The Spin Structure of the Proton and Polarized Collider Physics

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We summarise the present status of the proton spin problem and the physics possibilities for future polarized *ep* and *pp* colliders. This summary is based on the presentations and discussion sessions at the workshop "The Spin Structure of the Proton and Polarized Collider Physics" (Trento, July 23-28, 2001).

1. INTRODUCTION

Understanding the internal spin structure of the proton is one of the most challenging problems facing particle physics today. How is the spin of the proton built up from the intrinsic spin and orbital angular momentum of its quark and gluonic constituents ? What happens to spin and orbital angular momentum in the transition between current and constituent quarks in low-energy QCD ?

The small value of the flavour-singlet axial charge $g_A^{(0)}$ extracted from the first moment of g_1 (the nucleon's first spin dependent structure function)

$$g_A^{(0)}\Big|_{\rm pDIS} = 0.2 - 0.35 \quad (1)$$

in polarized fixed target deep inelastic scattering experiments has inspired vast activity on both the theoretical and experimental sides to understand the internal spin structure of the proton – for recent reviews see [1–5].

In relativistic quark models and in the naive (pre-QCD) parton model the flavour-singlet axial charge $g_A^{(0)}$ is interpreted as the fraction of the proton's spin which is carried by its quark and anti-quark (partonic) constituents. Relativistic quark models generally predict that $g_A^{(0)}$ should be approximately equal to the Ellis-Jaffe [6] (or OZI) value, about 0.6, implying the questions: where is the "missing" spin and what is the QCD physics of $g_A^{(0)}$?

The (initial EMC [7]) measurement of $g_A^{(0)}|_{\rm pDIS}$, one of the main "surprises" in recent high-energy physics, has inspired about 1000 theoretical papers and a new programme of dedicated experiments: high-energy polarized deep inelastic scattering at CERN [8], DESY [9], SLAC, and polarized proton-proton collisions at RHIC [10,11], as well as lower-energy experiments at Jefferson Laboratory [12], ELSA and MAMI [13] to understand the spin structure of the proton. Further proposals aimed at completing a definitive study exist for a polarized *ep* collider [14] (polarized HERA collider at DESY [15] or EIC collider at BNL [16,17]) and elastic νp scattering [18]. The proton spin problem has also inspired new theoretical thinking and experimental activity on the famous $U_A(1)$ problem of QCD.

In this summary of the workshop "The Spin Structure of the Proton and Polarized Collider Physics" (Trento, July 23-28, 2001) we review the key physics issues and experimental status. We start in this Section with a brief theoretical overview, following in Section 2 with an overview of the present experimental situation and future possibilities. The key measurements to disentangle to the proton's internal spin structure are discussed in more detail in the Sections after that.

Much theoretical work has revealed that, in QCD, $g_A^{(0)}$ receives contributions from quark and gluon partons [19,20] and a possible non-perturbative contribution at $x = 0$ from gluon topology [21]:

$$g_A^{(0)} = \left(\sum_q \Delta q - 3\frac{\alpha_s}{2\pi}\Delta g \right)_{\rm partons} + \ \mathcal{C} \qquad (2)$$

Here $\frac{1}{2}\Delta q$ and Δg are the amount of spin carried by quark and gluon partons in the polarized proton and $\mathcal{C}$ is the topological contribution.

Hence the key driving question is to pin down experimentally the size of each of the different contributions and to resolve the spin-flavour structure of the proton. This is the main goal of the present and next generation of experiments. So far the main experimental activity has focused on fully inclusive measurements of the proton's g_1 spin structure function with longitudinally polarized targets. The key issues for the new experiments are to measure the separate flavour- and spin-dependent parton distributions for the proton's valence, sea quark and gluonic constituents, and to investigate the spin structure of transversely polarized protons. We now briefly discuss the different contributions; further details on present status and measurability are given in the Sections below.

Physicswise, $\Delta q_{\rm partons}$ is associated with the hard photon scattering on quarks and antiquarks with low transverse momentum squared, k_t^2 of the order of typical gluon virtualities in the proton, and $\Delta g_{\rm partons}$ is associated with the hard photon scattering on quarks and antiquarks carrying $k_t^2 \sim Q^2$ [22,23]. The partonic decomposition (2) holds also in the AB [24] and JET [25] factorization schemes; in the $\overline{\rm MS}$ factorization scheme [26] the full partonic contribution is written as $\Delta q_{\overline{\rm MS}} = (\Delta q - \frac{\alpha_s}{2\pi}\Delta g)_{\rm partons}$. The product $\alpha_s \Delta g$ in (2) scales when $Q^2 \to \infty$ under QCD evolution [19]. This means that gluon polarization plays a potentially key role in any understanding of the proton spin puzzle. One possible explanation of the proton spin problem is that $(\Delta u + \Delta d + \Delta s)_{\rm partons}$ takes approximately the Ellis-Jaffe value, about 0.6, and that (in the absence of the topology term - see below) the OZI suppression of $g_A^{(0)}|_{\rm pDIS}$ is induced by large gluon polarization $\Delta g \sim 2$ at $Q^2 \sim 1{\rm GeV}^2$. Measuring the size of Δg is the key issue for high-energy investigations of the proton's internal spin structure.

QCD motivated fits have been applied to the existing g_1 data set to try to deduce information about the size of Δg. The main source of error in these QCD fits comes from lack of knowledge about g_1 in the small x region and (theoretical) the functional form chosen for the quark and gluon distributions in the fits [27–29]. Precise data from a future polarized ep collider at low x would be extremely valuable here. Various approaches are planned aiming at a direct measurement of Δg: through semi-inclusive measurements of charm and high p_t hadron pair production in polarized leptoproduction (COMPASS and HERMES) and photoproduction (SLAC) experiments, and studies of prompt photon production in polarized proton-proton collisions at RHIC – see Section 4 below. In the longer term one would like to make a decisive measurement via study of two-quark jet events in $\gamma^* g$ fusion at a future polarized ep collider (polarized HERA or EIC at BNL) [30].

The flavour dependence of the $\Delta q_{\rm partons}$ may be probed through semi-inclusive measurements in the current fragmentation region of (e.g.) fast pions in the final state of polarized leptoproduction experiments. Modulo assumptions on the fragmentation, these data may be used to reconstruct the polarized valence and sea distributions. More direct measurements will come from W boson production in polarized pp collisions at RHIC and from charged current exchange processes in high Q^2 deep inelastic scattering.

The topological contribution $\mathcal{C}$ in (2) is associated with Bjorken x equal to zero and is related to long range gluon dynamics [21]. Polarized deep inelastic scattering experiments cannot access $x = 0$ and measure $g_A^{(0)}|_{\rm pDIS} = g_A^{(0)} - \mathcal{C}$. The full $g_A^{(0)}$ may be measured through elastic Z^0 exchange in νp elastic scattering. A finite value of $\mathcal{C}$ is natural with spontaneous $U_A(1)$ symmetry breaking by instantons where any instanton induced suppression of $g_A^{(0)}|_{\rm pDIS}$ (the axial charge carried by partons with finite momentum fraction $x > 0$) is compensated by a shift of axial charge to the zero-mode so that the total axial-charge $g_A^{(0)}$ including $\mathcal{C}$ is conserved. An overview of instanton physics is given in [31]. A quality measurement of νp elastic scattering would provide very valuable information about the nature of $U_A(1)$ symmetry breaking in QCD. If some fraction of the spin of the constituent quark is carried by gluon topology in QCD (at $x = 0$), then the constituent quark model predictions for $g_A^{(0)}$ are not necessarily in contradiction with the small value of $g_A^{(0)}|_{\rm pDIS}$ extracted from deep inelastic scattering experiments. A decisive νp elastic experiment may be possible using the miniBooNE experiment at FNAL [18].

In the isotriplet channel things are much better understood. The fundamental Bjorken sum-rule [32]

$$\int_0^1 dx (g_1^p - g_1^n)(x, Q^2) = \frac{1}{6} g_A^{(3)} C_{NS}(Q^2) \qquad (3)$$

is experimentally verified to 10% accuracy by present fixed target experiments. Here $g_A^{(3)} = (\Delta u - \Delta d)_{\rm partons}$ is the proton's isotriplet axial-charge which is measured also in neutron β decay and $C_{NS}(Q^2) = (1 + O(\frac{\alpha_s}{\pi}))$ is the perturbative QCD correction. The Bjorken sum-rule is a rigorous prediction of current algebra and QCD. The Goldberger-Treiman relation from chiral symmetry, $2mg_A^{(3)} = f_\pi g_{\pi NN}$, relates $(\Delta u - \Delta d)$ to the pion-nucleon coupling constant $g_{\pi NN}$ extracted from dispersion relation analyses of low-energy πN scattering, meaning that the spin structure of the proton measured in high-energy polarized deep inelastic scattering experiments is intimately related to spontaneous chiral symmetry breaking in QCD.

The interplay between the proton spin problem and the $U_A(1)$ problem is further manifest in the flavour-singlet Goldberger-Treiman relation [33] which connects $g_A^{(0)}$ with the η'–nucleon coupling constant $g_{\eta' NN}$. Working in the chiral limit it reads

$$m g_A^{(0)} = \sqrt{\frac{3}{2}} F_0 \biggl(g_{\eta' NN} - g_{QNN} \biggr) \qquad (4)$$

where $g_{\eta' NN}$ is the η'–nucleon coupling constant and g_{QNN} is an OZI violating coupling which measures the one particle irreducible coupling of the topological charge density $Q = \frac{\alpha_s}{4\pi} G\tilde{G}$ to the nucleon (m is the nucleon mass and $F_0 \sim 0.1$GeV renormalises the flavour-singlet decay constant). There is presently a vigorous experimental programme aimed at studying the low-energy η'-nucleon interaction, including possible OZI violations, at COSY and Jefferson Laboratory.

The shape of g_1 is particularly interesting. Valuable information about the internal valence structure of the nucleon will come from studying the large x region (close to one) where SU(6) and perturbative QCD predict that the ratio of polarized to unpolarized structure functions for both proton and neutron should go to one when $x \to 1$ [34]. Precision measurements of large x spin asymmetries will be possible following the upgrade of Jefferson Laboratory to 12 GeV [12]. Small x measurements [35] from polarized ep colliders would provide valuable information about perturbative QCD dynamics at low x, where the shape of g_1 is particularly sensitive to the effects of $(\alpha_s \ln^2 \frac{1}{x})^k$ resummation and DGLAP evolution [36].

Spin transfer reactions also have the potential to provide valuable insight into the role of spin in QCD hadronization dynamics [37]. To obtain a leading twist spin-transfer asymmetry requires measurement of the polarization of one of the outgoing particles in addition to having a polarized beam or target. The self-analysing properties of the Λ hyperon through its dominant weak decay $\Lambda \to p\pi^-$ make it particularly appealing for experimental study; recent studies of Λ production at LEP have demonstrated the feasibility of successfully reconstructing the Λ spin [38]. The fragmentation functions $D_f^H(z, Q^2)$ which describe the non-perturbative hadronization process are the timelike counterpart of the usual parton distribution functions measured in spacelike deep inelastic scattering and represent the probability to find the hadron H with fraction z of the momentum of the parent parton f at a given value of Q^2. They are expected to satisfy perturbative QCD factorization and to evolve under QCD evolution equations. To date the best known fragmentation functions are those for the most copiously produced light mesons π and K. Measurement of the z dependence of semi-inclusive polarized Λ production in polarized deep inelastic scattering at HERMES and COMPASS will help to resolve different models of the fragmentation functions. The (V-A) structure of charged current exchange in deep inelastic scattering provides a source of polarized quarks with specific flavour [37]. Semi-inclusive Λ production events at (unpolarized) HERA could be analyzed to deduce valuable information on the polarized fragmentation functions. At the high energy and luminosity of RHIC the rapidity distribution of longitudinally produced Λ's in single-spin $\vec{p}p \to \vec{\Lambda}X$ collisions is particularly sensitive to the spin dependent structure of the Λ fragmentation.

