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Albert De Roeck and Thomas Gehrmann

Deutsches Elektronen-Synchrotron DESY, D-22603 Hamburg, Germany

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Introduction to the Proceedings of the
"Workshop on Physics with Polarized Protons at HERA", DESY, March–September 1997.

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The operation of HERA with polarized proton and electron beams will allow to study a wide variety of observables in polarized electron–proton collisions at $\sqrt{s} = 300$ GeV. The physics prospects of this project have been elaborated in detail in a dedicated working group, whose results we summarize in this report. We show that several important and often unique measurements in spin physics could be made at HERA. These include measurements of the polarized structure function $g_1(x, Q^2)$ at low x, a direct determination of the polarized gluon distribution $\Delta G(x, Q^2)$ for the region $0.002 < x < 0.2$ from polarized di-jet rates and hadrons with high p_t, polarized quark distributions from weak structure functions and semi-inclusive asymmetries, parton distributions in the polarized photon and information on the helicity structure of possible new physics at large Q^2. HERA could therefore make a significant contribution to our understanding of spin effects in high energy collisions and to the spin structure of the nucleon.

1 Introduction

The commissioning of the HERA electron-proton collider (27.5 GeV electrons on 820 GeV protons) five 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 structure of the proton and the photon since then. Some of the physics highlights from the first years of running are the measurement of the proton structure function $F_2(x, Q^2)$ at previously inaccessibly small values of x (fraction of parton momentum inside the proton) and large values of Q^2 (negative square of invariant momentum transfer from electron to proton), the production of jets in deep inelastic scattering and in photoproduction providing a new probe of the parton content of proton and photon, first studies of the proton structure at low Q^2 where a transition between hard and soft physics is expected, the observation and subsequent investigation of diffraction in deep inelastic scattering, and many more. It is therefore only natural to assume that the operation of HERA with polarized proton and electron beams [1] could add vital new information to our picture of the spin structure of the nucleon.

The HERA electron beam is in fact naturally transversely polarized due to the Sokolov-Ternov effect, and spin rotators can flip transverse into longitudinal polarization as needed for physics studies. The longitudinally polarized electrons are already used in the HERMES [2] experiment, operating a fixed polarized nucleon gas target in the HERA electron beam ($\sqrt{s} = 7$ GeV) to study polarized structure functions and semi-inclusive final states. The natural extension of this programme is to have a polarized proton beam, thus allowing to make a variety of physics studies in polarized electron-proton collisions at a centre of mass system (CMS) energy of $\sqrt{s} = 300$ GeV.

Polarization of the proton beam at HERA is technically more involved than for the electron beam, since protons do not polarize naturally in a storage ring. Polarized protons have to be generated with a high current polarized source (recent progress on polarized sources is reviewed in [3]), then accelerated from low energies while maintaining their polarization during the whole chain of pre-accelerators. Studies towards this challenging aim are ongoing, and so far the results look very encouraging. The technical aspects of this project are elaborated in [4]. 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 200 to 500 pb^{-1} integrated over several years. Precision studies of polarized observables require moreover a good knowledge on the absolute polarization of proton and electron beams. Present day technologies, as used for example at HERMES, allow to determine the polarization of the electron beam within about 4–5%. Measuring the polarization of the high energy proton beam is on the other hand still a challenge. Various designs for proton polarimeters have been proposed and are reviewed in [5], and it seems realistic that the proton polarization can be determined within about 5% accuracy.

Apart from protons, it would be also of interest to have data on polarized neutrons. Deuterium is not a viable option for HERA, due to problems in rotating the transverse polarization into a longitudinal one in the interaction regions, but ^{3}He seems to be a good candidate. For this workshop we have assumed a similar luminosity for polarized ^{3}He as for polarized protons.

The physics prospects of a polarized HERA collider were investigated for the first time in a working group of the 1996 "Future Physics at HERA" workshop [1]. The most important observables identified in this working group were the polarized structure function $g_1(x, Q^2)$, polarized weak structure functions, di-jet production in polarized DIS and polarized photoproduction of jets. The working group established the measurability of all these observables, given an integrated luminosity of at least 200 pb^{-1}.

It was shown that a measurement of $g_1(x, Q^2)$ at HERA could decide between different predictions for the small-x behaviour of this structure function, thus reducing the uncertainty on its first moment, the Ellis-Jaffe sum rule, from this region. Combining the HERA measurement at intermediate x with present fixed target data at lower Q^2, it is moreover possible to put constraints on the polarized gluon distribution from the evolution of g_1. Another possibility to access $\Delta G(x, Q^2)$ is the study of the di-jet rate in polarized DIS. A study of spin asymmetries in charged current events would allow unique access to the polarized weak structure functions which probe different combinations of polarized quark distributions than their electromagnetic counterparts. Finally, polarized photoproduction of jets was found to be sensitive to the polarized gluon distribution of the proton in the forward (proton) direction while testing the parton polarization in the photon in the backward (electron) direction.

In addition to the physics programme at the polarized ep collider, it would be possible to study polarized proton-nucleon collisions in a fixed target experiment in the polarized HERA proton beam. This proposed experiment, presently called HERA–$\vec{\mathrm{N}}$, would require a polarized internal nucleon target and a dedicated new spectrometer. It could add numerous hadron-hadron observables [6] to the HERA spin physics programme. Very interesting results are expected here, which are fully complementary to the RHIC [7] spin physics program. The two main issues are the careful investigation of twist-3 effects in the transition region between non-perturbative and perturbative QCD via single spin asymmetries and the measurement of $\Delta G/G$ in photon and charmonium production via double spin asymmetries.

The outcome of the previous workshop is however only the first step towards a spin physics programme at the HERA collider, since only a few promising channels had been identified and briefly investigated. These channels have now to be further explored, including in particular

realistic estimates of detector effects on potential observables. Moreover, one should expect that the physics programme of a polarized HERA collider would include many other interesting channels, which are yet to be identified.

Compared to the last workshop, progress has been made in various directions. It has been demonstrated that the asymmetries of jet rates in DIS and photoproduction as well as of polarized weak structure functions are only mildly affected by detector effects. Moreover, the direct extraction of $\Delta G(x, Q^2)$ from simulated di-jet rates in polarized DIS has been demonstrated. This measurement of $\Delta G(x, Q^2)$ can be accompanied by information from charged tracks at high p_t. Even tighter constraints on the polarized gluon distribution are obtained if data on $g_1(x, Q^2)$ and on di-jets are combined in a global fit. It is moreover illustrated that HERA can probe $\Delta G(x, Q^2)$ at x values at least one order of magnitude below any other experiment, thus being less sensitive on extrapolations for a determination of the first moment.

The possibility of studying spin asymmetries on transversely polarized protons has been briefly investigated on the example of the structure function $g_2(x, Q^2)$. The resulting asymmetries turned out to be at least one order of magnitude too small to be measured. It is expected that the same negative result holds for other transverse observables.

Up to now, semi-inclusive asymmetries had only been considered as probe of the polarized quark distributions at fixed target experiments. It has now been demonstrated that their study at the HERA collider will be worthwhile and will yield additional information on the flavour decomposition of the nucleon spin.

An exhaustive study of observables in polarized photoproduction has shown that jet and inclusive hadron production will be the most promising channels in a study of $\Delta G(x, Q^2)$ and of the partonic content of the polarized photon, while several other channels have been demonstrated to be unmeasurable. The total cross section for polarized photoproduction is moreover of interest, since it is related to the Drell-Hearn-Gerasimov sum rule.

The spin transfer in fragmentation processes, in particular to self-analyzing Λ particles is one of the new reactions studied in the present workshop. It could be shown that new information on fragmentation functions of quarks to Λ baryons could be obtained in photoproduction at HERA, already with unpolarized protons. The study of target fragmentation at a polarized HERA would moreover be of vital importance, since fundamental insight into the origin of the breaking of the Ellis-Jaffe sum rule could be gained from leading hadron production in the target fragmentation region.

