Experimental Studies of the Nucleon Spin Structure: from the Past to the Future

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Abstract. Twenty two years after the “proton spin crisis” has been declared, a review of the nucleon spin structure is presented and in particular the status of the ”proton spin puzzle” is discussed.

1. Introduction

Born with troubles, spin has for the first time manifested itself experimentally as a new and non–classical quantity in the Stern–Gerlach experiment (“good experiment for the wrong theory”) in 1921, before the birth of the modern quantum mechanics and essentially before (what is being accepted as) the spin discovery. The history [1] and the predictable future [2] of the spin research are both very exciting. Spin plays a central role in the modern physics. We belive that it is due to the space-time symmetry and thus determins the basic structure of the fundamental interactions. With current spin research programmes at BNL, CERN, JLAB and with prospects of an e–p collider and an e^+e^- linear collider, both eventually working also in a polarised mode, we are witnessing a wide attempt to understand the spin, to test the spin sector of QCD and possibly also use it in the search for the “new physics”. In the latter spin offers a rich spectrum of concepts, like the “$g-2$” experiments (*e.g.* the last one recently completed at BNL), proton weak charge studies (QWEAK planned at JLAB) or the neutron electric dipole moment measurements. Spin is also a tool to measure observables hard to obtain otherwise, *e.g.* the strangeness content of the nucleon and the neutron density in large nuclei are investigated using the parity–violating electron scattering (JLAB). A revolution in the nucleon electromagnetic form factor measurements was due to employing the recoil polarisation measurements (JLAB). Finally the spin is a tool to unravel the nonperturbative QCD dynamics in the nucleon, *e.g.* through measurements of spin–dependent structure functions, the quark helicity and transversity distributions, gluon polarisation, Generalised Parton Distributions, the (Generalised) Drell–Hearn–Gerasimov sum rule, Bjorken- and Ellis–Jaffe sum rules, single spin asymmetries, etc. This paper will be devoted to certain aspects of the nucleon spin structure, based on measurements of observables selected from the latter list.

The structure of the most common of hadrons, the nucleon, is still largely unknown, in particular in its spin-dependent aspects. Their intensive studies have commenced after the European Muon Collaboration, 22 years ago, had published a surprising result that total quark spin constitutes a rather small fraction of the spin of the proton, [3]. This result has been later confirmed by several experiments using polarised electrons (muons), different polarised nucleon targets and incident energies from few to few hundred GeV. Possible other nucleon spin carriers, gluons and the parton angular momenta, should be investigated. The latter are presently inaccessible experimentally. As for the former, the QCD evolution of the polarised inclusive DIS measurements has a limited sensitivity to the gluon helicity distribution, $\Delta g(x)$, due to the limited range in the Q^2 values covered by the data. Direct measurements of the gluon polarisation in the nucleon, through final states which select processes with gluons, have thus become an imperative.

The nucleon quark structure at the twist-two level and in the absence of (or after intergating over) the quark transverse momentum, k_T, is fully determined by a set of quark momentum ($q(x)$), helicity ($\Delta q(x)$), and transversity ($\Delta_T q(x)$) distributions. Helicity distribution is a difference of probabilities of quarks having spins parallel and antiparallel to the nucleon spin when the latter is oriented along the virtual photon. Definition of the transversity is similar but refers to the transverse polarisation of the nucleon. Since boosts and rotations do not commute, helicity and transversity need not to be the same in the relativistic (high energy beam) case. The $\Delta_T q$ distributions are C-odd and chiral-odd, thus they may only be measured with another chiral-odd partner, *e.g.* the fragmentation function. They have very interesting properties: their QCD evolution is simple since it does not involve gluons, they are related to the Generalised Parton Distributions and finally their first moment gives the nucleon tensor charge, now being studied on the lattice. Allowing for twists higher than two or for the non-zero k_T of quarks, results in additional distributions needed to describe the quark structure of the nucleon.

In this paper the following subjects will be discussed: spin experiments and observables (Section 2), the logitudinal spin structure of the nucleon (Section 3), the polarisation of gluons in the nucleon (Section 4), the transversity effects (Section 5), the nucleon spin decomposition and the parton angular momentum in the nucleon (Section 6) and finally the future spin projects and the outlook (Section 7).

The review of the sum rules as well as definitions of kinematic variables and the description of the formalism of the inelastic scattering of polarised leptons on polarised nucleons are given *e.g.* in [4].

