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# Spin Physics

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**Abstract**

A summary of new experimental results and recent theoretical developments presented in the "Spin Physics" working group is given.

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## I INTRODUCTION

One of the most intriguing, and yet unanswered, questions in particle physics is to find out how the spin of the proton is shared among its constituents, the quarks and gluons. The experimental observation [1] that the contribution of quarks to the proton spin is far smaller than naively expected in the Ellis–Jaffe sum rule [2], made by EMC nine years ago, initiated a huge experimental programme of spin structure function measurements at CERN, SLAC and DESY. All these experiments have confirmed the original EMC observation with a continuously improving level of precision and provided new insights into the nucleon spin structure from the measurement of various other inclusive and semi-inclusive observables. Moreover, the EMC result has motivated much theoretical work towards a better understanding of the nucleon's spin. The study of the spin structure of the nucleon has become by now an important aspect of deep inelastic scattering, and one working group of the present workshop was devoted to "Spin Physics". In this brief review, I will attempt to summarize the results and developments discussed in this group. The choice of material presented here is necessarily restricted and can only give a first impression of the current trends in spin physics.

## II NEW EXPERIMENTAL RESULTS

Deep inelastic scattering off polarized targets is presently studied at three different experiments. The SMC experiment [3,4] in the CERN 190 GeV polarized muon beam uses a large polarized solid state target; this experiment has been operational from 1992-96 and has recently finished data-taking. The major improvement in the 1996 run was the use of ammonia as target material which has a higher target dilution factor (fraction of polarizable protons in the

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target) than the previously used butanol. Of all polarized DIS experiments, SMC has the largest beam energy and therefore covers lower values of $x$ than its competitors.

A series of SLAC experiments is studying spin structure functions with the polarized SLAC electron beam. The most recent experiments [5] in this series were E154 and E155, working at an electron beam energy of 48.3 GeV, compared to beam energies of $10 - 29$ GeV available to their predecessors. Moreover, the degree of beam polarization has been improved with respect to the earlier SLAC measurements. These experiments use a target cell with polarized $^3$He (E154) or polarized ammonia (E155). The E154 experiment, which was carried out early last year, has already published first results; E155 has just completed data-taking.

The youngest competitor in polarized deep inelastic scattering is the HERMES experiment [6,7] operating a polarized internal gas target in the HERA 27.5 GeV positron beam, which is polarized naturally due to the Sokolov–Ternov effect. This experiment offers a presently unique identification of particles in hadronic final state of deep inelastic scattering and is therefore ideal for the measurement of semi-inclusive asymmetries.

## A Inclusive measurements and sum rules

The study of the polarized structure functions $g_1(x, Q^2)$ and $g_2(x, Q^2)$, measured in inclusive lepton-nucleon scattering in the above experiments yields various different insights into the spin structure of the nucleon. The structure function $g_1$ in particular has a simple partonic interpretation as the charge weighted sum of the quark polarizations in the nucleon,

$$g_1(x, Q^2) = \frac{1}{2} \sum_{q,\bar{q}} e_q^2 \left[ q^{\uparrow}(x, Q^2) - q^{\downarrow}(x, Q^2) \right] \ ,$$

thus yielding information on the polarized parton distributions in the nucleon. Sum rules due to Bjorken [8] and Ellis and Jaffe [2] relate the first moment of $g_1$,

$$\Gamma_1^{p,d,n}(Q^2) = \int_0^1 g_1^{p,d,n}(x, Q^2)\, \mathrm{d}x \ ,$$

to the axial vector coupling constants measured in $\beta$-decays. The test of these sum rules is clearly one of the key issues in spin physics. It should however always be kept in mind that only the Bjorken sum rule is a rigid prediction of isospin symmetry, while the Ellis–Jaffe sum rule is based on a much weaker footing in the naive quark parton model.

Based on the data taken in 1996, the SMC experiment has recently presented a new (preliminary) measurement of the proton spin structure function $g_1^p(x, Q^2)$ [3]. Compared with the earlier SMC measurement of $g_1^p(x, Q^2)$, statistical errors have now been reduced by a factor of 2. One of the most

striking results of this measurement is the behaviour of $g_1^p$ at small $x$. In contrast to earlier SMC results clearly indicating a rise of $g_1^p$, one finds this rise at small $x$ to be rather moderate now if all SMC proton data are combined, as can be seen in Figure 1. It must however be pointed out that the $x$ values currently probed at polarized fixed target experiments are about two orders of magnitude larger than the $x$ values probed in unpolarized collisions at HERA. It is therefore at least doubtful that the kinematic region covered at SMC can yield conclusive information on the small-$x$ behaviour of the polarized structure functions.

Using the 1996 proton data, SMC has moreover presented an improved measurement [3] of the Ellis–Jaffe proton sum rule $\Gamma_1^p(Q^2 = 10\ \mathrm{GeV}^2) = 0.149 \pm 0.012$, which is more than $1.5\sigma$ below the prediction of Ellis and Jaffe. The Bjorken sum rule is found to be $\Gamma_1^{p-n}(Q^2 = 10\ \mathrm{GeV}^2) = 0.209 \pm 0.026$, which is consistent with the predicted value of $0.187 \pm 0.002$.