Further experimental study of baryon fragmentation is also being actively investigated through semi-inclusive measurements of final state hadron multiplicities in deep inelastic scattering from nuclear targets using the RICH detector at HERMES [39]. These data may provide some insight into the hadron formation times. The present HERMES data from nitrogen and krypton targets show no significant difference between the multiplicity ratios for π^+ and π^- production, which are significantly greater than the multiplicity ratio for positively charged hadron production for both targets. These data have been interpreted [39] to mean that the proton has a longer formation time than a pion.

In polarized photoproduction the Gerasimov-Drell-Hearn sum-rule [40] provides a further important constraint on the spin structure of the proton. The GDH sum-rule relates the difference of the two cross-sections for the absorption of a real photon with spin anti-parallel σ_A and parallel σ_P to the target spin to the square of the anomalous magnetic moment of the target, viz.

$$\int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu}(\sigma_A - \sigma_P)(\nu) = -\frac{2\pi^2\alpha\kappa^2}{m^2} \tag{5}$$

Here m is the mass of the target; κ is the proton's anomalous magnetic moment. The GDH sum-rule is derived from general principles (see section 6 below) and any measured violation would yield new challenges for theorists to explain the QCD dynamics of such an effect. Dedicated real-photon experiments at ELSA, MAMI [13] and SLAC are presently planned or underway to test the GDH sum-rule. The low-energy part is dominated by spin structure in the resonance region; the high-energy part is expected to be dominated by spin-dependent Regge dynamics.

Exclusive measurements in deeply virtual leptoproduction have recently attracted much attention. Deeply virtual Compton scattering (DVCS) provides a possible experimental tool to access the quark total angular momentum, J_q, in the proton through generalized parton distributions (GPDs) [41]. The HERMES experiment [42] measure in the kinematics where they expect to be dominated by the DVCS-Bethe-Heitler interference term and observe the $\sin\phi$ azimuthal angle and helicity dependence expected for this contribution. At lower energies virtual Compton scattering experiments at Jefferson Laboratory and MAMI probe the electromagnetic deformation of the proton and measure the electric and magnetic polarizabilities of the target [43].

The study of single spin asymmetries from transversely polarized targets is currently a subject of much interest [44–47]. These asymmetries are expected to yield information about the density of transversely polarized quarks inside a transversely polarized proton. The difference between the transversity and helicity distributions reflects the relativistic character of quark motion in the nucleon [48].

The HERMES experiment at DESY is expected to start measurements with transverse target polarization in the near future. The observable is Collins' single spin asymmetry [49] for charged pion production in deep inelastic electron proton scattering. The azimuthal distribution of the final state pions with respect to the virtual photon axis carries information about the transverse quark spin orientation. Further possibilities to access transversity include proposed measurements of transverse single spin asymmetries in pp collisions at RHIC and via interference fragmentation functions extracted from light quark di-jet production in e^+e^- collisions at LEP or B-factories.

Finally, spin asymmetries offer new variables to search for new physics beyond the Standard Model, or, when found, to study the chiral structure of these new interactions. Already at polarized RHIC there are several examples of new physics searches and studies demonstrating the power of polarized beams. Therefore it would be useful to keep such a possibility also in mind for what one hopes will become the "parade horse" to study new physics, namely the Large Hadron Collider at CERN. If the new physics warrants it, polarization could be considered as an upgrade of this machine.

2. EXPERIMENTAL FACILITIES

Most of the data on polarized scattering to date is provided by deep inelastic scattering (DIS) experiments. Mirrored to the unpolarized scattering experiments, polarized lepton beams and polarized fixed targets have been employed. A pioneering experiment was the Yale-SLAC collaboration [50], which measured DIS down to $x = 0.1$. The measurements of this experiment were consistent with the naive parton model view that $\sim 60\%$ of the nucleon spin is carried by its quark parton constituents. The EMC experiment [7] at CERN used a muon beam and extended the inclusive measurements down to $x = 0.01$. The EMC data led to the spin puzzle, hinting that the contribution of the quarks to the spin of the proton is small. These findings triggered a whole program on DIS fixed target experiments, with electron beams at SLAC [51], a muon beam (SMC) [8] at CERN and the electron ring of the HERA collider on an internal target (HERMES) [9] at DESY. The latter uses the self-polarization of the electron beam via the Sokolov-Ternov effect [52] to achieve polarized electron beams with about 60% polarization. The lowest values in x for a Q^2 around 1 GeV^2 which can be achieved in these experiments amounts to approximately 10^{-3} in SMC, due to the high energy of the muon beam.

All of these experiments, apart from HERMES, have by now been concluded. They confirmed the spin puzzle with much increased precision, and launched a series of new measurements, such as semi-inclusive ones. Since a few years, the possible culprit to the spin puzzle is thought to be the polarized gluon distribution, which could be large. Hence a new fixed target experiment COMPASS [8] has been assembled in the last years, at the muon beam at CERN, with its main mission to make a direct measurement of Δg in the region $x \sim 0.1$. This experiment will start data taking in 2002.

At SLAC the experiments E159 and E161 are scheduled, and will use polarized real-photon nucleon interactions for spin studies. The former will study in particular the GDH sum rule, while the latter plans to measure Δg from open charm production.

Meanwhile it was realised that polarized pp collisions could also give information on the polarized gluon, and the pp and heavy-ion collider RHIC at BNL was 'upgraded' within its construction phase to include the option of polarized pp scattering [10]. Polarization of the proton beam is technically more involved than for the electron beam, since protons do not polarize naturally in a storage ring, at least not within any useful time span. Hence beams from a source of polarized protons have to be accelerated through the whole chain, keeping the polarization during the process. Special magnets called Siberian Snakes allow the protons to pass depolarizing resonances during the acceleration and correct for depolarizing distortions during the storage of the beam. Thus polarized pp collisions with a centre of mass system (CMS) energy in the range of 200 and 500 GeV could be provided at RHIC, with integrated luminosities of 320 and 800 pb^{-1} respectively.

On the DIS front, the commissioning of the HERA electron-proton collider (27.5 GeV electrons on 820 GeV protons) eight years ago opened up a completely new kinematical domain in deep inelastic scattering (DIS), and the two HERA experiments have provided a multitude of new insights into the unpolarized structure of the proton and the photon since then.

The success of HERA has prompted thinking about future ep collider opportunities for polarized scattering or eA collisions. Possible high energy ep collider projects presently under discussion are listed in Table 1.

All these projects are in different stages of development. HERA is in principle closest to reaching this goal. The accelerator exists and has just been upgraded to reach the luminosity quoted. It has well understood detectors, and the electron beam is already polarized. The polarization

Table 1
Possible future *ep*-collider facilities for polarized scattering

Machine	Lumi/year	$\sqrt{s}$
HERA	150 pb^{-1}	320 GeV
Electron-Ion Collider (EIC)	4 fb^{-1}	30-100 GeV
THERA (TESLA⊗HERA)	40 (250) pb^{-1}	1-1.6 TeV

of the proton beam can probably be achieved in the same way as for RHIC. The technical aspects of this project are elaborated in [53] and physics studies reported in [54,55]. Based on these studies, it seems realistic to assume that HERA could be operated with polarized electron and proton beams, each polarized to about 70%, reaching a luminosity of 500 pb^{-1} when integrated over several years. Note that the polarized protons from HERA could also be used to collide with a polarized internal target [56], producing polarized *pp* collisions, as at RHIC, but at a much reduced CMS energy.

The Electron Ion Collider (EIC) [57] – if built at BNL – will need a polarized electron accelerator, either a ring or LINAC, added to the RHIC polarized proton rings, and will probably also need a dedicated experiment. While an interesting program has been developed for the lower energy end of the EIC, in this paper we will usually refer to it as a machine with a CMS energy of 100 GeV. The advantage of the EIC is its large reachable luminosity, imperative for polarized studies. At HERA the luminosity is (just) enough for most topics but its advantage lies in its larger kinematical reach.

It would be very advantageous to have polarized low-x neutron data at future *ep* colliders, which would enable measurement of both singlet and non-singlet polarized structure functions at low x. A study was made of the potential for using polarized ^{3}He in HERA [15], which would enable g_1^n to be extracted. If the machine can provide polarized ^{3}He with a luminosity comparable to the one for the protons, such a program can be carried out. A recent new idea is to store polarized deuterons [58]. Due to the small gyromagnetic anomaly value the storage and acceleration problems are less severe for deuterons and it could be possible to keep the polarization at HERA even without the use of Siberian Snake magnets for deuterons. However the spin cannot be flipped by spin rotators from transverse to longitudinal polarization in the interaction regions, and other means, such as the recently suggested use of external radial frequency fields must be considered for arranging that the spins align longitudinally at the interaction points. For polarized deuteron beams the changes to the present HERA machine could be more modest and cheaper than protons, and, if one can instrument the region around the beam-pipe to tag the spectator in the deuteron nucleus, it can simultaneously give samples of scattering on p and n. An intense polarized deuteron source is however needed. Furthermore, so far the acceleration and storage of polarized deuteron beams has been studied to a much lesser extent than for polarized protons.

While the HERA and EIC projects could still be realised in the next 10 years, ideas for even longer term projects are already being discussed. In particular, several projects have been considered in connection with the proposal for the linear accelerator TESLA, at DESY, which can produce high energy polarized electron (and positron) beams. THERA proposes to collide the electron beam on the protons of HERA [59,60]. Thus THERA will need TESLA to be built at DESY (or tangential to the TEVATRON), polarized protons in the proton ring, and a new detector. THERA reaches even further in the kinematic plane, but its relatively low luminosity of 40 pb^{-1}/year may be a handicap for many studies.

It is also proposed to use the polarized electron beam of TESLA for fixed target experiments [61]. TESLA-N proposes to use beams in the energy range of 30-250 GeV on a (polarized) fixed target. ELFE@DESY proposes a 30 GeV beam, stretched in HERA to increase the duty cycle of the facility, on a fixed target.

Continuous 6 GeV electron beams (100% duty cycle) are presently available at Jefferson Laboratory; the proposed upgrade [12] to 12 GeV (also 100% duty cycle) would enable precision key studies of the valence structure of the proton in the large x region (greater than 0.6), semi-inclusive measurements of the spin-flavour structure at large x and studies of the spin structure of transversely polarized nucleon targets as well as investigations of exclusive reactions at intermediate Q^2.

Fig. 1 shows the luminosity versus CMS energy of most of these future facilities. Note that dilution factors as they appear in most fixed target experiments using targets such as NH_3 are not taken into account here (and would lower the luminosity of the fixed target experiments).

A neutrino factory from e.g. a 50 GeV muon beam with 10^{20} muon decays/year, would allow the use of polarized targets for polarized νp scattering experiments. These experiments would allow a plethora of new proton spin studies, in particular in disentangling the flavour dependence of the polarized parton distributions. Clearly there are still quite a few technical hurdles to be overcome before one can think of planning such a facility.

