targets. The functional form of such densities is based on MRST2001 results for unpolarized ones. We get for polarization of quarks (at $Q^2 = 1\,\mathrm{GeV}^2$): $\Delta u = 0.86, \Delta d = -0.37, \Delta s = -0.04$. The total quark polarization is rather big and we obtain: $\Delta\Sigma = 0.45$. As a result of our fit we get $a_3 \cong g_A = 1.23$, the value which is close to the experimental number. With negligible Δs and rather big $\Delta\Sigma$ (comparable to a_8) the results of our new fit are quite different in character from previous fits.

PACS numbers: 12.38.–t, 13.88.+e, 14.20.Dh

The experimental data on deep inelastic scattering of polarized leptons on polarized nucleons was collected for many years in experiments made in SLAC [1], CERN [2] and DESY [3]. The results were analyzed by many groups and next to leading order (NLO) QCD polarized parton distributions were determined [4–7]. In the present paper we do not consider any new experimental data. All the existing experimental data on polarized deep inelastic scattering were already included in our latest fits [6,7]. Contrary to some other fits our method of determination of spin densities depends very strongly on the parton distributions for unpolarized case. We assume that the asymptotic behavior of our polarized parton distributions is determined (up to the condition that the corresponding parton densities are integrable) by the fit to unpolarized data.

Recently a new determination of unpolarized parton densities performed by Martin, Roberts, Stirling and Thorne (MRST2001) [8] was published. These distributions have substantially modified (compared to older MRST98 [9] and MRST99 [10] fits) small x behaviour of valence u quark and gluon, as well as gluon density is not positive for all values of x variable. Hence, we are able to update our fit and to check how the new functional form of parton distributions influences it. We will follow the method presented in [5–7] where we use $\overline{\mathrm{MS}}$ renormalization scheme in QCD. Despite of the fact that we only modify the functional dependence of the fitted (at $Q^2 = 1\,\mathrm{GeV}^2$) parton densities the obtained polarizations of quarks (*i.e.*, $\Delta u, \Delta d$ and Δs) and gluons (ΔG) are significantly changed, the value of Δs is small and the value of total quark polarization $\Delta\Sigma$ is increased and comparable to a_8. We have found interesting that it is possible to get this type of solution for polarized parton densities with the new MRST fit. We will use all available data for spin asymmetry at given x and different Q^2 (431 experimental points).

Experiments on unpolarized targets provide information on the quark densities $q(x,Q^2)$ and $G(x,Q^2)$ inside the nucleon. These densities can be expressed in term of $q^{\pm}(x,Q^2)$ and $G^{\pm}(x,Q^2)$, *i.e.* densities of quarks and gluons with helicity along or opposite to the helicity of the parent nucleon:

$$q = q^+ + q^-, \qquad G = G^+ + G^-. \tag{1}$$

The polarized parton densities, *i.e.* the differences of q^+, q^- and G^+, G^- are given by:

$$\Delta q = q^+ - q^-, \qquad \Delta G = G^+ - G^-. \tag{2}$$

We will try to determine $\Delta q(x,Q^2)$ and $\Delta G(x,Q^2)$, keeping in mind relations between Eqs. (1) and (2).

The formulas for unpolarized quark and gluon distributions determined (at $Q^2 = 1\,\mathrm{GeV}^2$) in the fit performed by Martin, Roberts, Stirling and Thorne [8] (they use $\Lambda_{\overline{\mathrm{MS}}}^{n_f=4} = 0.323$ GeV and $\alpha_{\mathrm{s}}(M_Z^2) = 0.119$) are:

$$\begin{aligned}
u_v(x) &= 0.158x^{-0.75}(1-x)^{3.33}(1+5.61\sqrt{x}+55.49x)\,,\\
d_v(x) &= 0.040x^{-0.73}(1-x)^{3.88}(1+52.73\sqrt{x}+30.65x)\,,\\
2\bar{u}(x) &= 0.4M(x) - \delta(x)\,,\\
2\bar{d}(x) &= 0.4M(x) + \delta(x)\,,\\
2\bar{s}(x) &= 0.2M(x)\,,\\
G(x) &= 1.90x^{-0.91}(1-x)^{3.70}(1+1.26\sqrt{x}-1.43x) - 0.21x^{-1.33}(1-x)^{10}\,.
\end{aligned} \tag{3}$$