A variety of diffractive reactions are presently studied at the unpolarized HERA collider. The present workshop has addressed for the first time the question of a possible spin dependence of diffractive cross sections, studying diffractive vector meson production and diffractive deep inelastic scattering. While the former reaction was found to yield only unmeasurably small asymmetries, there is good hope that the latter could provide a very clean probe of perturbative approaches to diffractive reactions.

Finally, the anomalous excess of events at large Q^2 recently observed at HERA has triggered much interest in this kinematical region and motivated several interpretations invoking physics beyond the Standard Model as an explanation. Taking a new contact term at high Q^2 as an example, it has been demonstrated during the workshop which new information on the helicity structure of possible new interactions could be gained from studying spin asymmetries at large Q^2.

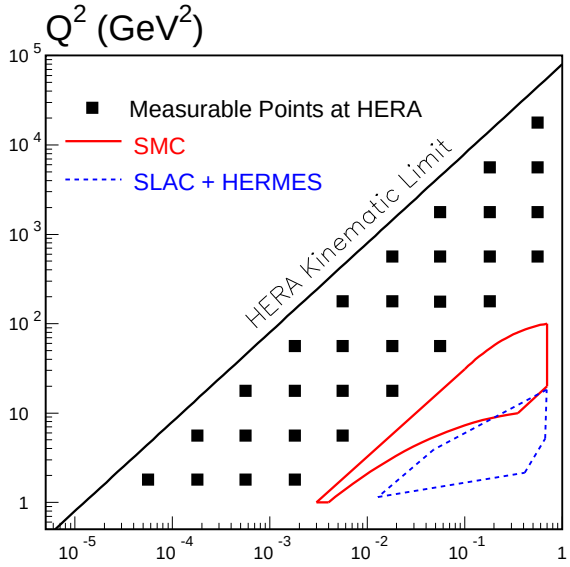

Figure 1: Measurable $x - Q^2$ region for a polarized HERA with the presently explored regions by CERN (SMC), SLAC and DESY (HERMES) experiments.

2 The polarized structure function $g_1(x, Q^2)$

The outstanding advantage of HERA is that it can measure structure functions at very small x and very large Q^2. The kinematical reach is shown in Fig. 1, with a possible binning for measurements of the polarized structure function $g_1(x, Q^2)$. In the quark parton model g_1 can be interpreted as the (charge square weighted) density of quarks with helicity parallel to the nucleon spin minus quarks with anti-parallel helicity. The region covered by present fixed target experiments is shown as well. HERA will extend the present region by two orders of magnitude both in x and Q^2, reaching values of Q^2 up to $2 \cdot 10^4$ GeV^2, and values of x down to $6 \cdot 10^{-5}$. This highlights immediately two very important contributions which HERA data can provide to the understanding of the proton spin: the knowledge on the low-x behaviour of g_1 and the large available $x - Q^2$ range, when including all polarized experiments so far, which will allow for detailed QCD tests similar to ones in the unpolarized case.

In particular the behaviour of structure functions at small x has received much theoretical interest in recent years. While one observes on the one hand that ordinary perturbative evolution in $\ln Q^2$ yields a satisfactory description of the unpolarized proton structure down to values as low as $Q^2 = 1$ GeV^2, one would on the other hand expect terms proportional $\ln(1/x)$ to become important, thus rendering a different expansion and resummation parameter.

The effects of small-x resummation on the polarized structure function $g_1(x, Q^2)$ have been derived in [8], where it was shown that the most singular terms in the polarized structure function behave like $\alpha_s^n \ln^{2n}(1/x)$, while only terms proportional $\alpha_s^n \ln^n(1/x)$ appear in the unpolarized case. First numerical studies, based on an insertion of the resummed splitting functions into the ordinary $\ln Q^2$ evolution equations were carried out in [9] but the results so far are inconclusive.

Using a unified evolution equation, which incorporates both the conventional leading $\ln Q^2$ terms and the leading $\ln^2(1/x)$ contributions, it was shown during the workshop [10] that resummation of the leading $\ln^2(1/x)$ terms should yield a sizable enhancement of the non-singlet content of the polarized structure function $g_1(x, Q^2)$ at small x. A prediction for the full struc-

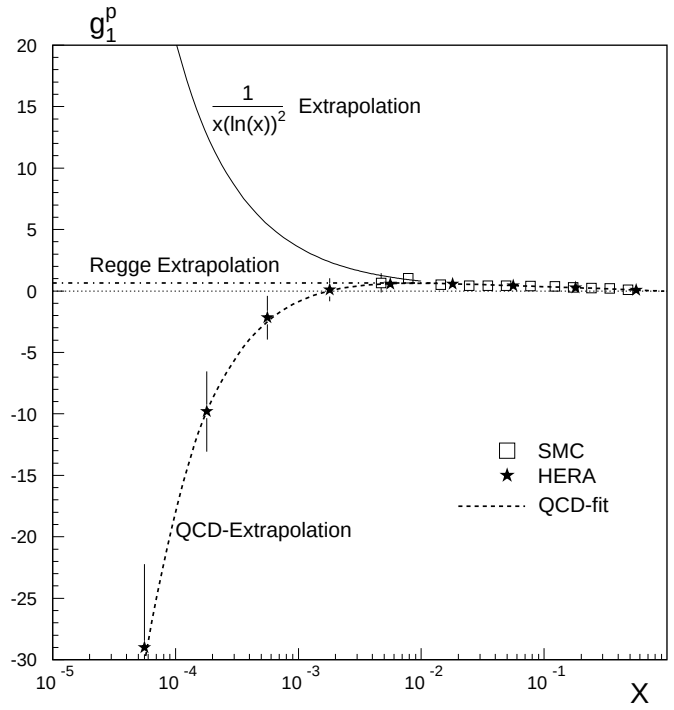

Figure 2: The statistical uncertainty on the structure function g_1 of the proton measurable at HERA, evolved to a value of $Q^2 = 10$ GeV^2 for an integrated luminosity of 500 pb^{-1}, is shown. The SMC measurements are shown for comparison (for curves see text).

ture function $g_1(x, Q^2)$, which contains both singlet and non-singlet components, is however not yet available in this unified approach. Given the behaviour of the $\ln^2(1/x)$ resummation at fixed Q^2 [8], one would however expect even stronger enhancement effects in the singlet sector.

Finally, the incorporation of infrared contributions from non-perturbative pion exchanges into the small-x resummations [11] allows to extend these spin-dependent small-x predictions to very low values of Q^2. This transition region between perturbative and non-perturbative physics has only recently become accessible at HERA. First measurements of the unpolarized proton structure at low x and low Q^2 show that the infrared behaviour of the proton structure is governed by strong interaction dynamics as described in Regge theory.