When looking into the far future, we should also include the LHC. The LHC will be the machine with the highest energy for a long time to come and will undergo upgrade programs (luminosity and energy) in the decade after the start-up. Technically one would need to make room for Siberian Snakes and spin rotator magnets in the machine, which are at presently not foreseen. To our knowledge no machine study has been made yet on how to polarize the LHC, but the success of RHIC in the years to come could become infectious. A study was made for the SSC [62] and the project was considered feasible. As a rule of thumb one snake would be necessary for each 2 km of accelerator. In particular if polarization would be a useful tool to study better the putative new physics which will open in the range of the LHC, this option will be very much wanted.

3. INCLUSIVE POLARIZED MEASUREMENTS

Deep inelastic structure functions are extracted from inclusive electron-proton or electron-nucleus

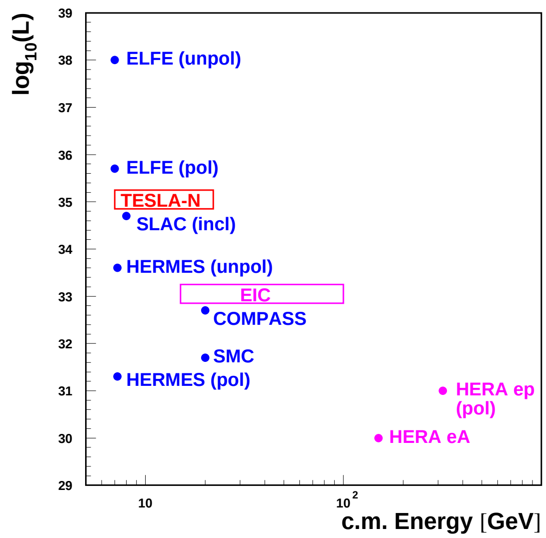

Figure 1. Luminosity versus CMS energy for existing and possible future facilities [61].

scattering. The corresponding observable of the F_1 structure function in unpolarized scattering is the structure function g_1, which in leading-order is directly related to the polarized quark distributions. Until now the quality of the polarized data cannot compete with the quality of the unpolarized data. The kinematic range is also smaller.

An overview of part of the world data on the nucleon spin structure is shown in Fig. 2. There is a general consistency between all data sets. HERMES is still collecting data. Also, their full deuterium set is not yet analysed; soon g_1^d will be of unprecedented statistical accuracy.

The largest range is provided by the SMC experiment [8], namely $0.00006 < x < 0.8$ and $0.02 < Q^2 < 100$ GeV^2. This experiment used proton and deuteron targets, with 100-200 GeV muon beams. The final results are given in [63]. The low x data [64] (not shown in Fig. 2) are correspondingly at a Q^2 well below 1 GeV^2, and the asymmetries are found to be compatible with zero.

With proton and neutron data available one

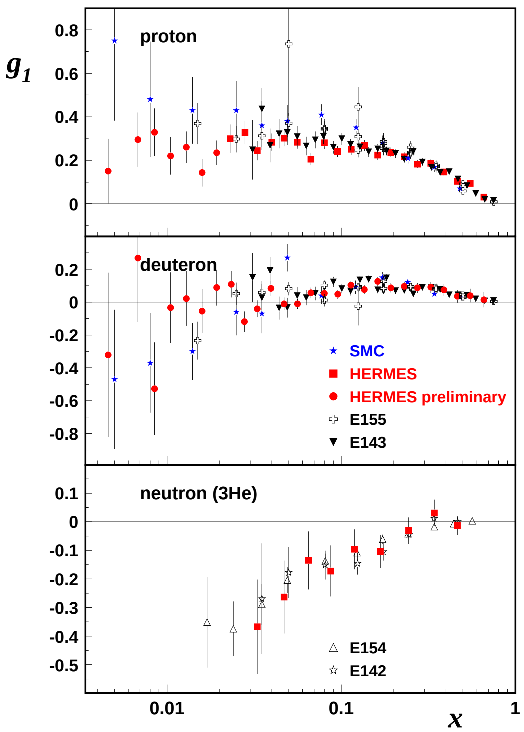

Figure 2. Compilation of g_1 data ($Q^2 > 1\text{GeV}^2$) [9].

can measure the Bjorken sum-rule $\int g_1^p dx - \int g_1^n dx$. For example, SMC finds $\Gamma_1^p - \Gamma_1^n = 0.174^{+0.024}_{-0.012}$ at $Q^2 = 5\text{GeV}^2$ which is in excellent agreement with theory $\Gamma_1^p - \Gamma_1^n = 0.181 \pm 0.003$. In general, the Bjorken sum-rule is confirmed to 10% as shown in Fig. 3.

Similar to the unpolarized data global NLO perturbative QCD analyses are performed on the polarized structure function data sets. Fits are performed in different schemes, e.g. the AB and $\overline{\text{MS}}$ schemes. In the $\overline{\text{MS}}$ scheme the polarized gluon distribution does not contribute ex-

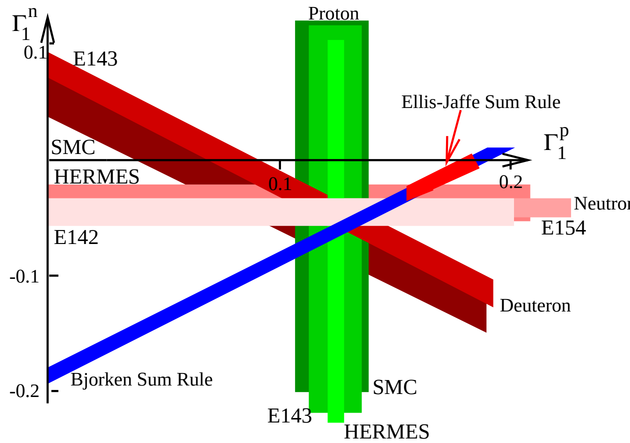

Figure 3. Compilation of Γ_1^p, Γ_1^n world data [9].

plictly to the first moment of g_1. In the AB scheme on the other hand the axial anomaly $\alpha_s \Delta g$ does contribute explicitly to the first moment. One finds for the $\overline{\text{MS}}$ (AB) scheme at a Q^2 of 1 GeV^2 [29]: $\Delta\Sigma = 0.19 \pm 0.05 (0.38 \pm 0.03)$ and $\Delta g = 0.25^{+0.29}_{-0.22} (1.0^{+1.2}_{-0.3})$ [29] where $\Delta\Sigma = (\Delta u + \Delta d + \Delta s)$. The main source of error in the QCD fits comes from lack of knowledge about g_1 in the small x region and (theoretical) the functional form chosen for the quark and gluon distributions in the fits [27–29]. Note that these QCD fits in both the AB and $\overline{\text{MS}}$ schemes give values of $\Delta\Sigma$ which are smaller than the Ellis-Jaffe value 0.6.

New fits are now being produced taking into account all the available data [65]. At this workshop a new fit to the data was presented in [66], which includes more recent g_1 data. Here one finds in the AB scheme and for $Q^2 = 1$ GeV^2: $\Delta\Sigma = 0.40 \pm 0.02 (stat.)$ and $\Delta g = 0.63^{+0.20}_{-0.19} (stat.)$, i.e. a somewhat lower value for the polarized gluon contribution. It is interesting to observe that this latest value for Δg is in agreement with the prediction [67] based on colour coherence and perturbative QCD.

In these pQCD analyses one ends up with a consistent picture of the proton spin: the low

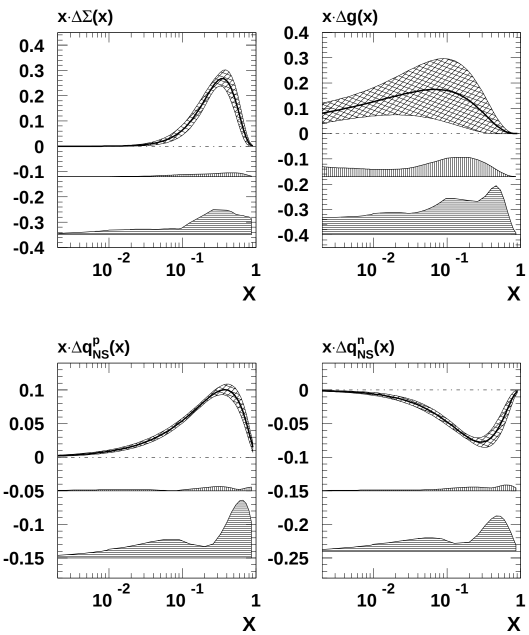

Figure 4. Polarized parton distribution functions determined at $Q^2 = 1$ GeV^2 with statistical (upper band), experimental systematic (medium band) and theoretical (lower band) uncertainties [8].

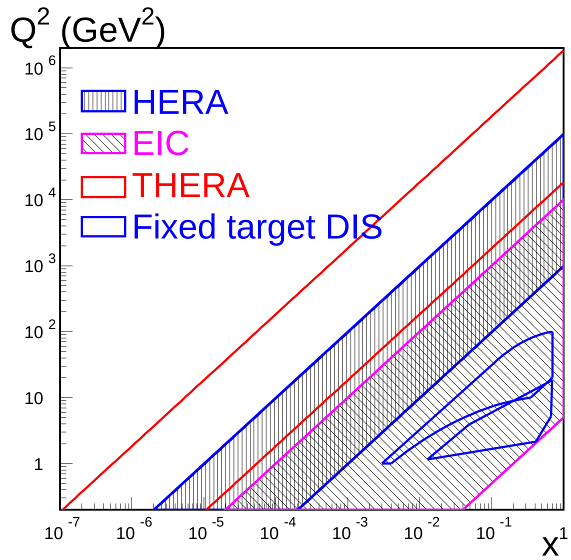

Figure 5. Measurable $x - Q^2$ region for a polarized HERA with the presently explored regions by fixed target experiments. The energies used are for THERA: $E_p = 920, E_e = 500$ GeV; HERA: $E_p = 920, E_e = 27$ GeV; EIC: $E_p = 250, E_e = 10$ GeV and $E_p = 50, E_e = 5$ GeV, and roughly $0.01 < y < 1.0$ [15].

value of $\Delta\Sigma$ may be compensated by a large polarized gluon. The precision on Δg is however still rather modest. Moreover, it is vital to validate this model with *direct* measurements of Δg, as we discuss in the next section. Also, the first moments depend on integrations from $x = 0$ to 1. Perhaps there is an additional component at very small x?

Parton distributions with experimental and theoretical uncertainties, resulting from the fits, are given in Fig. 4.

Some progress on g_1 will come from the improved precision with the new HERMES data and perhaps remeasurements in the SMC kinematic range by COMPASS, but no extension of the kinematic range. The kinematical reach is shown in Fig. 5 for the different machines discussed in the previous section, together with the region covered by present fixed target experiments. The region can be extended by several orders of magnitude both in x and Q^2.

