Polarized structure functions

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Abstract. The spin structure function $g_1(x,Q^2)$ and the related longitudinally polarized parton densities $\delta\overset{(-)}{f}(x,Q^2)$ are discussed in LO and NLO QCD for different factorization schemes within the common 'standard' scenario of polarized pdfs with a flavor–symmetric light sea (antiquark) distribution $\delta\bar{q}$ and a completely $SU(3)_f$ broken 'valence' scenario with totally flavor-asymmetric light sea densities ($\delta\bar{u} \neq \delta\bar{d} \neq \delta\bar{s}$). The latter flavor-broken light sea densities are modelled with the help of a Pauli–blocking ansatz which complies with predictions of the chiral quark–soliton model and expectations based on the statistical parton model as well as with the corresponding, well established, flavor–broken unpolarized sea ($\bar{d} > \bar{u}$). Various parametrizations of polarized pdfs and results of recent analyses are discussed and compared, with particular emphasis on their implications at small x and for the polarized gluon distributions $\delta g(x,Q^2)$. Further (future) direct measurements of $\delta\bar{u}$ and $\delta\bar{d}$ are discussed and suggested, such as polarized semi–inclusive DIS production processes of charged hadrons, polarized Drell–Yan (γ^*) dilepton production processes for future longitudinally polarized $\vec{p}\vec{p}$ and $\vec{p}\vec{d}$ collision experiments, and the production of weak vector bosons ($W^{\pm}$, Z^0) via singly and doubly longitudinally polarized pp and pn collisions.

1. The spin structure function $g_1(x,Q^2)$ and longitudinally polarized parton distributions

Measurements of longitudinally polarized deep–inelastic lepton nucleon scattering (DIS), $\overleftarrow{\ell}\,\overrightarrow{\overrightarrow{N}} \to \ell\, N$, yield direct information on the spin asymmetry [1]

$$A_1^N(x,Q^2) \equiv \frac{\sigma(\overleftarrow{\ell}\,\overrightarrow{N}) - \sigma(\overleftarrow{\ell}\,\overleftarrow{N})}{\sigma(\overleftarrow{\ell}\,\overrightarrow{N}) + \sigma(\overleftarrow{\ell}\,\overleftarrow{N})} \simeq \frac{g_1^N(x,Q^2)}{F_1^N(x,Q^2)} = \frac{g_1^N}{F_2^N/[2x(1+R^N)]}\ , \quad (1.1)$$

$N = p$, n and $d = (p+n)/2$ where in the latter case $g_1^d = (g_1^p + g_1^n)[1 - 3\omega_D/2]/2$ with $\omega_D = 0.058$, $R = F_L/2xF_1 = (F_2 - 2xF_1)/2xF_1$ and subdominant contributions [1] being, as usual, neglected. These structure functions are defined via the hadronic tensor by

$$W_{\mu\nu} = -g_{\mu\nu}F_1 + \frac{1}{p\cdot q}\, p_\mu\, p_\nu\, F_2 + i\frac{M}{p\cdot q}\,\varepsilon_{\mu\nu\alpha\beta}\, q^\alpha s^\beta g_1 + \ldots \quad (1.2)$$

with the proton's momentum and polarization satisfying $p^2 = M^2$ and $s^2 = -1$, respectively. (Effects of weak currents and structure functions [1] will be disregarded.) In terms of parton distribution functions (pdfs) of definite helicity, $f_\pm$ with $f = q, \bar{q}, g$, the unpolarized (spin averaged) pdfs $f(x,Q^2) = f_+ + f_-$ are related to the well known unpolarized structure functions $F_{1,2}$, and the longitudinally polarized pdfs $\delta f(x,Q^2) = f_+ - f_-$ determine g_1.

It should be emphasized that, as in our original analysis [2], we keep computing [3] *both* g_1 and F_1 entirely in leading–twist QCD, the reason being the smallness of possible higher–twist contributions to $A_1(x,Q^2)$, as effectively parametrized in terms of a factor $[1 + A_{HT}(x)/Q^2]$, i.e. present polarized DIS data [4] imply [3, 5] $A_{HT}(x) \simeq 0$. Thus possible higher–twist terms appear to effectively cancel in the ratio of g_1 and F_1 in (1.1) despite the fact that different operators contribute to the operator–product–expansion for g_1 and F_1. Several groups have analyzed $g_1(x,Q^2)$ along these lines recently [3, 5, 6, 7] in order to avoid contaminations from power-suppressed higher–twist contributions, since "safe" cuts ($Q \geq 4$ GeV^2, $W^2 \equiv Q^2(1-x)/x \geq 10$ GeV^2) as in unpolarized DIS cannot be applied to presently available polarized DIS data without losing too much information. Furthermore, in order to obtain $F_1(x,Q^2)$ in (1.1) we [3] used the GRV98 pdfs [8] along with the leading order (LO) (note that $R = 0$ at LO) or next–to–LO (NLO) coefficient functions for F_2 and R in (1.1).

An alternative, frequently adopted approach [9]–[16] is to take $F_2(x,Q^2)$ and $R(x,Q^2)$ from experimental measurements. In this case, $A_{HT}(x)$ turns out to be *sizeable* [3, 5] and thus possible higher–twist contributions to $g_1(x,Q^2)$ become uncontrollable. Similar remarks hold for 'mixed' approaches [17]–[19] where only R is taken from experiment, with F_2 being given by the usual leading–twist QCD expression.

