Physics with a polarized proton beam - a summary

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Abstract: The precise study of the nucleon spin structure has evolved over the last years into a broad field allowing to test many different aspects of QCD, some of them with outstanding precision, and most of them being unaccessible by other means. With a polarized proton beam at HERA several of the crucial questions in this field could be answered: the polarized gluon distribution $\Delta G(x, Q^2)$ could be deduced, primarily from jet production, spin asymmetries of charged current events would clarify the quark spin decomposition, measurements of the polarized structure function $g_1(x, Q^2)$ in a previously unaccesible kinematic domain would further constrain $\Delta G(x, Q^2)$ and could detect deviations from DGLAP evolution, polarized proton-proton collisions could open a completely new field of physics, and a large number of relevant details could be clarified by other measurements. HERA would be complementary to all presently planned lower energy experiments. To exploit the full potential of this option requires, however, 200 pb^{-1} of luminosity with electron and proton polarizations of order 70 percent. For 1000 pb^{-1} the physics potential would increase substantially, for luminosities below 100 pb^{-1} it becomes marginal. The availability of polarized deuteron and/or ^{3}He beams is also crucial to allow for a broad physics program. The charged current experiments would profit greatly from the availability of electron and positron beams.

1 Introduction

The understanding of spin-effects in QCD has improved dramatically since the first surprising data of EMC became available in 1988 [1]. On the experimental side the available data became much more precise and on the theoretical side many quite complicated questions could be fully analysed. Most of this work focussed on the first spin structure function $g_1(x, Q^2)$, which is, however, only one of several structure functions, namely the one most easily accessible in deep inelastic lepton-nucleon scattering. As a result of this work we have nowadays a generally accepted range of models for the polarized quark distribution functions entering $g_1(x, Q^2)$. These parametrisations imply that the quarks carry only about 30 percent of the nucleon spin. While being consistent with the data, as well as with the results of lattice gauge studies [2], these interpretations have not really been experimentally tested. Nearly all models predict a substantial polarization for both the gluons and the strange quarks (the distinction between these two contributions is scheme dependent, the polarization of the strange quarks is primarily due

to the gluon polarization), which has to be confirmed by direct experimental tests before the present standard interpretation of the data can be regarded as established. The polarized gluon distribution is of especial interest, because it could be surprisingly large. As $\alpha_s(Q^2)\Delta G(Q^2)$ with $\Delta G(Q^2) = \int_0^1 \Delta G(x, Q^2)dx$ is a renormalization group invariant, the reduction of α_s when Q^2 is evolved from a hadronic scale to a perturbative scale has to be counter balanced by a strong increase in ΔG. Typical parametrizations predict e.g. that for $Q^2 = 4$ GeV^2 the total gluon spin could be of order 1 to 2 although the nucleon as a whole has only the spin $\frac{1}{2}$. This astonishing prediction clearly has to be tested by dedicated direct experiments. Also, under NLO-evolution the parton distributions mix, such that the polarized gluons contribute also to $g_1(x, Q^2)$. This general feature of NLO-calculations has attracted great attention due to the fact, that the relevant graph involves the axial anomaly, which is probably the most important graph in all of quantum field theory. Spin experiments can thus test our understanding of its properties. In the unpolarized case the gluon distribution was determined by fits to DGLAP-evolution, from jet production, from prompt photons, and from vector meson production. All of these methods could be applied for $\Delta G(x, Q^2)$ at a polarized HERA, as will be discussed in detail in the next sections.
One crucially important point in spin physics is that the ratio of polarized to unpolarized distribution functions varies substantially with Bjorken-x, leading for the different observables in some kinematic domains to unmeasurably small asymmetries (sometimes as small as 10^{-4}) and in other kinematical domains to very large ones (up to 60 percent). This alone requires different experiments, sensitive to various x-ranges and makes most of the discussed projects rather complementary. In section 2 recent theoretical progress is reviewed. In section 3 we discuss the most favourable observables for HERA, primarily jet and charged current asymmetries. Section 4 will be devoted to the possibility of investigating fixed target polarized proton-nucleon collisions at HERA. In section 5 we try to put a polarized HERA in perspective to the various other planned or already running spin experiments.

2 Recent theoretical progress

Let us start our review with the structure function $g_1(x, Q^2)$. It is measured in inclusive collisions of longitudinally polarized nucleons and longitudinally polarized leptons. The latter have always to be polarized longitudinally. For transverse lepton polarization one cannot extract any additional information, but all asymmetries are reduced by the factor $\gamma = E_e/m_e$. However, transverse nucleon polarization gives accesss to new and even especially interesting information. It tests various well defined higher twist effects. To get an impression of the richness of structure functions and correlators involved we refer to [3]. Here we shall only discuss the twist-2 part of $g_1(x, Q^2)$ which can be written as

$$g_1(x, Q^2) = \sum_f Q_f^2 [q_f^{\uparrow}(x, Q^2) - q_f^{\downarrow}(x, Q^2)] \qquad , \quad f = u, \bar{u}, d, \bar{d}, s, \bar{s}, ... \tag{1}$$

with $q_f^{\uparrow}(x, Q^2)$ describing the probability that the virtual photon hits a quark of flavour f polarized in the direction of the nucleon spin and carrying momentum fraction x at a given resolution Q^2. Under Q^2-evolution the singlet part of $\Delta q(x, Q^2) = q^{\uparrow}(x, Q^2) - q^{\downarrow}(x, Q^2)$ mixes with the polarized gluon distribution $\Delta G(x, Q^2)$ and in the limit $Q^2 \to \infty$ the relevant graph becomes the well known triangle anomaly. It was realized early on, that this mixing could be strong enough to play a crucial role in the interpretation of the data, so this specific NLO-graph was added to the otherwise LO-analyses, creating quite a bit of confusion [4]. Over the last year this situation was clarified by the derivation of complete NLO evolution equations by Mertig and van Neerven [5], which were rederived independently by Vogelsang [6]. This work constitutes a major advance in our understanding of spin physics. Now the leading box-graph contribution to the anomaly is contained just as one contribution among others in the NLO-evolution equations. In principle it could still be that higher order, possibly completely non-perturbative graphs change the mixing significantly, but presently there is no indication for this. However, to know for certain that this is not the case one has to measure $\Delta G(x,Q^2)$ directly and confirm that the result is in agreement with the expectation from NLO-evolution fits to existing data. To do this would be one of the major aims of the experiments with a polarized HERA. We will discuss in the next section to which extent such HERA data would improve the NLO-fits and how $\Delta G(x,Q^2)$ could be measured directly from jet-asymmetries.