where:

$$\begin{aligned} M(x) &= 0.222x^{-1.26}(1-x)^{7.10}(1+3.42\sqrt{x}+10.3x)\,, \\ \delta(x) &= 1.195x^{0.24}(1-x)^{9.10}(1+14.05x-45.52x^2)\,. \end{aligned} \tag{4}$$

We will split q and G, as was already discussed in [5–7], into two parts in such a manner that the quark distributions $q^{\pm}(x,Q^2)$ remain positive. Our polarized densities for valence quarks, sea antiquarks (the same distribution we take for sea quarks) and gluons (at $Q^2 = 1\,\mathrm{GeV}^2$) are parametrized as follows:

$$\begin{aligned} \Delta u_v(x) &= x^{-0.75}(1-x)^{3.33}(a_1+a_2\sqrt{x}+a_4x)\,, \\ \Delta d_v(x) &= x^{-0.73}(1-x)^{3.88}(b_1+b_2\sqrt{x}+b_3x)\,, \\ 2\Delta\bar{u}(x) &= 0.4\Delta M(x)-\Delta\delta(x)\,, \\ 2\Delta\bar{d}(x) &= 0.4\Delta M(x)+\Delta\delta(x)\,, \\ 2\Delta\bar{s}(x) &= 0.2\Delta M_{\mathrm{s}}(x)\,, \\ \Delta G(x) &= x^{-0.91}(1-x)^{3.70}(d_1+d_2\sqrt{x}+d_3x)+x^{-0.83}(1-x)^{10}d_4\,. \end{aligned} \tag{5}$$

where:

$$\begin{aligned} \Delta M(x) &= x^{-0.76}(1-x)^{7.10}(c_1+c_2\sqrt{x})\,, \\ \Delta M_{\mathrm{s}} &= x^{-0.76}(1-x)^{7.10}(c_{1s}+c_{2s}\sqrt{x})\,, \\ \Delta\delta(x) &= x^{0.24}(1-x)^{9.10}c_3(1+14.05x-45.52x^2)\,. \end{aligned} \tag{6}$$

We have some problems with this new peculiar gluon distribution. Usual procedure used by us is to drop out in ΔG the part that is nonintegrable. But it would mean that an important part in $G(x)$ (which behaves as $x^{-1.33}$ at $x \to 0$) will not contribute to ΔG. Hence, we only decrease (by 1/2) the exponent of the most singular part (at $x \to 0$) of spin gluon distribution. (which gives a behaviour of density at small x). In order to have finite polarization for partons we use less divergent distributions at $x \to 0$ also for sea quarks. Let us define:

$$\begin{aligned} \Delta u &= \Delta u_v + 2\Delta\bar{u}\,, \\ \Delta d &= \Delta d_v + 2\Delta\bar{d}\,, \\ \Delta s &= 2\Delta\bar{s}\,, \end{aligned} \tag{7}$$

and

$$\begin{aligned} \Delta\Sigma &= \Delta u+\Delta d+\Delta s\,, \\ a_8 &= \Delta u+\Delta d-2\Delta s\,, \\ a_3 &= \Delta u-\Delta d = g_A\,. \end{aligned} \tag{8}$$