Both HERMES and E154 have measured the neutron spin structure function $g_1^n(x, Q^2)$ off polarized $^3$He-targets [5,6,9], the results are included in Figure 1. Based on these recent data, both experiments have presented new determinations of the Ellis–Jaffe neutron sum rule, HERMES: $\Gamma_1^n(Q^2 = 2.5\ \mathrm{GeV}^2) = -0.037 \pm 0.013 \pm 0.005$ and E154: $\Gamma_1^n(Q^2 = 5\ \mathrm{GeV}^2) = -0.041 \pm 0.004 \pm 0.006$. These measurements are consistent with each other and significantly below the value predicted by Ellis and Jaffe.

A compilation of all world data [1,3,5,6,10] on the structure function $g_1$ of the proton, deuteron and neutron, evolved to a common value of $Q^2 = 5\ \mathrm{GeV}^2$ is shown in Figure 1.

All above measurements of the spin sum rules for $\Gamma_1^p$ and $\Gamma_1^n$ face two common problems: the evolution of all data points taken in the experiment to a common value of $Q^2$, where the sum rule is evaluated, and the extrapolation of $g_1$ between the lowest measured $x$ point and $x = 0$.

The evolution of all data points to a common value of $Q^2$ was up to very recently made by assuming that the structure function ratio $A_1(x, Q^2) \sim g_1(x, Q^2)/F_1(x, Q^2)$ is independent of $Q^2$. This assumption is consistent with present experimental data on the $Q^2$–dependence of $A_1$, which cover however only a relatively narrow range in $Q^2$ for fixed $x$. Perturbative QCD on the other hand predicts a non-vanishing $Q^2$–dependence of $A_1$. An improved evolution procedure, incorporating the results of QCD analyses of the data on $g_1(x, Q^2)$, is now used – at least as a cross check of the above method – in all recent experimental evaluations of the Ellis–Jaffe sum rule. This method will be discussed below in Section III. The difference between the results obtained in both methods is however still significantly smaller than the present statistical and systematical errors on the measured values of $\Gamma_1^{p,n}(Q^2)$.

The extrapolation of $g_1(x, Q^2)$ into the experimentally unmeasured small $x$ region has by now become one of the major sources of uncertainty in measurements of the spin sum rules. This extrapolation has up to now been performed assuming $g_1(x \to 0) \sim const$, which is motivated by Regge theory.

This behaviour is however immediately broken by QCD evolution, which predicts $g_1(x)$ to rise at least logarithmically at small $x$. A study of the small $x$ behaviour of $g_1^n(x,Q^2)$ by E154 [5] showed that the present data are consistent both with $g_1(x) = const$ and the extreme behaviour $g_1(x) = C/x^{0.9}$, indicating that the neutron spin structure at small $x$ is still largely unknown – despite the experimental progress made on the neutron spin structure in recent times. This induces consequently a non-quantifiable uncertainty on the spin sum rules arising from the small-$x$ region.

Apart from the measurement of $g_1(x,Q^2)$ in deep inelastic scattering off longitudinally polarized targets, the SLAC experiments have as well measured [5,11] the second spin structure function $g_2(x,Q^2)$, which is accessible using transverse target polarization. The result of all SLAC measurements of $g_2^n(x,Q^2)$ at $Q^2 = 3$ GeV$^2$ is shown in Figure 2. This structure function has no simple partonic interpretation but is of particular interest, as it can receive sizable contributions from twist-3 operators. Using an exact integral relation [12] for the twist-2 contributions to $g_1$ and $g_2$, it is possible to predict the twist-2 content of $g_2$, indicated by the solid line in Figure 2. Using this integral relation, it is moreover possible to measure [5,11] the twist-3 matrix element $d_2^n = (-1.0 \pm 1.5) \times 10^{-2}$ from the second moment of $g_2$. This measurement is however not yet accurate enough to discriminate between different theoretical predictions obtained from QCD sum rules [13], in the bag model [14] and from lattice calculations [15].

## B Semi-inclusive measurements

The information on the individual quark and anti-quark polarizations in the nucleon obtained from inclusive measurements of the structure function $g_1$ is naturally limited by the fact that two independent functions, $g_1^p$ and $g_1^n$, are insufficient to disentangle the five different distributions $\Delta u_v$, $\Delta d_v$, $\Delta \bar{u}$, $\Delta \bar{d}$ and $\Delta s$. A possible way to access these individual distributions in deep inelastic scattering is the study of semi-inclusive asymmetries, defined by a particular hadron observed in the final state.

The first results on semi-inclusive asymmetries for positively and negatively charged hadrons were published already some time ago by SMC [16]. Based now on the whole SMC data sample, an improved (preliminary) determination of $\Delta u_v$, $\Delta d_v$ and $\Delta \bar{q}$ from semi-inclusive asymmetries has been presented during the workshop [4], the results of this analysis are shown in Figure 3. A measurement of semi-inclusive asymmetries for particular hadron species, required for a flavour decomposition of the light quark sea $\Delta \bar{q}$, is however not possible with the SMC apparatus, which does not have a dedicated hadron identification.

First hadron results obtained at HERMES [7], e.g. the decay angle distribution in $\rho \to \pi^+\pi^-$ or the ratio of the unpolarized valence quark distributions

$d_v/u_v$ demonstrate the potential of the HERMES apparatus for precision measurements of semi-inclusive asymmetries in polarized deep inelastic scattering. The first HERMES results on these can be expected in the near future.