A projection for a g_1 measurement at polarized HERA is shown in Fig. 6. The low-x behaviour of g_1 is indicated in the figure: the straight line is an extrapolation based on Regge phenomenology, and the upper curve presents a scenario suggested in [15] where g_1 rises as $1/(x\ln^2(x))$, which is the maximally singular behaviour still consistent with integrability requirements. The low x behaviour of g_1 by itself is an interesting topic as discussed in [36]. Small x measurements [35], besides reducing the error on the first moment and Δg, would provide valuable information about perturbative QCD dynamics at low x, where the shape of g_1 is particularly sensitive to the effects of $(\alpha_s \ln^2 \frac{1}{x})^k$

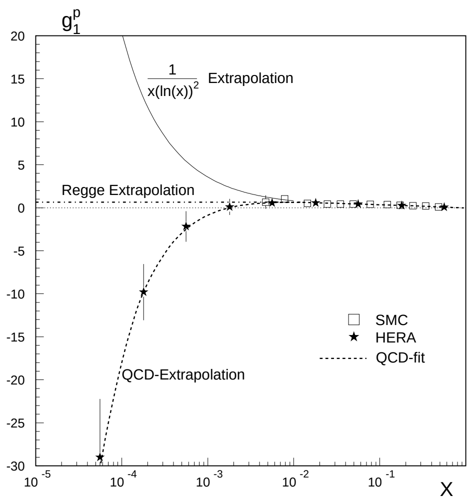

Figure 6. The statistical uncertainty on the structure function g_1 of the proton measurable at HERA, evolved to a value of $Q^2 = 10$ GeV^2 for an integrated luminosity of 500 pb^{-1}. The SMC measurements are shown for comparison [14].

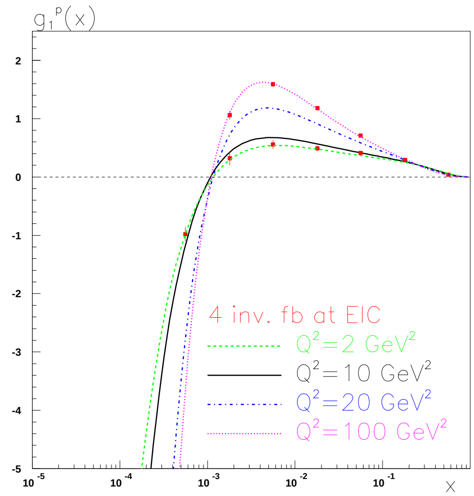

Figure 7. The statistical uncertainty on the structure function g_1 of the proton measurable at EIC, for an integrated luminosity of 4 fb^{-1} [15].

resummation and DGLAP evolution [36], and the non-perturbative QCD "confinement physics" to hard (perturbative QCD) scale transition. Much larger changes in the effective intercept which describes the shape of the structure functions at small Bjorken x are expected in g_1 than in the unpolarized structure function F_2 so far studied at HERA as one increases Q^2 through the transition region from photoproduction to hard (deep inelastic) values of Q^2 [68]. Polarized HERA would allow us to penetrate deeper into the small x region; EIC would be especially suited to studies of the transition region.

An EIC has as expected a more restricted range, as shown in Fig. 7. However the precision is substantially higher due to the high luminosity of 4 fb^{-1}/year. THERA would reach x values down to 10^{-6}, but needs at least one fb^{-1} of data.

Note that the expected asymmetries at low x, i.e. $x \sim 10^{-4}$ are relatively small, about 10^{-3}, which puts strong requirements on the control of the systematic effects, as discussed in [55]. At the lowest x values at THERA, the asymmetries may be even smaller, and the potential to actually extract a polarized structure function at these values still needs to demonstrated.

Looking in a little more detail to Fig. 2 we see that the present data at small-x correspond to a negative asymmetry and hence there must be a crossover at some intermediate x value. Locating the crossover is an important experimental challenge. From the theoretical point of view the value of x at which this occurs for the neutron spin asymmetry is the result of a competition between the SU(6) valence structure [69] and the chiral corrections [70,71]. Recent progress on extracting the neutron spin structure function from nuclear targets is reported in [34].

The large x region (close to one) is also especially interesting and is particularly sensitive to the valence structure of the nucleon. In the spin dependent case we have no idea whatsoever of the behaviour of g_{1n} beyond $x \sim 0.4$. On the

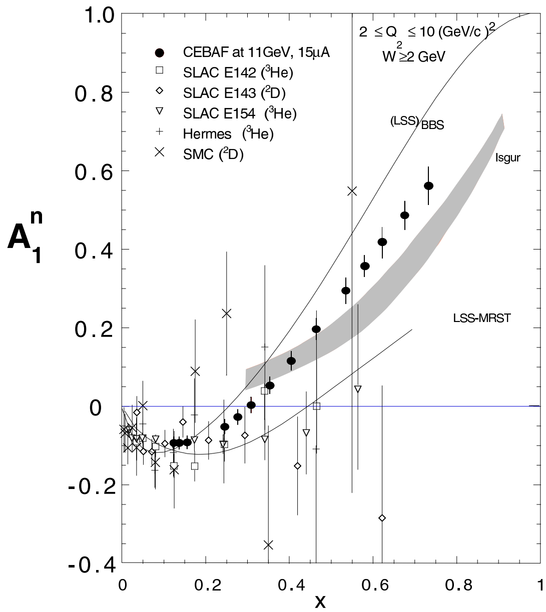

Figure 8. Projected data achievable on A_{1n} using an 11 GeV polarized electron beam at Jefferson Laboratory [12].

basis of both perturbative QCD *and* SU(6) [69], one expects the ratio of polarized to unpolarized structure functions, A_{1n}, should approach 1 as $x \to 1$ [72,73]. It is vital to test this prediction. If it fails we understand nothing about the valence spin structure of the nucleon! A precision measurement of A_{1n} up to $x \sim 0.8$ will be possible following the 12 GeV upgrade of Jefferson Laboratory (see Fig. 8).

With proton and neutron data available one can measure the Bjorken sum-rule $\int g_1^p dx - \int g_1^n dx$. EIC data would allow one to measure this sum-rule, a key test for QCD, to the order of 1% precision.

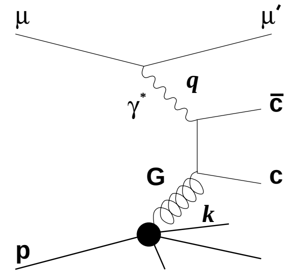

Figure 9. $c\bar{c}$ production in Photon Gluon Fusion

4. THE POLARIZED GLUON DISTRIBUTION $\Delta g(x, Q^2)$

In the present understanding of the spin puzzle, measuring directly the polarized gluon is the "Holy Grail" in spin physics. The precision from QCD fits is still limited, and the "Quest" is on.

COMPASS has been conceived to measure Δg via the study of the photon gluon fusion process, as shown in Fig. 9. Hence the cross section of this process is directly related to the gluon density at the Born level. The experimental technique consists in the reconstruction of charmed mesons. The final uncertainty on the measurement of $\Delta g(x)/g(x)$ from open charm is estimated to be $\delta(\Delta g(x)/g(x))$ =0.11. Additionally COMPASS will use the same process but with high p_t particles instead of charm to access Δg. This may lead to samples with larger statistics, but these have larger background contributions, namely from QCD Compton processes and fragmentation. The expected sensitivity on the measurement of $\Delta g/g$ from high p_t tracks is estimated to be $\delta(\Delta g/g) = 0.05$, and shown in Fig. 10.

HERMES was the first to attempt to measure Δg, from high p_t charged particles, as proposed for COMPASS above. The measurement is at the limit of where the perturbative treatment of the data can be expected to be valid, but the result

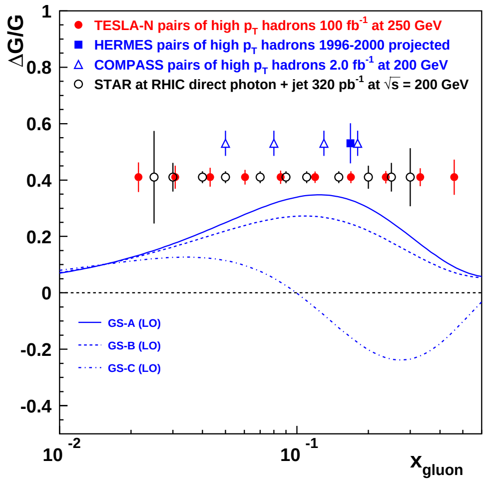

Figure 10. Projected statistical accuracies for the measurement of $\Delta g/g(x)$ at TESLA-N, based on a integrated luminosity of 100 fb^{-1} in comparison with predictions from COMPASS, HERMES and RHIC. The phenomenological predictions are calculated for $Q^2 = 10$ GeV^2[61].

is interesting: $\Delta g/g = 0.41 \pm 0.18 \pm 0.03$ at an average $< x_g >= 0.17$ [9]. The expectation for the HERMES data collected until now is shown in Fig. 10.

TESLA-N could perform similar analyses as COMPASS and HERMES. Its high luminosity would allow for precision measurements in the range of (gluon) x: $0.02 < x < 0.4$, as shown in Fig. 10.

The hunt for Δg is also one of the main physics drives for polarized RHIC. The key processes used here are high-p_t prompt photon production $pp \rightarrow \gamma X$, jet production $pp \rightarrow$ jets $+X$, and heavy flavour production $pp \rightarrow c\bar{c}X, b\bar{b}X, J/\psi X$. Due to the first stage detector capabilities most emphasis has so far been put on the prompt photon channel. The expected precision is plotted in Fig. 10. These anticipated RHIC measurements of Δg have inspired new theoretical developments [74] aimed at implementing higher-order calculations of partonic cross-sections into global analyses of polarized parton distribution functions, which will benefit the analyses of future polarized pp data to measure Δg.

Future ep colliders can add information in two ways: by extending the kinematic range for measurements of g_1 or by direct measurements of Δg. Including the future polarized HERA g_1 data will improve the experimental error $\delta(\int \Delta g dx)$ to about 0.2. The theoretical error is expected to decrease by more than a factor 2 once $g_1(x, Q^2)$ is measured at low x. At an EIC one expects to reduce the statistical uncertainty even to 0.08 with about 10 fb^{-1}, as discussed in [66].

It is however crucial for our full understanding of the proton spin that the prediction of a large polarized gluon is confirmed or refuted by direct measurements of Δg. HERA has shown that the large centre of mass system (CMS) energy allows for several processes to be used to extract the unpolarized gluon distribution. These include jet and high p_t hadron production, charm production both in DIS and photoproduction, and correlations between multiplicities of the current and target hemisphere of the events in the Breit frame.

The most promising process for a direct extraction of Δg at HERA is di-jet production, as discussed in [30]. The underlying idea is to isolate boson-gluon fusion events, i.e. a process where the gluon distribution enters at the Born level. Jets are selected with a $p_t > 5$ GeV and are restricted to the acceptance of a typical existing HERA detector by the requirement $|\eta^{jet}_{LAB}| < 2.8$, where η^{jet}_{LAB} is the pseudo-rapidity in the laboratory system. The resulting measurable range in x (of the gluon) is $0.002 < x < 0.2$. The results are shown in Fig. 11 and compared to several predicted gluon distributions. At EIC the measurable range is reduced to $0.02 < x < 0.3$, as shown in Fig. 12. The reach at THERA is $0.0005 < x < 0.1$ but an event sample of several hundred pb^{-1} will be needed.

These measurements allow for determination of the shape of $\Delta g(x)$ over a large region of x [61]. The errors on the individual points for the di-jet measurement on $\Delta g(x)/g(x)$ are in the range

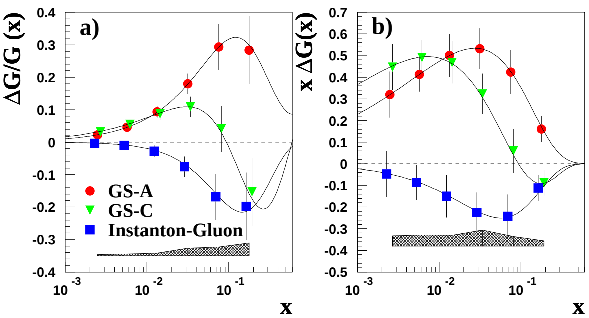

Figure 11. Sensitivity to $\Delta g/g$ (a) and $x\Delta g$ (b) at HERA for a luminosity of 500 pb^{-1} and three different assumptions for the shape of $\Delta g(x)$. The error bars represent statistical errors. The shaded band gives an estimate of the systematics [30].

from 0.007 to 0.1. The total error on $\Delta g(x)/g(x)$ in the complete range is 0.02.