2. Experiments and observables

A list of the recently accomplished and ongoing spin experiments comprise (table 1): a set of completed electroproduction measurements at SLAC (E142, E143, E154, E155, E156) and DESY (HERMES), both at the electron energy around 30 GeV, a rich spin programme carried on at the 6 GeV electron CEBAF machine at JLAB, three generations of ∼200 GeV muon beam experiments at CERN (EMC, SMC and the presently running COMPASS) and finally the proton–proton collider experiments at BNL (STAR, PHENIX, BRAHMS), after a couple of years of operating at $\sqrt{s} = 200$ GeV, now running at $\sqrt{s} = 500$ GeV.

Table 1. High energy experiments in spin physics

Experiment	Polarised beam	Polarised target	Energy (GeV)
SLAC (completed)	e	p, n, d	$\lesssim 50$
EMC (completed)	μ	p	100–200
SMC (completed)	μ	p, d	100, 190
HERMES (analysing)	e	p, n, d	∼30
COMPASS (running)	μ	p, d	160
JLAB (running)	e	p, n, d	$\lesssim 6$
BNL (running)	p	p	$\lesssim 250 + \lesssim 250$

In fixed-target experiments there is a strong correlation between the low x and low Q^2 regions. The latter usually means values below 1 GeV^2, *i.e.* the nonperturbative region, unless a variable different from Q^2 is used as a scale in the perturbative QCD series. The range of Q^2 values covered at low x is usually narrow, at most equal to one decade in x.

Electron and muon measurements are complementary: the former offer lower beam energies but very high beam intensities; their kinematic acceptance is limited to low values of Q^2 and moderate values of x. The latter, with much higher energy of beams, extend to higher Q^2 and to lower values of x (an important aspect in the study of sum rules) but due to limited beam intensities the data taking time has to be long to ensure satisfactory statistics. Electron beam experiments have to deal with substantial contribution of radiative processes.

The collider machines boost the centre-of-mass energy more than an order of magnitude, permit studies of the jet-, π meson- and photon production, and, in case of the planned electron–ion collider, allow a deep insight into the large parton density ("low x") region.

A nontrivial technical challenge is a preparation of highly polarised beams and targets, the latter of large volumes which also maintain a constant polarisation for periods of the order of 1000 hours and permit to reverse it periodically without losses. Another issue is a permanent and precise monitoring of the polarisation, especially at colliders.

Spin-dependent cross sections are only a small contribution to the total electroproduction cross section. Therefore they can best be determined by measuring the cross section asymmetries in which the spin-dependent contributions cancel. Direct result of the electroproduction measurements is thus the cross section asymmetry obtained from the scattering of the (longitudinally) polarised lepton off a (longitudinally or transversally) polarised nucleon target. The asymmetry may be determined either for the inclusive- or for the semiinclusive reaction channels. In the former only an incident and scattered leptons are registered; in the latter, additionally one or more hadrons are detected. After corrections for dilution and depolarisation effects and after inclusion of necessary input information like the spin-averaged structure functions, those asymmetries lead to determination of the Δq, $\Delta_T q$ and Δg distribution functions. Particularly important are asymmetries due to the Collins and Sivers mechanisms, the former being due to the combined effect of $\Delta_T q$ and a chirally–odd spin–dependent fragmentation function and the latter to a correlation between the intrinsic transverse momentum of a quark and the transverse polarisation of the nucleon.

3. Longitudinal spin structure of the nucleon: inclusive and semi–inclusive measurements

More than 40 years long studies of the spin-averaged deep inelastic scattering provided a wealth of precise data on the nucleon structure functions $F_i (i = 1, 2, 3)$. For the F_2 and in the perturbative region, $Q^2 > 1$ GeV^2, they extend to $Q^2 \sim 10^5$ GeV^2 and cover a wide range in x, $x \gtrsim 3 \cdot 10^{-5}$. The QCD analysis of those data results in a precise determination of parton distributions and reveals that about 50% of the proton momentum is carried by gluons. The measurements extend deeply into nonperturbative region, $Q^2 \ll 1$ GeV^2, and result in detailed studies of its dynamics.