In order to determine the unknown parameters in the expressions for polarized quark and gluon distributions (Eqs. (5), (6)) we calculate the spin asymmetries (starting from initial value $Q^2 = 1$ GeV^2) for measured values of Q^2 and make a fit to the experimental data on spin asymmetries for proton, neutron and deuteron targets. The spin asymmetry $A_1(x,Q^2)$ can be expressed via the polarized structure function $g_1(x,Q^2)$ as:

$$A_1(x,Q^2) \cong \frac{(1+\gamma^2)g_1(x,Q^2)}{F_1(x,Q^2)} = \frac{g_1(x,Q^2)}{F_2(x,Q^2)}\left[2x(1+R(x,Q^2))\right] , \qquad (9)$$

where $R = [F_2(1+\gamma^2) - 2xF_1]/2xF_1$, whereas $\gamma = 2Mx/Q$ (M stands for proton mass). We will take the new determined value of R from the [11]. In calculating $g_1(x,Q^2)$ and $F_2(x,Q^2)$ in the next to leading order we use procedure described in [5, 6]. Having calculated the asymmetries according to Eq. (9) for the value of Q^2 obtained in experiments we can make a fit to asymmetries on proton, neutron and deuteron targets. The value of a_3 is not constrained in such fit. We will also do not fix a_8 but we put a constraint on its value. Simply we will add it as an extra experimental point (from hyperon decays one has $a_8 = 0.58 \pm 0.1$, where we enhance (to 3σ) an error).

Not all parameters are important in our fits. We will assume that $c_{1s} = c_1$ (*i.e.* the most singular terms for strange and non-strange sea contributions are equal). Such assumption practically does not change the value of χ^2 but improves $\chi^2/N_{\rm DF}$. In this case we get the following values of parameters (at $Q^2 = 1\,{\rm GeV}^2$) from the fit to all existing data for spin asymmetries:

$$\begin{array}{lllll}
a_1 = 0.14\,, & a_2 = -2.48\,, & a_4 = 9.90\,, & & \\
b_1 = -0.04\,, & b_2 = -1.91\,, & b_3 = 0.63\,, & & \\
c_1 = -0.01\,, & c_2 = 2.29\,, & c_3 = 1.20\,, & & \\
c_{1s} = c_1\,, & c_{2s} = -0.67\,, & & & \\
d_1 = 12.69\,, & d_2 = -6.42\,, & d_3 = -33.02\,, & d_4 = -18.07\,. & (10)
\end{array}$$

The quark and gluon distributions obtained from our fit lead for $Q^2 = 1\,{\rm GeV}^2$ to the following integrated (over x) quantities: $\Delta u = 0.86, \Delta d = -0.37, \Delta s = -0.04, \Delta u_v = 0.73, \Delta d_v = -0.70, 2\Delta\bar{u} = 0.14, 2\Delta\bar{d} = 0.33$.

We have positively polarized sea for up and down quarks and small negatively polarized sea for strange quarks. One can see substantial breaking of SU(2) symmetry in a sea. We got the value of $a_3 \cong g_A = 1.23$, the number which is very close to the experimental figure (1.267 ± 0.003 [12]).

As is seen from Eqs. (5) and (6) the small x behaviour of expressions for valence u, d quarks and sea contribution ΔM have very similar behaviour at small values of x. So one cannot expect that the splitting into valence and sea contributions will be well determined in the fit. The integrated values of quantities that are well determined *i.e.*, $\Delta u = 0.86, \Delta d = -0.37, \Delta s = -0.04, \Delta\Sigma = 0.45$ and $g_A = 1.23$ can be compared with the values from previous fit (called A'_2 in [6]) $\Delta u = 0.77, \Delta d = -0.57, \Delta s = -0.19, \Delta\Sigma = 0.01$ and $g_A = 1.34$. More singular behaviour of Δu at small x in the present fit does not only directly influence the value of Δu. We have some increase in Δu and relatively big increase in Δd and Δs resulting in the higher value of $\Delta\Sigma$. It seems that improvement of the MRST2001 [8] in comparison to MRST98 [9] and MRST99 [10] changes significantly character of obtained results. On the other hand the value of $\chi^2 = 374.2$ for the present fit is higher then in our previous one [6], despite of the fact that we have used the same experimental data. As we will see later the increase in χ^2 is connected with positivity conditions.

