Future Physics with Polarized Protons at HERA

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The prospects of a physics program which can be addressed with polarized protons in HERA are summarized and compared to those of other existing or planned facilities. It is shown that polarised protons in HERA would provide unique access to several spin related observables of the nucleon and the photon in an unexplored kinematical range, if an appropriate level of polarization and luminosity can be achieved.

1. INTRODUCTION

The discovery of the breaking of the naive spin sumrule for g_1 [1] by the EMC experiment in 1985 [2] has led to a number of new polarization experiments [3–5] in deeply inelastic scattering which were directed towards confirmation, refinement and extensions of the original observations. Also theoretically the hadron spin and its relation to the helicity and angular momentum of the fundamental quark and gluon fields has received much attention [6]. The inclusive experiments have now reached their final phase and comprehensive NLO pQCD analyses of the world data on g_1 have become available [7]. Also the second inclusive polarized structure function g_2 has been measured [8,9] and found to be close to the prediction of NLO pQCD. While the fundamental Bjorken sumrule appears to be respected within the experimental accuracy the helicity of the proton is confirmed to not being carried by the quarks at the expected level ie. $a_0 < a_8$.

The analyses have shown that progress in the understanding of the spinstructure of the nucleon requires a further deepening of the experimental investigations. The next natural step would be a determination of the size of the individual contributions of the different flavours of quarks, antiquarks and in particular of the gluons to the spin of the nucleon. There are now several experiments running or being prepared which are addressed to these questions in semiinclusive DIS [5,10] or in double polarized $p-p$ collisions [11]. We have already seen first measurements of $\Delta u_v(x)$ and $\Delta d_v(x)$ [12,13] and we expect to get a first glimpse on the shape of the polarized gluon distribution and the polarized strange quark distributions in the next few years. The pQCD analyses are encouraging in the sense that they seem to require a sizeable amount of polarized gluons to explain the observed scalebreaking of g_1.

1.1. The kinematical range in x and Q^2

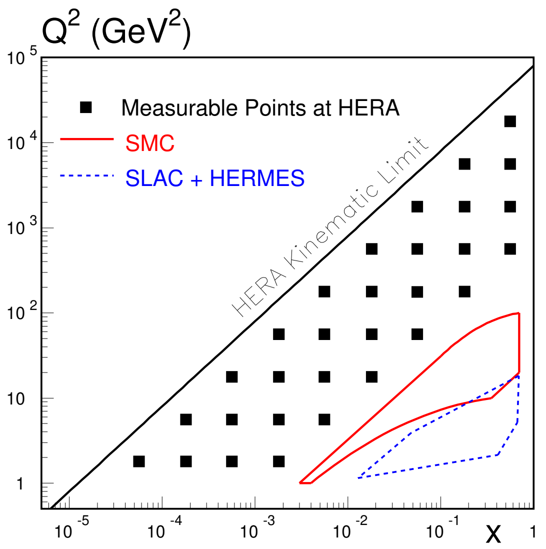

Figure 1. Extension of the kinematical range of polarized HERA compared to current experiments.

In Fig. 1 the kinematical range of the present polarized DIS experiments is plotted together with the extension which would be possible with polarized protons in HERA. At first sight the gain in "real estate" in the $x - Q^2$ plane appears quite large. The x-range can be extended by two orders of magnitude down to $x_{Bj} \approx 10^{-5}$. Also the lever arm in Q^2 for the currently covered x-range can be significantly enlarged. There is a caveat, however, since the virtual photon polarization drops almost linearly with y

$$D = \frac{2y - y^2}{2 - 2y + y^2}.$$

This means that at a given x the bins with the lowest Q^2 corresponding to low y will have very small asymmetries. Running at lower energies would be preferable in these cases.

1.2. Technical requirements

The technical requirements for having also polarized protons or ^{3}He in HERA in addition to the naturally polarized electrons or positrons are challengeing. There is need for a high current source of polarized protons with a very high polarization of better than 80%. It needs then considerable effort to preserve most of the initial polarization through the accelerator chain shown in Fig. 2. The three circular accelerators in the lower part need special devices to limit the effects of resonant depolarization. The situation is similar to the RHIC collider which is now in its commissioning phase with beam energies up to 250 GeV. The RHIC layout shown in Fig. 3 comprises spin rotators and so-called Siberian Snakes which help to manipulate and preserve the polarization state. The physics scope of a polarized HERA collider depends crucially on the luminosity and the product of the two polarizations $P_p \cdot P_e$ which can be obtained. There