Measurements of the spin–dependent nucleon structure functions g_1 and g_2, are more scarce and thus spin-dependent parton distributions are known only with limited accuracy. The status of proton and deuteron g_1 measurements is presented in figure 1. No clear spin effects are visible for $x \lesssim 0.03$. The $Q^2 < 1$ GeV^2 region for the g_1^d has been measured by COMPASS in the range $0.00004 < x < 0.02$ [5], with a statistical precision at least ten times higher than that of the previous experiment, the SMC. The resulting structure function is consistent with zero, *i.e.* no spin effects are visible in the nonperturbative region at low x. The moderate and large x measurements were not possible in high energy experiments since they lacked the necessary luminosity and resolution there. The situation has changed dramatically with the advent of the CEBAF machine at JLAB, cf. [6]. Around $Q^2 = 1$ GeV^2 down to $Q^2 \sim 0.01$ GeV^2 and moderate x, a large body of precise g_1 data is provided by the CLAS collaboration at JLAB [7]. They greatly improve the knowledge of the parton distribution functions. Experiments at JLAB also provided the first evidence that the neutron spin asymmetry, $A_1^n > 0$ at large x, a clear evidence for the SU(6) symmetry breaking. Data on proton and deuteron also exhibit a trend to exceed the asymmetry predicted by the SU(6) at large x [7, 8]. Measurements of the g_2 provide meaningful information only at low energies, *e.g.* at JLAB where they are successfuly performed, figure 2.

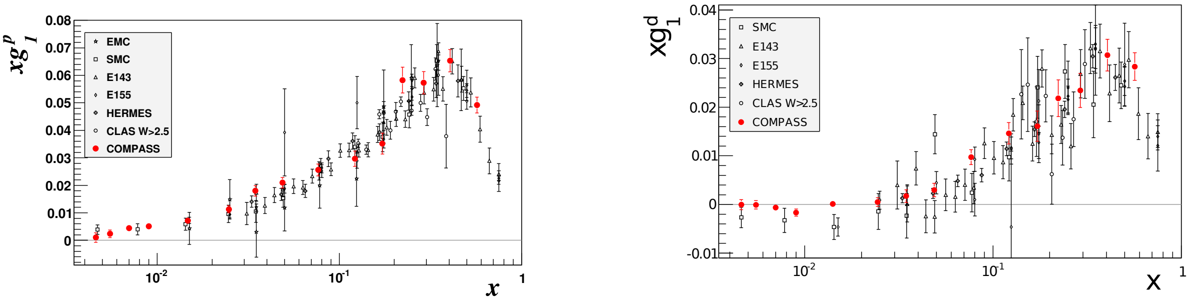

Figure 1. Results on xg_1^p (left) and xg_1^d (right) as a function of x for Q^2 >1 GeV^2. Error bars represent the systematic and statistical uncertainties added in quadrature.

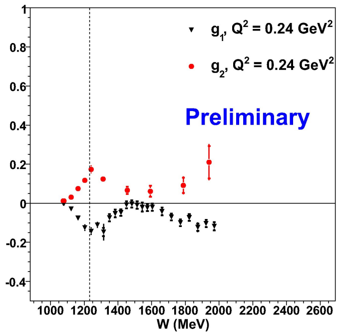

Figure 2. JLAB/Hall A results for the xg_1 and xg_2 on the ^{3}He target in the $\Delta(1232)$ region, [9]. Errors are total.

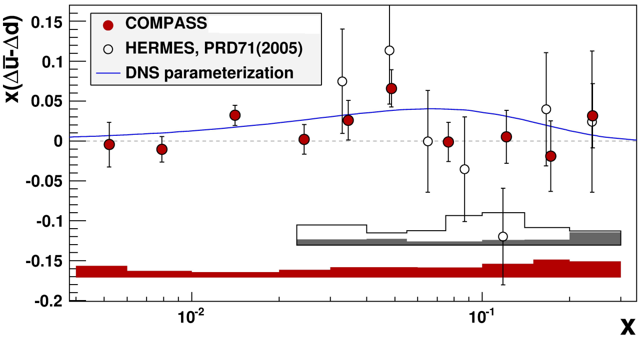

Figure 3. Values of $x(\Delta\bar{u} - \Delta\bar{d})$ as a function of x as measured by COMPASS and HERMES, [12].