The results in the "measured" region (*i.e.*, for $0.003 \leq x \leq 1$) are: $\Delta u = 0.75, \Delta d = -0.32, \Delta s = -0.04, \Delta\Sigma = 0.39$ and $g_A = 1.08$ which should be compared with our previous results (fit A'_2 in [6]): $\Delta u = 0.80, \Delta d = -0.43, \Delta s = -0.11, \Delta\Sigma = 0.26$ and $g_A = 1.23$. In present fit we have the value of $\Delta G = 42.6$ integrated in the whole region of x and $\Delta G = -1.15$ in the "measured" region of x, which have to be compared with results of a A'_2 fit: $\Delta G = -0.19$ in the whole region and the same value in the region: $0.003 \leq x \leq 1$. Negative value of ΔG in $0.003 \leq x \leq 1$ and highly positive in the whole region of x is connected with rather singular behaviour at small x. It seems that behaviour of ΔG is rather strange and not very reliable.

As we already mentioned the assumption that ΔG should be integrable was used by us in basic fit and the most singular part of G was removed from ΔG parametrization. We have not assumed positivity for gluon contribution because already in unpolarized case $G(x)$ was negative for small x values. When we take for $\Delta G(x)$ the same functional form as for $G(x)$ leaving most singular term for small x (not integrable) we get fit with smaller χ^2, namely 371.9 (there are some changes in parameters but the character of the fit does not change). We get: $\Delta u = 0.87, \Delta d = -0.38, \Delta s = -0.04, \Delta\Sigma = 0.45$ and $g_A = 1.25$. The value of gluon polarization (ΔG) is -0.37 in the measured region and positive but of course infinite in the whole region. We have made also a fit where we have not assumed any positivity conditions for parton densities. It means that functional form for such densities was used with arbitrary (unconstrained) parameters in Eqs. (5) and (6). We get, as expected, much smaller χ^2 value, namely 361.4 (smaller than in our basic fit). The integration in the whole x region gives: $\Delta u = 0.87, \Delta d = -0.39, \Delta s = -0.05, \Delta\Sigma = 0.43$ and $g_A = 1.26$. $\Delta G = 3.48$. The values of $\Delta u, \Delta d, \Delta s$ and $\Delta\Sigma$ are nearly the same as in basic fit. We consider that as an argument in favor of our determination of these parameters. Higher value of χ^2 in the basic fit is connected with positivity conditions. When we neglect the second term in gluon distribution (*i.e.*, when we put $d_4 = 0$) one gets $\chi^2 = 378.9$

and: $\Delta u = 0.84, \Delta d = -0.41, \Delta s = -0.07, \Delta\Sigma = 0.37$, $\Delta G = -4.8$. If we put (for $Q^2 = 1\,\mathrm{GeV}^2$) gluon polarization arbitrarily equal to zero (*i.e.* $d_1 = d_2 = d_3 = d_4 = 0$) we get substantial increase in $\chi^2 = 388.2$, whereas: $\Delta u = 0.84, \Delta d = -0.42, \Delta s = -0.08, \Delta\Sigma = 0.34$ and $g_A = 1.26$.

We consider various assumptions about polarized gluon contribution in order to see how it influences the values of other parameters. It seems that the values of $\Delta u, \Delta d, \Delta s, \Delta\Sigma$ and g_A do not change much when we use different assumptions about gluon contribution. We get in our fits small value of Δs and $\Delta\Sigma$ comparable with a_8 (such conclusions remind Ellis–Jaffe results [13]). This is what differs our present results (coming from updated MRST2001 [8] fit) from our previous fits [5, 6].

Our fitting procedure also determines + and − helicity components of parton densities. These components and the total polarized distributions for quarks of different flavors and gluons (calculated at $Q^2 = 1\,\mathrm{GeV}^2$) are presented in Fig. 1. The value of $\Delta G(x)$ is negative for higher x values and very big and positive for small x.