# III STATUS OF POLARIZED PARTON DISTRIBUTIONS

## A QCD analysis of polarized structure function data

Using the recently calculated polarized two-loop splitting functions [17], it is now possible to perform consistent next-to-leading order fits [18–21] of polarized parton distributions to the world data on $g_1(x, Q^2)$. There are various motivations for these fits: (i) the parton distributions are universal, process-independent features of the nucleon, their knowledge therefore enables the calculation of a variety of hard cross sections in polarized hadron–hadron collisions; (ii) the knowledge of the polarized parton distributions allows one to quantify the effects of QCD evolution on the structure function $g_1$, which is crucial for the comparison of data taken at different $Q^2$ and for the evaluation of spin sum rules (see above); (iii) the resulting distributions can be compared with non-perturbative calculations (e.g. in Lattice-QCD, see below).

All QCD fits assume simple parametric forms for the initial distributions at some low scale $Q_0^2$, which are then evolved according to the DGLAP evolution equations [22] and fitted to the experimental data on the structure function $g_1$ at higher $Q^2$. There is some ambiguity in the choice of factorization scheme at next-to-leading order. At present, two schemes are commonly used in the QCD fits: the well-known $\overline{\rm MS}$ scheme and the AB scheme, allowing for a non-zero gluonic contribution to the Ellis–Jaffe sum rule. Fits in both schemes yield equally good descriptions of the structure function data, as shown in [21]. Two new QCD analyses of the world data on polarized structure functions (excluding the only recently released new SMC proton data) were presented during the workshop [20,21].

All QCD analyses of the polarized structure function data come to the common conclusion that only the valence quark polarization and the total sea quark polarization are well constrained by the experimental data. The precise flavour decomposition of the polarized quark sea and the polarization of gluons in the nucleon are at present largely unknown. The $Q^2$ evolution between the data-sets of SLAC and SMC, taken at different beam energies, indicates however a positive overall gluon polarization $\Delta G(Q^2 = 5\ \mathrm{GeV}^2) \sim \mathcal{O}(2)$, but leaves the $x$–dependence of the corresponding distribution $\Delta G(x, Q^2)$ rather unconstrained. This is illustrated in Figure 4, showing four different parameterizations of $\Delta G(x, Q^2 = 10\ \mathrm{GeV}^2)$ obtained in the recent analysis of [20] together with one parameterization obtained earlier in [18]. Although these parameterizations are in different schemes (AB [20] and $\overline{\rm MS}$ [18]), they are

still comparable, as the corresponding scheme transformation leaves the polarized gluon distribution unaffected. All parameterizations shown in Figure 4 yield equally good descriptions of the polarized structure function data. Finally, all fits yield consistent values for the first moment of the singlet axial vector current $a_0$, which can in the $\overline{\rm MS}$ scheme be identified with total quark contribution $\Delta\Sigma$ to the proton spin. The current value for this quantity is $\Delta\Sigma^{\overline{\rm MS}}(Q^2 = 5\ {\rm GeV}^2) = 0.20 \pm 0.08$ [21].

Using the results of these QCD fits, it is possible to evolve all data points of an experiment to a common value of $\langle Q^2 \rangle$, as required for evaluations of the Ellis–Jaffe sum rule. Defining the shift parameter

$$\Delta g_1^{\rm fit}(x_i, Q_i^2, \langle Q^2 \rangle) \equiv g_1^{\rm fit}(x_i, Q_i^2) - g_1^{\rm fit}(x_i, \langle Q^2 \rangle)$$

for each data point $(x_i, Q_i^2)$, the value of $g_1^{\rm exp}(x_i, \langle Q^2 \rangle)$ can be approximated by

$$g_1^{\rm exp}(x_i, \langle Q^2 \rangle) = g_1^{\rm exp}(x_i, Q_i^2) - \Delta g_1^{\rm fit}(x_i, Q_i^2, \langle Q^2 \rangle).$$

This procedure enables a consistent estimate of the systematic error induced by the evolution effects. The integral of $g_1(x, Q^2)$ over the $x$ range covered by experimental data obtained with this method is usually consistent with the results obtained assuming $A_1$ to be independent of $Q^2$.

Believing that the present data are already sufficient to constrain the behaviour of the polarized quark and gluon distributions at small $x$, it is furthermore possible to predict the behaviour of the polarized structure function $g_1$ in the small $x$ region (disregarding potential effects due to resummations [23] of terms of $\mathcal{O}(\alpha_s^n \ln^{2n} x)$). The small $x$ extrapolations obtained from the fits in this way are systematically more singular [20,21] than the small $x$ extrapolations from Regge theory, predicting $g_1 \sim const$ at small $x$. In particular, both recent QCD analyses [20,21] found that the small $x$ contribution to $\Gamma_1^n$ shifts the central value of this sum rule by more than two standard deviations.

The Bjorken sum rule is on the other hand less affected by the uncertainties arising in the small $x$ region, in particular since it corresponds to a non-singlet combination of the polarized parton densities evolving independently of the polarized quark singlet and polarized gluon distribution. Using the small $x$ extrapolations motivated by the parton distribution fits, the Bjorken sum rule is found [20,21] to be within one standard deviation of the predicted value. This sum rule can finally be used for a determination of the nucleon axial vector coupling $g_A = 1.19 \pm 0.09$ [20], which is consistent with the value obtained from neutron $\beta$-decay $g_A = 1.257 \pm 0.003$.