One of the main aims of the unpolarized QCD program at HERA is to detect deviations from DGLAP evolution at small x. So far no unambiguous results were obtained. The present data seem to be compatible with DGLAP- as well as BFKL- and multi-reggon-behaviour. It is natural to ask, whether the phenomenological differences between these three approximations would be larger for the polarized structure functions in the HERA x-range. In fact in an analyses by Bartels, Ryskin and Ermolaev [7] in the multi-reggon kinematics and using a fixed, Q^2-independent coupling constant the authors reached the rather drastic asymptotic ($x \to 0$) prediction

$$\begin{aligned} g_1(x,Q^2)^{NS} &\sim x^{-0.41}\left(\frac{Q^2}{\mu^2}\right)^{0.2} \\ g_1(x,Q^2)^{S} &\sim x^{-1.02}\left(\frac{Q^2}{\mu^2}\right)^{0.52} \end{aligned} \tag{2}$$

suggesting a large deviation from NLO-behaviour at asymptoticaly small x. However, within this approach it is unclear how small x has to be to reach this behaviour and also everybody agrees that using a running coupling constant could change the situation substantially. We would like to stress that besides the test of small-x asymptotics, data points at very small x are very important to reduce the systematic error on the Bjorken- and Ellis-Jaffe sum rules. Let us remind that the Bjorken sum rule ist one of the most interesting firm predictions of QCD which should be tested with the utmost accuracy.

Blümlein and Vogt [8] implemented the additonal terms into the evolution equations and found that for the non-singlet part the deviation from NLO-DGLAP is unmeasurably small within the HERA range, but that it is very large for the singlet part, see figure 1. There is some discussion about the probable size of non-leading contributions, which presently cannot be calculated, but at least it is safe to say that the deviations could be dramatic.

Let us add that for the third twist-2 distribution function h_1, which is only accessible in nucleon-nucleon collisions or semi-inclusive lepton-nucleon collisions, the differences are even larger. It was shown by Kirschner et al. [9] that the leading double-logarithmic term of DGLAP is in this case non-leading when compared to the multi-reggon result, which is a constant as function of x (for $x \to 0$). The same caveats as for the case of $g_1(x,Q^2)$ apply also here, but with all due caution it seems clear that this would be a most interesting quantity to measure. Whether a measurement of h_1 at small x would be feasible at a polarized HERA depends on the size of a yet unknown parameter linking fragmentation properties to the transverse polarization of the

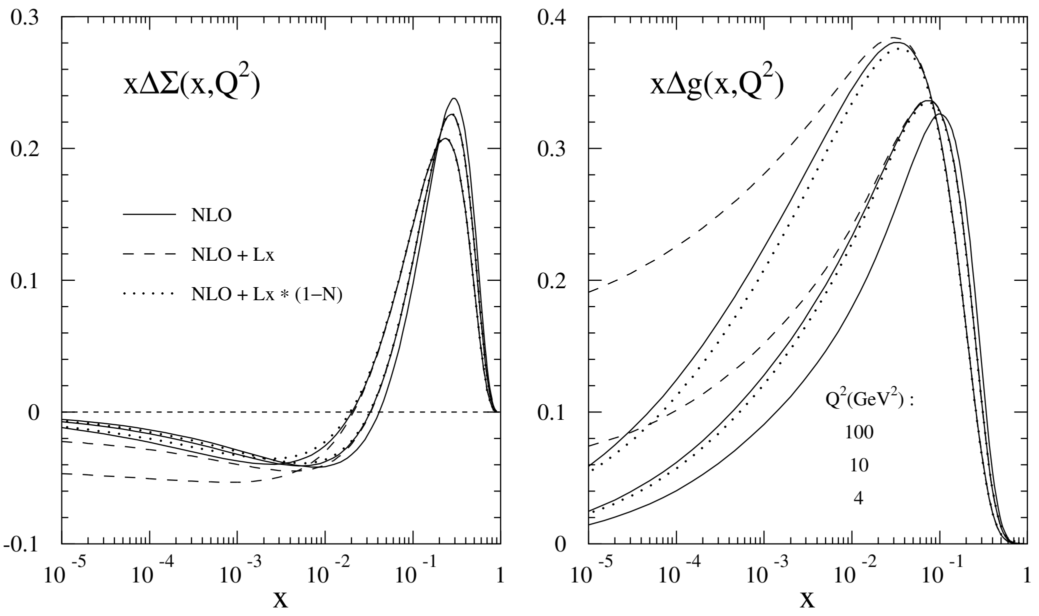

Fig. 1

Figure 1: *Predicted deviation for the singlet and gluon spin distribution function between NLO-evolution with and without the leading* $\log x$ *contributions.*

leading quark (this parameter characterizes the so called Collins effect [10]). If this parameter were sufficently large, this could open a field of investigation in addition to the measurements described below.

Let us stress that the singlet and non-singlet part of the distribution functions have widely different properties which have to be disentangled by measuring both the proton and neutron polarized structure functions. This requires to have polarized proton, deuteron and/or ^{3}He-beams. If eq. (2) holds both $g_1^p(x)$ and $g_1^n(x)$ are dominated by the singlet part at very small x. However, in the present SMC data the non-singlet part dominates. This makes it so very interesting to follow both structure functions down to lower x values.

As is pointed out by Düren in his contribution, a polarized deuteron beam with the possibility to tag both the spectator proton or the spectator neutron would practically double the effective luminosity and at the same time reduce systematic errors. However, the machine problems encountered for this option are substantial.

3 The most promising experiments with polarized electron-nucleon collisions

We shall discuss three main experiments to be performed at a polarized HERA, namely the measurement inclusive DIS, jet spin asymmetries and spin asymmetries for charged current events.

The outstanding advantage of HERA is that it can measure structure functions for very small x. For polarized reactions one has to know, however, that the probability for the exchanged