The world data on g_1 were QCD analysed at the NLO accuracy by several groups, including COMPASS [10] which obtained an accurate evaluation of the first moment of $g_1^d(x)$, and of the matrix element of the singlet axial current, a_0 (assuming the a_8 matrix element as determined from the weak decays of hyperons). In the $\overline{\text{MS}}$ renormalisation scheme the a_0 is the same as the quark spin contribution to the nucleon spin. At $Q^2 = 3$ GeV^2 it is equal to $a_0 = 0.35 \pm 0.03 \pm 0.05$, in a very good agreement with the HERMES result at $Q^2 = 5$ GeV^2. With this (and a_8) value and in the $Q^2 \to \infty$ limit, the first moment of the strange quark distribution is $(\Delta s + \Delta\bar{s})$ = –0.08 ± 0.01 ± 0.02. The gluon helicity distribution, $\Delta g(x)$ was however poorly constrained: two solutions with either $\Delta g(x) > 0$ or $\Delta g(x) < 0$, described the data equally well.

Quarks and antiquarks of the same flavour equally contribute to g_1 and thus the inclusive data do not permit to separate valence and sea contributions to the nucleon spin. Therefore additional, semi-inclusive spin asymmetries for positive and negative hadrons in the final state, h^+ and h^- are often measured, see *e.g.* [11], the hadrons being identified pions and kaons. Analysis based on such measurements normally requires the knowledge of the (very poorly known) fragmentation functions. However in the LO QCD, the difference asymmetry, $A^{h^+-h^-}$ does not require this; it measures the valence quark polarisation and provides an evaluation of the first moment of $\Delta u_v + \Delta d_v$ which in [11] was found to be equal to 0.41 ± 0.07 ± 0.06 at $Q^2 = 10$ GeV^2 and over the measured range of x. When combined with the first moment of g_1^d, this result favours a non-symmetric polarisation of light quarks, $\Delta\bar{u}(x) = -\Delta\bar{d}(x)$ at a confidence level of two standard deviations, in contrast to the often assumed symmetric scenario $\Delta\bar{u}(x) = \Delta\bar{d}(x) = \Delta\bar{s}(x) = \Delta s(x)$. Data taken by COMPASS on proton and deuteron targets confirm a small excess of $\Delta\bar{u}$ over $\Delta\bar{d}$, [12, 13], figure 3. The HERMES analysis of the kaon asymmetries on the deuteron [14] where all the necessary input information was determined from the same data, resulted in the strange sea polarisation $(\Delta s + \Delta\bar{s}) = 0.037 \pm 0.019 \pm 0.027$, at LO QCD, and in the x range 0.02 – 0.6. This should be compared with the recent results [13] where both Δs and $\Delta\bar{s}$ distributions are compatible with zero and with the slightly negative, inclusive result of COMPASS, mentioned before. The aparent contradiction between inclusive- and semiinclusive data might point at a substantial breaking of the SU$(3)_f$ or at the change in sign of the strange quark helicity distribution at values of x lower than measured, cf. [16, 18].

At high x a precise u and d flavour separation was done by CLAS and Hall A collaborations at JLAB, at LO QCD using their neutron, proton and deuteron data, [7, 8].

Very recently STAR at RHIC has presented results of their first measurement of the (parity violating) single–spin asymmetries for midrapidity decay e^+ and e^- from W^+ and W^- produced in longitudinally polarised proton–proton collisions at $\sqrt{s} = 500$ GeV [15]. The measured asymmetries are: $A_L^{W^+} = -0.27 \pm 0.10 \pm 0.02 \pm 0.03$ (norm.) and $A_L^{W^-} = 0.14 \pm 0.19 \pm 0.02 \pm 0.01$ (norm.). At midrapidity, $W^{+(-)}$ production probes a combination of the polarisation of the u and $\bar{d}$ (respectively d and $\bar{u}$) quarks at much larger scales (set by the electron p_T) than in previous and ongoing DIS experiments and agree well with the polarised parton distribution functions of [16], figure 4. Results of PHENIX support these conclusions, [17].

A special attention deserves the NLO QCD analysis of world data, performed by the DSSV group [16, 18]. Apart of the complete set of the inclusive and semi-inclusive spin dependent (deep) inelastic data from EMC, SMC, COMPASS, SLAC, JLAB and HERMES, also the RHIC high-p_T results from STAR (jets at $\sqrt{s} = 200$ GeV) and PHENIX (π^0 at $\sqrt{s} = 62$ and 200 GeV) were for the first time included. The results, figure 5, were compatible with those of COMPASS, mentioned above. Observe that errors on the polarisation of gluons are very large but there is an indication that it may have a node at $x \sim 0.1$ and that its first moment is close to zero.