Fig. 2 shows the statistical precision of the measurement of g_1 as a function of x [12]. Only the points with the highest y values (lowest depolarization factor) are shown for each x value. The calculation is performed for an integrated luminosity of 500 pb^{-1}, $Q^2 > 1$ GeV^2, and the inelasticity range $0.01 < y < 0.9$. The angle and energy of the scattered electron were required to be smaller than 177^0 (defined with respect to the proton beam) and larger than 5 GeV respectively. The radiative corrections have been studied in [13] for the HERA kinematics, and are well under control. Note that the expected asymmetries at HERA for $x \sim 10^{-4}$ are relatively small, about 10^{-3}, which puts strong requirements on the control of the systematic effects. Details on systematics are given in [12]. The data points were centred on a curve which presents a low-x QCD extrapolation resulting from a next to leading order (NLO) QCD fit to the present fixed target data (see below). Other possible scenarios for the low-x behaviour of g_1

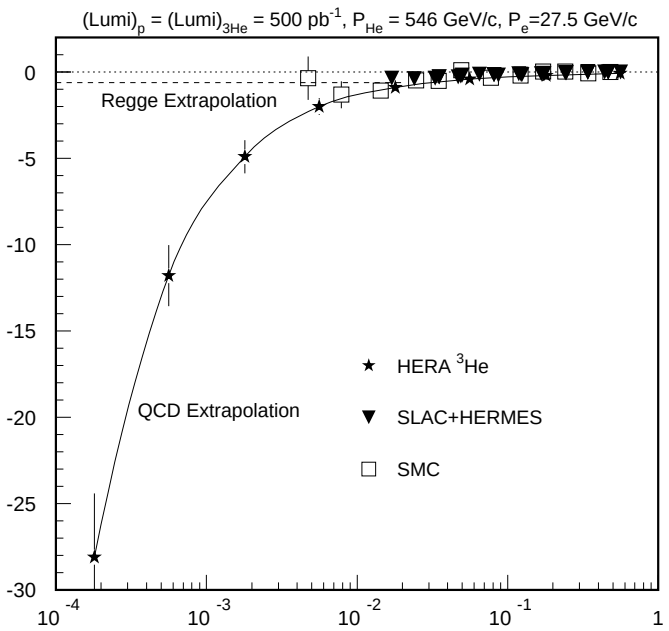

Figure 3: The statistical uncertainty on the structure function g_1 of the neutron, using an ^{3}He beam, measurable at HERA evolved to a value of $Q^2 = 10$ GeV^2 for an integrated luminosity of 500 pb^{-1}, is shown. Electron-neutron collisions are tagged via the remnant. The fixed target measurements are shown for comparison (for curves see text).

are indicated in the figure: the straight line is an extrapolation based on Regge phenomenology, and the upper curve presents a scenario suggested in [12] where g_1 rises as $1/(x \ln^2(x))$, which is the maximally singular behaviour still consistent with integrability requirements. All these scenarios are allowed by present day data from fixed target experiments. Hence it is fair to say that we do not know the low-x behaviour of g_1, and only HERA is able to solve this question, like it did in the unpolarized case for the structure function $F_2(x, Q^2)$.

The problem of the unknown low-x behaviour of the polarized structure functions is already very prominent in present polarized studies and questions, such as the measurement of the Bjorken sum rule [14]. This is a fundamental sum rule due to isospin symmetry. It relates the difference between the first moment of g_1 from proton and neutron to the weak coupling constants. Without QCD corrections it reads:

$$\Gamma_1^p - \Gamma_1^n = \int_0^1 g_1^p(x)\ \mathrm{d}x - \int_0^1 g_1^n(x)\ \mathrm{d}x = \frac{1}{6}\left|\frac{g_A}{g_V}\right| \qquad (1)$$

where g_A and g_V are the axial and vector weak coupling constants of neutron beta decay. QCD corrections up to $O(\alpha_s^3)$ have been computed for this sum rule [15]. This sum rule has been verified to about 10% precision in present fixed target experiments, the largest uncertainty being due to the unknown behaviour of the polarized structure functions at low x [16, 17, 18]. Hence

only a significant improvement of the Bjorken sum rule measurement can be expected when low-x HERA data on g_1 become available. The low-x extrapolation is at the same time the limiting factor for the determination of $\alpha_s(M_Z)$ from the Bjorken sum rule [18], which consequently could be improved considerably as well with data from polarized HERA.

While the proton data at low x by itself would be already very useful, allowing to discriminate between somewhat extreme low-x extrapolation scenarios as shown in Fig. 2, it would be very advantageous to have polarized low-x neutron data as well. Those data would additionally enable to measure the singlet and non-singlet polarized structure functions at low x. A study was made using polarized ^{3}He at HERA [12], from which g_1^n can be extracted. The energy per nucleon for ^{3}He is Z/A times the proton energy, i.e. 546 GeV, reducing the kinematic reach somewhat, but still allowing for measurements of g_1 down to $x = 10^{-4}$. The dilution factor for ^{3}He equals to 1/3. However, if the nucleus remnant can be tagged downstream of the detectors, such that events can be selected which correspond solely to electron-neutron scattering, this dilution factor can be bypassed. Fig. 3 shows the result for g_1 of the neutron, measurable at HERA, for tagged events and an integrated luminosity of 500 pb^{-1}. If it should turn out that remnant tagging with high efficiency is not possible, the anticipated errors would increase by a factor $\sqrt{3}$. Clearly this measurement is feasible and constitutes a strong encouragement for the machine group to continue to study this option.

The high quality data from the fixed target experiments allows for quantitative QCD studies of the polarized structure function data, from which polarized parton distributions are extracted. In perturbative QCD structure functions are decomposed into convolutions of perturbatively calculable coefficient functions and intrinsically non-perturbative parton distributions which then vary with Q^2 according to perturbative evolution equations. The present status of these studies is reported in [12]. Typically the singlet, non-singlet and gluon distributions are extracted. The latter is of particular interest. The violation of the Ellis-Jaffe sum rule in polarized deep inelastic scattering can be attributed to a large polarized gluon distribution and/or a negative polarized strange quark distribution, depending on the chosen factorization scheme. Hence any information on the polarized gluon is vital for our full understanding of the proton spin. Under evolution the singlet and gluon distributions mix, while the non-singlet evolves independently. It turns out however that the QCD fits constrain the gluon rather weakly, but some information on the first moment of ΔG can be obtained. The measurement from present day data gives $\int \Delta G(x)\ \mathrm{d}x = 0.9 \pm 0.3(\mathrm{exp}) \pm 1.0(\mathrm{theory})$ at $Q^2 = 1$ GeV^2. The theoretical error on this quantity is essentially dominated by the interpolation into the yet unmeasured low-x region [18]. Including future HERA data will improve the experimental error to about 0.2. The improvement in the theoretical error has not yet been quantified, but it is expected that it will decrease by more than a factor 2 once $g_1(x, Q^2)$ is measured at low x.

In short the measurement of the polarized structure function g_1 at HERA at low x and large Q^2 is unique and vital for future quantitative QCD studies of the spin structure of the proton.

3 The polarized gluon distribution $\Delta G(x, Q^2)$

From the NLO QCD fits discussed in the previous section, and from polarized parton density analyses in general, a large polarized gluon distribution is suggested. The error on the polarized gluon from these fits is however large: although the first moment of the it can be determined with some accuracy, there is still much freedom on its precise shape in x. Moreover, it is crucial that these predictions are confirmed by direct experimental test before the present standard

interpretation of the data can be regarded as established. Thus, important progress towards our understanding of the gluon contribution to the spin structure of the proton can be made only by direct measurements of ΔG. Polarized HERA is particularly suited for this task. It has been demonstrated by the present unpolarized studies at HERA that the large CMS energy allows for several processes to be studied which show a clear sensitivity the gluon distribution in the proton. These processes include jet and high p_t hadron production and charm production both in DIS and photoproduction. In this section we report on the studies on the extraction of ΔG in deep inelastic scattering, while complementary studies on photoproduction data will be commented upon in Sec. 5.