The longitudinally polarized structure function g_1 defined in (1.2) is, up to NLO, related to the longitudinally polarized (anti)quark and gluon densities (δf) in the following well known way:

$$g_1(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \Big\{ \delta q(x,Q^2) + \delta\bar{q}(x,Q^2) + \frac{\alpha_s(Q^2)}{2\pi}\,[\delta C_q * (\delta q + \delta\bar{q}) + 2\delta C_g * \delta g] \Big\} \tag{1.3}$$

with the convolutions $\delta C_f * f$ being defined in the usual way. The $\overline{\rm MS}$ coefficient functions $\delta C_f(x)$ can be found in [2], where all the necessary ingredients for the Q^2–evolutions have been formulated as well. The marginal charm contribution to g_1 stemming from the subprocess $\vec{\gamma}^*\vec{g} \to c\bar{c}$ will be neglected [20]. The NLO quantities $\delta C_i(x)$ and the 2–loop splitting functions $\delta P_{ij}^{(1)}(x)$ separately depend on the factorization scheme chosen. In other words, if one chooses a different factorization scheme according to $\delta C \to \delta C + \Delta$, in a generic but obvious notation, this change has to be compensated by an appropriate change of $\delta P^{(1)}$,

$$\delta P^{(1)} \to \delta P^{(1)} + \frac{\beta_0}{2}\Delta - [\Delta,\, \delta P^{(0)}] \tag{1.4}$$

in order to keep g_1 invariant, i.e. convention (scheme) independent to $\mathcal{O}(\alpha_s^2)$ [21]. In the $\overline{\rm MS}$ scheme the gluonic coefficient function in (1.3) satisfies

$$\Delta C_g \equiv \int_0^1 \delta C_g(x) dx = 0 \qquad (\overline{\rm MS}) \tag{1.5}$$

i.e. the total gluon helicity $\Delta g(Q^2)$ decouples from the first ($n = 1$) moment of $g_1(x, Q^2)$. Nevertheless, $\delta g(x, Q^2)$ plays an important role in analyses of $g_1(x, Q^2)$ since, for the time being, current measurements [4] always refer to $x \gtrsim 0.01$. On the other hand, in the gluon 'off–shell' ($-p^2 > 0$), chirally invariant (CI) or JET, or 'Adler–Bardeen' schemes [1, 6, 22, 23, 24] one has

$$\Delta C_g = -\frac{1}{2} \qquad (\text{'off}-\text{shell'}, \text{ CI/JET or AB scheme}) \,. \tag{1.6}$$

(In the somewhat artificial AB scheme [24] the coefficient Δ_g in (1.4), which appears in the transformation of δC_g, is chosen to be independent of x.) In these latter schemes the total (anti)quark helicity $\Delta\Sigma$ is conserved, i.e. Q^2–independent, and thus can remain 'constituent–like' at any scale.

The total helicity of a specific parton $f = u, \bar{u}, d, \bar{d}, s, \bar{s}, g$ is given by the first ($n = 1$) moment, as in (1.5),

$$\Delta f(Q^2) \equiv \int_0^1 \delta f(x, Q^2)\, dx \,. \tag{1.7}$$

Thus, according to (1.3) in the $\overline{\rm MS}$ scheme,

$$\Gamma_1(Q^2) \equiv \int_0^1 g_1(x, Q^2)\, dx = \frac{1}{2} \sum_q e_q^2 \left[\Delta q(Q^2) + \Delta\bar{q}(Q^2)\right] \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) \tag{1.8}$$

which is usually reexpressed in terms of diagonal flavor $\mathrm{SU}(3)_f$ quantities

$$\Gamma_1^{p,n}(Q^2) = \left[\pm \frac{1}{12}\, \Delta q_3 + \frac{1}{36}\, \Delta q_8 + \frac{1}{9}\, \Delta\Sigma(Q^2)\right] \left(1 - \frac{\alpha_s(Q^2)}{\pi}\right) \tag{1.9}$$

with the conserved (Q^2–independent) flavor–nonsinglet components

$$\Delta q_3 \equiv \Delta(u + \bar{u}) - \Delta(d + \bar{d}) \tag{1.10}$$

$$\Delta q_8 \equiv \Delta(u + \bar{u}) + \Delta(d + \bar{d}) - 2\Delta(s + \bar{s}) \tag{1.11}$$

and the flavor–singlet component is given by

$$\Delta\Sigma(Q^2) \equiv \sum_{q=u,d,s} \Delta(q + \bar{q}) = \Delta q_8 - 3\Delta(s + \bar{s})(Q^2) \,. \tag{1.12}$$

Before discussing possible constraints and scenarios for these polarized (sea) pdfs of the nucleon, let me remind you that present polarization experiments [4] typically yield, at a scale $Q^2 = 5$ GeV^2,

$$\Gamma_1^p(5) = 0.12 \pm 0.01 \,, \qquad \Gamma_1^n(5) = -0.06 \pm 0.01 \,. \tag{1.13}$$

1.1. SU(3)$_f$ symmetric 'standard' (unbroken–sea) scenario

This is the most commonly used scenario for analyzing polarization data, where one assumes the polarized sea to be fully flavor–symmetric

$$\delta\bar{q}(x,Q^2) \equiv \delta\bar{u} = \delta u_{\rm sea} = \delta\bar{d} = \delta d_{\rm sea} = \delta s = \delta\bar{s} \tag{1.14}$$

which, nevertheless, appears to be rather unrealistic in view of the strongly flavor–broken unpolarized sea ($\bar{d} > \bar{u} \gg \bar{s}$), see, for example [8]. Furthermore, the flavor–nonsinglet total helicities in (1.10) and (1.11) are entirely constrained by neutron and hyperon β–decay rates [25]:

$$\Delta q_3 = F + D = g_A = 1.2670\,(35) \tag{1.15}$$

$$\Delta q_8 = 3F - D = 0.58 \pm 0.15\,. \tag{1.16}$$

Note that the first constraint (1.15) is very solid, being nothing else than the Bjorken sum rule,

$$\Gamma_1^p(Q^2) - \Gamma_1^n(Q^2) = \frac{1}{6}\, g_A(1 - \alpha_s(Q^2)/\pi)\,, \tag{1.17}$$

including the NLO α_s–corrections according to (1.9), since it follows from the fundamental isospin SU(2)$_f$ symmetry [1]. The second 'standard' constraint (1.16) is, however, controversial because it relies on the full SU(3)$_f$ symmetry for the baryon octet, since data from $\Sigma^- \to n$ transitions are needed.