The global result is shown in Fig. 13, for HERA and EIC and compared to results from other planned or possible future polarized experiments: pp scattering at RHIC [10] (STAR, $\sqrt{s} = 200$ GeV), μp scattering in COMPASS [8], and pp scattering in HERA-N [56]. All measurements are shown at LO. Clearly EIC can produce the (statistically) most precise measurements, and HERA covers the range to lowest possible x values which can only be beaten by THERA, if it would be able to deliver sufficient luminosity.

An exploratory study was made [15], using the values of $\Delta g(x)$ obtained from the di-jet analysis as an extra constraint in the fit of g_1 data discussed above. The improvement of the errors on the first moment of Δg due to the inclusion of di-jet data is shown in Table 2. The first two rows give the values quoted before, namely for the NLO QCD analysis without and with projected polarized HERA data for g_1. The third row shows the expected error if only the di-jet asymmetry is added to the fixed target g_1 data, and the fourth row shows the total improvement using all avail-

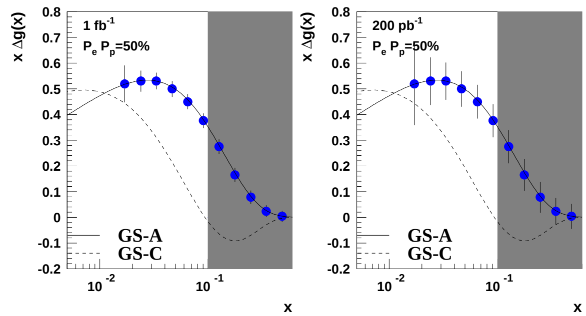

Figure 12. The statistical precision of $x\Delta g$ from di-jets at LO for EIC, for two different luminosities, with predictions of GS-A and GS-C [30].

Table 2
The expected statistical uncertainty in the determination of the first moment of the gluon distribution at $Q^2 = 1$ GeV^2 (500 pb^{-1}), see text.

Analysis Type	$\boldsymbol{\delta(\int \Delta g\ \mathrm{d}x)}$
1. g_1 fixed target	0.3
2. g_1 fixed target + HERA	0.2
3. di-jets at HERA	0.2
4. combined 2 & 3	0.1

able information. Hence the first moment of the gluon can be determined with a precision of about 10%. Looking further to the future the projected error from one year of running with TESLA-N could be reduced to $\delta(\int \Delta g\ \mathrm{d}x) \pm 0.06$ [75].

5. POLARIZED QUARK DISTRIBUTIONS

In present fixed target experiments information on the flavour decomposition can be obtained from semi-inclusive measurements, i.e. measurements where a final state hadron is tagged, in the current fragmentation region. The extracted spin distributions for the up, down and sea quarks, as obtained by the HERMES and SMC collabora-

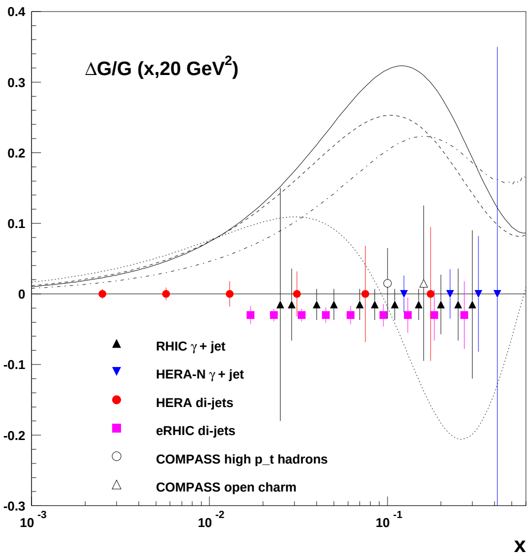

Figure 13. Summary of the sensitivity of future measurements of $\Delta g/g$ for HERA (500 fb^{-1}) and EIC/eRHIC (4 fb^{-1}) compared with other experiments (see text)[30].

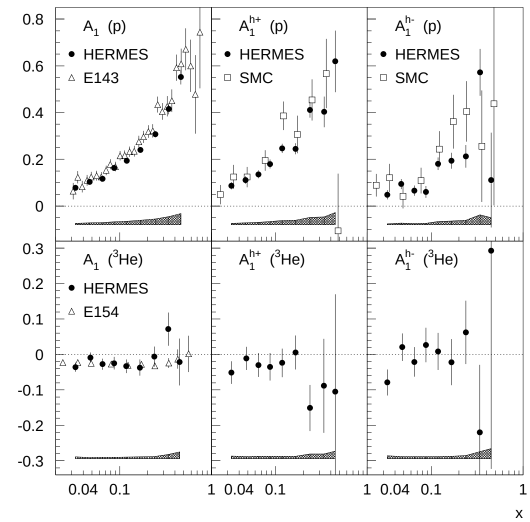

Figure 14. Inclusive A_1 and semi-inclusive A_1^h asymmetries form polarized H and ^{3}He targets. The data points are given at the measured mean at each value of x, which is different for each experiment [9].

tions are shown in Fig. 14 [9]. For this extraction it was assumed that the polarization of the sea quarks is flavor independent. Furthermore, the analysis was carried out using leading-order QCD (the naive parton model). The polarization of the up and down quarks are positive and negative respectively, while the sea quark polarization remains negative within the measured range and consistent with zero. In future the data of the RICH detector in the HERMES spectrometer, together with the large sample of deuterium data still to be analysed, will allow for more precise results with less assumptions. Further accuracy will come from a next-to-leading order QCD analysis from the data.

The number for $\Delta u - \Delta d$ extracted from these measurements is $\Delta u - \Delta d = 0.84 \pm 0.07 \pm 0.06$ at $Q^2 = 2.5\mathrm{GeV}^2$, which compares with the prediction 1.01 ± 0.05 for the Bjorken sum-rule at this Q^2 *after* higher-order radiative corrections have been applied in the Bjorken sum-rule. While this comparison looks at first quite attractive it should be noted that the data analysis is done using only leading order formulae, so that the correct quantity to compare with for full self-consistency is the value of $g_A^{(3)}$ $(= 1.267)$. A next-to-leading order analysis of the data along the lines presented in [28] would be very useful.

Semi-inclusive measurements of g_1 in the target fragmentation region with a polarized *ep* collider would enable one to test the target (in-)dependence of the small value of $g_A^{(0)}|_{\mathrm{pDIS}}$ [76].

The dependence on the details of the fragmentation process limits the accuracy of the method above. At RHIC [10] however the polarization of the $u, \overline{u}, d$ and $\overline{d}$ quarks in the proton will be measured directly and precisely using W boson production in $u\overline{d} \to W^+$ and $d\overline{u} \to W^-$.

The charged weak boson is produced through a

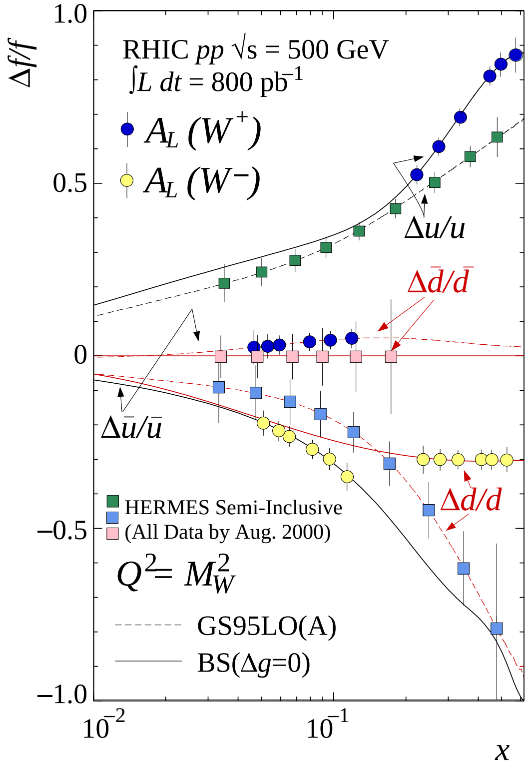

Figure 15. Polarization of $u, d, \overline{u}, \overline{d}$ as functions of x modelled by [77,78]. Both the sensitivities of HERMES semi-inclusive DIS and RHIC W measurements are shown [10].

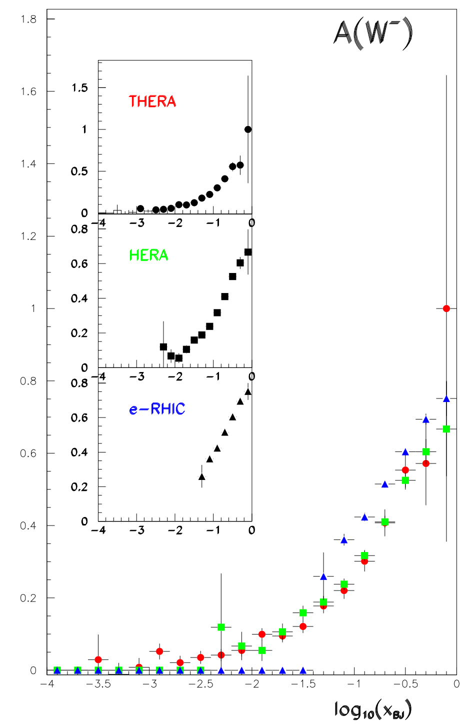

Figure 16. Spin asymmetries A^{W^-} for charged current events for a total luminosity of 500 pb^{-1}. The error bars represent the statistical uncertainty of the measurement [80].

pure V-A coupling and the chirality of the quark and anti-quark in the reaction is fixed. A parity violating asymmetry for W^+ production in pp collisions can be expressed as

$$A(W^+) = \frac{\Delta u(x_1)\overline{d}(x_2) - \Delta\overline{d}(x_1)u(x_2)}{u(x_1)\overline{d}(x_2) + \overline{d}(x_1)u(x_2)} \qquad (6)$$

For W^- production u and d quarks should be exchanged. The expression converges to $\Delta u(x)/u(x)$ and $-\Delta\overline{d}(x)/\overline{d}(x)$ in the limits $x_1 >> x_2$ and $x_2 >> x_1$ respectively. The momentum fractions are calculated as $x_1 = \frac{M_W}{\sqrt{s}} e^{y_W}$ and $x_2 = \frac{M_W}{\sqrt{s}} e^{-y_W}$, with y_W the rapidity of the W. The experimental difficulty is that the W is observed through its leptonic decay $W \rightarrow l\nu$ and only the charged lepton is observed. With the assumed integrated luminosity of 800 pb^{-1} at $\sqrt{s}$ = 500 GeV, one can expect about 5000 events each for W^+ and W^-. The resulting measurement precision is shown in Fig. 15.

Furthermore, information on the quark densities will be extracted using Drell-Yan production into lepton pairs, and the measurement of inclusive particle production.