The most promising process for a direct extraction of ΔG at HERA remains di-jet production. The underlying idea is to isolate boson-gluon fusion events, i.e. a process where the gluon distribution enters at the Born level. The exploratory leading order (LO) Monte Carlo study, reported in [19] which showed the asymmetries at parton and detector level, was further pursued [20]. The Monte Carlo generator `PEPSI 6.5` [21] was extended with parton showers to approximate higher order effects. A more realistic detector simulation program [22] was used to check the detector smearing effects on the asymmetries. Exact polarized NLO calculations were performed and compared with the LO ones [23]: the NLO QCD corrections were found to be moderate. Finally a full unfolding of ΔG from the measured, background corrected (i.e. QCD Compton events), asymmetries was made, and the systematical errors were evaluated. The event sample used was selected with $5 < Q^2 < 100$ GeV^2 and $0.3 < y < 0.85$. Jets are defined using the cone scheme, are required to have 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 results are shown in Fig. 4. The measurable range in x (of the gluon) is $0.002 < x < 0.2$. Statistical errors are shown for six data points for three different assumptions on ΔG, and the error band for the systematics is given. The assumed luminosity is 500 pb^{-1}. The average Q^2 of this event sample is very close to 20 GeV^2 therefore results for ΔG are presented at this value. The gluon distributions are the Gehrmann-Stirling (GS) sets A and C [24], which result from a QCD analysis of g_1 data, and a gluon distribution obtained from instanton calculations [25]. The distributions shown in Fig. 4, purposely selected, indicate how poorly $\Delta G(x)$ is constrained by the present polarized data. All of these distributions are compatible with the available data, stressing the need for direct measurements of $\Delta G(x)$. The $\Delta G(x)$ distribution extracted from the di-jet event is clearly able to judge between these scenarios.

We stress here that this measurement allows the determination of the *shape* of $\Delta G(x)$. Furthermore it reaches x values lower than any other measurement planned in future so far, and (for a GS-A type of gluon) will measure about 75% of the first moment $\int \Delta G(x)\, \mathrm{d}x$.

Note that the gluon distribution will be also measured at RHIC [7] in polarized pp collisions, in the range $0.03 < x < 0.4$, with a comparable overall quality, but from an entirely different process (prompt photon + jet) with consequently different systematic and theoretical errors. For RHIC the errors quoted [26] on $\delta(\Delta G(x)/G(x))$ range from 0.01 to 0.3, while for the di-jet measurement at HERA they range from 0.007 to 0.1. In the range of overlap HERA and RHIC are very complementary. The fixed target experiment COMPASS [27] at CERN is dedicated to the measurement of ΔG. From the proposed charm measurement the expected precision [26] amounts to $\delta(\Delta G(x)/G(x)) = 0.10$ for a (single) measurement covering the range $0.06 < x < 0.35$. At HERA, when taking the six data points together, we can achieve $\delta(\Delta G(x)/G(x)) = 0.02$ [20] covering the range $0.0015 < x < 0.32$.

A different method to isolate photon-gluon fusion events at HERA was investigated. Instead

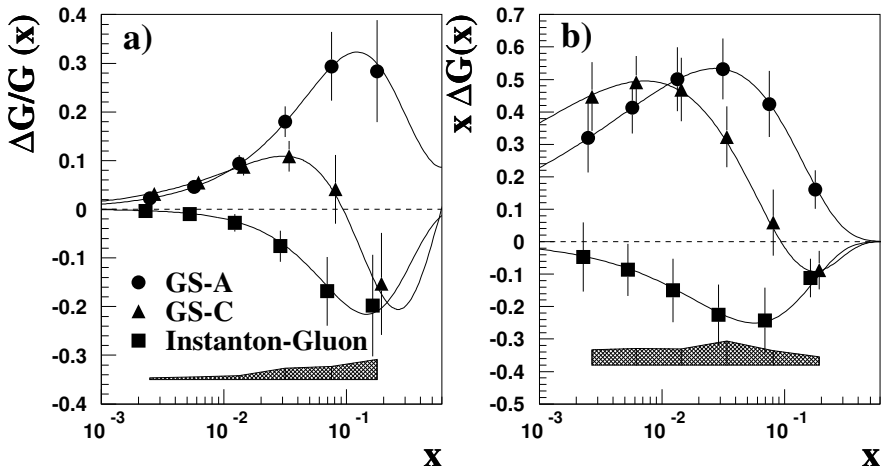

Figure 4: Di-jets: Sensitivity to $\Delta G/G$ (a) and $x\Delta G$ (b) for three different polarized gluon distributions shown as solid lines and a luminosity of 500 pb^{-1}, for $Q^2 = 20$ GeV^2.

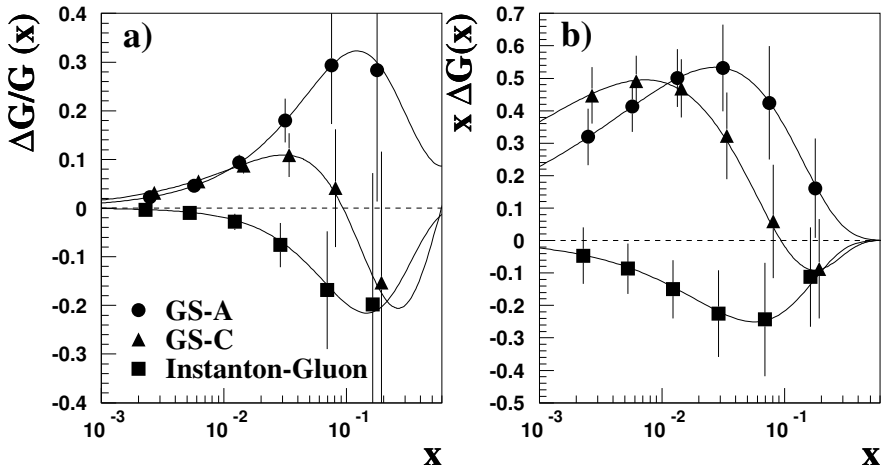

Figure 5: High p_t hadrons: Sensitivity to $\Delta G/G$ (a) and $x\Delta G$ (b) for three different polarized gluon distributions shown as solid lines and a luminosity of 500 pb^{-1}, for $Q^2 = 20$ GeV^2.

of tagging these events with two jets, two hadrons with high transverse momentum p_t opposite in azimuthal angle in the $\gamma^* p$ frame were required. This method has recently been proposed for μp polarized fixed target experiments [28]. The PEPSI Monte Carlo program was used, and DIS

Analysis Type	$\delta(\int \Delta G \, dx)$
1. QCD analysis of present g_1 data	0.3
2. QCD analysis of present & projected HERA g_1 data	0.2
3. di-jets at HERA	0.2
4. combined 2 & 3	0.1

Table 1: The expected statistical uncertainty in the determination of the first moment of the gluon distribution at $Q^2 = 1$ GeV^2 using different information in a NLO QCD analysis. For the projected data an integrated luminosity of 500 pb^{-1} is assumed.

events were selected in the same kinematic range as for the di-jets. Two charged tracks with a p_t larger than 1.5 GeV are required. The resulting asymmetries at hadron level are very similar to the ones for the di-jet case [29]. The result of the unfolded gluon distribution is shown in Fig. 5. A similar level of discrimination power as for the di-jet events is obtained, except in the highest x region, where the latter is superior.

We turn now back to the QCD fits on g_1 data for a moment. The poorly determined gluon resulting from these fits suggests that one could gain substantially by combining the g_1 scaling violation information with the direct measurement from the di-jets. An exploratory study was made, using the values of $\Delta G(x)$ obtained from the di-jet analysis as an extra constraint in the fit. The improvement of the errors on the first moment of ΔG due to the inclusion of di-jet data is shown in Table 1. The first two rows give the values quoted before, namely for the NLO QCD analysis without and with projected 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 available information.

In all, polarized HERA can make a very important contribution to the measurement of ΔG and hence to the understanding of the spin structure of the nucleon, in a unique kinematic range. This constitutes therefore one of the major trump cards for the physics case of polarized HERA.

4 Polarized quark distributions

The inclusive g_1 measurements from neutral current interactions ($\gamma^\star$ exchange), discussed in Sec. 2, are sensitive to the sum of all quark flavours weighted by their charge squared. Neutron data in addition to proton data allow the extraction of singlet and non-singlet distributions. To separate different quark flavours and valence quark distributions, additional information is required.

Such information can be obtained from semi-inclusive measurements, i.e. measurements where a final state hadron is tagged. The aim is to select those particles which contain the quark which has been struck by the incoming boson. In practice one measures a convolution of the fragmentation function with the parton densities, hence the study of both topics is interconnected.