With these assumptions and constraints, eq. (1.9) becomes

$$\Gamma_1^{p,n}(Q^2) = \left[\pm\frac{1}{12}\,(F+D) + \frac{5}{36}\,(3F-D) + \frac{1}{3}\Delta(s+\bar{s})(Q^2)\right] \times (1 - \alpha_s(Q^2)/\pi)\,, \tag{1.18}$$

i.e. one needs here a finite sizeable strange sea polarization $\Delta s(Q^2) < 0$ in order to achieve the experimentally required reduction of the Ellis–Jaffe LO expectation [26] (which is obtained by assuming a vanishing helicity of th strange sea, $\Delta s = \Delta\bar{s} \stackrel{!}{=} 0$)

$$\Gamma_{1,\rm EJ}^p = \frac{1}{12}\,(F+D) + \frac{5}{36}\,(3F-D) = 0.186(4) \tag{1.19}$$

etc., to be compared with (1.13).

1.2. SU(3)$_f$ broken 'valence' (broken–sea) scenario

The assumption of the flavor–symmetric 'standard' scenario with its unbroken sea density in (1.14) is expected to be unrealistic, following our experience in the unpolarized case, $\bar{d} > \bar{u} \gg \bar{s}$, where the experimentally required suppression of the strange sea has been accomplished by a vanishing input $s(x,\mu^2) = \bar{s}(x,\mu^2) = 0$ in GRV98 [8] at the dynamical input scales $Q_0^2 \equiv \mu_{\rm LO,NLO}^2 = 0.26,\ 0.40$ GeV^2. Along these lines we therefore suggested and analyzed a fully flavor-broken polarized sea scenario [3] where

$$\delta\bar{u}(x,Q^2) \neq \delta\bar{d}(x,Q^2) \neq \delta\bar{s}(x,Q^2) \simeq 0\,, \tag{1.20}$$

or, more precisely, corresponding to an input

$$\begin{aligned}
&\delta\bar{u}(x,\mu^2) = \delta u_{\rm sea}(x,\mu^2) \neq \delta\bar{d}(x,\mu^2) = \delta d_{\rm sea}(x,\mu^2) \\
&\delta s(x,\mu^2) = \delta\bar{s}(x,\mu^2) = 0\,. \qquad (1.21)
\end{aligned}$$

Since, as in the unpolarized case, polarized DIS alone is insensitive to $\delta\bar{u} \neq \delta\bar{d}$ we need, for the time being, some model assumptions for substantiating the $\mathrm{SU}(2)_f$ broken part of the input in (1.21), as will be discussed below. (Notice that $g_1^{(\gamma^*)} \sim \delta q + \delta\bar{q}$ remains invariant for $\delta q \to \delta q - \delta\phi_q$ and $\delta\bar{q} \to \delta\bar{q} + \delta\phi_q$ with restrictions on $\delta\phi_q(x)$ occurring only in the 'valence' scenario where [3] $\Delta\phi_d = -\Delta\phi_u$).

Furthermore the full $\mathrm{SU}(3)_f$ flavor symmetry, giving rise to the constraints (1.15) and (1.16), is broken in the 'valence' scenario to the extent [27] that the flavor–changing hyperon β–decay data fix only the total helicity of valence quarks $\Delta q_v \equiv \Delta q - \Delta\bar{q}$, i.e. $\Delta u_v(Q_0^2) - \Delta d_v(Q_0^2) = F + D$ and $\Delta u_v(Q_0^2) + \Delta d_v(Q_0^2) = 3F - D$. Thus at the input scale $Q_0^2 = \mu^2$ we have instead of (1.15) and (1.16)

$$\Delta q_3 = \Delta u_v(\mu^2) - \Delta d_v(\mu^2) + 2\left[\Delta\bar{u}(\mu^2) - \Delta\bar{d}(\mu^2)\right] = F + D \qquad (1.22)$$

$$\begin{aligned}
\Delta q_8(\mu^2) &= \Delta u_v(\mu^2) + \Delta d_v(\mu^2) + 2\left[\Delta\bar{u}(\mu^2) + \Delta\bar{d}(\mu^2)\right] \\
&= 3F - D + 2\left[\Delta\bar{u}(\mu^2) + \Delta\bar{d}(\mu^2)\right] \\
&= \Delta\Sigma(\mu^2) \qquad (1.23)
\end{aligned}$$

on account of (1.21). The imposed constraint (1.22) guarantees the Bjorken sum rule (1.17) to hold manifestly. Now eq. (1.9) becomes

$$\begin{aligned}
\Gamma_1^{p,n}(Q^2) = &\left[\pm\frac{1}{12}(F+D) + \frac{5}{36}(3F-D) + \frac{10}{36}\left(\Delta\bar{u}(Q^2) + \Delta\bar{d}(Q^2)\right)\right] \\
&\times (1 - \alpha_s(Q^2)/\pi) \qquad (1.24)
\end{aligned}$$

apart from a marginal contribution $\Delta s(Q^2) = \Delta\bar{s}(Q^2) < 0$ which is generated dynamically via the NLO evolution to $Q^2 > \mu^2_{\rm NLO}$ even for the vanishing input in (1.21). Thus, in this case [3], only the total light–quark sea contribution in (1.24) has to be negative, $\Delta\bar{u}(Q^2) + \Delta\bar{d}(Q^2) < 0$ (with $\Delta s(Q^2) \simeq 0$), in order to achieve the experimentally required reduction of the Ellis–Jaffe expectation (1.19).