photon to be polarized, if the electron is polarized depends on $y = q \cdot P / p \cdot P$ with the photon momentum q_μ, the incoming electron momentum p_μ and the Proton momentum P_μ. For small values of y the measurable asymmetry simply scales with y. Knowledge of this fact, together with the general smallness of the asymmetries for very small x, is crucial to understand why a polarized HERA would do well in some cases and not so well in others and why in general a much higher luminosity is needed than for the current meassurements of the unpolarised structure function. There is, however, also an advantage going along with this. At medium and large x the values for Q^2 become large resulting in large values of y. Therefore one can obtain more precise results in this domain.
However, it is very difficult to make use of this for polarized DIS reactions because the spin asymmetry for small x is very small e.g for $x = 2 \cdot 10^{-4}$ it is only of the order 10^{-3} unless there are strong deviations from the predictions of present day NLO-fits, which is, however, possible for such small x values as discussed in the previous section. (Measuring such small asymmetries requires polarimeters of a quality of order 10^{-2}, a problem which is not yet solved, but for which several methods have been proposed.) The low x behaviour is predicted to be highly Q^2 dependent. Lichtenstadt et al. have analysed the situation in great detail and some of their results are combined in figure 2. Here the expected asymmetry for various x and Q^2 bins is shown, however, for the somewhat optimistic luminosity of 1000 pb^{-1}. The central curve in each plot shows the prediction from the best present NLO fit, while the dashed and dotted curve represent the expected signal for a very small respectively large (but not excluded) ΔG. The unusual feature that the statistical precision increases with Q^2 for a given x is due to the spin-dilution factor $\approx y$. Obviously with this luminosity one would just have the sensitivity to distinguish between the three cases, by combining all $x - Q^2$-bins. In judging the quality of these results one has, however, to realize that the NLO-fits which were used predict that the asymmetry goes through zero close to $x = 10^{-3}$ and this spoils the signal just in the region of highest statistical sensitivity, see figure 3. If this would not be the case the signal would be far more significant. This statement can be inverted. The increase in precision of typical NLO-fits due to the anticipated data is in fact quite significant [11]:

predicted total gluon spin from present day NLO-fit : 1.52 ± 0.74
predicted total gluon spin including the data from figure 2 : 1.29 ± 0.22
predicted total gluon spin including HERA data for 200 pb^{-1} : 1.29 ± 0.28

Such an experiment would be outstanding to check at high Q^2 and very small x that such a fit is justified.
Let us add here that as usually an important systematic uncertainty comes from QED radiative corrections, which are in principle well known, but for which the accuracy of the employed codes has recently become a topic of discussion. We refer to the working group report on unpolarized structure functions for details. For spin asymmetries the radiative corrections are much smaller than for the cross-sections themselves.
The statistical sensitivity would be substantially improved if the HERA proton energy could be reduced, keeping the same luminosity. This might interfere, however, with the two very promising experiments to be discussed next.
We conclude that the measurement of $g_1(x, Q^2)$ at HERA energies would provide an important complement to high precision experiments at lower energy, proposed e.g. for CERN (COMPASS) and SLAC.

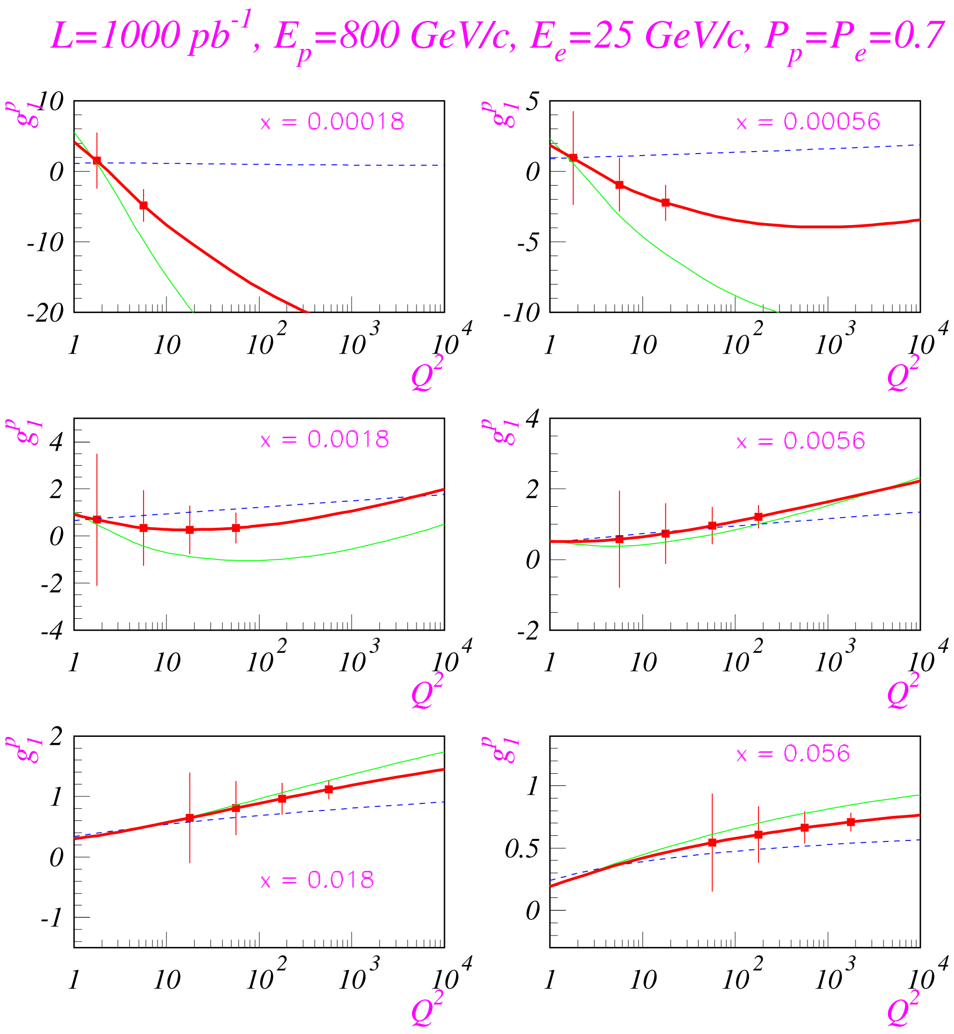

Figure 2: *Anticipated results of a 1000 pb^{-1} run for various $x-Q^2$-bins. The errors are statistical only. The solid line represents the prediction from the best NLO-fit to present data. The dashed and dotted curves show the predictions for an especially small respectively large gluon polarisation.*

One domain in which the high HERA energies really pay off is the study of jets. (This was already discussed at the last workshop [12].) Jets can in principle also be studied at lower energy and in proton-proton collisions, however, the main problem of all such studies is the control of higher order corrections. Thus the main emphasis for the determination of $\Delta G(x, Q^2)$ (respectively $G(x, Q^2)$) lies on the control of the theoretical systematic errors. In this respect jet spin asymmetries at HERA are a very favorable case [13]. The studies of Mirkes et al. [14] show that systematic uncertainties in the cross sections cancel to a large degree for the spin asymmetries and in addition the large HERA energies allow to impose cuts (most notably on the invariant jet-jet mass squared s_{jj}) which further reduce these uncertainties.
The processes leading to two-jet events (we do not count the proton remanent jet) are shown in figure 4. Luckily it turns out that for the standard sets of NLO polarized parton distributions the annihilation graph, which is proportional to $\Delta G(x)$ dominates over the Compton graph, which is proportional to $\Delta q(x)$. Therefore the 2-jet event rates are highly sensitive to the