## B Lattice results

The calculation of the lower moments of (unpolarized and polarized) parton distribution functions in the nucleon has made considerable progress over the

last two years [24]. The most recent improvement in this field is a systematic procedure for the removal of all terms linear in the lattice spacing from the lattice observables, yielding a better extrapolation towards the continuum limit. First results obtained with this method were shown during the conference. These include improved lattice determinations of the first moment of the polarized $u$ and $d$ valence quark distributions, the axial vector current $g_A$ (Bjorken sum rule) for the ratio of the hyperon decay constants $F/D$ (Ellis-Jaffe sum rule). The interpolation of these results towards the continuum limit is shown in Figure 5. The results obtained for the polarized valence quark distributions are in very good agreement with the results of recent fits to the structure function data [18]. While the determination of the $F/D$ ratio is consistent with experimental data from hyperon decay, there appears to be a discrepancy of about 10% between the lattice result for $g_A$ and the value obtained from neutron $\beta$-decay. The source of this discrepancy is not understood at present, it might however indicate a failure of the naive parton model identification of this current on the lattice.

# IV THEORETICAL DEVELOPMENTS

## A Progress in higher order corrections

While QCD corrections [25,26] to the spin sum rules are already known to $\mathcal{O}(\alpha_s^3)$ (these corrections to the Ellis–Jaffe sum rule were calculated only recently and are discussed in [26]), one was restricted to lowest order approximations in studies of most other spin-dependent observables up to now. Only the calculation [17] of the space-like polarized two loop splitting functions $\Delta P_{ji}(x)$, crucial ingredients for a determination of polarized parton distributions at next-to-leading order [18–21], enables now consistent studies of polarized observables beyond leading order. Several new results on higher order corrections to spin-dependent processes were presented during the workshop.

Much information on the unpolarized sea quark distributions in the nucleon was gained from experiments on lepton pair production at fixed target energies (the Drell-Yan process, for recent results see e.g. [27]). Moreover, the production of vector bosons at collider energies is mediated by the same process. Given the importance of higher order corrections to the unpolarized Drell–Yan cross section, the knowledge of QCD corrections to the polarized Drell–Yan process will be crucial for a reliable interpretation of future data on vector boson production at RHIC. The complete $\mathcal{O}(\alpha_s)$-corrections to the polarized Drell–Yan cross section as function of the rapidity $y$ and the Feynman-parameter $x_F$ have been calculated recently [28]. These corrections turn out to be similar to the corrections in the unpolarized case and hence numerically sizable even at collider energies. Furthermore, some progress towards the calculation of the Drell–Yan cross section at $\mathcal{O}(\alpha_s^2)$ has been made with

the calculation of the non–singlet contributions to the Drell–Yan cross section for non-zero transverse momentum at this order [29].

Finally, the time-like polarized splitting functions $\Delta P_{ij}(z)$, related to the spin transfer in fragmentation processes have been recently derived [30,31] by use of analytic continuation relations applied to their space-like counterparts. First applications to polarized $\Lambda$-production will be discussed in the following.

## B Spin-transfer in semi-inclusive reactions

The polarized parton distributions describe the probability of finding a parton of a particular species having its spin aligned or anti-aligned with the spin of the nucleon. Correspondingly, one can define polarized fragmentation functions parameterizing the probability of a polarized parton fragmenting into a hadron with spin aligned or anti-aligned to the parent parton spin. These polarized fragmentation functions are however experimentally only very hard to access for most hadrons, as they require the measurement of the spin state of a final state particle. Such a measurement is in practice only feasible for particles with dominant parity violating decay modes such as the $\Lambda$ baryon. First studies [31,32] on the polarized fragmentation functions into $\Lambda$'s have been carried out recently. These studies consider two possible scenarios for the spin transfer to the $\Lambda$: a naive approach [33] in which the $\Lambda$ spin is carried only by the $s$ quark and an approach due to [34], where the spin is shared among the $u, d, s$ quarks in the $\Lambda$. It has been shown in [31] that a fit to LEP data [35] only is insufficient to discriminate the two scenarios, whereas a clear distinction would be possible in semi-inclusive DIS with a polarized lepton beam onto an unpolarized proton target, as can be seen in Figure 6.

## C Instanton calculations

Several attempts to calculate contributions to deep inelastic structure functions induced by instantons have been made recently (see e.g. [36] for a review). There are two substantially different approaches to the phenomenology of instanton effects in deep inelastic scattering. Several predictions for instanton contributions to the polarized parton distributions obtained in the instanton liquid model [37] have been presented during this workshop [38]. This approach predicts a large and negative contribution to the polarized gluon distribution and an approximate relation $\Delta\bar{d}(x) \approx -2\Delta\bar{u}(x)$. Factorization properties and infrared behaviour within this model, based on an instanton lagrangian for fixed instanton radius, are however not yet clear at present. A substantially different approach is the systematic treatment within instanton perturbation theory [39]. This approach is free of infrared problems, as a dynamical cut-off on the instanton size is provided by the typical hard scale of the scattering process. Predictions obtained with this method concern mainly

the structure of the multi-particle final state in deep inelastic scattering [36], and predictions for polarized observables are not yet available.

## D $g_2(x, Q^2)$ at small $x$

Analytical calculations [23] of the asymptotically dominant logarithmic contributions $(\alpha_s \ln^2(1/x))^n$ to the polarized structure function $g_1(x, Q^2)$, based on the resummation of soft gluon contributions in an infra-red evolution equation [40], have now been available for some time, and contributions to the chirally-odd polarized structure function $h_1$ have been calculated recently [41]. Based on a similar approach, the non-singlet contribution to the polarized structure function $g_2(x, Q^2)$ has now been studied in [42]. This calculation yielded a simple relation

$$g_2^{\text{n.s.}} \sim \frac{\partial g_1^{\text{n.s.}}}{\partial \ln \alpha_s} \ ,$$

with $\alpha_s$ corresponding to ladder gluon contributions only, between $g_1^{\text{n.s.}}$ and $g_2^{\text{n.s.}}$, suggesting both to have the same small-$x$ behaviour. It is however not clear at present, to which extent the above result is consistent with the Wandzura-Wilczek sum rule [12] and whether contributions to $g_2$ from twist-3 operators become important at small $x$.