As mentioned above g_1–data are insensitive to flavor–isospin breaking effects $\delta\bar{u} \neq \delta\bar{d}$ and presently available polarized semi–inclusive DIS $\vec{e}\,\vec{p}\,(\vec{d}) \to e\,h^{\pm}X$ experiments [28, 29] are, unfortunately, not yet accurate enough to delineate differences between $\delta\bar{u}$ and $\delta\bar{d}$. Therefore, for the time being, we have to resort to some models which may provide us with the required input densities $\delta\bar{u}(x,\mu^2) \neq \delta\bar{d}(x,\mu^2)$ as will be discussed in the following Section.

2. Parametrizations of polarized pdfs and results

For the determination of the NLO(LO) polarized pdfs $\delta f(x,Q^2)$ one commonly relates, due to the limited statistics of present polarization data, the polarized input densities

to the unpolarized ones multiplied by an appropriate x–dependent 'dilution' factor to be determined by the polarization data under consideration:

$$\delta f(x,Q_0^2) = N_f x^{\alpha_f}(1-x)^{\beta_f} f(x,Q_0^2)\,. \tag{2.1}$$

Prefactors of this kind guarantee that the positivity constraints $|\delta f(x,Q^2)| \leq f(x,Q^2)$ will be fulfilled almost automatically and comply to some extent with intuitive (perturbative) theoretical arguments [30], such as 'helicity retention' $\delta f(x,Q_0^2) \to f(x,Q_0^2)$ as $x \to 1$ and 'color coherence' for sea and gluon densities $\delta f(x,Q_0^2)/f(x,Q_0^2) \sim x^a$ as $x \to 0$ with $a = \mathcal{O}(1)$ which is compatible with Regge a_1–exchange. Despite the fact that our recent fits [3] resulted mainly in sizeable α_f and small β_f in (2.1), it is not known at what scale Q_0 such intuitive theoretical constraints are supposed to apply for the nonperturbative input distributions. Anyway, enforcing in our fits all β_f to vanish increases the total χ^2 by several units, giving rise to worse fits than our optimal ones. Alternatively, one may choose an input parametrization [15]

$$\delta f(x,Q_0^2) = A_f x^{\alpha_f}(1+\gamma_f x^{\lambda_f}) f(x,Q_0^2) \tag{2.2}$$

which allows 'helicity retention' to be fulfilled straightforwardly. In any case the quality of the various fits to the data is similar. Frequently, the unpolarized valence–like GRV [8] input distributions $f(x,\mu^2)$ are used [3, 10, 14] at their dynamical input scale $Q_0^2 = \mu^2_{\rm LO,\,NLO}$ as fixed, via Q^2–evolutions, by experiment, or at some larger arbitrarily chosen [15] scale $Q_0^2 = 1$ GeV^2. Other unpolarized input densities which result from global data analyses, like the ones of MRST [31], are of course employed as well [5, 6].

Alternatively, one may parametrize just $\delta q_{3,8}$, $\Delta\Sigma$ and Δg in order to reduce the amount of free fit–parameters, but in this case [9, 11] one ends up with less 'predictive' power for the individual polarized pdfs $\delta f(x,Q^2)$.

2.1. Results of the 'standard' unbroken–sea scenario

The fitted asymmetries $A_1^N(x,Q^2)$ are in very good agreement with all presently available data (including the recent SLAC-E155 A_1^p data [32]), see fig. 1 of [3], with our optimal fits [3] corresponding to a total χ^2 of

$$\begin{aligned} \chi^2/209 \text{ data pts.} = 174.9 \quad & \text{LO} \\ 169.8 \quad & \text{NLO}(\overline{\rm MS})\,. \end{aligned} \tag{2.3}$$

These 'optimal' results are statistically not too significant for the polarized gluon distributions obtained, since drastically different choices for the gluon input $\delta g(x,\mu^2) = \pm\, x g(x,\mu^2),\ 0, \ldots$ change the total χ^2 in (2.3) by just one unit, $\delta\chi^2 = \pm 1$, but give rise to very different predictions for $g_1^N(x,Q^2)$ in the small–x region, $x < 0.01$, i.e. below present measurements (see fig. 3 of [3]). The importance of the gluon input for the small–x behavior of $g_1(x,Q^2)$ can be best illustrated with the help of the double–leading–logarithmic (DLL) approximation where [1]

$$g_1(x,Q^2) \overset{\rm DLL}{\underset{x\to 0}{\sim}} \left(\frac{4}{3}\,\delta\Sigma_0 - 3\delta g_0\right)\, exp\, \left[2\left(\frac{24}{\beta_0}\,\ln\frac{\alpha_s(Q_0^2)}{\alpha_s(Q^2)}\,\ln\frac{1}{x}\right)^{1/2}\right]. \tag{2.4}$$

For example, a positive δg_0 input will eventually cause the positive g_1^p to turn negative at small x. Therefore a fixed-power Regge (a_1) extrapolation of $g_1 \sim x^{0.5\ldots 0}$ for calculating, for example, $\Gamma_1(Q^2)$ is unreliable. Notice, in particular, that a vanishing gluon input $\delta g(x,\mu^2) = 0$ is, for the time being, entirely compatible with all present data as shown by the dashed curves in fig. 3 of [3]. On the other hand, fully saturated (via the positivity constraint) gluon inputs $\delta g = \pm g$ appear to be disfavored by present data as shown by the dotted curves in fig. 3 of [3].