4. Measurements of the gluon polarisation

They are very difficult. Due to the limited range in Q^2 at fixed x, covered by experiments, the QCD fits, cf. [10, 16, 18], show very limited sensitivity to the gluon helicity distribution, $\Delta g(x)$ and to its first moment, ΔG. The determination of $\Delta g(x)$ has therefore to be complemented by direct extraction from the measured semi-inclusive asymmetries. Contrary to the fits, this approach results in ΔG which is independent of any assumptions concerning the shape of the x dependence. However this happens at the expense of a complicated experimental selection of a defined, gluon–initiated process. The proton–proton collisions at RHIC are a special challenge here, since the corresponding (pion, photon and jet production) asymmetries are bilinear in the parton distributions. The gluon polarisation models used to predict asymmetries are in this case validated through successful comparison of the measured, spin-averaged, cross sections to the NLO QCD calculations.

The RHIC measurements begin to significantly constrain the gluon spin contribution. For example the PHENIX double helicity asymmetries in neutral pion production for $p_T = 1$ to 12

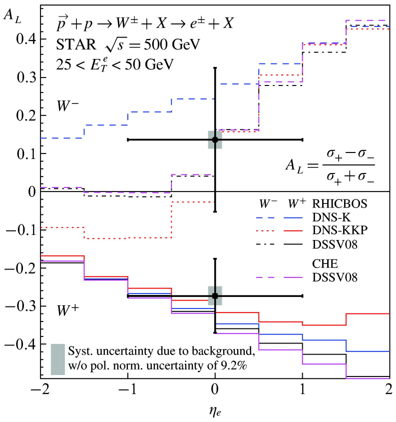

Figure 4. Longitudinal single–spin asymmetry, for $W^{+(-)}$ events as a function of the electron pseudorapidity for $25 < E_T^e < 50$ GeV compared to theory, [15].

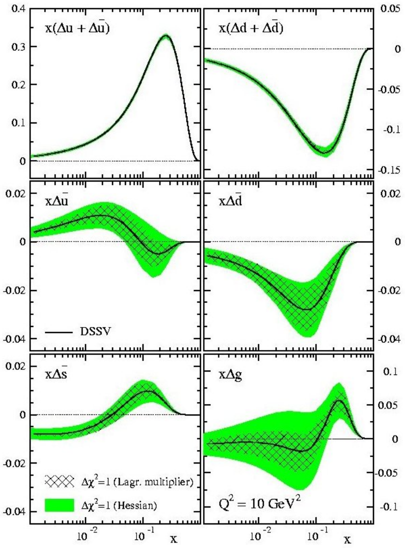

Figure 5. Results of the DSSV global parton analysis for the proton at $Q^2 = 10$ GeV^2, in the $\overline{\text{MS}}$ scheme, [18].

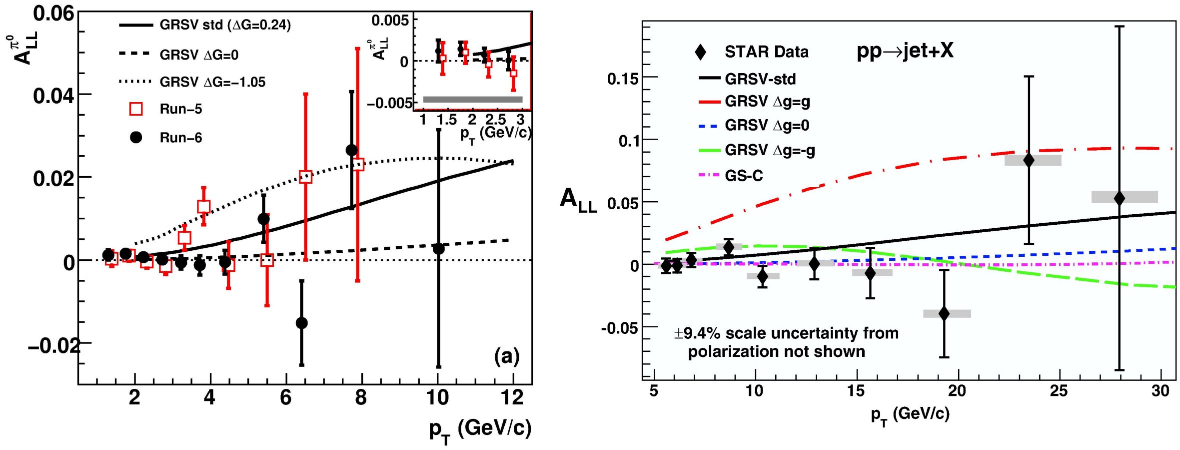

Figure 6. RHIC polarised proton–proton results at $\sqrt{s} = 200$ GeV. Curves mark different ΔG scenarios. **Left:** PHENIX results, [19] for the asymmetry in π^0 production as a function of its p_T. Errors are statistical. **Right:** STAR results, [20] for the longitudinal double-spin asymmetry A_{LL} for inclusive jet production as a function of jet p_T. Errors are statistical.