At HERA, apart from semi-inclusive studies, one also has the option to study quark flavours via charged current interactions [14,80]. The asymmetry is defined by

$$A^{W\mp} = \frac{d\sigma_{\uparrow\downarrow}^{W\mp} - d\sigma_{\uparrow\uparrow}^{W\mp}}{d\sigma_{\uparrow\downarrow}^{W\mp} + d\sigma_{\uparrow\uparrow}^{W\mp}} \approx \frac{g_5^{W\mp}}{F_1^{W\mp}} \quad (7)$$

with $g_5^{W^-} = \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}$, $g_5^{W^+} = \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c}$. [80]. The total missing transverse momentum (which is a signal for the escaping neutrino) was required to be $P_{Tmiss} > 15$ GeV, and the region $Q^2 > 225$ GeV^2 has been selected for this analysis. The results for the asymmetries for both HERA, EIC and THERA are shown in Fig. 16. The error bars indicate the statistical precision of the measurement. The asymmetries are very large and significant measurements can be produced at THERA down to $x = 10^{-3}$. These charged current measurements, with both e^+ and e^- beams, can be used to extract e.g. the Δu and Δd distributions.

It has been pointed out that neutrino factories are an ideal tool for polarized quark flavour decomposition studies. These would allow one to collect large data samples of charged current events, in a kinematic region (Q^2, x) of the present fixed target data. A complete separation of all four flavours and anti-flavours becomes possible, and in particular the role of Δs – which may be quite different in e.g. 'anomaly', 'instanton' and 'skyrmion' models – can be determined.

Pseudo-data for charged current structure functions have been calculated [79] according to these three models, and used in NLO pQCD fits. It was shown that the singlet quark moment can be improved by a factor 2-3 or so. The Bjorken sum rule could be tested to the few % level. C-even and C-odd polarized quark distributions can be measured with an accuracy of a few % for the u and d quark, while the strange components can be measured to the level of 10%, which is sufficient to distinguish between the models above.

Finally, we note that complementary measurements of the spin dependent parton distributions from different experimental conditions (in polarized ep and pp collisions) are necessary to experimentally check factorization in spin dependent processes – that is, that the extracted parton distributions are indeed process independent. Factorization is commonly assumed to hold (beyond perturbative QCD) but has so far not been checked in experiment for spin dependent processes.

6. PHOTOPRODUCTION

Important information about QCD spin physics will also come from polarized photoproduction measurements. The fundamental Gerasimov-Drell-Hearn sum-rule (5) [40] ($\int_{\nu_{th}}^{\infty} \frac{d\nu}{\nu}(\sigma_A - \sigma_P)(\nu) = -\frac{2\pi^2\alpha\kappa^2}{m^2}$) follows from general principles of quantum field theory: causality, unitarity, Lorentz and electromagnetic gauge invariance plus one assumption: that we can use an unsubtracted dispersion relation for the spin dependent part of the forward Compton amplitude. Modulo the no-subtraction hypothesis, the Gerasimov-Drell-Hearn sum-rule is valid for a target of arbitrary spin S, whether elementary or composite [81]. Regge arguments imply that the GDH integral is expected to converge. Failure of the GDH sum-rule would imply a (finite) subtraction constant in the dispersion relation. Such a term would follow from a $J = 1$ Regge fixed pole with non-polynomial residue [82]. There is no such fixed pole in perturbation theory, at least up to $O(\alpha^3)$ in QED. Any violation of the GDH sum-rule would be most interesting indeed and yield new challenges for theorists to explain the (non-)perturbative QCD dynamics of such an effect.

The "generalized" GDH integral

$$I(Q^2) = \frac{2m^2}{Q^2} \int_0^1 dx g_1(x, Q^2) \quad (8)$$

(with $I(0) = -\frac{1}{4}\kappa^2$) changes sign between photoproduction and deep inelastic Q^2 (assuming that the GDH sum-rule is correct); the zero crossing point in $I(Q^2)$ is particularly sensitive to spin structure in the resonance region [83]. Dedicated low Q^2 investigations of g_1 are underway at Jefferson Laboratory [12].

Present experiments at ELSA and MAMI are aimed at measuring the GDH integrand through the range of incident photon energies $E_\gamma = 3.1$ 0.14 - 0.8 GeV (MAMI) and 0.7 - 3.1 GeV (ELSA) [13]. The presently analysed GDH integral on the proton (up to 1.9 GeV) is shown in Fig. 17 and

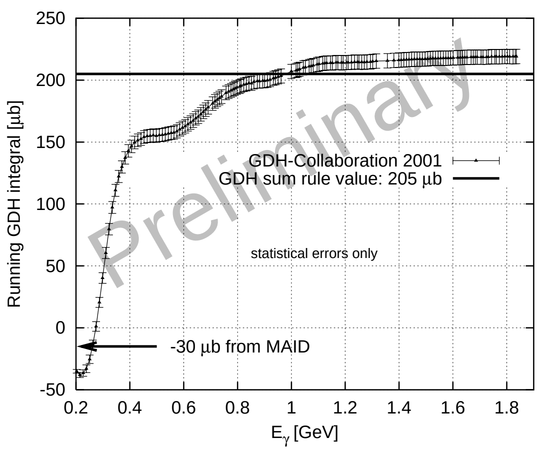

Figure 17. Running GDH integral for the proton (ELSA and MAMI)[13].

is dominated by the Δ resonance contribution. Intriguing is that the preliminary GDH integral for the proton up to the presently analysed 1.9 GeV seems to be converging to a value two standard deviations greater than the GDH prediction. Further experiments are planned to measure the neutron GDH integral via a polarized deuteron target.

Clearly, it will be very important to measure the high-energy part of the sum-rule, both to check the sum-rule itself and also to test spin dependent Regge theory. First measurements will be made at SLAC for E_γ between 5 and 40 GeV for both proton and neutron. Finally, at collider energies, it can be pointed out that a measurement of the total polarized photoproduction cross section $\Delta\sigma_{\gamma p}(\nu)$ as a function of the photon-proton CMS energy ν at HERA or EIC would contribute to a precise understanding of the Gerasimov-Drell-Hearn sum rule, as discussed in [68]. In particular the Regge behaviour of the energy dependence of the polarized cross section can be tested. Spin dependent Regge theory (totally untested at the present time) provides a baseline for investigations of the small x behaviour of g_1 at deep inelastic values of Q^2. The sensitivity which could be reached with EIC is about one order of magnitude larger than the one for HERA.

High-energy photoproduction processes have also been shown to be sensitive probes of the polarized parton structure in the proton *and* in the photon. These processes would allow us to obtain, for the first time, unique information on the polarized structure of the photon. Single jet production has been studied in [54]. In [84] it was shown that also a high p_t track analyses yields a similar sensitivity, with only modest luminosity requirements.

Polarized photoproduction of di-jets has been investigated in detail, including in particular effects due to parton showering, hadronization, jet finding and jet clustering. It could be demonstrated that, although these effects yield sizable corrections, the measurable asymmetry will be largely preserved at the hadron level [84]. An example for the correspondence of parton and hadron level asymmetries is shown in Fig. 18, obtained with a moderate integrated luminosity of only 50 pb^{-1}. A first idea on the discriminative power on the photon structure of future measurements can however be gained by comparing the predictions obtained with the two (minimal and maximal) polarization scenarios proposed in [85], as done in Fig. 18.

7. TRANSVERSITY

A degree of freedom which is currently of considerable interest [44–46] is the density of transversely polarized quarks inside a transversely polarized proton.

The transversity can be interpreted in parton language as follows: consider a nucleon moving with (infinite) momentum in the $\hat{e}_3$-direction, but polarized along one of the directions transverse to $\hat{e}_3$. $\delta q_a(x, Q^2)$ counts the quarks of flavor a and momentum fraction x with their spin parallel the spin of a nucleon minus the number antiparallel. If quarks moved nonrelativistically in the nucleon, δq and Δq would be identical, since rota-

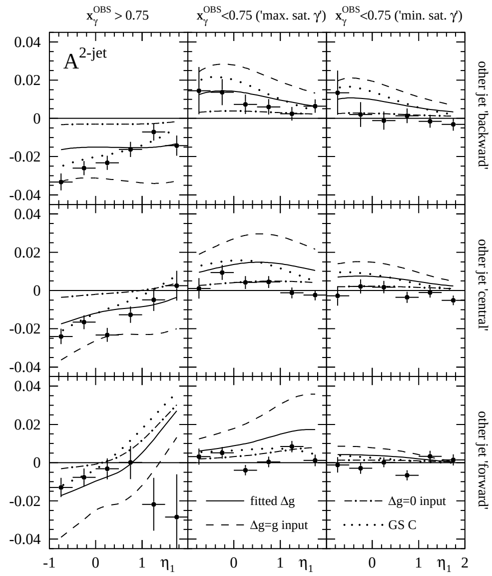

Figure 18. Polarized photoproduction at HERA of di-jets ($E_{T,1} > 8$ GeV, $E_{T,2} > 6$ GeV): asymmetries for direct (first column) and resolved (second and third column) photon contributions as function of the rapidity of the first jet and for different orientations of the second jet. Second and third column correspond to different scenarios for the parton content of the polarized photon suggested in [85]. The error bars shown correspond to a Monte Carlo sample of 50 pb^{-1} [84].

tions and Euclidean boosts commute and a series of boosts and rotations can convert a longitudinally polarized nucleon into a transversely polarized nucleon at infinite momentum. So the difference between the transversity and helicity distributions reflects the relativistic character of quark motion in the nucleon. There are other important differences between transversity and helicity. For example, quark and gluon helicity distributions (Δq and Δg) mix under Q^2-evolution. There is no analog of gluon transversity in the nucleon, so δq evolves without mixing, like a nonsinglet distribution function. The lowest moment of the transversity is proportional to the nucleon matrix element of the tensor charge, $\bar{q} i \sigma^{0i} \gamma_5 q$, which couples only to valence quarks (it is C-odd). Not coupling to glue or $\bar{q}q$ pairs, the tensor charge promises to be more quark-model–like than the axial charge and should be an interesting contrast [48].

The experimental study of transversity distributions at leading twist requires observables which are the product of two objects with odd chirality. In pp collisions the transverse double spin asymmetry, A_{TT}, is proportional to $\delta q \delta \bar{q}$ with even chirality. Recent studies show however that these could only be accessed at RHIC for very large luminosity samples, perhaps after a possible upgrade.

The HERMES experiment at DESY is expected to start measurements with transverse target polarization in the near future. The observable is Collins' single spin asymmetry [49] for charged pion production in deep inelastic electron proton scattering The azimuthal distribution of the final state pions with respect to the virtual photon axis carries information about the transverse quark spin orientation. In a partonic picture of the nucleon the transverse single spin asymmetry A_T is related to the transversity distributions as follows:

$$A_T(x,z) \sim \frac{\sum_q e_q^2 \delta q(x) H_1^{\perp q}(z)}{\sum_q e_q^2 q(x) D_1^q(z)} \qquad (9)$$

where $H_1^{\perp q}$ is the Collins function for a quark of flavor q and D_1^q is the regular spin independent fragmentation function. An analysis procedure for the HERMES transverse asymmetries has been proposed [86] that results in the extraction of the shape for $\delta u(x)$ and the ratio $H_1^{\perp}/D_1^u$. It is assumed that the u-quark dominates and $\delta u(x_0 = 0.25) = \Delta u(x_0)$ at some soft scale, $Q_0^2 \approx 0.4$ GeV. Alternatively, one could try to measure the ratio $H_1^{\perp}/D_1^u$ from fragmentation function measurements in e^+e^- annihilation using LEP and B-factory data.