## E Sum rules in twist-2 and twist-3

A variety of different sum rules and integral relations for the polarized structure functions appearing in the deep inelastic scattering cross sections for neutral and charged current exchange, mostly only valid for the twist-2 contributions, have been derived in the past. Motivated by several apparent discrepancies in the literature, a detailed re-investigation of the validity of sum rules and integral relations in twist-2 in polarized deep inelastic scattering has been performed [43] over the past year. This study, consistently carried out in the operator product expansion and cross-checked in the covariant parton model, confirmed only some of the earlier results while disproving others. Moreover, several new relations involving the polarized charged current structure functions have been derived in [43], yielding finally a self-consistent and complete picture of the twist-2 contributions to polarized deep inelastic scattering. Moreover, higher twist contributions to the polarized structure functions, in particular the presumably non-negligible twist-3 contributions to $g_2$ and $g_3$, can be extracted by using exact relations for their twist-2 content. A new relation between the twist-3 contributions to $g_2$ and $g_3$ has been derived in [43].

Finally, the work of [43] could verify that a sum rule for the valence content of $g_1$ and $g_2$,

$$\int_0^1 \mathrm{d}x\; x\left[g_1^V(x) + 2g_2^V(x)\right] = 0,$$

which was derived earlier in [44] is consistent with the operator product expansion in massless QCD, although it cannot be explicitly proven in this approach.

## F Exclusive reactions

The total spin of the nucleon does not only receive contributions from the spin carried by its constituents, quarks ($\Delta\Sigma$) and gluons ($\Delta G$), but as well from the orbital angular momentum of quarks $L_\Sigma$ and gluons $L_G$:

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_\Sigma + L_G.$$

Only the partonic spin contributions $\Delta\Sigma$ and $\Delta G$ to the nucleon spin can be accessed in inclusive or semi-inclusive reactions studied at present and future spin experiments. Up to very recently, no experimental observable was known to access the orbital angular momentum of the partons. It has been proposed recently [45], that the total quark angular momentum $J_\Sigma = \Delta\Sigma/2 + L_\Sigma$ could be related the form factors accessible in the (unpolarized) exclusive reaction $\gamma^\star p \to p\gamma$ (Deeply Virtual Compton Scattering, DVCS) at large virtualities of the incoming photon and zero momentum transfer to the proton. First numerical studies of this reaction [46] indicate that these form factors may be measurable at the COMPASS experiment discussed below, while the DVCS cross section at HERMES is concealed by a large QED background.

Although the identification of the total quark angular momentum with exclusive form factors is not undisputed, it has triggered a large interest in the perturbative description of exclusive reactions involving a large momentum transfer. It has already been proposed about ten years ago [47] that exclusive reactions in $ep$ scattering at large momentum transfers $Q^2$ and small proton deflection $t$ could be described by non-forward parton distributions, being hybrids of ordinary parton distributions [22] and distribution amplitudes [48] describing e.g. meson formation from two parton initial states. These non-forward parton distributions [49], functions of two scalar variables describing all hard partonic momenta in the exclusive reaction, obey evolution equations which can be reduced to the common DGLAP [22] or BL [48] evolution equations for parton distributions or distribution amplitudes by respective integration. Moreover, various integral relations between non-forward parton distributions and elastic form factors or parton distributions can be derived [49]. The unpolarized one-loop evolution kernels for non-forward parton distributions have already been known for some time [47], and the full spin dependence of these kernels was derived recently [50].

# V FUTURE EXPERIMENTS

The completion of the SLAC programme and the SMC experiment marks the end of the "second generation" of dedicated polarized structure function measurements. Only the HERMES experiment will continue to provide new data on $g_1$ and $g_2$, together with the first precision measurements of semi-inclusive asymmetries.

Our knowledge on the spin structure of the nucleon is at present largely based on the structure function measurements discussed above and therefore inevitably incomplete. The study of the unpolarized proton structure has shown that information obtained from structure functions alone is insufficient for an unambiguous determination of all different parton distribution functions in the nucleon. Only the combination of various observables from lepton-nucleon and nucleon-nucleon collisions in a global fit enables the extraction of quark distributions of different flavour and of the gluon distribution. Numerous experiments devoted to the study of such complementary observables are presently constructed, others are proposed or under discussion.

Two experimental projects probing the spin structure of the nucleon were presented in more detail during the workshop: the recently approved COMPASS experiment [51,52] at CERN and the operation of the HERA collider with a polarized proton beam [53,54], which is one possible option for the mid-term future of HERA and currently under study. The physics prospects of these two projects will be discussed in more detail below.

Another major project in spin physics is the polarized proton programme [55] at the RHIC collider at BNL, offering the possibility of studying polarized proton-proton collisions at centre-of-mass energies varying between 60 GeV and 500 GeV. This programme is expected to start in the year 2001 and will cover the broad range of physics observables accessible in hadronic collisions.

Among the various spin experiments discussed at the moment are a measurement of the polarized neutron structure function $g_1^n$ at large $x$ at CEBAF [5] and an upgrade of the HERMES spectrometer to enable measurements of open charm production [7].