GeV are consistent with zero, and at a theory scale of 4 GeV^2 give Δg from 0.1 to 0.2 for x between 0.02 and 0.3, cf. figure 6 [19]. Their future measurements will be required to measure at $x < 0.02$ where large uncertainty remains [18] and which may still contribute a significant amount of the proton spin. The STAR measurement of longitudinal double spin asymmetry for inclusive jet production at midrapidity, for jet transverse momenta $5 < p_T < 30$ GeV give a constraint that $\Delta G(Q_0^2 = 0.4\ \text{GeV}^2) < 65$ % of the proton spin with 90% confidence, figure 6, [20].

The gluon polarisation in the nucleon was recently determined in two ways by COMPASS, from the cross–section asymmetry for the virtual photon–gluon fusion (PGF), $\gamma^* g \rightarrow q\bar{q}$. The PGF process was selected depending on the products of the $q\bar{q}$ pair fragmentation, either through production of hadron pairs with high transverse momenta, p_T (typically 1–2 GeV), with respect to the virtual photon direction, or through the open-charm production, *i.e.* when $q \equiv c$ and the $c\bar{c}$ pair fragments into a pair of the D mesons. The former process results in a very high statistics but relies on Monte Carlo generators simulating the QCD processes; the latter provides the cleanest sample of interesting events albeit at a low rate.

The cross–section helicity asymmetry for events with at least two high-p_T hadrons in addition to the incoming and outgoing muon, contains an asymmetry from the background processes apart from the contribution from the PGF. This background asymmetry and the PGF contribution were estimated by a simulation which introduces a model dependence in the evaluation of ΔG. The $Q^2 > 1$ GeV^2 and the $Q^2 < 1$ GeV/^{2} events were considered separately. Results are $\Delta g/g$ = +0.08 ± 0.10 ± 0.05 and $\Delta g/g$ = +0.02 ± 0.06 ± 0.06 respectively, both at a scale $\approx$ 3 GeV^2 and an average gluon momentum fraction $\langle x \rangle \approx 0.08$, [21].

Production of the open charm D mesons was assumed to be dominated by the PGF mechanism (charm quark *not* pre-existing in the nucleon). The method has the advantage that in the lowest order of the α_s there are no other contributions to the cross section. A leading order QCD approach gave an average gluon polarisation of $\Delta g/g$ = –0.08 ± 0.21 (stat.) at a scale $\approx$ 13 GeV^2 and $\langle x \rangle \approx 0.11$, [22]. Here the g denotes the gluon momentum distribution and the error given is statistical; systematic errors are under study. Preliminary results from the NLO QCD analysis, [23] bring that number even closer to zero and shift the $\langle x \rangle$ to about 0.2, figure 7.

Presently all measurements of Δg are situated around x ~0.1 and point towards a small gluon polarisation there, figure 7 (see also figure 5 and [18]). This, in principle, still does not exclude a large value of the first moment of the gluon helicity distribution.

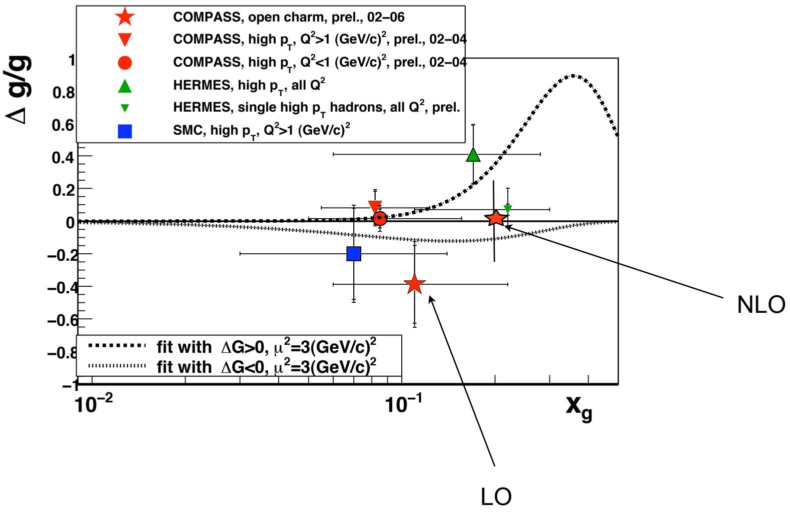

Figure 7. Compilation of the measurements of the average gluon polarisation in a limited range of x_g, $\langle \Delta g/g \rangle$, from the open charm and high p_T hadron pair production together with the results of the NLO analysis of the open charm. Curves display two parametrisations from the COMPASS NLO QCD analysis, [10]. Figure from [23].