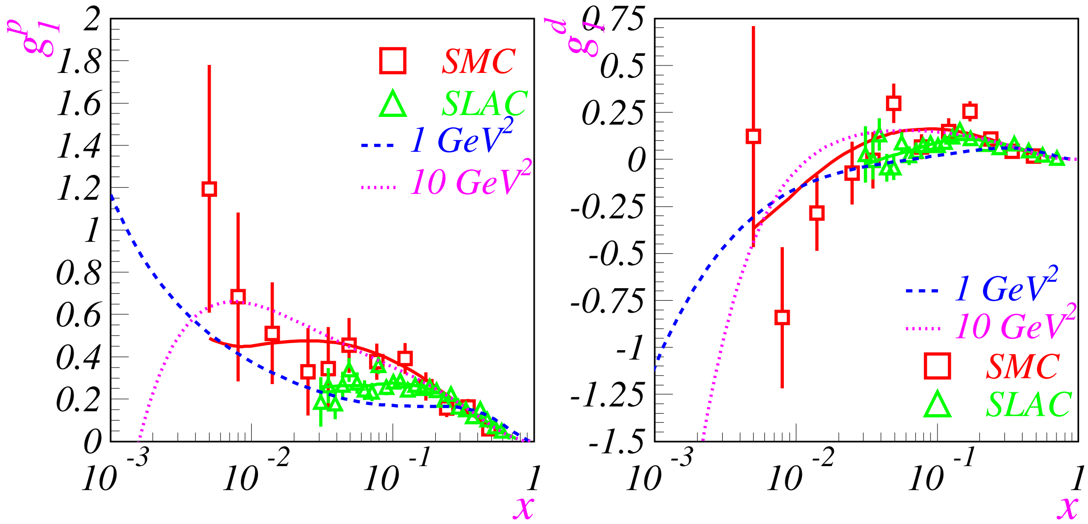

Figure 3: *Expected x-dependence for $g_1^p(x)$ and $g_1^d(x,Q^2)$ for two values of Q^2, showing the strong evolution effects for small x.*

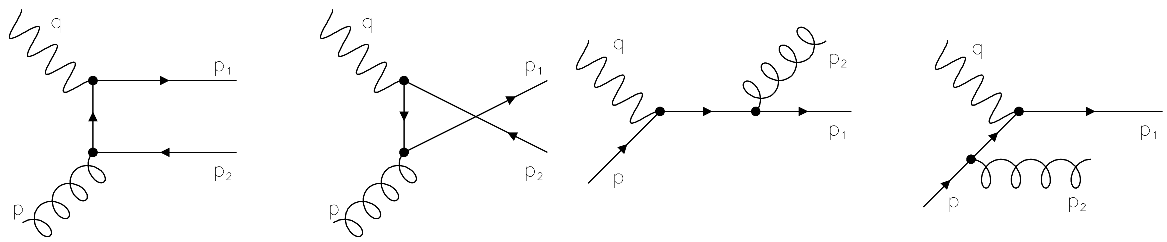

Figure 4:

polarized gluon distribution and already a relatively crude measurement would allow to decide between scenarios with large and small ΔG in the best accessible x_g-range between a few times 10^{-3} and several times 10^{-2}. Note that for 2-jet events the momentum fraction x_g and the Bjorken variable x differ strongly. With the total invariant mass squared of the outgoing jets $s_{jj} = (q + x_g P)^2 = -Q^2 + 2x_g\nu$ they are related by $x_g = x(1 + s_{jj}/Q^2)$. Typically x_g is about an order of magnitude larger than x.

We have studied the expected 2-jet events with the help of two computer codes called MEPJET and PEPSI2. MEPJET [14] was developed to describe unpolarized jet-production. It does not yet contain hadronization and describes the physics only at the parton level, but in its unpolarized version it uses either LO or NLO matrix elements and distribution functions, allowing thus to estimate the size of higher order corrections and to select the most suitable kinematic range to minimize systematic errors. PEPSI2 [15] is a polarized version of LEPTO 6.2 and as

such a general multi-purpose code. It contains hadronization and is altogether constructed in a completely different manner than MEPJET. Comparing the results of both codes one should therefore get a rather reliable feeling for the theoretical uncertainties involved. It turns out that the results for the asymmetries agree quite nicely. The predictions we can presently make and which will be discussed in the following might still have a quite substantial theoretical uncertainty (of the order 10 percent or so) but we expect that by the time experiments at a polarized HERA would start, these uncertainties will be substantially reduced, allowing to make full use of the good expected statistical accuracy.
Figure 5 shows the theoretical prediction for the spin asymmetry for three different scenarios, the standard one, one with an extremely small $\Delta G(x)$ and one with a very large $\Delta G(x)$. The cross section for photon-gluon fusion contains a factor $(2x_g - 1)$, which is responsible for the fact that in the accessible x_g-range the resulting asymmetry is negative and cancels partly with the much smaller positive contribution from the Compton graph.

Figure 6 shows the expected results for a run with 200 pb^{-1} respectively 100 pb^{-1} and