HERMES will measure $\delta u(x)$ between $0.02 < x < 0.7$ with a statistical error of about $\delta u \pm 0.3$ at the lowest x and $\delta u \pm 0.1$ at highest x [61] and comparable systematic errors. COMPASS also

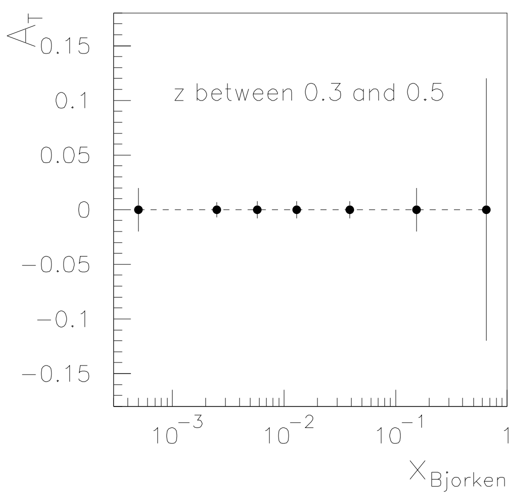

Figure 19. Projected sensitivities for the single spin asymmetries in single inclusive pion production at the EIC for $\int_{day} L dt = 20\,\mathrm{pb}^{-1}$ and $0.3 < z = E_\pi/E_\gamma < 0.5$[44].

plans such a measurement. The higher beam energy, $100 - 200\,\mathrm{GeV}$ compared to $27.5\,\mathrm{GeV}$ may allow, for the first time, to explore the interference fragmentation processes.

However, the most promising experiments to measure transversity distributions and their first moments, the tensor charge are EIC and TESLA-N. For TESLA-N the first moment of δu can be measured to about one percent and for δd to 6% [61]. A measurement with the statistical precision of HERMES can be reached at the EIC, but at lower x, see Fig. 19 for only 20 pb^{-1}.

For polarized hadron colliders such as RHIC, in addition to the double spin asymmetry measurements in Drell Yan, several single spin asymmetry measurements have been suggested: single spin asymmetries in two pion interference fragmentation; the measurement of azimuthal asymmetries in the production of pions around the jet-axis (Collins fragmentation function); interference fragmentation and Collins fragmentation in direct photon jet events. With the presently available luminosities and detectors the proposal of Collins et al. [87] and Jaffe et al. [88] to utilize chiral odd two pion interference fragmentation processes appears to be the most promising approach to measure transversity at RHIC.

All future transversity measurements have in common that their success critically depends on the knowledge of the spin dependent and chiral odd fragmentation functions giving sensitivity to transverse quark spin in the final state. A detailed recipe how to extract interference fragmentation functions from light-quark di-jet events in e^+e^- collisions is given in [89]. A recent discussion of the prospects of transversity measurements using future fragmentation function information from e^+e^- can be found in reference [90].

Additional studies in e^+e^- have been proposed using the high statistics data sample of the BELLE experiment at the KEK B-factory [91] with the goal to measure the two relevant fragmentation functions: namely the Collins function $H_1^\perp$ and the interference fragmentation functions $\delta\hat{q}^{h_1,h_2}$: For the first one measures the fragmentation of a transversely polarized quark into a charged pion and the azimuthal distribution of the final state pion with respect to the initial quark momentum (jet-axis). For the second one measures the fragmentation of transversely polarized quarks into pairs of hadrons in a state which is the superposition of two different partial wave amplitudes; e.g. π^+, π^- pairs in the ρ, σ invariant mass region. The high luminosity and particle identification capabilities of detectors at B-factories makes these measurements possible.

In all transversity measurements have a bright future and may reveal some surprises.

8. DVCS AND EXCLUSIVE PROCESSES

Deeply virtual Compton scattering (DVCS) provides a possible experimental tool to access the quark total angular momentum, J_q, in the proton through generalized parton distributions [41]. The form-factors which appear in the forward limit ($t \to 0$) of the second moment of the spin-independent generalized quark parton distribution in the (leading-twist) spin-independent part of the DVCS amplitude project out the quark total angular momentum defined through the proton matrix element of the QCD angular-momentum tensor. Going from J_q to the orbital angular momentum L_q is non-trivial in that one has to be careful to quote the perturbative QCD factorization scheme and process (polarized deep inelastic or νp elastic scattering) used to extract information about the intrinsic spin contribution S_q [92]. [1]

DVCS studies have to be careful to chose the kinematics not to be saturated by a large Bethe-Heitler background where the emitted real photon is radiated from the electron rather than the proton. The HERMES and Jefferson Laboratory experiments measure in the kinematics where they expect to be dominated by the DVCS-BH interference term and observe the $\sin\phi$ azimuthal angle and helicity dependence expected for this contribution. A first measurement of the single spin asymmetry has been discussed [42,93], which has the characteristics expected from the DVCS-BH interference. Recent JLab measurements are reported in [94].

Further measurements have been performed on exclusive π^+ production. At lower energies virtual Compton scattering experiments at Jefferson Laboratory and MAMI probe the electromagnetic deformation of the proton and measure the electric and magnetic polarizabilities of the target. Preliminary cross section measurements show clear effects of polarizabilities [43].

Higher twist corrections to the helicity-conserving DVCS amplitude appear not to be dramatically large. In contrast, the twist-two photon helicity-flip amplitude in DVCS starts at order α_s. Here leading higher-twist correction may arise at the tree-level already and therefore be large as compared to the leading-twist amplitude [95].

In future the HERMES and COMPASS experiments will explore DVCS measurements further. HERMES plans to run in 2004-2006 with an unpolarized target [61], allowing one to collect large statistics samples. This will allow one to study the t dependence of these asymmetries, and perhaps even a first approximate determination of the GPD H, for the u quark. Since also the knowledge on the GPD E is necessary to make contact with J_q, precision data with an unpolarized beam on a transversely polarized target would be needed. Even with 3 years of data with a (factor 2) improved target density, it seems marginal to achieve that goal.

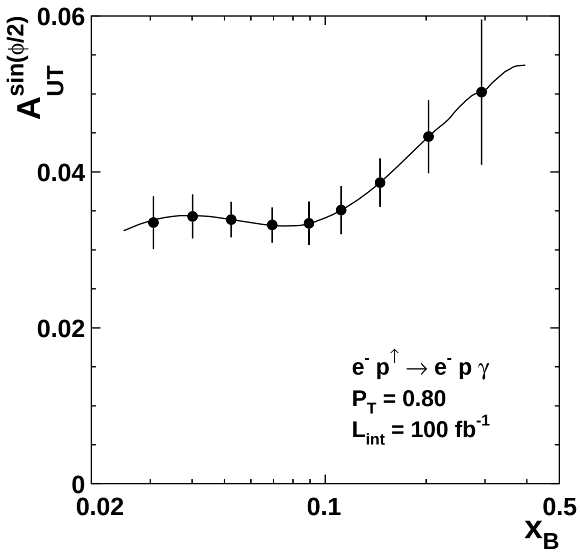

Figure 20. Projected statistical accuracy for the x_B dependence of the $\cos(\phi/2)$ moment in a high-luminosity experiment with unpolarized electron beam and polarized target, including detector acceptance [61].

A real breakthrough could be achieved with a high statistics experiment such as TESLA-N [61]. Fig. 20 shows a typical observable at such an experiment: the $\cos(\phi/2)$ moment of the cross section asymmetry for a 30 GeV beam on a NH_3

[1] The quark total angular momentum J_q is anomaly free in QCD so that QCD axial anomaly effects occur with equal magnitude and opposite sign in L_q and S_q. L_q is measured by the proton matrix element of $[\bar{q}(\vec{z} \times \vec{D})_3 q](0)$. Besides its sensitivity to the axial anomaly, L^q is also sensitive to gluonic degrees of freedom through the gauge-covariant derivative — for a recent discussion see [48].

target. The error bars are for one year of running. It shows that even the measurement of two-dimensional dependences (x and t) is within reach. It is therefore hopeful that the GPD's can be mapped in future, and perhaps deeper insight into the angular momentum structure can be gained.

In other exclusive channels, measurements of exclusive coherent vector meson production have been proposed [96] to look for colour transparency effects at COMPASS. Measurements of low-energy form-factors in exclusive strangeness production processes have been used to test models of confining constituent quark propagators [97]. The spin structure of light-cone wavefunctions [98] may be probed in hard exclusive processes.

9. POLARIZATION AND NEW PHYSICS

The recent precision measurement of the muon's anomalous magnetic moment $(g-2)$ at BNL [99] has revealed a 2.6 standard deviations difference from the Standard Model prediction, and created renewed excitement about possible "new physics".

The use of high energy polarized beams for discovering and in particular disentangling properties of new physics beyond the Standard Model, has been studied in [100,101]. Polarized beams allow one to define new observables: the spin asymmetries. These asymmetries typically involve ratios of cross sections, thus minimizing the systematics which often dominate the precision, a well known example being the high E_t production at the Tevatron. Hence such asymmetries can improve the discovery potential of an accelerator. Moreover such spin asymmetries offer the opportunity to extract information on the chiral structure of the new interaction.

For RHIC, some specific examples have been studied and reported [102]. E.g. a useful variable is the single parity violating asymmetry

$$A_L = \frac{d\sigma(-) - d\sigma(+)}{d\sigma(-) + d\sigma(+)} \qquad (10)$$

for single jet production cross sections ($pp \to jet + X$) where only one of the protons is polarized. A contact interaction analysis of this variable yields the limits as given in Table 3.

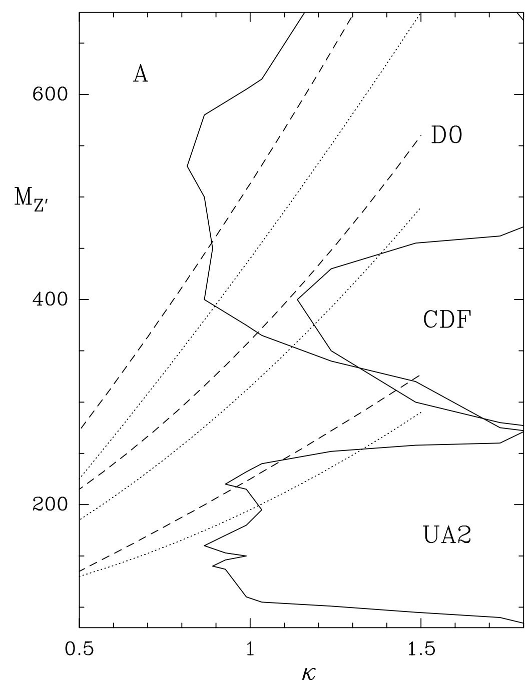

Figure 21. Bounds on the parameter space for leptophobic flipped SU(5) models, see [103].

At the Tevatron the expected sensitivities to Λ (the compositeness scale) are 3.2 TeV (3.7 TeV) for a 1 fb^{-1} (10 fb^{-1}) data sample [102]. Hence for comparable luminosity the polarized RHIC sensitivity is considerably larger, despite the lower energy.