5. Transverse spin structure of the nucleon

To complete the nucleon quark structure at the twist-two level and neglecting the quark transverse momenta, their transversity ($\Delta_T q(x)$) distributions need to be determined. This is accomplished through asymmetry measurements on a tranversally polarised target, particularly the Collins and Sivers asymmetries. HERMES has found the evidence for both mechanisms, [24] for the pions produced on a proton target. The corresponding asymmetries measured on the deuteron and at much higher energy by COMPASS, showed no visible effect, for any of the identified hadrons measured (charged pions and kaons, neutral kaons), [25]. This is in line with the previously published COMPASS results for not identified charged hadrons [26], and with the expected cancellation between the u- and d-quark contributions in the deuteron.

Recently COMPASS has obtained results on the transversely polarised proton target for positive and negative hadrons, [27]. These are the first such measurements at high energy. The data extend the kinematic range to large Q^2, large W and small values of x. They show a signal of nonzero Sivers asymmetry for positive hadrons, which persists to rather small x values. The data give an indication for a possible W dependence of this asymmetry, but the present statistical and systematic uncertainties do not allow definite conclusions. The measured Collins asymmetry is sizable at large x, for both positive and negative hadrons, figure 8. This means that it is large also at high energy and large Q^2, as expected for leading twist effects. Therefore Collins asymmetries measured in semiinclusive DIS are an appropriate tool to investigate the transversity parton distribution functions.

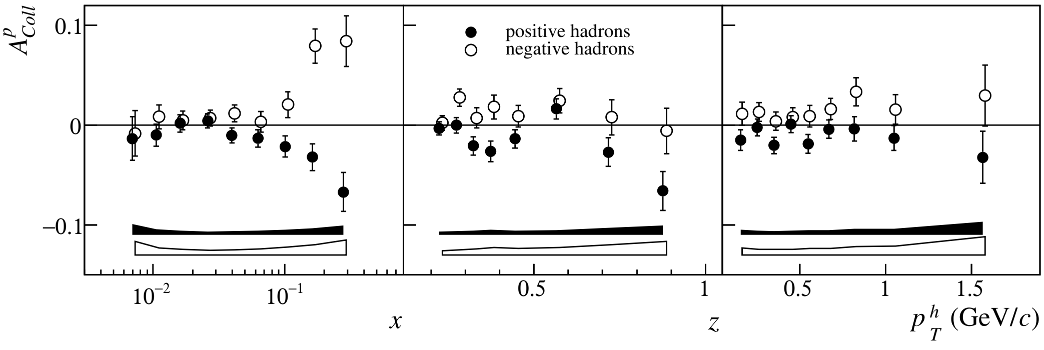

Figure 8. Collins asymmetry as a function of x, z, and p^h_T, for positive and negative hadrons. The bars show the statistical errors. Figure from [27].

Transverse spin programme at RHIC has also come of age and provided many surprising and interesting measurements: single spin asymmetries in various reactions in midrapidity, near $x_F \sim 0$ (results consistent with zero) and in the forward rapidity where large asymmetries were observed by STAR in the inclusive π^0 production, [28].

Finally it should be mentioned that the global analyses of the transverse parton distributions have already been performed and point towards small values of $\Delta_T q$ as compared to Δq [29].

6. Nucleon spin decomposition. Angular momentum of partons.

So where does the nucleon spin come from?

In QCD the nucleon spin decomposition into the quark and gluon helicites, $\Delta\Sigma$ and ΔG, and orbital angular momenta, L_q and L_g, may be expressed as follows:

$$\frac{\hbar}{2} = J_q + J_g = \left(\frac{1}{2}\Delta\Sigma + L_q\right) + (\Delta G + L_g)$$

where each term is renormalisation scale–dependent and the $J_g = \Delta G + L_g$ decomposition is not gauge–invariant. There is no analogous sum rule involving transversity since there is no transverse analogue of the gluon helicity.