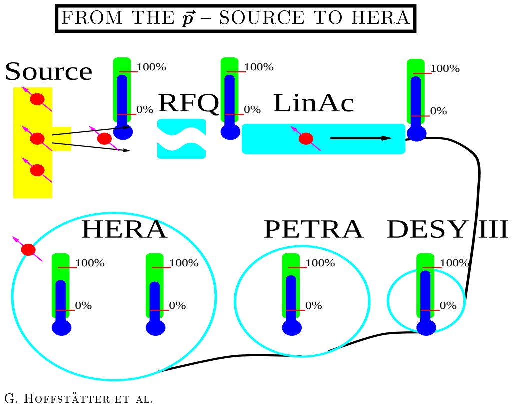

Figure 2. Schematic view of the projected HERA accelerator chain for polarized protons. The expected level of polarization at each stage is indicated.

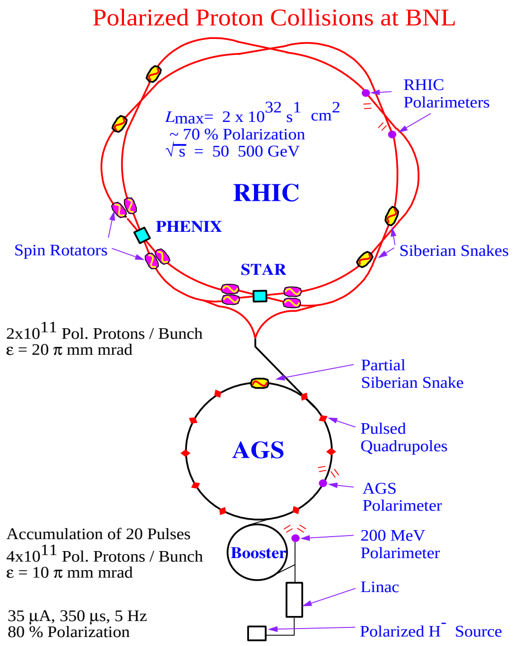

Figure 3. Layout of accelerator chain for the polarized RHIC collider.

has been a series of workshops, the most recent one took place a few weeks after this conference (see: www.desy.de/heraspin), which have dealt with both: the accelerator aspects and the physics opportunities. Reports from these workshops have been published [14] and summaries have been given on conferences [15]. Estimates of the statistical significance of the proposed measurements have been made on the assumption of $P_p \cdot P_e = 0.7 \cdot 0.7$ and an integrated luminosity of $\int L\ dt = 500\ \mathrm{pb}^{-1}$. It is presently not possible to guarantee that these values can be obtained simultaneously. In particular one has to wait for first results from the polarized RHIC beams to learn whether the basic predictions about the efficiency of the snakes are correct under real conditions.

2. INCLUSIVE MEASUREMENTS

In Fig. 4 the polarized structure function $\mathrm{g}_1(x)$ of the proton at a scale of Q^2=10 GeV^2 as measured by the SMC collaboration is shown together with the projected accuracy which can be obtained by HERA in the extended kinematical range down to $x = 5 \cdot 10^{-5}$. The shape of g_1 was assumed to follow the prediction of a NLO QCD fit to the world g_1 data [16]. While the unpolarized HERA experiments have discovered the steep rise of $\mathrm{F}_2(x)$ towards small x, the steep fall of $\mathrm{g}_1(x)$ and the change of its sign around $x \approx 10^{-3}$ is waiting for its confirmation. A measurement at small x would also reduce the uncertainties in the determination of the spin sum-rule which relied for a long time on the "Regge Extrapolation". Although there are now predictions for the asymptotic behaviour on the basis of the NLO pQCD fits available, there is an ongoing discussion on the relevance of an all-order resummation which leads to terms in powers of $\alpha_s\ \ln^2(1/x)$ in the polarized structure function [17–19]. Fig. 5 shows the low x-region of Fig. 4 with the NLO extrapolation together with a theoretical prediction including resummation. Even

