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FUTURE PHYSICS WITH POLARIZED PROTONS AT HERA*

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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 paper. 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. Additionally, a program of polarized proton–proton scattering is proposed, using the high energy polarised proton beam on a polarized fixed target. In all, HERA could make a significant contribution to our understanding of spin effects in high energy collisions and to the spin structure of the nucleon.

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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. It is therefore only natural to assume

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that the operation of HERA with polarized proton and electron beams [1,2] 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 [3] 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. Hence beams from sources of polarized protons have to be accelerated through the whole chain, while keeping the polarization on the way. 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.

In this report we discuss mainly the physics program for the *ep* collider mode and related measurements: $g_1(x, Q^2)$ at low x, the extraction of the polarized gluon density $\Delta G(x, Q^2)$ in a wide kinematic range, using several processes, the extraction of the spin structure function $g_5(x, Q^2)$ from charged current events, photoproduction studies and studies on the helicity structure of the high Q^2 region.

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 [5]. The two main physics 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.

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.

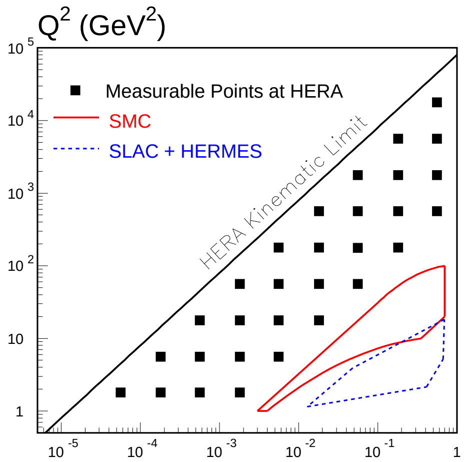

Fig. 1. Measurable $x - Q^2$ region for a polarized HERA with the presently explored regions by CERN (SMC), SLAC and DESY (HERMES) experiments.

Fig. 2 shows the statistical precision of the measurement of g_1 as a function of x [6]. 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° (defined with respect to the proton beam) and larger than 5 GeV respectively. 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. 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 are indicated in the figure: the straight line is an extrapolation based on Regge phenomenology, and the upper curve presents a scenario suggested in [6] where g_1 rises as $1/(x \ln^2(x))$, which is the maximally singular behaviour still consistent with integrability requirements. The low x behaviour of g_1 by itself is an interesting topic. Large effects are expected at HERA as detailed in another contribution at this workshop [7]. All these scenarios are allowed by present day data from fixed target experiments.

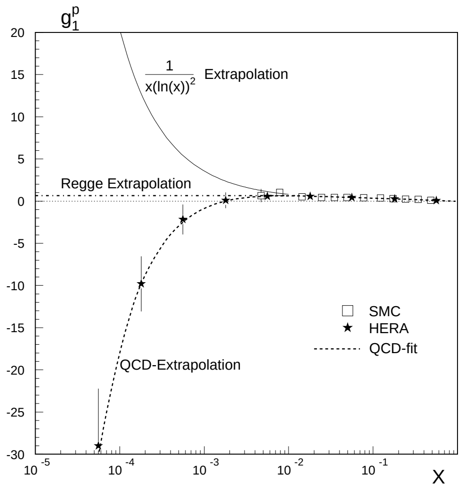

Fig. 2. The statistical uncertainty on the structure function g_1 of the proton measurable at HERA, evolved to a value of $Q^2 = 10$ GeV^2 for an integrated luminosity of 500 pb^{-1}, is shown. The SMC measurements are shown for comparison (for curves see text).

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 [6], from which g_1^n can be extracted. If the machine can provide polarized ^{3}He with a luminosity comparable to the one for the protons, such a program can be carried out.

The high quality data from the fixed target experiments allow for quantitative QCD studies of the polarized structure function data, from which polarized parton distributions are extracted. The present status of these studies is reported in [6]. 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. 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 $\int \Delta G(x)\ dx = 0.9 \pm 0.3(\text{exp}) \pm 1.0(\text{theory})$ 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 [8]. 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 $\Delta G(x, Q^2)$

It is crucial for our full understanding of the proton spin that the predictions for a large polarized gluon are confirmed by direct experimental test. 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 of the gluon distribution in the proton. These processes include jet and high p_t hadron production and charm production both in DIS and photoproduction.