In the Quark Parton Model the nucleon spin is given by the quark spins, $\Delta\Sigma$, while ΔG and $L_{q,g}$ vanish. The quark contributionis now confirmed to be around 0.3, smaller than the expected value of 0.6 [30] which keeps the “nucleon spin puzzle” alive for 22 years.

In principle the puzzle can be solved by the QCD axial (or U(1)) anomaly, steming from the axial vector current nonconservation. The anomaly generates a gluonic contribution to the measured singlet axial coupling, $a_0(Q^2)$, which does not vanish at $Q^2 \to \infty$. As a result, $\Delta\Sigma(Q^2)$ becomes scheme dependent and may differ from the observable a_0 while ΔG is scheme–independent at least up to the NLO. In the Adler–Bardeen factorisation scheme, $\Delta\Sigma^{AB}$ is independent of Q^2. As a consequence, the measured quantity is in fact not the $\Delta\Sigma$ but

$$a_0(Q^2) = \Delta\Sigma^{AB} - \left(\frac{n_f \alpha_s}{2\pi}\right) \Delta G(Q^2)$$

Restoring the Ellis–Jaffe value of $\Delta\Sigma^{AB} \sim 0.6$ (or solving the "spin crisis") would thus require a value of $\Delta G(Q^2) \approx 2$ and $L = L_q + L_g \sim -2$ at $Q^2 \approx 5$ GeV^2. If indeed the ΔG is close to zero as all the measurements seem to point to, then the axial anomaly plays only a marginal role in the nucleon spin balance. Further, if $a_0 = 0.35 \pm 0.03 \pm 0.05$ as *e.g.* the COMPASS fit at $Q^2 = 3$ GeV^2 shows [10] then the only way out is through a large orbital angular momentum contributions, $L_{q,g}$. They have to be measured precisely in order to finally settle the proton spin problem.

The L_q may in principle be accessed through the Generalised Parton Distribution functions measured in the Deeply Virtual Compton Scattering. Several DVCS data have already been taken and are being analysed; several other measurements are expected to be performed in the next few years. In particular the JLAB and HERMES results give the first determination of u- and d-quark angular momenta, albeit model dependent, [31, 32]. Preliminary conclusions together with the results from the lattice QCD calculations [33] seem to indicate that the L_q might be close to zero even if a finite orbital momentum seems to be essential for many nucleon observables [34] and even if the perturbative QCD indicates that the orbital angular momentum must play an important role [35].

7. Outlook

During the 22 years since the "proton spin puzzle" emerged we have learned a lot about the longitudinal and transverse spin degree of freedom in the nucleon. Average gluon polarisation around $x \sim 0.1$ is small and its first moment is limited to about 0.2–0.3 in absolute value. A large first moment of the gluon polarisation, *i.e.* a large gluon polarisation contribution to the nucleon spin, is thus unlikely. Restoration of the naive expectations of the nucleon spin content *via* the axial anomaly seems improbable. On the other hand significant orbital angular momentum in the proton is expected; ways of exposing it must be found.

Flavour symmetric polarised sea seems disfavoured. Flavour separation of quark helicities, down to low values of x, is progressing; the case of the strange sea where the strong dependence on the assumed fragmentation functions seems to exist, needs special attention. Transversity effects appear weak, especially for the deuteron. The latter data obtained exclusively by COMPASS are however necessary to make a separation between the transverse u and d distributions and thus may substantially influence global analyses of the $\Delta_T q$.

In the near future the nucleon spin physics will be pursued at several old and new facilities: COMPASS runs on transverse proton target in 2010 and 2011, and, as well as HERMES will continue analysing its data; COMPASS also prepared a new long-term ($\gtrsim$ 2012) proposal, [36] to study the Generalised Parton Distribution functions *via* measurements of the Deeply Virtual Compton Scattering and to study the Transverse Momentum Dependent distributions *via* measurements of the Drell–Yan process. RHIC will extend its running parameters and upgrade its detectors. Finally the JLAB, now in the course of upgrading into 12 GeV, has a rich spin programme, especially for the measurements of the DVCS and transversity, [6].

A crucial extension of the kinematic domain of the spin electroproduction will take place with the advent of the polarised Electron–Ion Collider, EIC (eRHIC/ELIC) in USA or LHeC at CERN, [37]. These machines will open a field of perturbative low x spin physics where also semi-inclusive and exclusive observables will be accessible for testing the high parton density mechanisms.

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