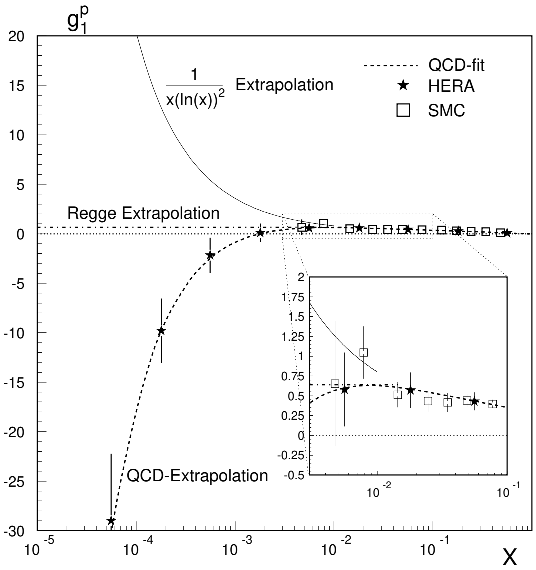

Figure 4. Predictions of the low-$x$behaviour of$\mathrm{g}_1^p(x)$ together with SMC data. The statistical accuracy which can be obtained at HERA is based on 500 pb^{-1}.

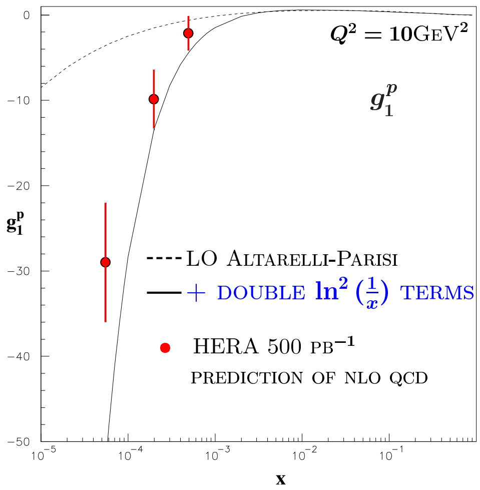

Figure 5. Next to leading order extrapolation of g_1 from Fig. 4 compared to a resummed calculation [xx].

more important is the measurement of the scaling behaviour of g_1 in this region. Fig. 6 shows the projected accuracy for a measurement with $\int L\,dt = 500\ \mathrm{pb}^{-1}$ and $P_e \cdot P_p = 0.7 \cdot 0.7$. The

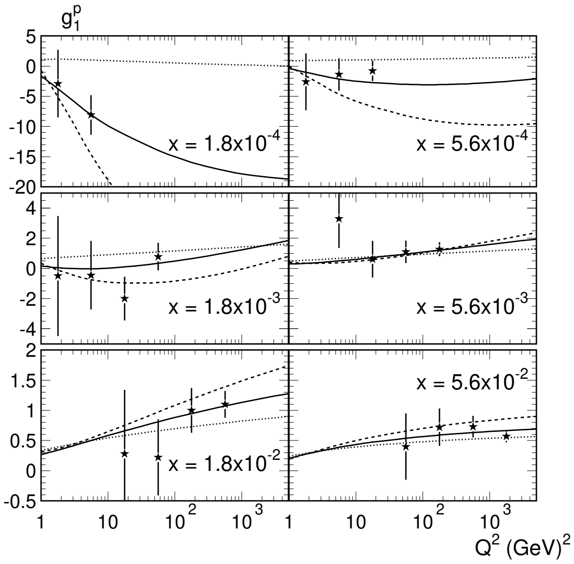

Figure 6. Simulation of HERA data of the Q^2 dependence of $g_1(x)$. The solid line corresponds to the fit of the world data. The dotted and dashed lines correspond to the assumption of a maximal and minimal polarized gluon distribution.

fact that the photon polarization increases with Q^2 at a given x and even overrules the decrease in countrate with Q^{-4} in the statistical errorbar is clearly visible. The simulation assuming a "Standard Glue" shows that at small x there is a sizeable sensitivity of the scalebraking to the integrated polarized gluon distribution ΔG. It has been estimated that the experimental error in ΔG can be reduced to $\delta(\Delta G) = \pm 0.2$. As shown in Fig. 7 there are presently sizeable theoretical errors in the extraction of ΔG due to uncertainties in the choice of the factorisation and renormalisation scale. HERA data would reduce these uncertainties by a factor of three [16]. Nevertheless