The main differences between our corresponding new LO/NLO input densities [3] and our old GRSV95 ones [2] are somewhat harder δd (due to the new neutron data) and δg distributions (mainly caused by the recent SLAC-E155 A_1^p data [32]) although, as discussed above, the polarized gluon from our 'optimal' fit is only slightly preferred (cf. fig. 4 of [3]). These "optimal" pdfs at $Q^2 = 5$ GeV^2 (see fig. 5 of [3]) are similar to the δu, δd and $\delta\bar{q}$ results obtained in [14, 15]. The polarized gluon densities of AAC [15], where the new SLAC-E155 A_1^p data[32] have not been taken into account, are, however, sizeably larger in the medium to large x region than our new ones and the ones of [14]; similarly large $x\delta g(x,5)$ have been obtained in our old GRSV95 analysis [2]. The allowed bands of our weakly constrained new LO/NLO gluon distributions [3] are similar to the ones obtained in [14].

The corresponding total polarizations (first moments) are at NLO and $Q^2 = 5$ GeV^2

$$\Delta\Sigma(5) = 0.20\,, \qquad \Delta\bar{q}(5) \equiv \Delta s(5) = \Delta\bar{s}(5) = -0.064\,, \tag{2.5}$$

which are similar to the LO results [3], and imply $\Gamma_1^p(5) = 0.132$ and $\Gamma_1^n(5) = -0.062$ to be compared with the experimental values in (1.13). These quantities are weakly dependent on Q^2, in contrast to the gluon polarization $\Delta g(Q^2)$ which turned out to be $\Delta g(5) = 0.71$ according to our 'optimal' fit [3] corresponding to an input $\Delta g(\mu^2_{\rm NLO}) = 0.24$ at $\mu^2_{\rm NLO} = 0.40$ GeV^2. As already emphasized $\delta g(x,Q^2)$, and thus $\Delta g(Q^2)$, are only weakly constrained by present data: changing the total χ^2 in (2.3) by just one unit, $\delta\chi^2 = \pm 1$, results in the somewhat more reliable bound

$$-0.81 \lesssim \Delta g(5) \lesssim 1.73 \tag{2.6}$$

corresponding to an input $-0.45 \lesssim \Delta g\,(\mu_{\rm NLO}) \lesssim 0.7$, and similar results hold in LO. It is also interesting to observe that the nucleon's spin carried by the total helicities of quarks and gluons amounts, according to our 'optimal' fit, to

$$\frac{1}{2}\Delta\Sigma(\mu^2_{\rm NLO,\,LO}) + \Delta g(\mu^2_{\rm NLO,\,LO}) \simeq 0.35,\ \ 0.32 \tag{2.7}$$

which implies already a sizeable orbital contribution $L_{q+g}(\mu^2_{\rm NLO}) \simeq 0.15$ to the spin of the proton at low input scales according to the fundamental helicity sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma(Q^2) + \Delta g(Q^2) + L_{q+g}(Q^2)\,. \tag{2.8}$$

This is in contrast to our somewhat more intuitive previous GRSV95 result [2] $L_{q+g}(\mu^2_{\rm NLO,\,LO}) \simeq 0$, but the rather weakly constrained $\Delta g(Q^2)$, cf. (2.6), allows of course such an option.

Similar agreeable fits [3] are of course also obtained within the 'standard' scenario if one chooses to employ a different factorization scheme. For example, in the CI or JET scheme [6, 22, 23] one has, cf. (1.6),

$$\Delta\Sigma(Q^2) = \Delta\Sigma_{\rm CI} - 3\,\frac{\alpha_s(Q^2)}{2\pi}\,\Delta g(Q^2)_{\rm CI} \tag{2.9}$$

with $\Delta\Sigma_{\rm CI}$ being conserved. The resulting total polarizations turn out to be about twice as large as the above $\overline{\rm MS}$ quantities, $\Delta\Sigma_{\rm CI} \simeq 0.4$ and a large positive $\Delta g(\mu^2_{\rm NLO})_{\rm CI} \simeq 0.6 - 0.7$, as might be expected according to (2.9), with the individual $\delta\bar{q}_{\rm CI}$ and $\Delta\bar{q}_{\rm CI}$ being about 50% smaller than the $\overline{\rm MS}$ ones in (2.5), $\Delta\bar{q}_{\rm CI}(Q^2) \simeq -0.03$.

2.2. Results of the 'valence' broken–sea scenario

As emphasized in Sect. 1.2, polarized DIS data alone are insensitive to flavor–isospin breaking effects $\delta\bar{u} \neq \delta\bar{d}$. Thus some model assumptions are needed to fix the $\bar{d} - \bar{u}$ splitting. Generalizing the suggestion [33] that the unpolarized asymmetry is related to the Pauli exclusion principle ("Pauli–blocking") to the polarized case we suggested the following relation [34]

$$\delta\bar{d}(x,\mu^2)/\delta\bar{u}(x,\mu^2) = \delta u(x,\mu^2)/\delta d(x,\mu^2) \tag{2.10}$$