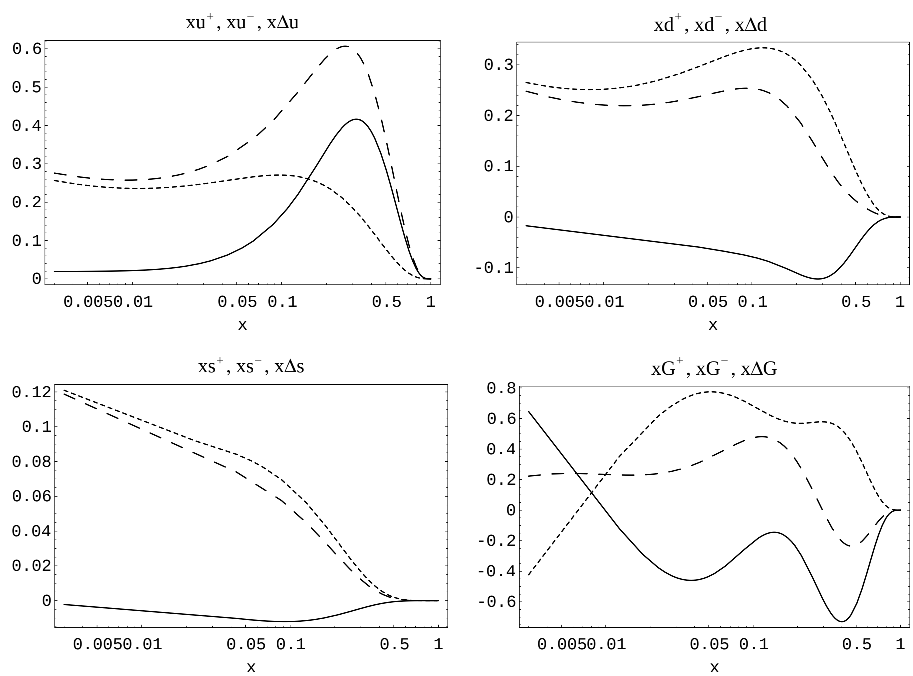

Fig. 1. The quark (for different flavors) and gluon densities versus x obtained from our fit. The solid lines represent parton polarization, whereas dashed (dotted) lines correspond to + (−) helicity component of parton distribution.

In Fig. 2 the values of functions of $\Delta u(x), \Delta d(x), \Delta\Sigma(x)$ and $\Delta G(x)$ obtained in the present fit are compared with the corresponding ones from our previous fit called A_2' [6]. One can see significant changes in these distributions.

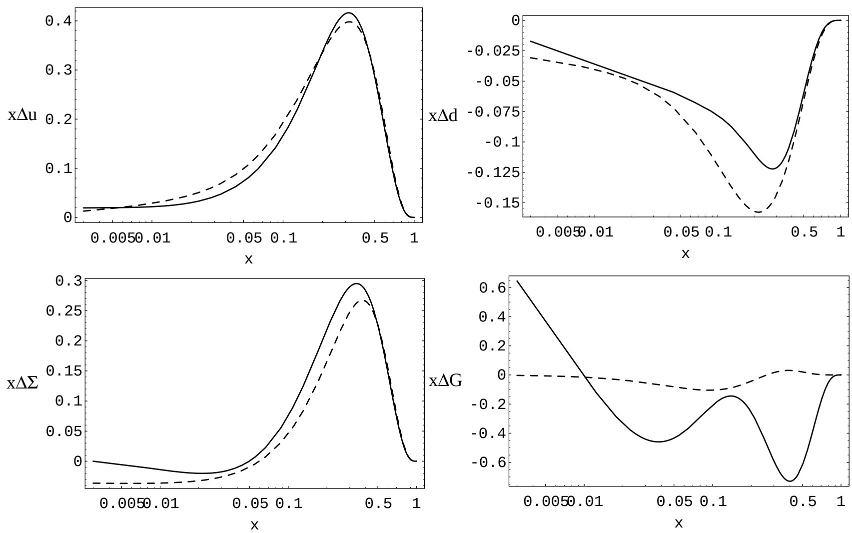

Fig. 2. The parton densities versus x obtained from our fit (solid lines) compared with the results from our previous fit [6] (dashed lines).