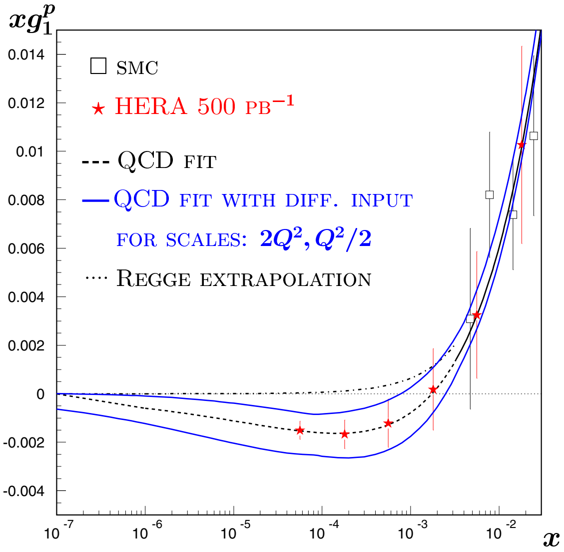

Figure 7. Sensitivity of the pQCD analysis to changes in the renormalisation and factorisation scales.

a direct access to the polarized gluon distribution and its shape is much needed.

3. MEASUREMENT OF THE POLARIZED GLUON DISTRIBUTION $\Delta G(x)$

At leading order the (polarized) virtual photon couples to gluons only through the photon-gluon fusion graph (PGF) shown in Fig. 8c. This process competes with the Compton process in Fig. 8b and the dominating LO DIS. The analysis of 2+1 jet events singles out the processes b) and c). Such an event, observed in the HERA H1 experiment, is shown in Fig. 9. The proton remnant has mostly escaped through the beam pipe. The momentum fraction of the gluon (or the quark in case b)) can be reconstructed from the jets. This is shown in Fig. 10 which shows the PGF process into jets in the photon gluon rest system and the lab system. The relevant variables are the sqared energy in the subsystem $\hat{s}$ and the cm-angle $\hat{\theta}$. Both can be reconstructed from the jets

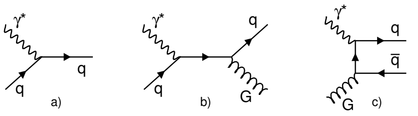

Figure 8. Diadrams for a) LO DIS, b) the gluon Compton process and c) the PGF process.

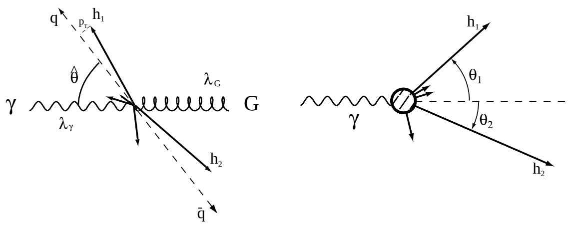

Figure 10. Leading hadrons in two+1 jet events.

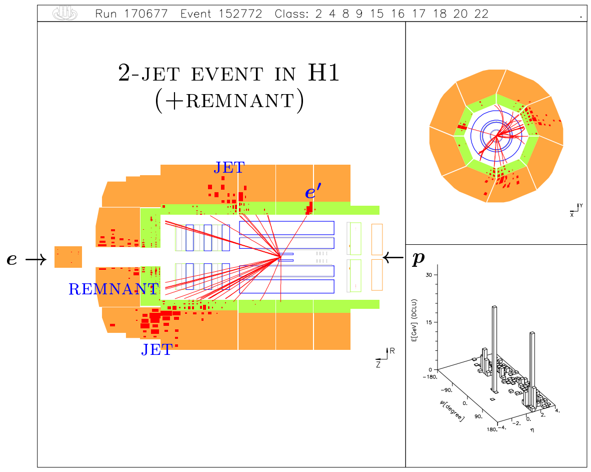

Figure 9. A 2+1 jet event observed in the H1 experiment at HERA.

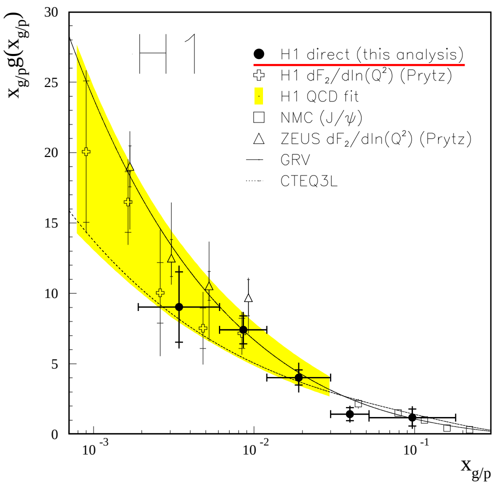

Figure 11. Comparison of $G(x)$ determined from 2+1 jet events with other data.