for estimating the flavor–symmetry breaking of the polarized sea. This empirical relation is derived from the a posteriori observation [34] that the unpolarized pdfs satisfy $\bar{d}/\bar{u} \simeq u/d$ for $x \lesssim 0.3$ at the input scale which holds for almost all present parametrizations [8, 31, 35]. In other words, $\bar{d} > \bar{u}$ since $u > d$, i.e. $u\bar{u}$ pairs in the sea are suppressed more than $d\bar{d}$ pairs by the exclusion principle because there are more u– than d–quarks in the proton. Similarly, (2.10) implies $|\delta\bar{d}| > \delta\bar{u}$ since experimentally $\delta u > |\delta d|$. The quality of our recent LO and NLO fits $A_1^N(x,Q^2)$ in this broken 'valence' scenario is practically identical to the one in the unbroken 'standard' scenario of the previous Section where, instead of (2.3), we now obtained [3]

$$\begin{aligned} \chi^2/209\ \text{data pts.} = 172.0 \quad & \text{LO} \\ 170.5 \quad & \text{NLO}(\overline{\rm MS}) \end{aligned} \tag{2.11}$$

and the same ambiguities persist (weakly constrained gluons, etc.) by changing this 'optimal' χ^2 by $\delta\chi^2 = \pm 1$ as obtained above for the 'standard' scenario. The resulting δq and $\delta\bar{q}$ are of course different than the ones in the unbroken 'standard' scenario, with δg remaining rather similar (see figs. 6 and 8 of [3]). It should be emphasized that we always expect for the broken light–sea input densities

$$\delta\bar{u} > 0\,, \qquad \delta\bar{d} < 0 \qquad \text{with} \qquad |\delta\bar{d}| > \delta\bar{u}\,, \tag{2.12}$$

i.e. $\delta\bar{u} - \delta\bar{d} > 0$ and $\delta\bar{u} + \delta\bar{d} < 0$. Our predicted flavor asymmetry $x(\delta\bar{u} - \delta\bar{d})(x,\mu^2)$ compares favourably with predictions of the relativistic field theoretic chiral quark–soliton model (CQSM) [36, 37, 38], as shown in fig. 7 of [3], which is also operative for unpolarized pdfs, with the only free parameter residing in the average instanton size $\bar{\rho}$, chosen to be $Q_0 = \mu \sim \bar{\rho}^{-1} \sim 0.6$ GeV. (Unfortunately, so far it has not been possible to

derive the important $1/N_c$ "suppressed" polarized and unpolarized gluon distributions.) Similar results have been obtained by a recent analysis based on the statistical parton model [39]. Notice that $\delta\bar{u}-\delta\bar{d} > \bar{d}-\bar{u}$, with the polarized sea asymmetry being roughly twice as large as the unpolarized $\bar{d}-\bar{u}$ one ! This is in contrast to conventional ρ–meson cloud models [40, 41] where typically $0 < (\delta\bar{d}-\delta\bar{u})_{\rho-\mathrm{cloud}} \ll -(\delta\bar{d}-\delta\bar{u})_{\mathrm{CQSM}}$. Finally it should be mentioned that the data select the solution of (2.10) which satisfies $\delta q\delta\bar{q} > 0$ for $q = u,\, d$. Even this inequality, which fixes the *sign* of each individual polarized light (anti)quark distribution, can be understood as a consequence of Pauli–blocking and the expected predominant pseudoscalar configuration of the quark–antiquark pairs in the nucleon sea [34, 3].

The corresponding total polarizations are at NLO and $Q^2 = 5$ GeV^2 [3]

$$\Delta\Sigma(5) = 0.273\,, \qquad \Delta\bar{u}(5) + \Delta\bar{d}(5) = -0.15\,, \qquad \Delta s = \Delta\bar{s} \simeq 0 \tag{2.13}$$

where $\Delta\bar{u}(5) = 0.085$ and $\Delta\bar{d}(5) = -0.235$, to be compared with (2.5), and similar results hold in LO. Furthermore $\Delta g(5) = 0.974$, corresponding to an input $\Delta g(\mu^2_{\mathrm{NLO}}) = 0.33$, which is somewhat larger than in the unbroken 'standard' scenario. However, $\delta g(x, Q^2)$ is again weakly constrained and allowing for $\delta\chi^2 = \pm 1$ results again in a similar band for $\Delta g(5)$ as in (2.6). Contrary to (2.7), our 'optimal' fit (2.11) gives now rise to $\frac{1}{2}\Delta\Sigma(\mu^2_{\mathrm{NLO}}) + \Delta g(\mu^2_{\mathrm{NLO}}) = 0.48$, implying a practially vanishing orbital component $L_{q+g}(\mu^2) \simeq 0$ according to (2.8). At larger scales $Q^2 > \mu^2$, however, hard radiative effects will give rise to sizeable orbital components due to the increasing k_T of the partons, which eventually have to compensate in (2.8) the strongly increasing gluon polarization $\Delta g(Q^2) \sim \alpha_s^{-1}(Q^2)$. Unfortunately, it is still an unsolved problem how to relate $L_{q+g}(Q^2)$ to realistic experimental observables. Therefore, the spin sum rule (2.8) constitutes a somewhat empty statement.

3. Further (future) direct measurements of $\delta\bar{u}$ and $\delta\bar{d}$

As already mentioned, polarized semi–inclusive DIS (SIDIS) processes [42], $\vec{e}\,\vec{p}\,(\vec{d}) \to e\,h^{\pm}X$, may play an important role for observing differences between $\delta\bar{u}$ and $\delta\bar{d}$. It has been recently emphasized [19] that a simultaneous analysis of polarized DIS and SIDIS asymmetry data will – and to some extent can already – delineate the flavor structure of the polarized light sea. In particular the more recent high precision SIDIS HERA–HERMES data [29] on $h^{\pm}$ production ($h = \pi,\, K$ dominantly) off a proton target, $\vec{e}\,\vec{p} \to e\,h^{\pm}X$, seem to play a decisive role in favoring a flavor SU(3)$_f$ broken sea, despite the fact that these asymmetry data on $A_{1p}^{h\pm}$ refer to rather small scales $Q^2 \gtrsim 1$ GeV^2. The reason for this discriminative power is due to the fact that