In [30] several issues on semi-inclusive measurements have been studied. A `PEPSI` Monte Carlo study was performed to check the purity of the so-called favoured fragmentation functions (i.e. when the fragmenting quark is flavour compatible with the hadron, like $u \to \pi^+$) as function of the classical fragmentation variable $z = P \cdot P_h/(P \cdot q)$. Here P, P_h and q are the four-vectors of the incoming proton, produced hadron and exchanged boson, respectively. The purity is the probability that the hadron contains the struck quark or at least a quark with the same flavour as the struck quark. It is shown that the purity at HERA can reach 90% at large z, hence the

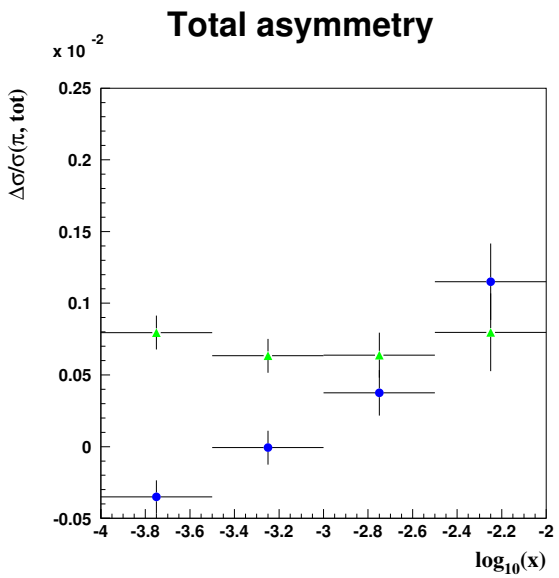

Figure 6: Total pion asymmetry $\frac{1}{P_e P_p}\frac{\Delta\sigma(\pi^+)+\Delta\sigma(\pi^-)}{\sigma(\pi^+)+\sigma(\pi^-)}$ for 500 pb^{-1} per relative polarization and $P_e = P_p = 0.7$, using PEPSI. The triangles correspond to GS set A, the circles to GRSV-LO (STD) [31] polarized parton densities.

hadronic final state of HERA is a suitable environment for semi-inclusive studies.

Semi-inclusive asymmetries were studied for HERA at low x ($x < 0.01$), by defining asymmetries which use combinations of π^+ and π^- production. By using either the sum or the difference of the π^+ and π^- production asymmetries, it was shown [21] that the valence and sea quark contributions can be disentangled at small x. A typical expected measurement of the semi-inclusive asymmetry is shown in Fig. 6, for a total integrated luminosity of 1000 pb^{-1}.

While semi-inclusive pion measurements allow to separate the valence and the sea contributions, one can distinguish positively and negatively charged flavours via $W^{\pm}$ exchange, i.e. via charged current interactions. A study [30] shows that for an integrated luminosity of 200 pb^{-1} measurable asymmetries are obtained for W^- exchange, and that pion and kaon based asymmetries allow to measure the relative importance of the spin contribution of $\bar{d}$ and $\bar{s}$ quarks, compared to that of the u quark.

Another source of information is the inclusive measurement of charged current events. The asymmetry defined by

$$A^{W\mp} = \frac{d\sigma^{W\mp}_{\uparrow\downarrow} - d\sigma^{W\mp}_{\uparrow\uparrow}}{d\sigma^{W\mp}_{\uparrow\downarrow} + d\sigma^{W\mp}_{\uparrow\uparrow}} = \frac{\pm 2bg_1^{W\mp} + ag_5^{W\mp}}{aF_1^{W\mp} \pm bF_3^{W\mp}} \approx \frac{g_5^{W\mp}}{F_1^{W\mp}} \qquad (2)$$

with $a = 2(y^2 - 2y + 2)$ and $b = y(2 - y)$, and $g_5^{W^-} = \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}$, $g_5^{W^+} = \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c}$. A Monte Carlo study, including detector effects, was made for the measurements of the asymmetry and the extraction of g_5 [32]. The total missing transverse momentum (which is a signal for the escaping neutrino) was required to be $P_{Tmiss} > 15$ GeV, and the region $Q^2 > 225$

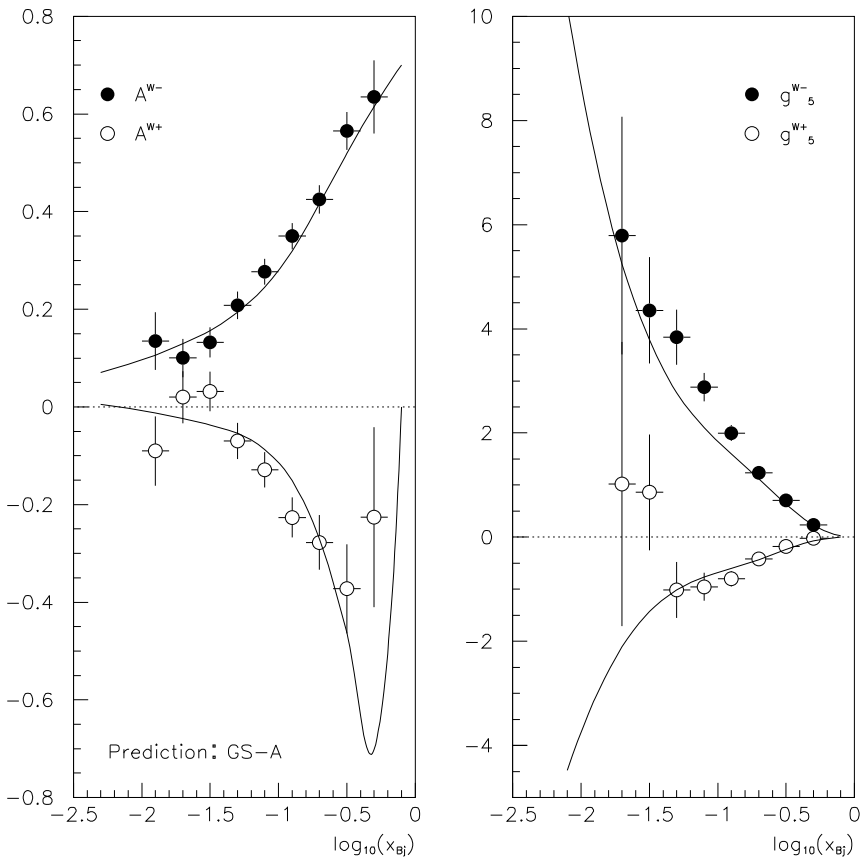

Figure 7: Spin asymmetries A^{W^-} (full circles, left side) and A^{W^+} (open circles, left side) for charged current events are presented for a total luminosity of 500 pb^{-1}. Also shown are the structure functions $g_5^{W^\pm}$ (right side) extracted from the asymmetries. The parton densities GS–A from [24] were used. The error bars represent the statistical uncertainty of the measurement.

GeV^2 has been selected for this analysis. This is a reasonable assumption based on the present day experience at HERA. The results for the asymmetries, including detector effects, are shown on the left side of Fig. 7. The error bars indicate the statistical precision of the measurement. The asymmetries are very large, as noticed before in [33], so that the data allow for a significant measurement. The solid line is the result of the exact analytical calculation of the asymmetry. It shows that the detector smeared asymmetries are in good agreement with the true ones. For the figure on the right side the approximation of $A^{W\mp} = g_5^{W\mp}/F_1^{W\mp}$ is tested. The measured asymmetry has been multiplied with $F_1^{W\mp}$ and compared with the analytical calculation for g_5. It shows that the approximation works well (to the 10-20% level) in our kinematic range. Hence these measurements can be used to extract e.g. the Δu and Δd distributions at high x.