or the leading hadrons within the jets. The observation of charmed hadrons in the jets suppresses the Compton contribution of Fig. 8b. For a perturbative treatment of the PGF process there is no need for a high photon virtuality Q^2 if the scale $\hat{s}$ and $p_\perp$ is sufficiently high. We will, however, discuss the quasireal photon processes later. In Fig. 11 a determination of the unpolarized gluon density by a measurement of di-jets from the H1 collaboration [20] is shown. The results obtained in the region $10^{-3} < x_g < 10^{-1}$ agree well with other data obtained with other methods. In Figs. 12 and 13 the expected statistical accuracy for the measurement of $\Delta G(x)$ by the analysis of di-jets and leading hadrons in di-jets are displayed. In these simulations with the standard assumptions for the effective luminosity virtual photon events with $5 < Q^2 < 100$ GeV^2 and $0.3 < y < 0.85$ were accepted. A transverse jet momentum larger than 5 GeV was required for the events in in Fig. 12 and a pair of correlated leading hadrons with a transverse momenta larger than 1.5 GeV in Fig. 13. Both methods predict a reasonable sensitivity in the range $2 \cdot 10^{-3} < x_g < 2 \cdot 10^{-1}$ and would allow to discriminate between the various

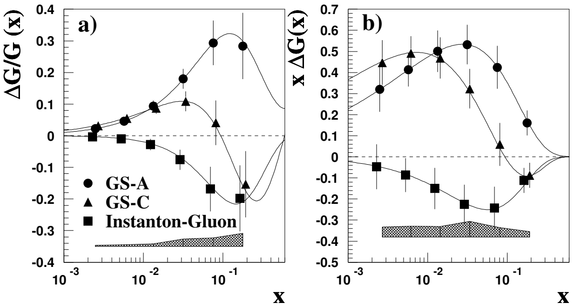

Figure 12. $\Delta G(x)$ from 2+1 jet events.

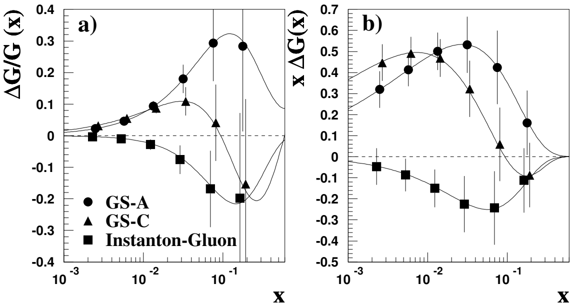

Figure 13. $\Delta G(x)$ from high $p_\perp$ hadrons.

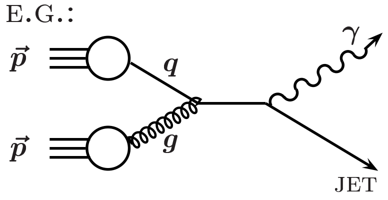

Figure 14. Hard photons from pp collisions.

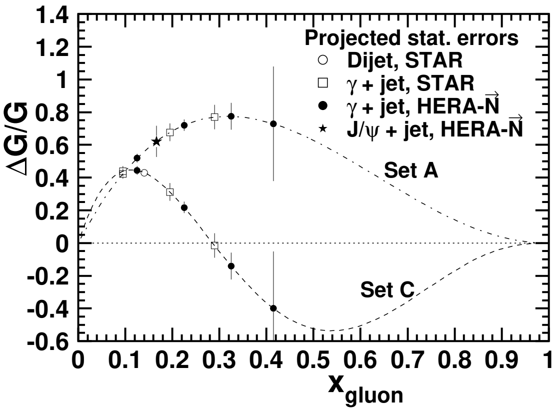

Figure 15. $\Delta G(x)/G(x)$ from pp collisions at RHIC and HERA-N.

predictions giving the same integrated value of ΔG. The NLO corrections have been investigated [21] and found to be of order 10%.