$$\begin{aligned} 2g_{1p}^{\pi^{\pm}} \sim\; & \frac{4}{9}(\delta u + \delta\bar{u})\, D_u^{\pi^{\pm}} + \frac{1}{9}\,(\delta d + \delta\bar{d})\, D_d^{\pi^{\pm}} \pm \frac{1}{9}\,(\delta\bar{d} - 4\delta\bar{u})\, D_u^{\pi^+} \\ & + \text{small 'unfavored' contbs.} \end{aligned} \tag{3.1}$$

with the 'favored' fragmentation functions $D_u^{\pi^+} = D_{\bar{u}}^{\pi^-} = D_d^{\pi^-} = D_{\bar{d}}^{\pi^+}$ and the 'unfavored' ones $D_u^{\pi^-} = D_{\bar{u}}^{\pi^+} = D_d^{\pi^+} = D_{\bar{d}}^{\pi^+}$ etc. Apart from the two dominant valence

contributions in (3.1) which are almost completely fixed by the inclusive DIS data alone and which are insensitive to a $\delta\bar{u} - \delta\bar{d}$ splitting, the interesting third term in (3.1), multiplied by a 'favored' fragmentation function as well, is significantly more sensitive to $\delta\bar{u}$ than $\delta\bar{d}$. This latter unconstrained component of both asymmetries is proportional to the same factor $(\delta\bar{d} - 4\delta\bar{u})$ but with opposite signs. On account of present SIDIS data, a clear preference for a *positive* $\delta\bar{u}$ has been observed [19] which is very similar to our NLO $\delta\bar{u}$ in the broken 'valence' scenario using (2.10) (cf. fig. 6(b) of [3] and fig. 6 of [19]). Present SIDIS cannot yet constrain $\delta\bar{d}$, since $\delta\bar{s}$ has been kept finite for the input fit with $\delta\bar{s} < 0$ [19]. Therefore it has been concluded [19] that flavor SU(3)$_f$ of the sea seems to be clearly *broken* and a flavor symmetric 'standard' light sea scenario appears to be strongly disfavored.

We have also calculated [3] at NLO the spin asymmetries for SIDIS using our results for the polarized pdfs of the 'standard' and 'valence' scenario with their flavor–symmetric and flavor–broken light sea densities, respectively, without changing any parameters obtained from our inclusive DIS analysis and employing the fragmentation functions suggested in [43]. Although the high precision HERMES SIDIS data [29] seem to favor slightly the broken 'valence' scenario, the results of the 'standard' scenario cannot yet be ruled out since they give rise to a comparable $\chi^2/$ (9 data pts.) of 7.6 and 8.5, respectively (see fig. 10 of [3]). Perhaps the new (1998 – 2000) very high statistics $\vec{D}$–data of HERMES, which are being analyzed at present, will be more decisive.

Nevertheless, we need further *direct* measurements of $\delta\bar{u}(x, Q^2)$ and $\delta\bar{d}(x, Q^2)$, and possibly of δs and $\delta\bar{s}$, for delineating the flavor structure of the polarized sea distributions. The LO Drell–Yan (γ^*) dilepton production process for future longitudinally polarized $\vec{p}\vec{p}$ and $\vec{p}\vec{d}$ collision experiments has been suggested [44, 45] for testing $\delta\bar{u} \neq \delta\bar{d}$ expectations. Here, for example,

$$A_{\vec{p}-\vec{n}}^{DY} \equiv \frac{\Delta\sigma_{\vec{p}\vec{p}}^{DY} - \Delta\sigma_{\vec{p}\vec{n}}^{DY}}{\sigma_{\vec{p}\vec{p}}^{DY} + \sigma_{pn}^{DY}} \underset{x_F \to 1}{\overset{\text{LO}}{\simeq}} \frac{(4\delta u_1 - \delta d_1)\,(\delta\bar{u}_2 - \delta\bar{d}_2)}{(4u_1 + d_1)\,(\bar{u}_2 + \bar{d}_2)} \tag{3.2}$$

in an obvious notation where for $x_F \to 1$, i.e. $x_1 \to 1$ and $x_2 \to 0$, the small $\delta\bar{q}_1$ terms can be neglected, or

$$R_{p+n} \equiv \frac{1}{2}\left(1 + \Delta\sigma_{\vec{p}\vec{n}}^{DY}/\Delta\sigma_{\vec{p}\vec{p}}^{DY}\right) \underset{x_F \to 1}{\overset{\text{LO}}{\simeq}} \frac{1}{2}(1 + \delta\bar{d}_2/\delta\bar{u}_2)\,. \tag{3.3}$$

(These observables are obvious generalizations of the well known unpolarized Drell–Yan $\mu^+\mu^-$ production [46] pp and pn experiments [47] which were instrumental in establishing $\bar{d} > \bar{u}$). The NLO($\overline{\text{MS}}$) expressions [48] for such asymmetries have been recently analyzed in detail [49] for the unbroken and broken light sea scenarios. Similarly, the production of weak vector bosons ($W^{\pm}, Z^0$) via singly and doubly longitudinally polarized (as well as unpolarized) $pp(n)$ collisions, $pp(n) \to W^{\pm}X \to \mu^{\pm}\overset{(-)}{\nu}_{\mu}X$ and $pp(n) \to Z^0X \to \mu^+\mu^-X$, can provide us with direct measurements of the individual $\delta\bar{u}(x, Q^2)$ and $\delta\bar{d}(x, Q^2)$ distributions [50, 45], although at far larger scales $Q^2 \sim M^2_{W^{\pm},\,Z^0}$. These production processes afford of course higher c.m. energies available at RHIC ($\sqrt{s}_{\max} = 500$ GeV) [51]. For example, typical single and double spin asymmetries are