The most promising process for a direct extraction of ΔG at HERA is 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. Exploratory leading order (LO) Monte Carlo studies are reported in [9] and show that the asymmetries at parton and detector level are substantial. Exact polarized NLO calculations were performed [10] and showed that the NLO QCD corrections are 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 [11], using the Monte Carlo generator `PEPSI 6.5` [12]. 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 $|\eta^{\text{jet}}_{\text{LAB}}| < 2.8$, where $\eta^{\text{jet}}_{\text{LAB}}$ is the pseudo-rapidity in the laboratory system.

The results are shown in Fig. 3. 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

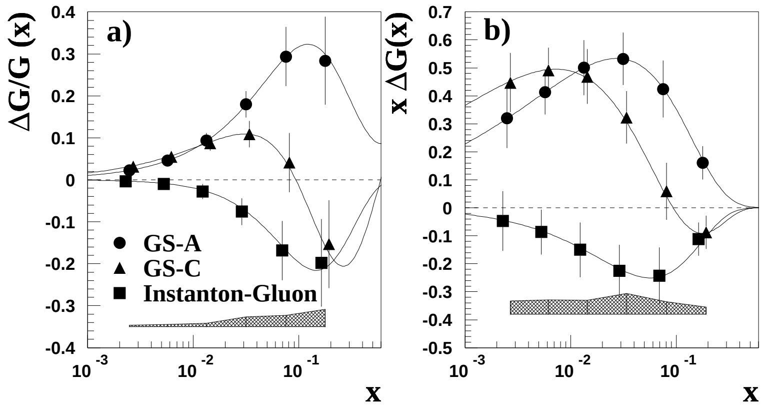

Fig. 3. Di-jets: Sensitivity to $\Delta G/G$ (a) and $x\Delta G$ (b) for three different polarized gluon distributions shown as solid lines and a luminosity of 500 pb^{-1}, for $Q^2 = 20\ \mathrm{GeV}^2$.

value. The gluon distributions are the Gehrmann–Stirling (GS) sets A and C [13], which result from a QCD analysis of g_1 data, and a gluon distribution obtained from instanton calculations [14]. The distributions shown in Fig. 3, 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 $\int \Delta G(x)\, \mathrm{d}x$.

A different method to isolate photon–gluon fusion events at HERA was investigated. Instead 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 [15]. The PEPSI Monte Carlo program was used, and DIS 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 [16]. The result of the unfolded gluon distribution is shown in Fig. 4. 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. 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

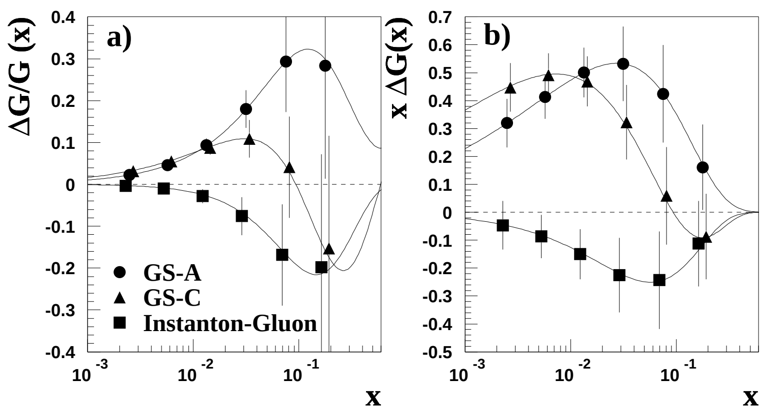

Fig. 4. High p_t hadrons: Sensitivity to $\Delta G/G$ (a) and $x\Delta G$ (b) for three different polarized gluon distributions shown as solid lines and a luminosity of 500 pb^{-1}, for $Q^2 = 20$ GeV^2.

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 I. The first two rows give the values quoted be-

TABLE I

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.

Analysis Type	$\delta(\int \Delta G \, \mathrm{d}x)$
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

fore, 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

Information on the flavour decompostion 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.

Semi-inclusive asymmetries were studied for HERA [17] 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 [12] that the valence and sea quark contributions can be disentangled at small x.