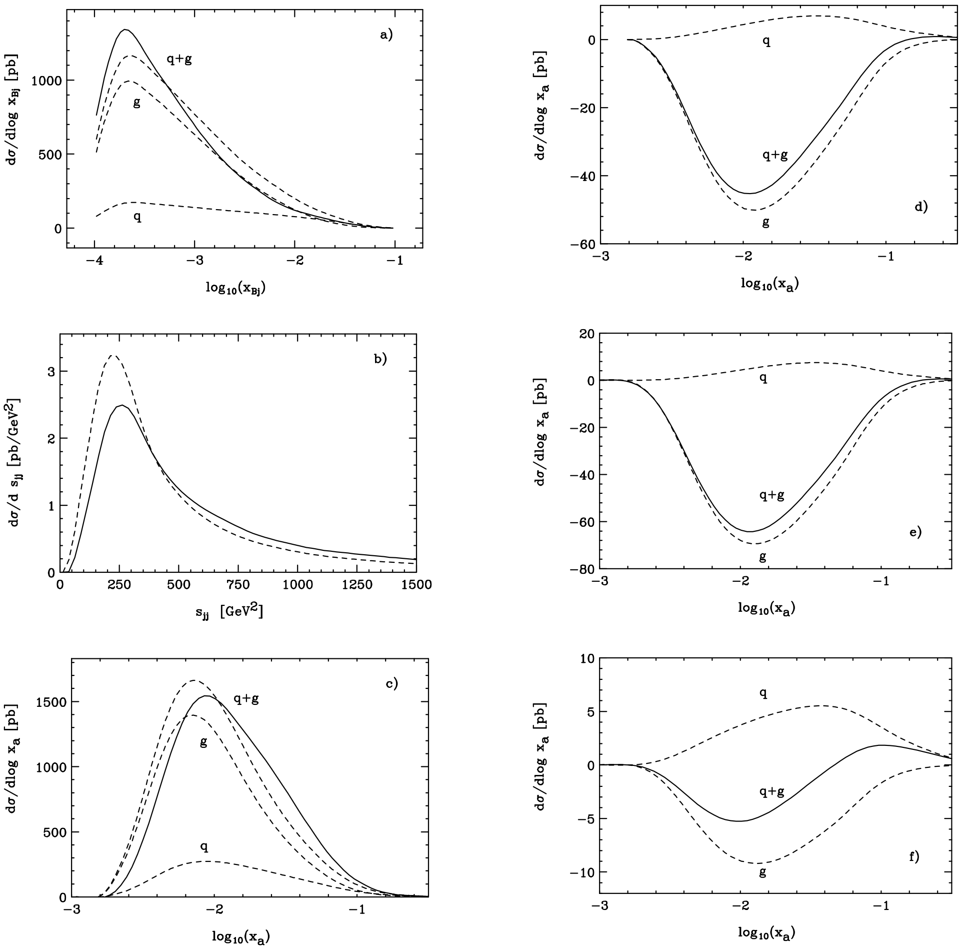

Figure 5: *a) Dependence of the* **unpolarized** *two-jet cross section on Bjorken x_{Bj} for the quark and gluon initiated subprocesses and for the sum. Both LO (dashed) and NLO (solid) results are shown; b) Dijet invariant mass distribution in LO (dashed) and in NLO (solid) for unpolarized dijet production; c) Same as a) for the x_a distribution, x_a representing the momentum fraction of the incident parton at LO; d,e,f) Results for the LO* **polarized** *two-jet cross sections. Three different scenarios were used, the standard scenario (d), a scenario with a very small polarized gluon distribution function (f) and with a larger one (e).*

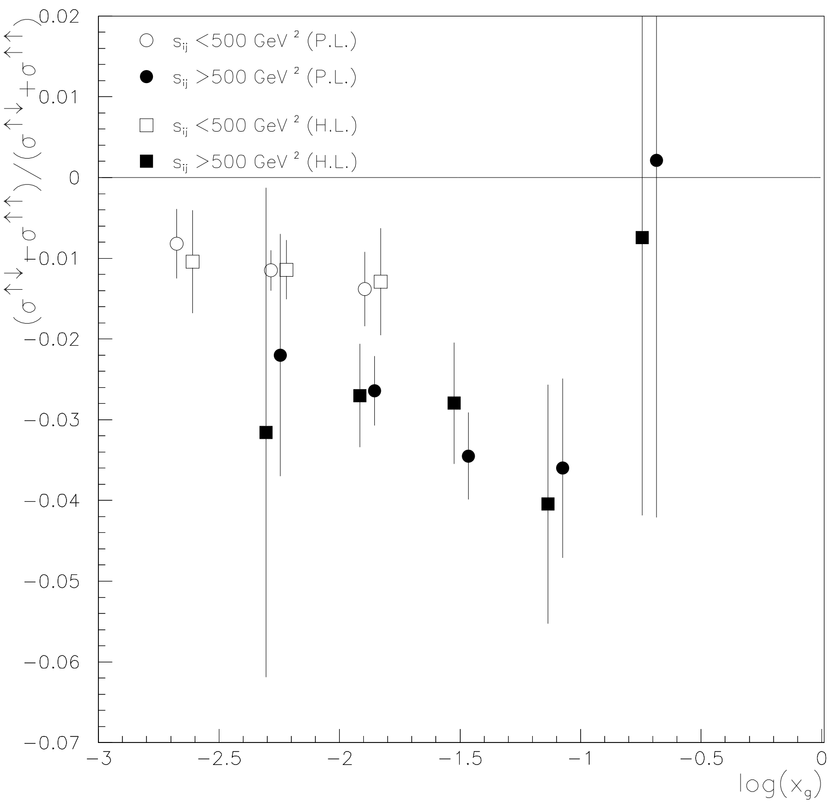

Figure 6: *Expected statistical accuracy for a standard HERA run where P.L. stands for a parton level simulation using MEPJET with a luminosity of 200 pb*$^{-1}$ *(*$P_e = P_p = 0.7$*), and H.L. stands for a hadron level simulation using PEPSI and the realistic acceptances of the H1 detector with a luminosity of 100 pb*$^{-1}$*.*

$P_e \cdot P_p = 0.5$, and compares MEPJET and PEPSI2 predictions. Both agree reasonably well. Most important are the expected statistival errors which clearly demonstrate that the polarized 2-jet asymmetry would in fact determine $\Delta G(x)$ with quite good accuracy and would thus answer the most important open question regarding the intenal spin structure of the nucleon. For the second graph in figure 6 a $s_{jj} > 500$ GeV^{-2} cut was implemented to reduce the uncertainties due to higher orders. Obviously such a cut does not increase the relevant error, mainly because it gives more weight to the larger x_g events which have a larger spin asymmetry. The fact that such cuts are unproblematic supports our hope that one will be able to reduce the systematic errors to a very small level such that one could even make full use of a further luminosity increase, possibly up to 1000 pb^{-1}.

Since in the unpolarized case many processes at HERA have first and most accurately been studied in photoproduction, Stratmann and Vogelsang [16] have examined the photoproduction of jets and heavy flavors for the situation with longitudinally polarized beams with regard to their sensitivity to ΔG. While open-charm production turns out to be less useful to pin down ΔG unless one can achieve very large luminosities (1000 pb^{-1}), the asymmetry for the rapidity distribution of the single-inclusive jet cross section shows a particularly strong dependence on ΔG and is measurable even for 100 pb^{-1} (see fig. 7). Furthermore, polarized photoproduction experiments may in principle allow to not only determine the polarized parton distributions of the proton, but also to get a glimpse at those of the circularly polarized *photon* which are completely unknown so far. For example, at larger rapidities the single-inclusive jet cross section shown in fig. 7 becomes also sensitive to the hadronic structure of the photon. Definitely photoproduction would be one of the most interesting processes to be studied at a polarized HERA.