## A COMPASS at CERN

The COMPASS experiment [51,52] in the CERN polarized muon beam will use a newly built hadron and muon spectrometer to study inclusive and semi-inclusive scattering off a polarized nucleon target. It will start data taking in the year 2000.

The key process studied at COMPASS is the production of open charm, induced by quasi-real photons. This process is mediated by photon-gluon fusion

and hence provides a direct probe of the polarized gluon distribution in the nucleon. Detailed simulations of the detection of open charm from reconstructed $D \to K\pi$ decays have shown [52] that COMPASS will be able to measure the ratio of polarized to unpolarized gluon distribution $\Delta G(x,Q^2)/G(x,Q^2)$ within an accuracy of $\pm 0.11$ for $x \approx 0.1$ and $Q^2 \approx 4m_c^2$. This accuracy can be further improved by considering other decay channels of the $D$ meson, such studies are in progress.

Another potential probe of the polarized gluon distribution at COMPASS could be the production of oppositely charged hadron pairs back-to-back at large transverse momentum. This process is currently under study, and first results look promising [52].

The COMPASS physics programme covers moreover improved measurements of the polarized structure functions $g_1$ and $g_2$ and of semi-inclusive asymmetries. Furthermore, studies of transversity distributions which are only accessible in semi-inclusive deep inelastic scattering will be carried out. Finally, COMPASS will be able to study the spin transfer in semi-inclusive $\Lambda$ production discussed above [31,32].

## B Future prospects for spin physics at HERA

The commissioning of the HERA electron-proton collider five years ago opened up a completely new kinematical domain in deep inelastic scattering, and the two HERA experiments have provided a multitude of new insights into the structure of the proton and the photon since then. It is therefore only natural to assume that the operation of HERA with polarized proton and electron beams could add vital new information to our picture of the spin structure of the nucleon. The technical feasibility and physics prospects of this project have been investigated for the first time in a working group of last year's "Future Physics at HERA" workshop [53]. More detailed studies for several key observables are presently carried out in an ongoing workshop on "Physics with Polarized Protons at HERA" [54].

The HERA electron beam is polarized naturally due to the Sokolov–Ternov effect, and stable electron polarization can be maintained over the whole beam lifetime. The polarization of the proton beam is on the other hand a major challenge in accelerator physics, since this requires the acceleration of polarized protons from low energies. The proton polarization has to be monitored and maintained during in the whole chain of DESY pre-accelerators, which requires several major modifications in the beam optics. Despite the complexity of this undertaking, it appears to be technically feasible that a polarized proton beam could be operated at DESY in the mid-term future [56].

The physics programme at a polarized HERA collider would be a natural continuation of the present unpolarized programme. A measurement of the structure function $g_1^p$ will considerably reduce the uncertainty [20,21] on the

Ellis–Jaffe sum rule arising from the extrapolation towards $x \to 0$ and provide information on the yet unknown behaviour of the polarized parton distributions at small $x$. A polarized HERA collider would be a unique place to study the weak polarized structure functions [57] from the charged current cross section at large $Q^2$ and to explore the spin structure of photon from photoproduction of jets and heavy quarks [58]. Finally, a competitive measurement of the polarized gluon distribution could be obtained from the 2+1 jet rate in deep inelastic scattering [59].

# VI SUMMARY AND OUTLOOK

New measurements of the polarized structure function $g_1$, which have become available in the past year, have considerably improved on the precision of earlier data. However, these new measurements have as well raised new questions. The QCD analysis of the new data, which has become a standard procedure in all experimental studies by now, shows that the uncertainty on spin sum rules arising from the extrapolation of structure functions into the small $x$ region is far larger than previously assumed on the basis of Regge theory. These analyses illustrate moreover that the inclusive structure function alone is insufficient for a precise determination of the polarized gluon distribution from scaling violations and for a flavour decomposition of the polarized quark sea. These two aspects of the nucleon's spin structure will only become accessible in dedicated measurements at future spin experiments.

The first measurements of the second spin structure function $g_2$ are now becoming available. With improving precision of the experimental data expected in the near future, this structure function will become an important laboratory to access the twist-3 component of the nucleon's spin structure.

Much theoretical work has been devoted to various aspects of spin physics over the past year. Several advancements in higher order corrections to spin observables and progress towards a perturbative description of exclusive reactions at large momentum transfer are among the theoretical highlights reported during the workshop.

A variety of new experimental information on the spin structure of the nucleon can be expected in the next years. The HERMES and E155 experiments will yield improved measurements of the inclusive structure functions $g_1$ and $g_2$, and HERMES will provide the first precision measurements of semi-inclusive asymmetries. The recently approved COMPASS experiment will start data-taking three years from now and will presumably yield the first direct measurement of the polarized gluon distribution from open charm photoproduction. A year later, the polarized proton programme at RHIC is expected to start operation. Finally, the polarization of the HERA proton beam, which is presently under discussion, would open up a completely new kinematic domain in the study of the spin structure of the nucleon and provide

a multitude of new spin observables which are unique to HERA.