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 [17] 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

$$A^{W\mp} = \frac{d\sigma_{\uparrow\downarrow}^{W\mp} - d\sigma_{\uparrow\uparrow}^{W\mp}}{d\sigma_{\uparrow\downarrow}^{W\mp} + d\sigma_{\uparrow\uparrow}^{W\mp}} = \frac{\pm 2bg_1^{W\mp} + ag_5^{W\mp}}{aF_1^{W\mp} \pm bF_3^{W\mp}} \approx \frac{g_5^{W\mp}}{F_1^{W\mp}} \tag{1}$$

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 [18]. The total missing transverse momentum (which is a signal for the escaping neutrino) was required to be $P_{\rm Tmiss} > 15$ GeV, and the region $Q^2 > 225$ 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. 5. The error bars indicate the statistical precision of the 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.

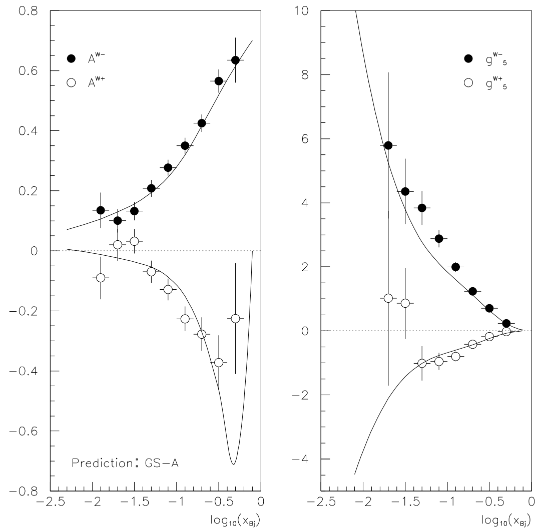

Fig. 5. Spin asymmetries A^{W^-} (full circles, left side) and A^{W^+} (open circles, left side) for charged current events are presented for a total luminosity of 500 pb^{-1}. Also shown are the structure functions $g_5^{W^\pm}$ (right side) extracted from the asymmetries. The parton densities GS–A from [13] were used. The error bars represent the statistical uncertainty of the measurement.

5. Photoproduction

A first investigation of polarized photoproduction has already been carried out during the last workshop [19]. 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 ($\eta_{\rm LAB} \lesssim 0$) 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 ($\eta_{\rm LAB} \gtrsim 0$), 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 [20] during the present workshop has shown that the sensitivity on the polarized photon structure is maximal for $\eta_{\rm LAB} \gtrsim 2$, where still sizable jet rates guarantee small statistical errors on the 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 [20]. Although the production rate for