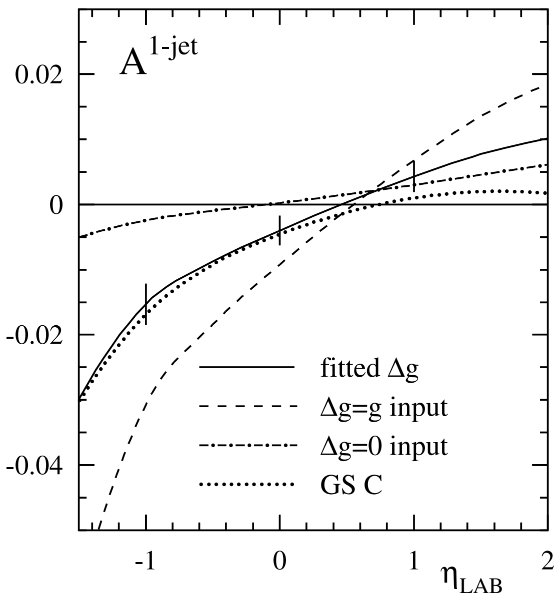

Figure 7: *Expected accuracy for photoproduction of large $P_\perp$ jets for a standard, small and large polarized gluon distribution, for the luminosity 100 pb^{-1}. For large values of the rapidity the result becomes sensitive to the resolved photon structure.*

Its large energy allows HERA to study also charged current events through e.g. the reaction

$$e + p \to \nu_e(\text{missing momentum}) + X \quad .$$

This requires high luminosity and was investigated in detail by the working group on 'Electroweak Physics'. The great advantage of charged current reactions is that here the spin asymmetries are large because W's couple only to left-handed currents. Thus the luminosity required to study spin asymmetries is not much larger than for the rest of the charged current program [17]. Also due to parity violation the charged current spin asymmetries couple primarily to a different structure function called $g_5(x, Q^2)$.

$$\begin{aligned} g_5^{W-}(x,Q^2) &= -\left(\Delta u - \Delta\bar{d} + \Delta c - \Delta\bar{s} \ + \ ...\right)(x,Q^2) \\ g_5^{W+}(x,Q^2) &= -\left(\Delta d - \Delta\bar{u} + \Delta s - \Delta\bar{c} \ + \ ...\right)(x,Q^2) \end{aligned} \tag{3}$$

More precisely the inclusive CC cross section asymmetry is given by

$$A_{CC} = \frac{d\sigma^{\uparrow\downarrow} - d\sigma^{\uparrow\uparrow}}{d\sigma^{\uparrow\downarrow} + d\sigma^{\uparrow\uparrow}} = \frac{a g_5^{W^\pm} + b g_1^{W^\pm}}{a F_1^{W^\pm} + b F_3^{W^\pm}} \tag{4}$$

with $a = 2(2 - 2y + y^2)$ and $b = y(2 - y)$. Obviously g_5 has no singlet part and is therefore not at all sensitive to ΔG. g_1 has a singlet part, but its contribution is strongly suppressed (y is much smaller than one for most reactions). Therefore CC spin asymmetries would serve primarily to extract information on the valence quark spin decomposition. Knowing the valence quark distributions and the combined valence and sea contributions to g_1 from usual DIS fixes, however, also the sea distribution functions and the associated anomalous gluon contribution. Note that at HERA the valence quark distributions would be measured at very large Q^2, whereas HERMES measures them at small Q^2. This would open the very exciting possibility to follow the Q^2-evolution of the quark spin decompostion in detail. The expected statistical accuracy is shown in figure 8 for various Q^2 bins as a function of x. Especially the W$^-$ asymmetries, obtained for an electron beam look very good, because the polarized valence up-quark distribution is much larger than the down-quark one. The imposed Q^2-cut depends on the experimental requirements to detect unambigously the missing momentum carried by the neutrino. Recent unpolarized experiments at ZEUS suggest that this cut could be chosen as small as 200 GeV^2 which would improve the statistics still further.

A possibility to obtain results for the singlet spin distribution in CC events is to detect D mesons in the final state. The resulting spin asymmetries are proportional to $-(\Delta\bar{s} + \tan^2(\theta_c)\Delta\bar{d})/(\bar{s} + \tan^2(\theta_c)\bar{d})$ respectively $(\Delta s + \tan^2(\theta_c)\Delta d)/(s + \tan^2(\theta_c)d)$. Here θ_c is the Cabbibo mixing angle. A sensitive determination of these quantities requires, however, a luminosity of 1000 pb^{-1} [17]. Let us finally add that by comparing semi-inclusive CC pion-asymmetries and inclusive CC asymmetries one can investigate in a very clean manner the possible spin-dependence of fragmentation, which is probably the principle theoretical uncertainty in all semi-inclusive spin experiments.

There are many more interesting quantities one could investigate in principle. However, for many of them the advantages of HERA with respect to planned lower energy experiments is not obvious, so that we do not want to discuss them here in detail. However, they would be part of the extensive spin program once a polarized HERA would be available. Such experiments include the measurement of new, up to now basically unstudied structure and fragmentation functions of leading and higher twist, an improved determination of the low-x contribution to Bjorken sum rule, which will probably in the end serve to get a more precise measurement of α_s (see the contribution by Gardi et al.), studies of spin dependent nuclear effects for deuterium and ^{3}He which would allow to test current ideas on shadowing (Strikman), and the search for T-violating effect (Gehrmann). As an example let us mention that at a polarized HERA it would be possible to study the spin dependence of diffractive processes, or loosly speaking the spin-flip coupling of the pomeron. Existing models and expert opinions differ substantially when it comes to the question how large the spin dependence could be for various observables. This topic obviously needs much further study, see the contribution of Goloskokov.