3.1. The HERA-N option

Once HERA would have a circulating polarized proton beam also fixed target experiments with polarized and unpolarized proton or deuteron gas targets would become possible. This corresponds to a center of mass energy of $\sqrt{s} = 40$ GeV which has to be compared with that of the upcoming RHIC spin experiments which is ranging from 200 to 500 GeV. Several hard scattering processes have been proposed for a measurement of the polarized gluon density in the proton. The hard photon production as shown in Fig. 14 is considered as one of the most promising. Another channel would be the J/Ψ+jet production. The statistical accuracy for the determination of $\Delta G/G$ obtained from a measurement at HERA-N with 240 pb^{-1} is shown together with the projections of the two RHIC experiments in Fig. 15. It appears that the kinematical coverage in the gluon momentum $0.1 < x_g < 0.5$ is quite similar while the perturbative scales are $2 < p_\perp < 8$ GeV for HERA-N and $10 < p_\perp < 30$ GeV for RHIC. In Fig. 16 a summary of all projected measurements of $\Delta G(x)$ is given. It demonstrates that HERA-N and polarized e-p at HERA would not only compete with the currently approved experiments at RHIC and CERN [10] but would be unique in covering the low x-range $2 \cdot 10^{-3} < x < 4 \cdot 10^{-2}$.

With a transversely polarized beam HERA-N could not only measure single spin asymmetries but also perform measurements with both

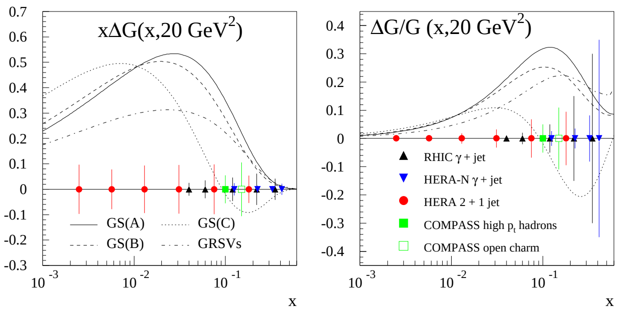

Figure 16. Comparison of the proposed measurements of $\Delta G(x)$.

protons transversely polarized. In this case the measurement of azimuthal asymmetries of Drell-Yan pairs gives access to the transverse spin distributions $\delta q(x)$ or $\Delta_{\perp} q(x)$. These are leading twist parton distributions which are presently not known experimentally.

3.2. Photoproduction processes in ep-collisions

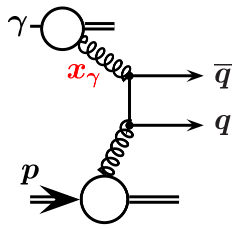

Figure 17. Two jets in resolved photoproduction.

As already mentioned the pQCD interpretation of 2+1 jet events do not require high photon virtualities but large quark masses or large tranverse momenta in the final state. There enters however the complication that the polarized photons hadronic component can be resolved. The corresponding high p$_\perp$ processes then bear some resemblance to polarized hadron-proton collisions studied in RHIC or HERA-N. If the two jets

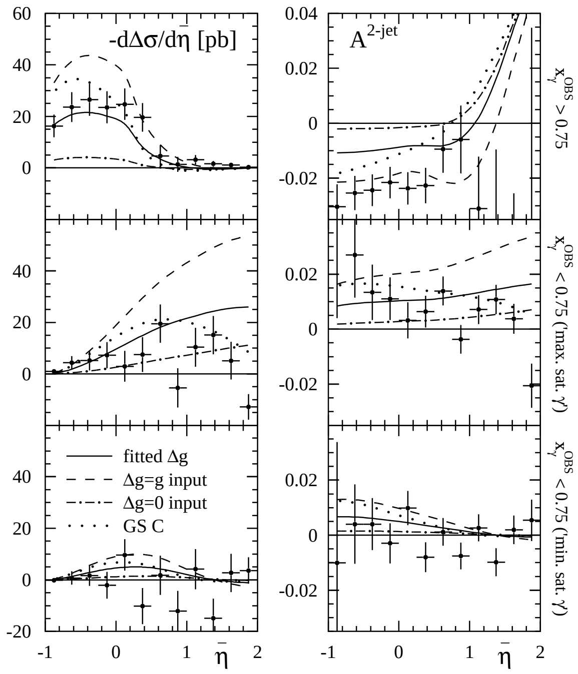

Figure 18. Two jets in photoproduction.