In addition to the above probes of different polarized quark and anti-quark distributions, it might be possible to determine the total contribution (spin + angular momentum) of quarks to the proton spin from a study of Deeply Virtual Compton Scattering (DVCS: $\gamma^* p \to \gamma p$). It has been recently suggested in the literature [34] that the DVCS cross section in unpolarized ep collisions could be related to the total quark contribution to the proton spin. DVCS studies at low energies suffer from large QED background, which could be shown to be completely negligible

at HERA [35]. A measurement of this reaction appears therefore to be favourable already at the present unpolarized HERA collider.

5 Photoproduction

Cross sections in electron-proton collisions become largest, if the virtuality of the photon mediating the interaction is small. In this photoproduction limit, one can approximate the electron-proton cross section as a product of a photon flux factor and an interaction cross section of a real photon with the proton. Many unpolarized photoproduction reactions are presently measured at HERA, and their study has continuously improved our knowledge on proton and photon structure as well as our understanding of the transition between real and virtual photons over the last years.

A first investigation of polarized photoproduction has already been carried out during the last workshop [36]. This study showed that photoproduction of single inclusive jets is one of the most promising probes of both the polarized gluon distribution and the parton content of the polarized photon. Jet production in the photon direction ($\eta_{LAB} \lesssim 0$) originates mainly from photon-gluon fusion processes, and thus reflects the gluon polarization in the proton. The situation is more involved in the proton direction ($\eta_{LAB} \gtrsim 0$), where most events are induced by the yet unknown resolved partonic content of the polarized photon. Given the polarized parton distributions in the proton to be known from other sources, jet photoproduction in the proton direction can be used to determine the polarized parton distributions in the resolved photon. An improved study of single inclusive jet photoproduction [37] during the present workshop has shown that the sensitivity on the polarized photon structure is maximal for $\eta_{LAB} \gtrsim 2$, where still sizable jet rates guarantee small statistical errors on the expected asymmetries.

A process very similar to single inclusive jet production is the single inclusive production of charged hadrons, which has been investigated in the present workshop for the first time [37]. Although the production rate for individual hadrons is generally lower than the corresponding rate for jets, one expects a similar sensitivity on the polarized parton distributions in the photon and the proton from the measurement of this process, in particular since less stringent kinematical cuts for single hadrons can be chosen.

In the case of single inclusive jet and hadron production, it is not possible to make a clean separation between direct and resolved photon contributions, the selection of a certain rapidity region only enhances or suppresses one of them. A better discrimination is possible, if the inclusive production of di-jets is considered, since the di-jet rapidities allow (at lowest order) for a reconstruction of the incoming parton momenta, in particular to define the 'observed' parton momentum inside the photon x_γ^{OBS}. The resulting data can then be binned in x_γ^{OBS}, and one usually attributes all events with $x_\gamma^{OBS} > 0.75$ to 'direct' processes. The so-defined 'direct' sample has still a contribution from the resolved photon content, which is however small.

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 largely be preserved at the hadron level [37]. An example for the correspondence of parton and hadron level asymmetries is shown in Fig. 8, obtained with a moderate integrated luminosity of only 50 pb^{-1}. A direct determination of the polarized parton distributions in the photon from simulated data has up to now not been attempted. A first idea on the discriminative power of future measurements can however be gained by comparing the predictions obtained with the

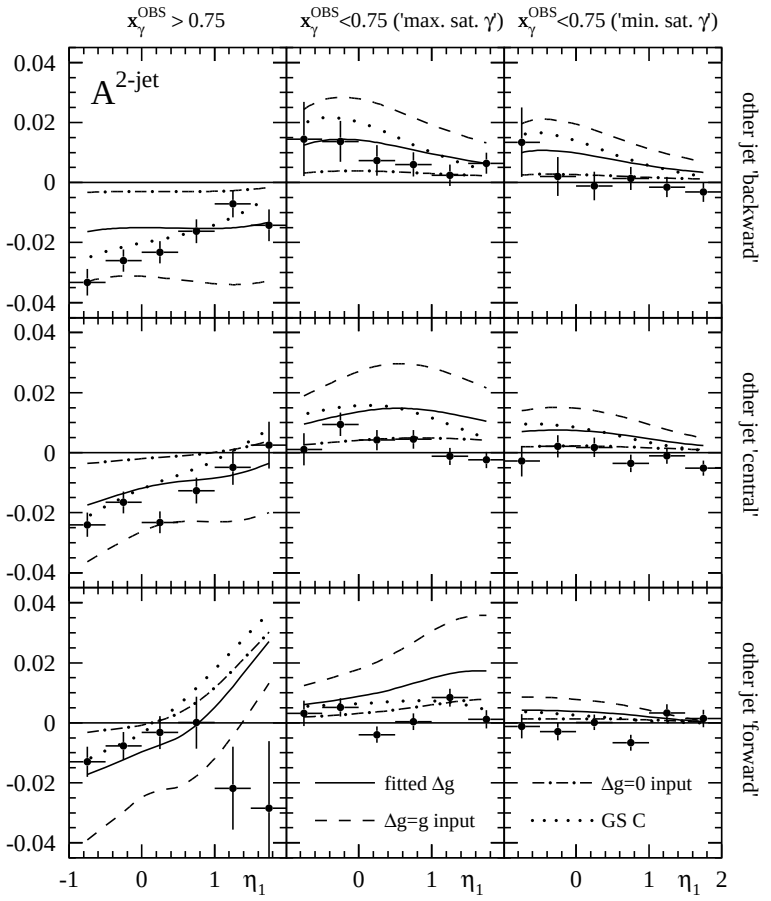

Figure 8: Polarized photoproduction of di-jets ($E_{T,1} > 8$ GeV, $E_{T,2} > 6$ GeV): asymmetries for direct (first column) and resolved (second and third column) photon contributions as function of the rapidity of the first jet and for different orientations of the second jet. Second and third column correspond to different scenarios for the parton content of the polarized photon suggested in [38]. The error bars shown correspond to a Monte Carlo sample of 50 pb^{-1} for the GS(C) parton distributions and include parton showering, hadronization, jet finding and jet clustering effects.

two (minimal and maximal) polarization scenarios proposed in [38], as done in Fig. 8. Given the above results for the di-jet case, it should be expected that the asymmetries in inclusive single jet production will survive at hadron level as well.

In summary, polarized photoproduction of jets and hadrons at HERA has been proven to be a sensitive probe of polarized gluon distribution and parton content of the polarized photon. Good results can already be achieved with a rather low integrated luminosity of 50 pb^{-1}. While the determination of the proton's polarized gluon distribution could be achieved from other processes at HERA or elsewhere as well, it must be emphasised that these processes are unique in probing the partonic content of the polarized photon.

In addition to the above processes, several other photoproduction channels, which are currently measured in unpolarized collisions at HERA, have been studied for the expected magnitude

of polarization asymmetries. The most promising among these channels is the production of open charm, however the asymmetries will become experimentally accessible only if the charm tagging efficiency can be improved considerably [37]. For the Drell-Yan process, large-p_T photons [37] and inelastic J/ψ production [39], the situation is even worse since the production cross sections are relatively low, thus implying statistical errors larger than the anticipated asymmetries.

Finally, it should be pointed out that a measurement of the total polarized photoproduction cross section $\Delta\sigma_{\gamma p}(\nu)$ as function of the photon-proton CMS energy ν at HERA would contribute to a precise determination of the Drell-Hearn-Gerasimov sum rule [40]. This fundamental sum rule, relating the total polarized photoproduction cross section to the anomalous magnetic moment of the nucleon, is presently tested in precision measurements at fixed target energies, which however rely on Regge-type extrapolations of $\Delta\sigma_{\gamma p}(\nu)$ for $\nu \to \infty$. A measurement of the polarized photoproduction cross section at HERA would test these Regge-theory predictions and put rigid constraints on the high energy contribution to the Drell-Hearn-Gerasimov sum rule.

6 Spin effects in fragmentation

The polarized parton distributions that have been discussed in detail above 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 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 Λ baryon.