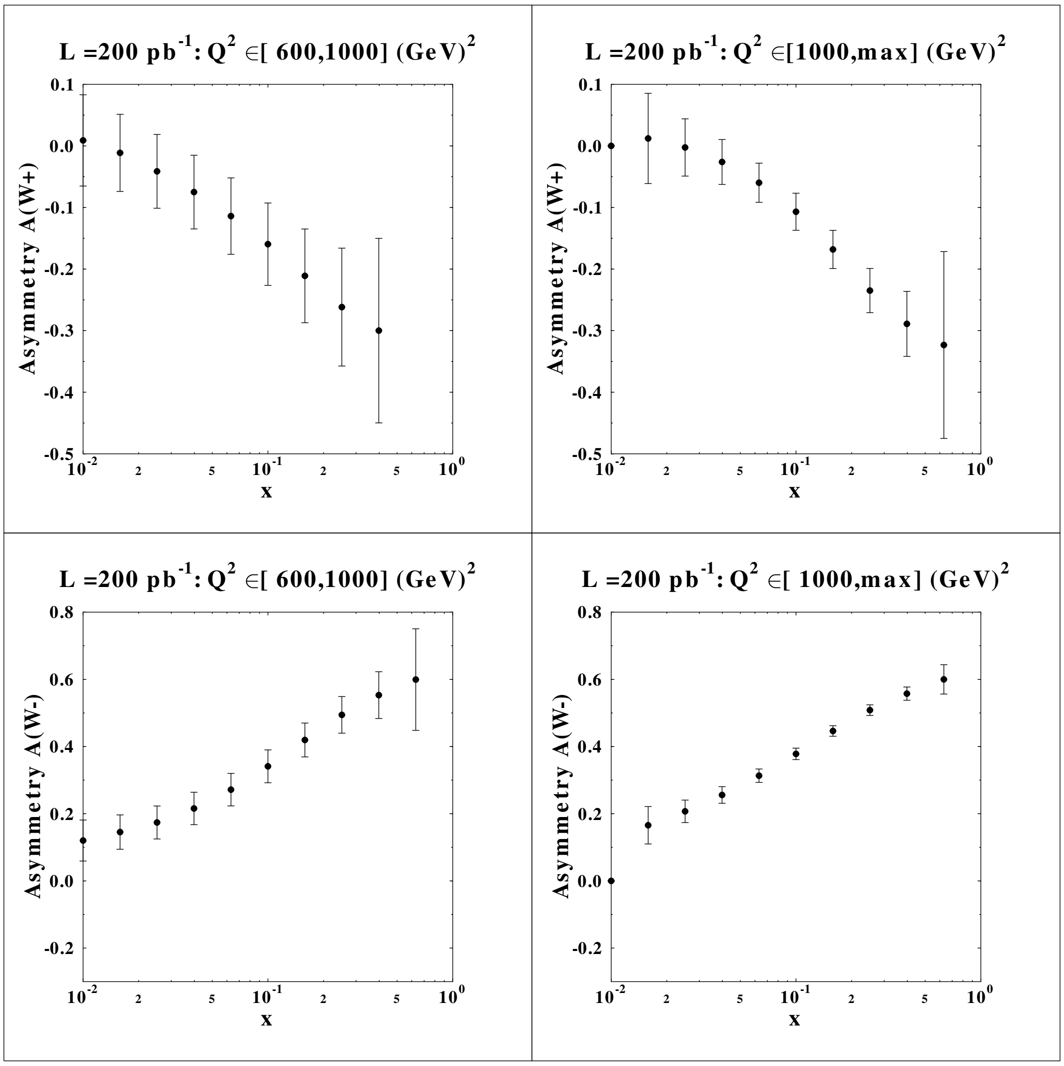

Figure 8: *Expected statistical accuracy for a standard HERA run (luminosity 200 pb^{-1}, i.e. 100 pb^{-1} per relative polarization, and and fully polarized beams) for the CC spin asymmetries for a positron and electron beam.*

4 Polarized proton-proton collisions - HERA-$\vec{N}$

One idea entering the construction of the presently running spin experiment HERMES at HERA was the option to eventually rotate it by 180 degrees and to use it as spectrometer for fixed target proton-proton physics, either double-polarized (target plus beam polarization) or single-polarized (only target polarization) [18]. The Hermes detector could not, however, handle the counting rates expected for a high-luminosity run and its angular acceptance would be too small. For this purpose one rather needed a detector of the HERA-B type. High luminosities are in fact indispensible for such an experiment to be competitive with the RHIC spin program which investigates very similar physics at comparable energies, see next section.
Polarised proton-nucleon collisions open a still wider field of phenomena than polarized lepton-nucleon reactions. Even with an unpolarized proton beam one can investigate a quite large number of single-spin asymmetries, the sizes of which are proportional to well defined twist-3 correlators. Knowledge of such correlators constraints strongly the internal nucleon wave func-

tion and thus can lead to a much better understanding of the nucleon structure. However, presently one cannot make optimal use of this possibility because those higher-twist asymmetries which can be calculated rigorously from QCD turn out to be small, typically of the order percent [19], and those which are found experimentally to be large, like single spin pion production [20], see figure 9, involve complicated fragmentation effects and are not yet understood theoretically. HERA would measure this latter effect up to much higher transverse momentum. The asymmetry which is for the present data still growing with $p_\perp$ should finally bend over and go to zero. How and where this happens is crucial to understand this fascinating effect.

In the following we shall only comment on the twist-2 observables which are less difficult to

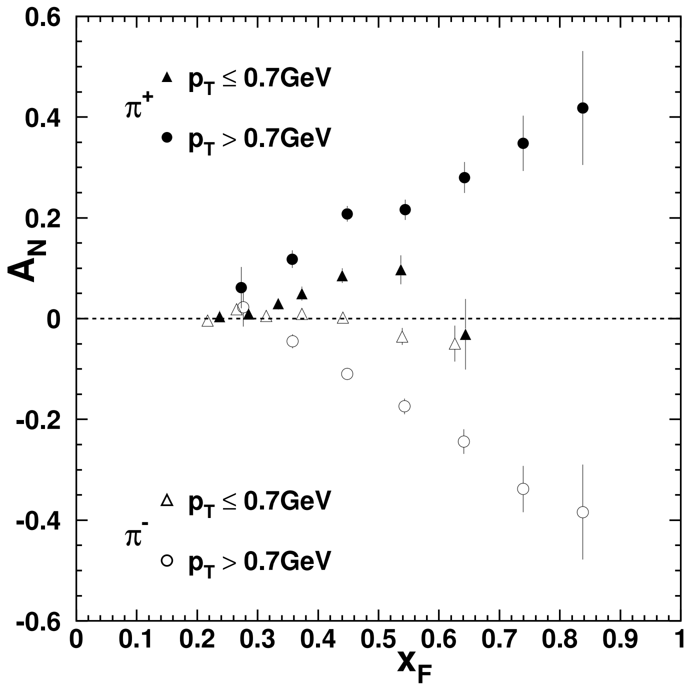

Figure 9: *The large observed single-spin pion asymmetry [20]*

measure and interpret, which require, however, both a polarized target and a polarized beam. The main aim of such experiments is to extract information on the polarized gluon distribution $\Delta G(x, Q^2)$ just as for the jet-spin asymmetries in polarized lepton-proton reactions. The sensitive x-range lies in this case between 0.1 and 0.4, such that these experiments would complement the jet-experiments in an ideal manner. Together they would cover all of the interesting x-range. In principle there are quite a number of spin dependent observables, but most of them are theoretically not very clean, more precisely the quality of the result is not only a question of statistics but also of the theoretical uncertainties. One has to rely to a large extent on the Monte-Carlo codes which are used and one can only compare the predictions for different parametrizations of the spin dependent structure functions rather than extracting the quantities of interest directly from the data. For the envisaged fixed target HERA experiment we confined our studies to reactions like $\vec{p} + \vec{p} \to \gamma + X$ and $\vec{p} + \vec{p} \to \gamma + \text{jet} + X$.