## ACKNOWLEDGEMENTS

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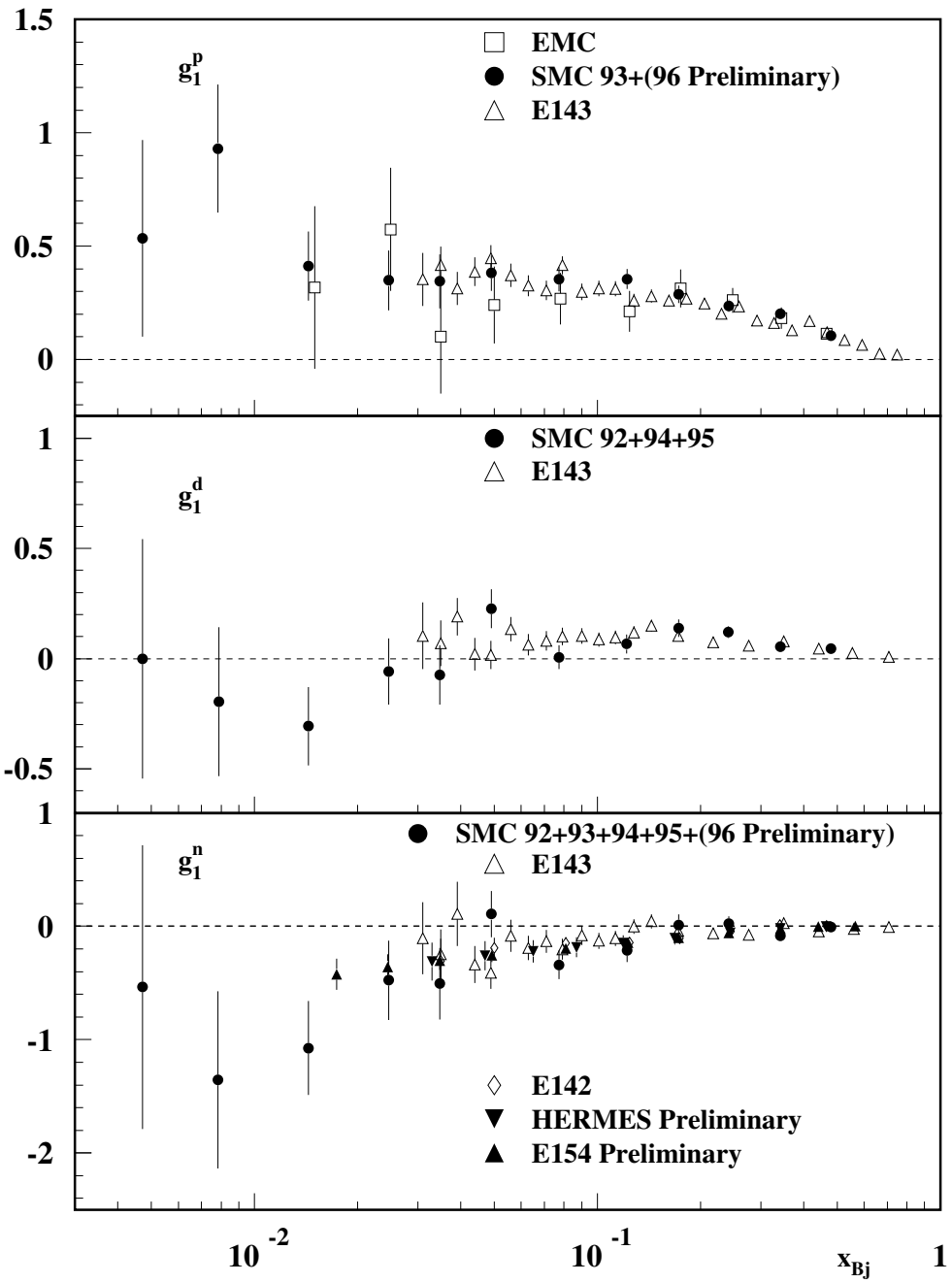