First studies [41, 42] on the polarized fragmentation functions into Λ's have been carried out recently. These studies consider three possible scenarios for the spin transfer to the Λ. A naive approach, based on the non-relativistic quark model would predict that the Λ spin is carried only by the s quark, while the u and d quarks do not contribute to its spin. Secondly, in analogy to the Ellis-Jaffe sum rule for nucleon spin structure functions, one can deduce $SU(3)_f$-based relations between the polarized Λ fragmentation functions for different quark flavours [43]. Assuming a breaking of this sum rule similar to the well known breaking of the Ellis-Jaffe sum rule, one obtains a positive contribution only from s quarks, while u and d quarks contribute with negative sign to polarized Λ fragmentation. Finally, it could be possible that, in complete contradiction to the above models, the polarized fragmentation functions of u, d, s quarks into Λ's are simply identical. These three scenarios have been elaborated in [41], where they have been imposed as low-scale boundary conditions for the perturbative evolution of the polarized fragmentation functions into Λ's.

It has been demonstrated [41] that a fit to LEP data only is insufficient to discriminate the above scenarios. Studying the production of polarized Λ's in collisions of polarized electrons on unpolarized protons would on the other hand enable a distinction of the scenarios already with a moderate integrated luminosity of 100 pb^{-1} and an assumed Λ reconstruction efficiency of 0.1 in the photoproduction channel (see Fig. 9), more luminosity would allow a similar distinction from semi-inclusive Λ production in DIS as well [41].

It should be kept in mind that these studies of polarized Λ fragmentation at HERA only require longitudinal polarization of the electron beam, while the protons can be unpolarized. This programme could therefore start already two years from now, once electron spin rotators

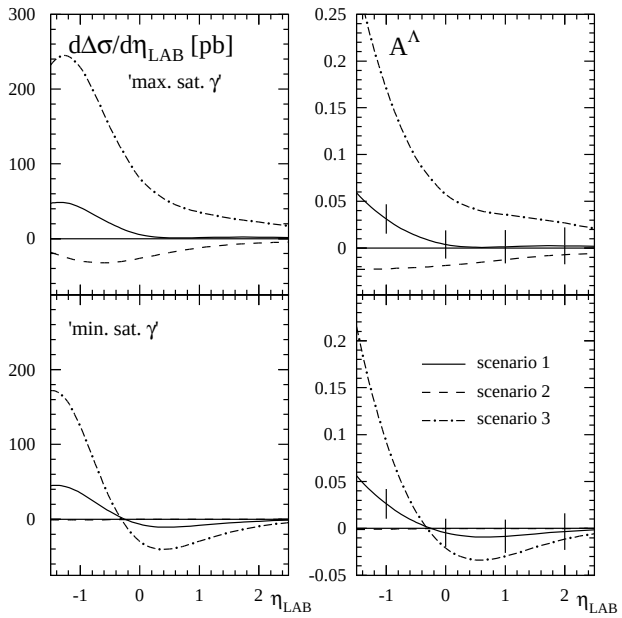

Figure 9: Photoproduction of polarized Λ's in collisions of polarized electrons on unpolarized protons: cross sections and asymmetries for $p_T > 2$ GeV. Upper and lower row correspond to different parametrizations for the parton content of the polarized photon [38], the three scenarios for polarized Λ fragmentation are explained in the text. Expected statistical errors are for an integrated luminosity of 100 pb^{-1} and a Λ reconstruction efficiency of 0.1.

are installed around the two HERA collider experiments. Polarization of the HERA proton beam would then give access to different combinations of asymmetries in polarized Λ production. This case has up to now only been investigated [41] for semi-inclusive deep inelastic scattering in view of a possible determination of the strange quark polarization in the proton, which was found to be not feasible.

Most studies of hadron fragmentation in deep inelastic scattering that have been carried out up to now were only concerned about the fragmentation of the current parton, that has been struck by the virtual photon. The fragmentation of the target remnant has on the other hand not received very much attention: it could hardly be accessed in the fixed target experiments and until recently no theoretical models for it existed. With the start of the HERA collider, where current fragmentation and target fragmentation take place in well separated regions of the detectors, the target fragmentation region has become accessible experimentally in principle. A possible theoretical description of phenomena in the target fragmentation region is given by the fracture functions introduced in [44], which parametrize the probability of tagging a particular hadron species in the target fragmentation region of a DIS event at fixed kinematics.

A case of particular interest in spin physics is the configuration where a meson carrying almost the whole incident proton momentum is detected in the target fragmentation region of polarized DIS. In this configuration, one would expect the fracture function to factorize into a factor for the transition of a proton into a meson and another baryon (e.g. $p \to \Delta^{++}\pi^-$) and the structure function of the baryon. The study of events with a highly energetic meson

in polarized deep inelastic scattering would thus allow to access the spin structure functions of unstable baryonic excitations [45]. Such measurements on various baryons would then enable the determination of the Ellis-Jaffe sum rule for a variety of baryon targets, thus testing whether the observed violation is indeed target independent and related to a fundamental property of the QCD vacuum, as suggested in [46]. This type of spin structure measurement from tagged mesons in the target fragmentation region would be unique at a polarized HERA collider. It requires however apart from polarized protons also polarized neutrons (^{3}He), and a much improved instrumentation of the present detectors in the proton remnant direction.

To summarize, a variety of spin effects in fragmentation could be studied at HERA. The starting point of a spin physics programme could be marked by measurements of the polarized Λ fragmentation functions, which requires only polarization of the electron beam. Once the proton beam is polarized also, several other observables become accessible. Apart from measurements in the current fragmentation region of polarized deep inelastic scattering, which have been discussed already in Section 4, the target fragmentation region should receive particular attention: a measurement of forward meson production could make substantial contributions to our understanding of the origin of Ellis-Jaffe sum rule violation.

7 Diffractive processes

A sizable fraction of electron-proton collisions at HERA shows one remarkable feature in the hadronic final state: the incoming proton is either left intact or dissociates into a low mass state, separated by a large rapidity gap from the rest of the hadronic final state. At HERA either the proton or a large rapidity gap can be observed. These events are predominantly produced by a phenomenon termed diffraction and occur for a variety of reactions. Examples are diffractive final states in deep inelastic scattering, diffractive production of jets or heavy flavours and diffractive vector meson production. The first observation of diffractive phenomena shortly after the start of the HERA physics programme has triggered much theoretical effort towards an understanding of diffraction in electron-proton interactions. Although much progress both in the theoretical description and the experimental study of diffractive reactions has been made in the meantime, it is still fair to say that this phenomenon is not unambiguously understood at present, since it contains both perturbative and non-perturbative components. However, various theoretical descriptions for diffractive reactions have been proposed, emphasising either the perturbative or non-perturbative components of the reaction cross section, a unified description is still due.

The spin dependence of diffractive reactions can in principle be studied both in perturbative and non-perturbative models. Studies in the present workshop have focused in particular on perturbative approaches, in which predictions for the polarized cross sections in diffractive deep inelastic scattering and diffractive vector meson production were made. The non-perturbative contribution to spin-dependent diffractive reactions has been investigated [47] in the framework of Regge theory. It could be demonstrated that diffraction at zero invariant momentum transfer off the proton receives only contributions from three particle cuts in Regge theory. The suppression factor between these cuts and the dominant unpolarized pomeron pole exchange is identical to the suppression between polarized and unpolarized inclusive structure functions at small x. One expects however that the coupling factor of the three particle cut appearing in the polarized cross section is small compared to the pole exchange appearing in the unpolarized cross section.