from the photon gluon fusion process are observed the kinematics of the $\hat{s}$ subsystem can be reconstructed. In particular the momentumfraction of the resolved parton of the photon is given by

$$x_\gamma^{OBS} = \frac{\sum_{JETS} p_\perp^{JET} e^{-\eta_{JET}}}{2yE_e}.$$

Large values of $x_\gamma^{OBS} > 0.75$ correspond to an unresolved or pointlike photon. In the top row of Fig. 18 a simulation [22] of the spin dependent cross section (left side) and the asymmetry (right side) of two jet events is shown as a function of the average jet rapidity $\overline{\eta}$. In contrast to the other simulations shown in this paper an integrated luminosity of only $L = 50$ pb^{-1} has been assumed. The jets observed at large negative rapidities, dominated by the photon momentum, are sensitive to the polarized gluon distribution $\Delta G(x)$ of the proton. This can be seen from the comparison of the simulated events in Fig. 18(top row), assuming a polarized glue obtained from fits to the data, with predictions for a maximal ($\Delta G(x) = G(x)$) and a minimal ($\Delta G = 0$) polarized gluon distribution. The determination of $\Delta G(x)$ with 2 jet events from quasireal photons only requires moderate luminosities. A really exciting new possibility can be read from the two lower rows of Fig. 18 which show the result of the simulation for the resolved photon events in which the parton - mostly a gluon - in the photon carries only a smaller fraction $x_\gamma^{OBS} < 0.75$ of the photons momentum. Nothing is known experimentally about the polarization of a gluon within the photon. Again one can make the extreme assumptions of a maximal $\Delta G_\gamma(x) = G_\gamma(x)$ and minimal $\Delta G_\gamma = 0$ polarized gluon distribution, corresponding to the middle and lower rows in Fig. 18. The predictions for the spin dependent cross section on the left hand side and the asymmetries on the right hand side differ considerably for the different assumptions on ΔG_γ in the region of large $\overline{\eta}$. If the polarized glue in the proton is sufficiently well known the polarized glue in the photon can be measured.

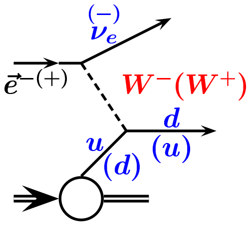

Figure 19. Charged current events in DIS.

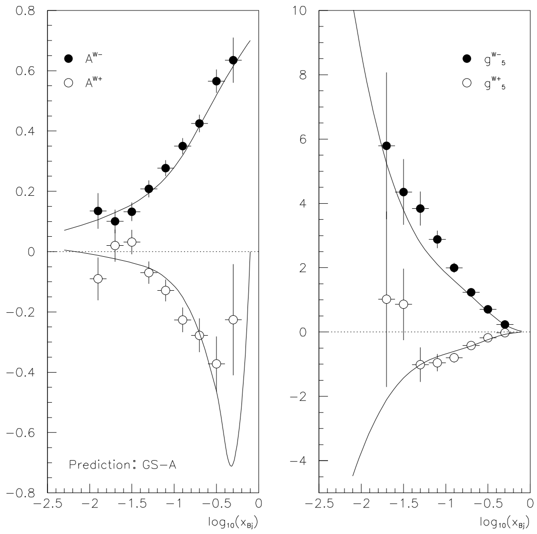

Figure 20. Polarized parton distributions from charged current events.

4. PARITY VIOLATING SPIN STRUCTURE FUNCTION

In charged lepton scattering at large Q^2 charged current events, with an unobserved neutrino in the final state shown diagrammatically in Fig. 19, become important and give rise to additional parity violating structure functions. In particular there is a polarized analogon to the well known unpolarized nonsinglet structure function $\mathrm{F}_3(x)$ called $\mathrm{g}_5^{W^\pm}$. This structure function can be measured in charged current events with polarized electrons or positrons on polarized protons at HERA [23]. The asymmetries of the process shown in Fig. 20 are essentially given by the ratio $\mathrm{g}_5/\mathrm{F}_3$. For W^- events i.e. electrons going to neutrinos $\mathrm{g}_5^{W^-}$ has the following structure

$$g_5^{W^-} = \Delta u + \Delta c - \Delta\bar{d} - \Delta\bar{s}$$

while for a positron beam we get

$$g_5^{W^+} = \Delta d + \Delta s - \Delta\bar{u} - \Delta\bar{c}.$$

The sum of both correspond to the contribution of the valence quarks to the proton spin. Fig. 20 shows the result of a simulation for the asymmetries and the structure functions g_5 in charged current events induced by polarized electrons and positrons on polarized protons assuming an integrated luminosity of 250 pb^{-1} for each species.

The simulation shows that the input values derived from a fit to available data can be reproduced. The sensitivity at large values of x makes this an attractive alternative for the measurement of the flavour separated components of the spin structure function. In contrast to the alternative methods, using semiinclusive measurements, the analysis of charged current events does not need input or assumptions about the fragmentation process.