$A^{W^\pm}_{\vec{p}\,\vec{p}\,(\rightarrow)} \equiv \Delta\sigma^{W^\pm}_{\vec{p}\,\vec{p}\,(\rightarrow)}/\sigma^{W^\pm}_{pp}$ which, in specific kinematic regions, behave in LO like

$$A^{W^+}_{\vec{p}p} \stackrel{\rm LO}{\simeq} \delta\bar{d}_1/\bar{d}_1\,, \qquad A^{W^-}_{\vec{p}p} \stackrel{\rm LO}{\simeq} \delta\bar{u}_1/\bar{u}_1 \qquad \text{for} \quad y \lesssim -0.5 \tag{3.4}$$

$$A^{W^+}_{\vec{p}\vec{p}} \stackrel{\rm LO}{\simeq} -(\delta u_1/u_1)(\delta\bar{d}_2/\bar{d}_2), \qquad A^{W^-}_{\vec{p}\vec{p}} \stackrel{\rm LO}{\simeq} -(\delta d_1/d_1)(\delta\bar{u}_2/\bar{u}_2) \qquad \text{for} \quad y \gtrsim +0.5$$

or

$$\Delta\sigma^{W^+}_{\vec{p}\,(\rightarrow)\,d}/\Delta\sigma^{W^-}_{\vec{p}\,(\rightarrow)\,d} \stackrel{\rm LO}{\simeq} \delta\bar{d}_1/\delta\bar{u}_1 \qquad \text{for} \quad y \lesssim -0.5\,. \tag{3.5}$$

There is a plethora of charged and neutral current spin asymmetries, and their NLO($\overline{\rm MS}$) expressions [52] have been analyzed in great detail as well [49] for the unbroken 'standard' and broken 'valence' scenarios, which will be tested by RHIC experiments [51].

4. Summary

All present longitudinal polarization data can be equally well described [3] by either the 'standard' scenario, characterized by (1.15), (1.16) and referring to the common simplified (but probably unrealistic) assumption of an $SU(3)_f$ flavor–symmetric polarized light sea ($\delta\bar{u} = \delta\bar{d} = \delta\bar{s}$) with $\Delta\bar{s} \simeq -0.06$, or by a 'valence' scenario, characterized by (1.22), (1.23) and employing (a probably more realistic) totally broken polarized light sea ($\delta\bar{u} \neq \delta\bar{d} \neq \delta\bar{s}$) with $\Delta\bar{u} + \Delta\bar{d} \simeq -0.15$. Since inclusive polarized DIS data cannot fix the flavor–broken sea densities, we have modelled the broken sea $\delta\bar{u} \neq \delta\bar{d}$ using a Pauli–blocking ansatz in (2.10), because similar blocking effects can also explain the flavor–asymmetry of the unpolarized sea ($\bar{d} > \bar{u}$) and are furthermore in agreement with predictions of the relativistic field theoretical chiral quark–soliton model [36, 37, 38] and of the statistical parton model [39] (typically, $\delta\bar{u} > 0$, $\delta\bar{d} < 0$ with $|\delta\bar{d}| > \delta\bar{u}$). These results are also supported by a combined analysis [19] of polarized DIS and semi–inclusive DIS data.

Apart from the polarized (anti)quark distributions and their total helicities, the longitudinally polarized gluon distribution $\delta g(x, Q^2)$ is still weakly constrained by present data in both scenarios. In particular, a vanishing gluon input $\delta g(x, Q_0^2) = 0$ is equally compatible with all present measurements; only a fully saturated (via the positivity constraint) gluon input $\delta g(x, Q_0^2) = \pm g(x, Q_0^2)$ appears to be disfavored. The resulting total gluon helicity is again weakly constrained by $-0.8 \lesssim \Delta g(5) \lesssim 1.7$ at $Q^2 = 5$ GeV^2.

Further dedicated experiments are needed for determining or better constraining $\delta g(x, Q^2)$ via $\vec{e}\,\vec{p} \to e\,c\bar{c}\,X$ at CERN (COMPASS) and SLAC, and $\vec{p}\,\vec{p} \to c\bar{c}, b\bar{b}X$ and $\vec{p}\,\vec{p} \to \gamma X$ at RHIC; in particular for delineating the flavor structure of the polarized light sea ($\delta\bar{u}$, $\delta\bar{d}$, $\delta\bar{s}$) via $\vec{e}\,\vec{p} \to e\,h^\pm X$ at DESY (HERMES) and via polarized Drell–Yan production processes $\vec{p}\,\vec{p}\,(\vec{d}) \to \mu^+\mu^-$, $W^\pm X$ at RHIC.

Finally I would like to remind you of the chiral–odd 'transversity' pdfs $\delta_T \overset{(-)}{q}(x, Q^2)$ which are related to the quark tensor current [1, 53, 54]. They are leading twist–2

densities and complete the twist-2 sector of the nucleon's pdfs, and are as interesting in principal as the familiar $f(x,Q^2)$ and $\delta f(x,Q^2)$ with $f = q,\, \bar{q},\, g$. We face the curious situation of having reached a remarkably advanced theoretical sophistication, without having any experimental measurement whatsoever. Despite the difficulties [1, 54, 55] to extract such densities from transverse polarization asymmetries experimentally, only a measurement of the 'transversity' pdfs will *complete* our knowledge of the leading twist–2 sector of the nucleon's parton distributions (f, δf, $\delta_T \overset{(-)}{q}$).

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