Most perturbative approaches to diffractive reactions are based on the two gluon exchange model, which assumes that the diffractive reaction is mediated by the exchange of two gluons

(in a color singlet state) between the proton and the virtual photon. The unpolarized diffractive cross section in this model is predicted to be proportional to the square of the unpolarized gluon structure function. An extension of the two gluon exchange model to spin-dependent diffraction has recently been discussed in [47, 48]. In this approach, which takes up to now only the leading $\ln Q^2$ terms into account [48], one finds that the diffractive cross section is proportional to the product of unpolarized and polarized gluon structure functions with a small admixture from the polarized quark structure function. For the fraction of diffractive events observed at small x, one should expect that a resummation of leading $\ln(1/x)$ is necessary to obtain reliable predictions [47]. This resummation of terms proportional to $\alpha_s^n \ln^{2n}(1/x)$ for the polarized quark and gluon structure functions has been performed in [8]. The resummation effects are even more pronounced than in the unpolarized gluon structure function, which contains only singular terms like $\alpha_s^n \ln^n(1/x)$. For the case of polarized diffraction, one expects therefore that the ratio of perturbative to non-perturbative contributions is more favourable than in the unpolarized case for two reasons: the suppression of the relevant non-perturbative three particle cuts and the enhancement of the perturbative cross section due to large logarithmic terms.

A different perturbative approach to diffraction in spin-dependent deep inelastic scattering has been studied in [49]. In this approach, it is assumed that the diffractive process is mediated by the emission of a non-perturbative pomeron off the proton, the pomeron subsequently splits into a $q\bar{q}$ pair, which interacts with the virtual photon. The spin dependence of this reaction is induced by a spin-flip component of the pomeron emission vertex and the spin dependence of the pomeron-$q\bar{q}$ coupling. Using model estimates for these spin-dependent couplings, it was found that spin asymmetries in diffractive deep inelastic scattering could amount up to several percent.

The spin dependence of diffractive vector meson production can as well be predicted in the perturbative two gluon exchange model. Such studies have been carried out so far [39] for diffractive photoproduction of J/ψ mesons and for diffractive leptoproduction of ρ mesons at HERA. The observable electon-proton spin asymmetries were in both cases found to be only of the order of a few per mille, which is below the anticipated statistical errors of a measurement even with an integrated luminosity of 1000 pb^{-1}. A study of the spin dependence of the diffractive vector meson production cross sections thus appears not to be feasible.

In summary, the spin dependence of diffractive deep inelastic scattering and diffractive vector meson production have been studied during the workshop. It turned out that in particular polarized diffractive deep inelastic scattering could provide a crucial test for the perturbative description of diffraction. It is expected that this observable receives only small non-perturbative contributions and is thus largely predictable within perturbative QCD. Within the perturbative framework, one would moreover anticipate that the polarized diffractive cross section at small x displays even stronger logarithmic enhancement than its unpolarized counterpart. Its measurement would therefore be a crucial test of the perturbative interpretation of diffraction in deep inelastic scattering.

8 Effects at high Q^2

Recently the HERA collaborations [50] have reported a significant excess over Standard Model expectation of events produced in the region of Q^2 larger than 10000 GeV^2. A statistical fluctuation of the data is not yet excluded as an explanation, and the observed effect will need confirmation from larger statistics data samples collected in 1997 and thereafter. However, if

this excess is real, it could be a first sign of new physics, such as leptoquarks, squarks with R-parity violation or contact interactions. Alternatively the excess could be a result of our incomplete knowledge on the proton structure and/or its perturbative evolution. On all these topics a plethora of papers has been produced since the announcement of the excess.

In this workshop the impact of a polarized HERA on the study of this effect was considered. A general study was made based on the contact interaction formalism [51], which in principle can mimic any new physics manifestation in $eq \to eq$ scattering. It was demonstrated that a fully polarized HERA would be very instrumental in disentangling the chiral structure of the new interactions. Assuming the availability of both positron and electron beams, and for each beam a data sample of 250 pb^{-1} with the spin aligned and anti-aligned to the proton spin, seven different asymmetries were formed, including two parity violating ones, four parity conserving ones, and a mixed asymmetry (for details see [51]). With these data samples the asymmetries are sensitive to contact interactions to scales larger than 7 TeV (95% C.L.), and give better limits than equivalent data samples with unpolarized beams or with polarized lepton beams only. 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).

Also in more specific scenarios which imply the production of new particles to explain the HERA excess, polarized HERA will play a pivotal role. E.g. for the leptoquark production scenario, the compatibility of the HERA result with results from pion decays and from $(g-2)_\mu$ experiments, induces large effects in the parity violating asymmetries. A special case was studied in [52] for stop squark production off strange and down quarks in the proton within an R-parity violating supersymmetric scenario. It was shown that one can take advantage of our knowledge of the polarized quark distributions in the proton, which in this case are different for down and strange quarks, to differentiate between different possible scenarios from the measured production rates at a polarized HERA.

At this time it is not established that the reported excess invokes new physics, and more conservative scenarios, particularly those concerned with the structure of the proton, have been explored as well. The present Standard Model cross section estimate is based on parton densities measured at low Q^2 and high x which are evolved to the high Q^2 region. Within the framework and limits of present day modern global fits, the expected uncertainty on the parton distributions is claimed to be of the order of 10%. However, it has been pointed out that the low Q^2 data do not exclude the presence of additional components in the high-x range, such as additional gluons, charmed quarks or meson-cloud effects. A particularly interesting possibility is the effect induced by QCD instantons [25]. Non-perturbative instanton fluctuations describe the quantum tunneling between different gauge rotated classical vacua in QCD (see e.g. [53]). Due to the quark helicity flip at the quark-instanton vertex, the contribution to the spin-dependent cross sections of instantons is very different from the one of the perturbative quark-gluon vertex. Furthermore, in the instanton liquid model [53] the contribution of instantons to the proton structure is expected to become increasingly more important with increasing Q^2 [25]. The instanton liquid model yields definite predictions [25] for both unpolarized and polarized structure functions at large Q^2, and the prediction in the unpolarized case is consistent with the presently observed excess. A measurement of the spin-dependent cross sections at large Q^2 with at a polarized HERA would immediately and unambiguously test this instanton interpretation.

In all, if HERA continues to produce more events at high Q^2 than expected, a polarized

HERA will be essential for our complete understanding on the origin of this effect.

9 Conclusions

The operation of HERA with polarized beams appears as a natural continuation of the successful physics programme of HERA, both in the unpolarized sector with H1 and ZEUS, as well as in the polarized sector with HERMES. It will allow to make unique measurements in polarized deep inelastic scattering as well as photoproduction at centre of mass energies of a few hundred GeV. HERA is the only machine in the world where this could be realized, and a rich programme of spin-dependent physics will emerge if data samples corresponding to a few hundred inverse picobarns can be collected. The high energy polarized proton beam also leads to the opportunity of a fixed target polarized pp experiment to study single and double spin asymmetries at a CMS energy of about 40 GeV [6].

Several potential measurements have been studied in great detail in this workshop, and many new channels have been tackled. The necessity for low-x measurements of the structure functions, and determination of the polarized gluon distribution ΔG have been wildly advocated by the spin physics community over the last 2 years. HERA can play a pivotal role in this field since it is able to give conclusive insight on both of these issues. No other accelerator is able to provide data for the measurement of the polarized structure functions in the region covered by HERA.

HERA will also contribute to the flavour decomposition of the quark spin distributions, spin transfer in quark fragmentation, spin effects in diffractive scattering, and the very intruiging possibility to measure polarized parton distributions in the photon. Finally, a polarized HERA will be very instrumental in the study and interpretation of possible deviations from the Standard Model expectation in the high-Q^2 region. The physics scope can be considerably extended if polarized ^{3}He beams would become available as well, and if the present detectors could be further instrumented in the proton remnant region.

The results obtained during both workshops in 1996 and 1997 clearly show that a polarized proton beam at HERA, in conjunction with the already successfully operating polarized electron beam, would undoubtedly pave the way to significantly improve our present understanding of the spin structure in hadrons, which is one of most interesting challenges of QCD these days. Polarized beams at HERA constitute a very strong physics case that should be considered for the future planning of research at DESY.

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