The physical origin of all discussed asymmetries is very similar. In each case the dominant contribution comes from the Compton processes $q^\uparrow + G^\downarrow \to q + \gamma$ and $q^\uparrow + G^\downarrow \to q + G$. In both cases the polarized quark cannot absorb a gluon which is polarized in the same direction and this results in a spin-asymmetry. For direct photons the cross section reads e.g.

$$E_\gamma \frac{d^3\Delta\sigma(pp \to \gamma X)}{d^3p_\gamma} \approx \sum_q \int dx_a dx_b \left\{ \Delta q(x_a) \Delta G(x_b) E_\gamma \frac{d^3\Delta\sigma(qG \to \gamma X)}{d^3p_\gamma} + (x_a \leftrightarrow x_b) \right\} + ... \tag{5}$$

If also the jet of the outgoing quark in the Compton graph is detected one obtains a signal which is not only proportional to a convolution of $\Delta G(x)$, but to $\Delta G(x)$ directly. The corrections due to misidentifications of the quark-jet have to be calculated reliably enough with Monte-Carlo to keep the systematic error smaller than the statistical one. The resulting signal is shown in figure 10, together with the expectation for RHIC. Obviously the anticipated accuracy is impressive for the asumed luminosity of 320 pb^{-1}. The limiting factor for the luminosity is in this case the degradation of the beam. Thus the scope of experiments which could be done

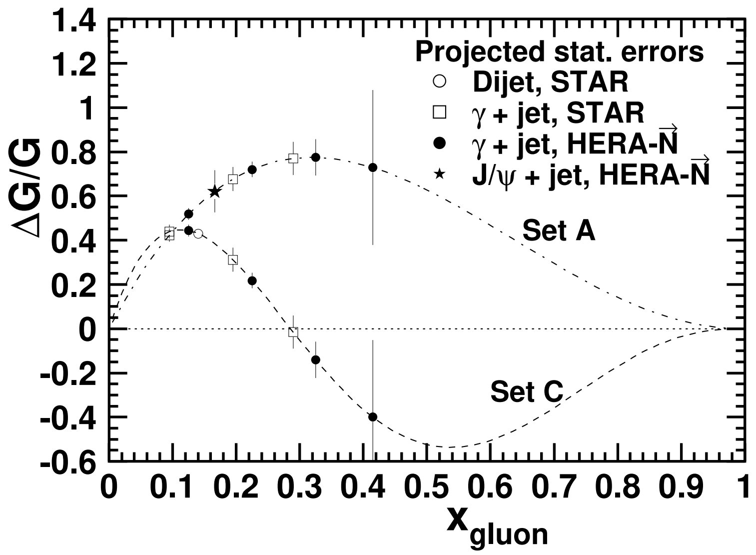

Figure 10: *Expected statistical accuracy for the determination of* $\Delta G(x)$ *from* $\vec{p}+\vec{p} \to \gamma+\text{jet}+X$, *assuming a luminosity of 320 pb*$^{-1}$ *and an optimized detector.*

with polarized proton-nucleon collisions at HERA is large and the expected results are quite impressive. However, such experiments would require an additional dedicated detector rather similar to HERA-B. Alternatively such experiments could be done in some far future, after the original program of HERA-B is finished, using that detector, but by then most interesting questions will possibly have already been answered by RHIC.

5 Comparison with other projects in spin physics

Hadronic spin physics is presently one of the most active fields of QCD which is also reflected by the fact that nearly all great laboratories have running experiments and discuss improved ones for the future. At DESY the HERMES fixed target experiment is running and should provide very interesting results on the quark spin decomposition by analysing semi-inclusive reactions. Measuring spin asymmetries in $\pi^\pm$ production will provide information of the valence quarks and the difference between inclusive asymmetries and semi-inclusive pion asymmetries is sensitive to the sea quark polarisation. Thus these experiments should provide combinations of polarised distribution functions, which are linearly independent from both $g_1(x)$ measured so far and $g_5(x)$, which could be measured in CC spin asymetries. This possibility, especially open charm production, is one of the major aims of the COMPASS project at CERN, which is planned to be an improved version of SMC combined with a hyperon experiment. Such an experiment would also improve the data on $g_1(x, Q^2)$ and thus the precision with which $\Delta G(x, Q^2)$ can be predicted from NLO-fits, it could analyse Λ-polarisation as a signal for Δs, it could improve substantially the accuracy of $g_2(x, Q^2)$, look for semi-inclusive asymmetries, and could possibly determine h_1. A similar project is discussed for SLAC. If realized these projects will provide partial answers to the questions addressed by a polarized HERA. Depending on their outcome these experiments might lead to a still further increased interest in the HERA experiments under discussion. It should be kept in mind that our present understanding of the nucleon spin structure is based on a consistent model but not on unambigous facts. The detailed studies planned for the future could very well lead to surprising results. Also these projects are not yet funded. In any case, due to its high energy the HERA experiments are complementary to these fixed target experiments.

This is also true for the RHIC spin program. Again the interest is concentrated on $\Delta G(x)$, however RHIC is rather sensitive in the x-range of the fixed target lepton-experiments (see figure 10) than in the low-x range covered by the HERA jet experiments. One should also note that RHIC can investigate the production of $W^{\pm}$ via the Compton-graph, a process which is theoretically much cleaner. We would like to stress, however, that it is a vital check to show that both, DIS experiments and proton-proton experiments can be described by the same distribution functions. Only this would prove that one really understands the physics. Therefore, one definitely needs both types of experiments. According to theoretical predictions and Monte Carlo studies and in view of the fact that it is already funded RHIC will eventually measure $\Delta G(x)$ at large x, the main open question is when it will happen. This is hard to predict because it depends, in additon to all the usual imponderabilities, on the relative priority given to the heavy ion experiments and the spin experiments. It seems realistic to assume that the time scales of the RHIC spin physics experiments and experiments with a polarized HERA would be rather similar.

Thus we conclude that in spite of the many other ongoing activities HERA would provide most relevant results, especially if polarization would be realized in the not too far future.

6 Conclusions

Spin physics provides possibly the best testing ground for QCD, especially if one is interested in effects beyond standard leading twist perturbation theory. This is mainly due to the large number of observables and the possibility to extract well defined quantities by constructing specific ratios or differences of ratios. To the extent that HERA aims at a better understanding of QCD the many options opened by a polarized nucleon beam are certainly most attractive. Some of the informations which could be deduced from HERA experiments cannot be obtained by any other existing or planned experiment and for many others HERA would be competitive or complementary to experiments at lower energy.

To make full use of these possibilities requires, however, very substantial machine upgrades. One needs about 200 pb^{-1} of luminosity with electron and proton polarization fulfilling $P_e \cdot P_p = 0.5$. To use the full potential of a polarized HERA one needs furthermore polarized proton, ^{3}He and (best of all but also most difficult) polarized deuteron beams. In addition the charged current experiments would profit from having an electron as well as a positron beam.

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