Another example is leptophobic Z' production, i.e. new Z' gauge bosons which couple very weakly or not at all to leptons. Fig. 21 shows the constraints on the parameter space $\kappa = g_{Z'}/g_Z$ and the mass $M_{Z'}$. Dashed curves are for RHIC

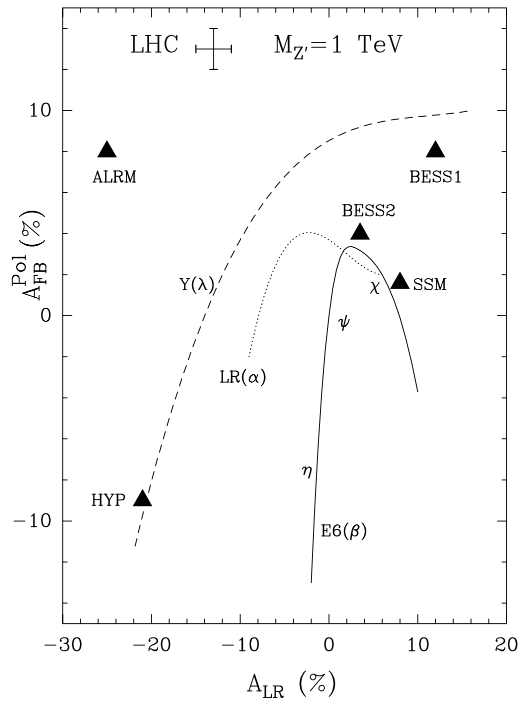

Figure 22. $A_{FB}^{\rm pol}$ versus A_{LR} according to the various models, see [103].

corresponding to $\sqrt{s}=650$ GeV and dotted to $\sqrt{s}=500$ GeV. From bottom to top the curves correspond to $L=1,10$ and 100 fb^{-1}. The increase in luminosity seems to be more effective than the increase in energy. In conclusion one finds that RHIC is competitive/complementary with the Tevatron to discover a new weak force belonging purely to the quark sector.

The LHC will give access to a complete new energy domain, and is being built with the mission to discover new physics. Once found the main task will be to try to understand it and disentangle the underlying dynamics. Generally, one finds that if the signals of new physics are leptonic, then polarization will not be needed to discover it. However the following example shows the power to interpret the results. Assume that a new Z' boson is observed: $pp \to l^+l^-X$. With one polarized beam one can define 2 parity violating asymmetries:

L(fb^{-1})	0.8	4	20	100
Λ (TeV)	3.2	4.55	6.15	7.55

Table 3
Limits on Λ_{LL} at 95% for RHIC with $\sqrt{s}=500$ GeV

$$A_{LR} = \frac{d\sigma^- - d\sigma^+}{d\sigma^- + d\sigma^-} \quad (11)$$

$$A_{FB}^{\rm pol} = \frac{(d\sigma_F^- - d\sigma_B^-) - (d\sigma_F^+ - d\sigma_B^+)}{(d\sigma_F^- + d\sigma_B^-) + (d\sigma_F^+ + d\sigma_B^+)}$$

Here $A_{FB}^{\rm pol}$ is the polarized forward backward asymmetry. Fig. 22 shows the predictions of different models for Z' in the $A_{LR} - A_{FB}^{\rm pol}$ plane. The LHC error bars correspond to 1000 e^+e^- and 1000 $\mu^+\mu^-$ events, with 100% polarization. Obviously, it will be very easy to separate the various models with these variables [102].

For new physics channels in the hadronic final states, one expects the reach to be larger for polarized compared to non-polarized measurements, as for RHIC. Studies for the LHC suggest a possible improvement of a factor of two for e.g. contact interactions or leptophobic Z's [102].

At a high energy *ep*-collider the region of high Q^2 offers the largest chance of discovering new physics. Such new physics could manifest itself through the production of new particles, such as Leptoquarks or SUSY particles in RP violating models, contact interactions, etc. A general study was made based on the contact interaction formalism [103]. It was demonstrated that a fully polarized HERA would be very instrumental in disentangling the chiral structure of the new interactions. With 250 pb^{-1} data samples for polarized e^+ and e^- beams, for each of the 2 spin orientations, the asymmetries are sensitive to contact interactions to scales larger than 7 TeV (95% C.L.). In the presence of a signal these different combinations of cross sections into the seven different asymmetries allow a complete identification of the chiral structure of the new interactions, i.e. whether the interactions are LL, RR, LR or LR or a combination of those (where L and R denote the left and right handed fermion helicities for the lepton and quark respectively).

This study has been further extended to the special case of leptoquark-like production [104]: asymmetries like the ones above would allow one to pin down the chiral properties of the couplings to these new particles.

These high Q^2 studies may be most relevant for HERA and THERA. For THERA both e^+ and e^- beams will be needed and minimum integrated luminosities of order 100-200 pb^{-1}/beam.

In conclusion the studies for RHIC, LHC and HERA show that for the leptonic channels, polarization in general does not help to improve the search limits. In hadronic channels however, the analysis of spin asymmetries may help to considerably extend the search reach. In all cases polarization will be instrumental to analyse the chiral structure of new dynamics, if discovered.

10. FUTURE FACILITIES

The study of the spin structure of the proton and high-energy spin phenomena has only just begun!

There are many urgent and open questions in spin physics requiring dedicated experimental and theoretical input. Several newly proposed avenues of exploration, such as generalized parton distributions and transversity studies, will be only barely touched upon by the presently planned experiments in the next few years. The first measurements on Δg, flavour-separation, DVCS, transversity... will be made by HERMES, RHIC-SPIN, COMPASS and experiments at Jefferson Laboratory and SLAC in the next five years — see Table 4. However, it is clear even now that to really pin down the underlying physics, measurements in a larger kinematical range and/or with more precision will be required. Only with a strongly focused and united position can the spin community be successful in keeping such a programme developing.

From the high energy end, what are the options ? The HERA accelerator may match the time schedule best. The HERA luminosity has been upgraded and is expected to be around 200 pb^{-1}/year/experiment. HERA is now starting its phase II. It has recently been decided that this programme will run up to and including 2006. After that there may be room for a HERA phase III, depending on the strength of the physics programme, the community interested to carry such a program through, and the schedule of TESLA.

Polarized protons in HERA is a possibility for HERA III. HERA already has a polarized electron beam, which will be used from now by the collider experiments H1 and ZEUS, as well. These experiments could probably be continued to be used for polarized measurements, unless detector aging issues would be preventive.

The experience of RHIC, which starts to be commissioned as a polarized *pp* collider in 2001, will be of vital importance. If successful, high energy polarized beams could become a 'standard' for proton machines. To be useful for experiments one should be able to have stable proton beams with a polarization of larger than 50%. Present estimates for HERA and RHIC are for a polarization of 70%. An important issue is the measurement of the polarization of such a proton beam. At BNL the CNI mechanism in pC scattering is presently exploited for this purpose [11].

Preliminary price estimates for HERA are reported in [105] and amount to 30M Euro to polarize HERA, possibly cheaper for deuterons. Hence, it looks like this option can be realized for a reasonable price bargain. One could then pursue polarized deep inelastic scattering in a totally new regime sometime in the second half of this decade. Since it could be technically simpler to have polarized deuteron beams instead of proton beams, it is opportune that some of the key physics studies will be repeated for deuterons. The machine group should however judge whether this initial enthusiasm can be backed up by calculations, like was done for polarized protons.

Continuing the HERA program would also encourage HERMES to plan further beyond their present aims. Ideas exist [61] to study the possibility of higher density polarized targets to better tackle e.g. DVCS and transversity measurements.

At RHIC possible upgrades include increasing the luminosity for *pp* collisions by a factor 25-40 and upgrading the beam energy from 250 GeV to 325 GeV. With such a collider, more subtle spin effects such as transversity in double spin asymmetries could become practicable.

The idea to add an electron accelerator onto RHIC is catching on [16]. Two possible solutions are being investigated: adding an electron ring and adding an electron LINAC with an energy of 10 GeV and with an intensity such that high luminosities, more than a factor of 100 larger than at HERA, can be achieved. The polarization of the electron beam will be in the range of 70-80%. Note that the energy of the proton beam can be varied from 25 GeV to 250 GeV, hence collisions with a CMS energy in the range of 10-100 GeV are possible at RHIC. If this scenario will be realized then a new experiment would be needed, carefully adapted to the interaction region and well integrated with the beam line magnets, allowing for *ep*, *eA* and *pA* collisions. This scenario offers the opportunity to built a real optimized detector for such type of physics, with e.g. good particle identification, and in particular paying special attention to the beam-pipe regions [17].

The program of this Electron Ion Collider (EIC) or e-RHIC is very rich, and much of the physics potential can be appreciated from the polarized HERA physics studies. The high luminosity is a clear advantage. In case polarized HERA will not happen, one should also seriously consider what the highest possible energy is that could be reached with the EIC. For example, with a 30 GeV electron beam the reach in x and Q^2 is less than a factor 3 smaller than for HERA. The status of the EIC project is that an R&D program is being pursued in order to have a proposal ready by about 2004. If all goes well *ep* physics could be studied at BNL by about 2010. If funding can be found for such a program, EIC may turn out to be the most attractive option in terms of expected performance and time-scale.

Possible projects beyond this time-line include those associated with an e^+e^- linear collider which may come into operation some time after 2010. If such a collider were to be built close to a Laboratory with a high energy proton beam *and* if this proton beam is polarized, then one can push the frontier of DIS. The THERA studies have briefly looked into this option. Otherwise one can use the high intensity electron beam in fixed target mode, like TESLA-N or ELFE@DESY. Uncanny precision measurements could be obtained at such a facility. However one should note that if there were to be no continuation of a spin program beyond already planned and approved experiments, then the experimental side of this field may stop around 2006, leaving too long a gap before the start-up of these far-future facilities...

At intermediate energy, the proposed upgrade of Jefferson Laboratory to 12 GeV would provide continuous electron beams at high luminosity enabling precision studies of the valence structure of the nucleon and QCD “confinement dynamics”. A definitive νp elastic experiment (as suggested for miniBooNE at FNAL [18]) would provide a complementary window on the spin structure of the proton and enable one to make an independent measurement of $g_A^{(0)}$ (including any possible contribution from $x = 0$).

Building on the programme of polarized proton-proton collisions presently underway at RHIC it is worthwhile to investigate the physics potential of future polarized proton-proton collisions in the Large Hadron Collider, LHC, at CERN. High-energy polarized proton-proton collisions could be particularly useful to probe the chiral and spin structure of supersymmetric couplings and extensions to the minimal Standard Model with an elementary Higgs sector which might be discovered with the (unpolarized) LHC, including any possible strong (dynamical) electroweak symmetry breaking. Certainly the LHC will be a collider facility for a long time to come with e.g. luminosity and perhaps energy upgrades still to be planned. The new physics may dictate that the use of polarized proton beams would be a vital discriminator between models and theories. Hence the option to polarize the LHC in future should be kept open.

In summary, the workshop led us to believe that the spin community has sufficient dynamics (and youth) to believe in the future of a long range program, in a similar way that NASA has set itself different landmark experiments for the next 20 years [106]. The community should not lose this energy, converge on a solid physics program and bring up the strength to see to it that it happens.

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Table 4
Key observables and experiments which will measure them

Quantity	Experiment	Dates
Δg	COMPASS	2003
	HERMES	2002 +
	RHIC	2002-05
	SLAC E-161	2005
Flavour separation	HERMES	2002
	RHIC	2002-04
Λ polarization	RHIC	2002+
Transversity, h_1	COMPASS	2004+
	HERMES	2002-03
	RHIC	2002+
Transversity from e^+e^-	BELLE	2002
DVCS plus meson production	COMPASS	2004+
	HERMES	2004-05
High energy GDH integrand	SLAC E-159	2006

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