**FIGURE 1.** World data on the spin structure function $g_1(x, Q^2)$ evolved to $Q^2 = 5$ GeV$^2$.

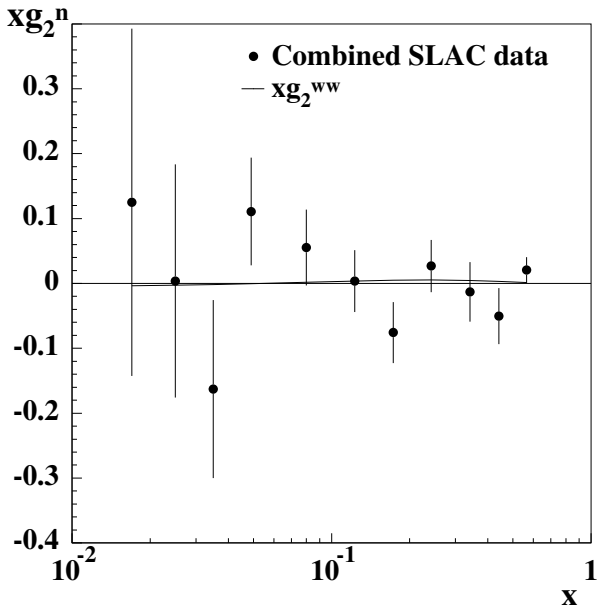


**FIGURE 2.** Combined SLAC data on the neutron spin structure function $g_2^n(x)$.

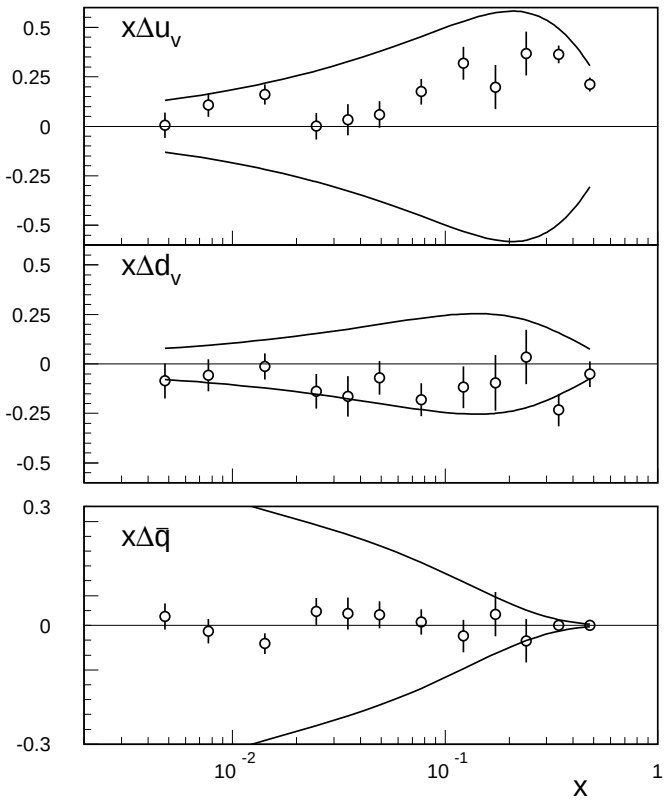


**FIGURE 3.** Polarized parton distributions obtained from the SMC analysis of semi-inclusive asymmetries (preliminary). The corresponding unpolarized distributions are indicated by the solid lines.

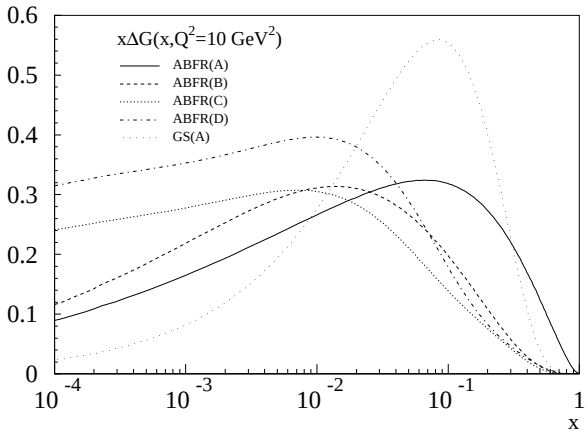


**FIGURE 4.** Different parameterizations of the polarized gluon distribution equally allowed by present data from the recent ABFR analysis [20] and the earlier GS analysis [18].

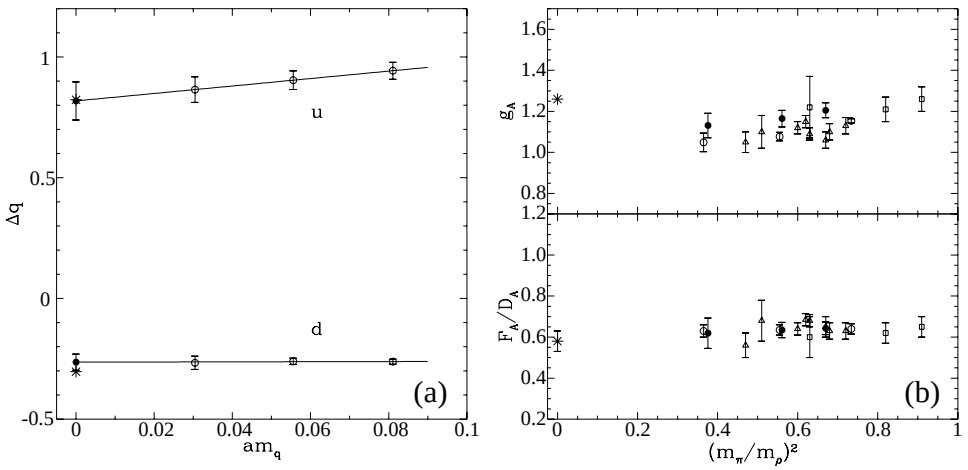


**FIGURE 5.** Lattice results on (a) the first moments of the polarized valence quark distributions compared to fit results (stars) and (b) the $SU(3)_f$ axial vector coupling constants.

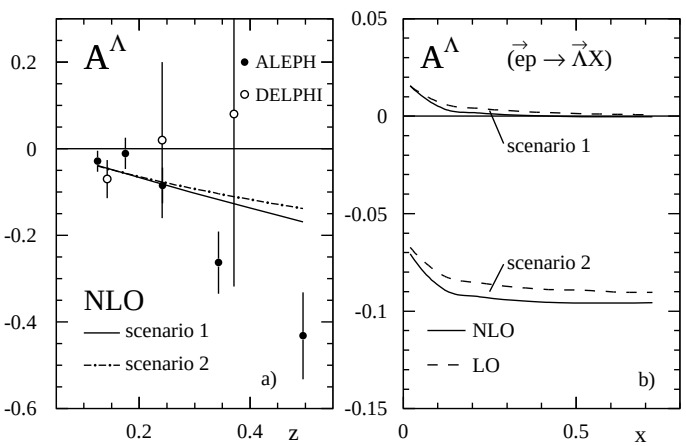


**FIGURE 6.** $\Lambda$ polarization in $Z$ boson decays (a) and semi-inclusive DIS with polarized leptons at HERMES (b) for different scenarios of the spin transfer in $\Lambda$ fragmentation.