4.1. Physics beyond the standard model

The search for new interactions beyond the standard model is one of the main issues of contemporary high energy physics. Substructure of quarks and leptons or the existence of leptoquarks are much discussed possibilities. If the new interaction is connected to a mass scale beyond the accessible $\sqrt{s}$ as schematically shown in Fig. 21 it can effectively be described by a contact interaction with an energy scale Λ. Current lower experimental limits are of order $\Lambda \approx 5-10$ TeV. Several asymmetries can be measured with longitudinally polarized protons in HERA interacting with longitudinally polarized electrons or positrons. This allows to investigate the chiral structure of the hypothetical new interaction. Eight different cross sections $\sigma_t^{\lambda_e \lambda_p}$ can be measured. Here t means the charge of the lepton and λ_e and λ_p the helicities of the lepton and the proton. Virey [24] has studied sixty asymmetries constructed out of these. In Fig. 22 the asymmetries

$$A_{LL}^{PV} = \frac{\sigma_+^{--} - \sigma_+^{++}}{\sigma_+^{--} + \sigma_+^{++}} \quad \text{and} \quad B_2^2 = \frac{\sigma_-^{++} - \sigma_+^{++}}{\sigma_-^{++} + \sigma_+^{++}}$$

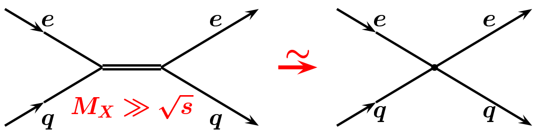

Figure 21. Description of new physics by a contact interaction.

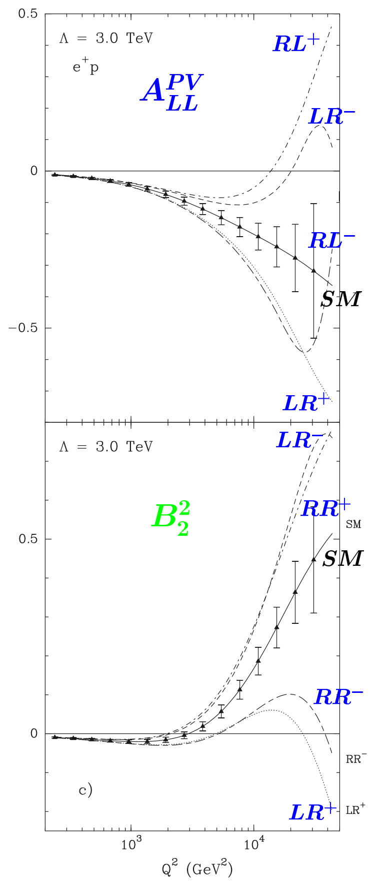

Figure 22. The asymmetries A_{LL}^{PV} and B_2^2 as a function of Q^2 simulated within the standard model (continous lines) assuming 250 pb^{-1} per spin and charge configuration. The dashed lines show the effect of an additional contact interaction of different chiral structure.

are shown as a function of Q^2 together with a simulation, assuming the standard model as input and an integrated Luminosity of 250 pb^{-1} per spin and charge configuration. The sensitivity to an additional contact interaction with $\Lambda = 3$ TeV having different chiral structures (R or L leptons coupling to R or L quarks) and relative sign to the standard model is shown. It appears that at large Q^2 there is a large sensitivity of $\Lambda \approx 7$ TeV for the new mass scale.

5. SUMMARY

There is a wide field of physics questions which can be addressed if the HERA proton and possibly also a ^{3}He beam can be polarized. Spin observables are crucial for the understanding of the strong interaction. There are unique possibilities to study the spin structure functions and the polarized gluon structure of the proton and the photon in a kinematical range not accessible by any other experiment at an existing or planned facility. Experiments with quasireal photons which require only moderate integrated luminosities of order 50 pb^{-1} could provide unique information on the structure of the polarized photon already in the commissioning phase. The measurement of asymmetries in charged current interactions is another highlight allowing the flavour separation of the spin structure in the cleanest possible way. Finally polarization provides a handle to investigate the chiral structure of new interactions beyond the standard model.

Acknowledgements: I want to thank Albert de Roeck and Vernon Hughes who helped me to find most of the material used in this talk. Much was taken from the Proceedings of the Workshop on Deep Inelastic Scattering off Polarized Targets, Zeuthen, Germany, DESY 97-200, edited by J. Blümlein, A. De Roeck, T. Gehrmann and W.D. Nowak, and also from viewgraphs of a talk given by G. Rädel at DIS98.

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