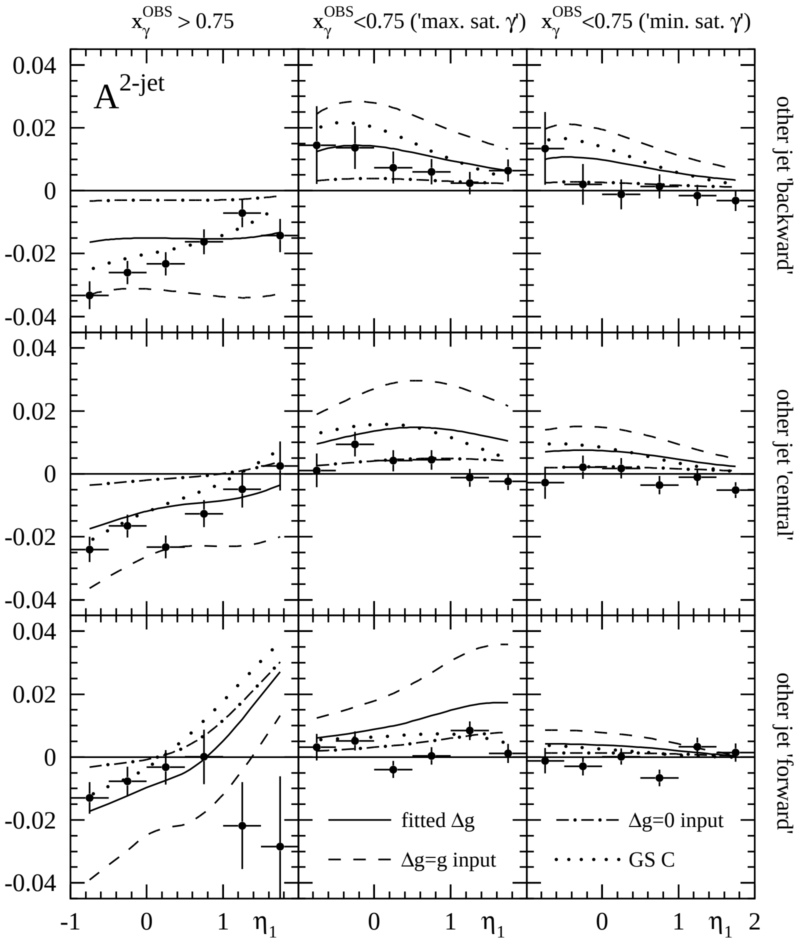

Fig. 6. Polarized photoproduction of di-jets ($E_{T,1} > 8$ GeV, $E_{T,2} > 6$ GeV): asymmetries for direct (first column) and resolved (second and third column) photon contributions as function of the rapidity of the first jet and for different orientations of the second jet. Second and third column correspond to different scenarios for the parton content of the polarized photon suggested in [21]. 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.

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 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 $x_\gamma^{\rm OBS}$. The resulting data can then be binned in $x_\gamma^{\rm OBS}$, and one usually attributes all events with $x_\gamma^{\rm OBS} > 0.75$ 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 [20]. An example for the correspondence of parton and hadron level asymmetries is shown in Fig. 6, 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 two (minimal and maximal) polarization scenarios proposed in [21], as done in Fig. 6. 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.

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 study of the Drell–Hearn–Gerasimov sum rule, as discussed in [22].

6. Effects at high Q^2

Recently the HERA collaborations [23] have reported a significant excess over Standard Model expectation of events produced in the region of Q^2 larger than 10000 GeV^2. 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 [24], 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 [24]. With 250 pb^{-1} data samples for polarized e^+ and e^- beams, for each of the 2 spin orientations, the asymmetries are sensitive to contact interactions to scales larger than 7 TeV (95% C.L.). In the presence of a signal these different combinations of cross sections into 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).

A special case of new particle — leptoquark-like — production was studied in [25] 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. An interesting possibility is the effect induced by QCD instantons [14] to the proton structure function. Non-perturbative instanton fluctuations describe the quantum tunneling between different gauge rotated classical vacua in QCD. 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 [26] the contribution of instantons to the proton structure is expected to become increasingly more important with increasing Q^2 [14]. 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.

7. Polarized proton–proton collisions

Finally we note that the polarized physics program also contains a proposal for a fixed target experiment, namely to use the 820 GeV polarized proton beam on a polarized proton target and study single and double spin asymmetries [5]. The physics program is similar to the one of the hadron–hadron collider RHIC, but at a CMS energy of about 40 GeV. Thus complementary measurements can be made, in particular on ΔG, from J/ψ and photon plus jet production in polarized pp collisions. This is illustrated in Fig. 7, where the statistical accuracy of the measurements is compared with two scenarios for $\Delta G(x)$. A luminosity of 320 pb^{-1} is assumed for the HERA measurement, corresponding to a few years of data taking (assuming 3.10^{13} atoms/cm^2 for the polarized target). Since this measurement accesses the polarized gluon density in the high x region, it is complementary to the measurements discussed before. This measurement however requires a new experiment with a wide angle acceptance, presently called HERA-$\vec{N}$.

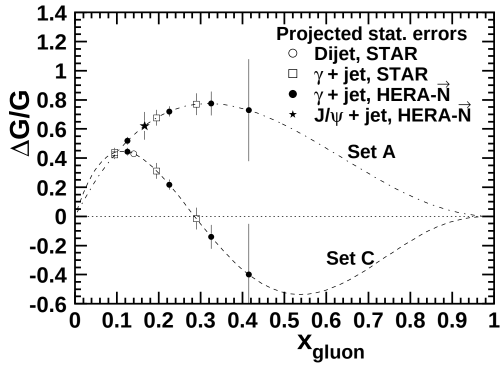

Fig. 7. Expected statistical accuracy for the determination of $\Delta G(x)$ from polarized $pp \to \gamma + \text{jet} + X$, for a luminosity of 320 pb^{-1} in an optimized detector.

8. Conclusions

HERA 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

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.

HERA will also contribute to the flavour decomposition of the quark spin distributions, and the very intriguing possibility to measure polarized parton distributions in the photon. Furthermore — not discussed in this review — new insight is expected on spin transfer in quark fragmentation and spin effects in diffractive scattering. 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.

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