In Fig. 3 we present the comparison of our predictions for the structure functions g_1^p, g_1^d and g_1^n got from our fit (calculated at the values of Q^2 corresponding to data) with the corresponding experimental points. We stress that our curves are fitted to spin asymmetries and not to these points. For comparison, the curves for polarized structure functions obtained in [6] from fit A_2' are also presented. The increases of g_1 (however within experimental errors) are seen only for very small x values for data from SMC experiments (on proton and deutrium targets) and for E154 data on neutron target.

We have made fits to precise data on spin asymmetries on proton, neutron and deuteron targets. Our model for polarized parton distributions is based on new MRST2001 fit [8] to unpolarized data. Because of different functional form of fitted parton densities (*e.g.* more singular behaviour at $x = 0$ for u quark and gluons) the new fit is different in character from the other fits [4–6]. We have got relatively small value of Δs and relatively high value of $\Delta\Sigma$ (comparable with a_8) with g_A (unconstrained) very close to experimental value. Gluon contribution comes out relatively high and is (as usual) not very reliable. It seems that in our model the problem of so called "spin crisis" begins to disappear.

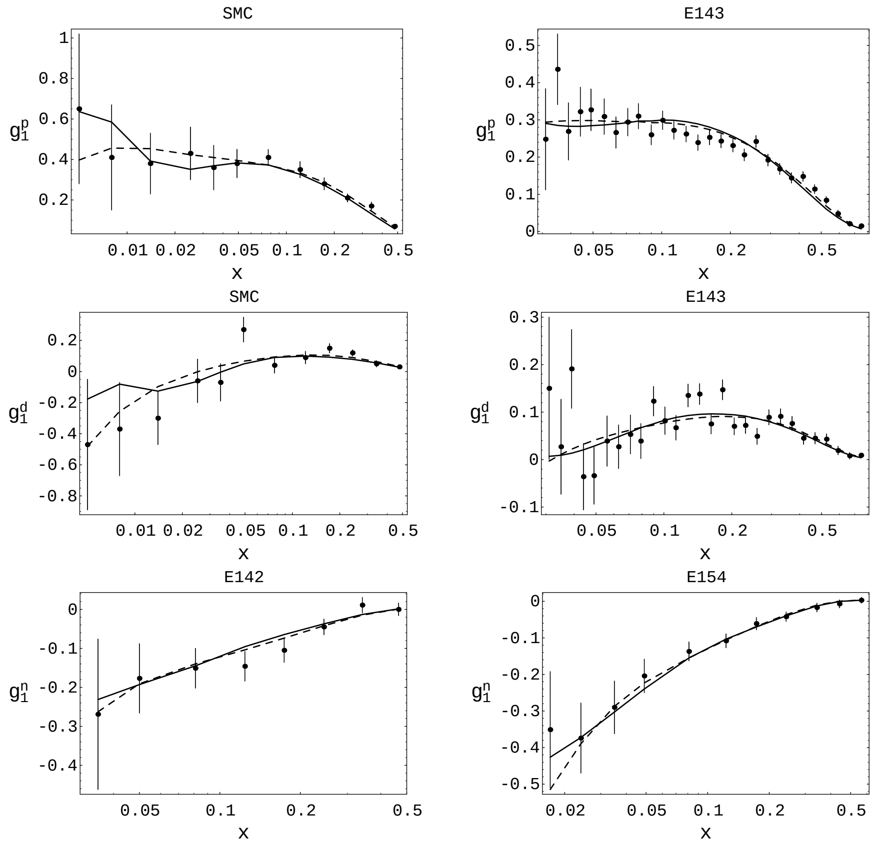

Fig. 3. The comparison of our predictions for $g_1^N(x, Q^2)$ versus x with the experimental data from different experiments. Solid curves are calculated using the distributions from our fit, the dashed ones are calculated using the parameters of fit $A_2^{'}$ from [6].

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