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Summary of Physics Prospects for Polarized Nucleon-Nucleon Scattering at HERA- \vec{N} [★]

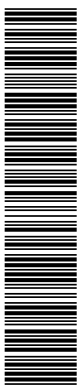
V.A. Korotkov ^{a,b}, W.-D. Nowak ^a

^a*DESY-IfH Zeuthen, D-15735 Zeuthen, Germany*

^b*IHEP, RU-142284 Protvino, Russia*

The physics scope of polarized nucleon–nucleon collisions originating from an internal polarized target in the HERA proton beam is summarized. Based on 240 pb^{-1} integrated luminosity at 40 GeV c.m. energy, statistical sensitivities are given over a wide (x_F, p_T) –range for a variety of inclusive and exclusive final states. By measuring single spin asymmetries unique information can be obtained on higher twist contributions and their p_T -dependence. From double spin asymmetries in both photon and J/ψ production it appears possible to measure the polarized gluon distribution in the range $0.1 \leq x_{gluon} \leq 0.4$ with a good statistical accuracy. Drell-Yan pair production asymmetries in doubly longitudinal mode, measurable in the mass range $3 \div 10 \text{ GeV}$, allow discrimination between different parametrizations of the polarized light sea quark distributions. In doubly transverse mode access to the quark transversity distribution might become possible. Statistically significant results can be expected in the elastic channel.

[★] Invited talk presented by W.-D. Nowak at the 2nd ELFE Workshop (St. Malo, September 1996).



1 Introduction

A complete theoretical picture of the nucleon structure will certainly have to incorporate the polarization degree of freedom, both in its perturbative and non-perturbative aspects. Although a largely consistent scheme exists since some time within the framework of perturbative Quantum Chromodynamics (pQCD) to describe short distance processes in strong interactions, the long distance scales are far from being fully understood in QCD even when appreciating the considerable progress made in recent lattice calculations (see e.g. [1]). Spin measurements have always been sources of unexpected surprises; the most recent example given by the simple and hitherto successful Quark Parton Model which could not describe the nucleon spin structure ('spin crisis') [2]. This caused a lot of theoretical papers and the recent next-to-leading order calculations [3] were found to reconcile the QCD improved Quark Parton Model with the results of the experiments. However, it is fair to say that the present knowledge of the polarized gluon distribution is still completely insufficient and the same applies to the polarized sea. No measurements exist yet on polarized quark distributions in case of transverse nucleon polarization.

The 'spin crisis' induced enormous theoretical and experimental activities. A number of new experiments was proposed to investigate in more detail the longitudinal spin structure of the nucleon by measuring double spin asymmetries in lepton nucleon collisions. Several measurements are already completed (E142 [4] and E143 [5] at SLAC) and some are still taking and/or analysing data (SMC [6] at CERN and E154 [7] at SLAC). Others have just started (HERMES [8] at DESY) or will start data taking soon (E155 [9] at SLAC). Nevertheless, it has to be mentioned that purely inclusive measurements determining the longitudinal spin structure functions $g_1(x, Q^2)$ for proton, neutron, and deuteron are unfortunately restricted to probe only certain combinations of the polarized valence, sea, and gluon contributions to the nucleon spin. A full analysis would require additional inputs from other measurements to separate the different components.

With the target polarization vector being oriented perpendicularly to the beam direction the transverse spin structure of the nucleon becomes partly accessible by measuring the spin structure functions $g_2(x, Q^2)$ which contain a twist-3 part that has recently been probed by SMC [10] and E143 [11], although still with large error bars. We note here that the underlying QCD correlators are at the same time describing the expected performance of single spin asymmetries measurable in nucleon-nucleon collisions [12].

Semi-inclusive measurements with SMC [13] and HERMES [8] will allow access to a variety of (combinations of) polarized parton distributions and to some polarized fragmentation functions. However, direct and separate measurements of the polarized gluon and sea quark distributions will remain of limited significance for quite some years.

An experiment ('HERA- \vec{N} ' [15]) utilising an internal polarized nucleon target in the 820 GeV HERA proton beam would constitute a natural extension of the studies of the nucleon spin structure in progress at DESY with the HERMES experiment [8]. Conceivably, this would be the only place where to study high energy nucleon-nucleon spin physics besides the dedicated RHIC spin program at BNL [16] supposed to start early in the next decade.

An internal polarized nucleon target offering unique features such as polarization above 80% and no or small dilution, can be safely operated in a proton ring at high densities up to 10^{14} atoms/cm² [17]. As long as the polarized target is used in conjunction with an unpolarized proton beam, the physics scope of HERA- \vec{N} would be focused to 'phase I', i.e. measurements of single spin asymmetries. Once later polarized protons should become available, the same set-up would be readily available to measure a variety of double spin asymmetries. These 'phase II' measurements would constitute an alternative – fixed target – approach to similar physics which will be accessible to the collider experiments STAR and PHENIX at the low end of the RHIC energy scale ($\sqrt{s} \simeq 50$ GeV) [14].

We recall [15] that the integrated luminosity calculation is based upon realistic figures. For the average beam and target polarisation $P_B = 0.6$ and $P_T = 0.8$ are assumed, respectively. A combined trigger and reconstruction efficiency of $C \simeq 50\%$ is anticipated. Using $\bar{I}_B = 80$ mA = $0.5 \cdot 10^{18}$ s⁻¹ for the average HERA proton beam current (50% of the design value) and a rather conservative polarized target density of $n_T = 3 \cdot 10^{13}$ atoms/cm² the projected integrated luminosity becomes $\mathcal{L} \cdot T = 240$ pb⁻¹ when for the total running time T an equivalent of $T = 1.6 \cdot 10^7$ s at 100 % efficiency is assumed. This corresponds to about 3 real years under present HERA conditions. At present there are no arguments that the HERA design current of 160 mA should not be reachable in the polarized mode, as well. In addition, experience from UA6 running at CERN shows that after having gained some practical running experience it presumably becomes feasible to operate the polarized gas target at about 3 times higher density without seriously affecting the proton beam lifetime. Hence in a few years even 500 pb⁻¹ *per year* might presumably become a realistic figure. The sensitivities shown in the rest of the paper are calculated based upon 240 pb⁻¹.

This paper intends to present a summary of the activities undertaken so far to study the physics scope and the experimental possibilities when placing an internal polarized target into the (polarized) HERA proton ring. In principle there exist three different future options to study polarized nucleon-nucleon interactions in fixed target mode at HERA. One obvious possibility would be to equip the future HERA West Hall experiment HERA-B [18] with a polarized internal target once the approved physics program be concluded. The spectrometer, under assembly at present, will have a rather large acceptance, a huge rate capability, and a quite complete particle identification system.

Secondly, in the East Hall about 40% of the floor is occupied by the HERMES experiment whose rather limited aperture poses, however, considerable constraints onto the nucleon–nucleon spin physics menu. Nevertheless, rotating the whole set–up by π and moving it into the proton beam line was kept as an option in the HERMES design from the beginning, although the high rate in the proton beam would require considerable upgrades. Last but not least, the remaining free space in the East Hall could be used for a completely new experiment in the proton beam line which could be specifically designed according to the spin physics requirements. However, at the moment any site discussion appears premature and hence this study aims at being as much as possible independent of a final site decision.

2 Single Spin Asymmetries

Single spin asymmetries in large p_T inclusive production, both in proton-nucleon and lepton-nucleon interactions, have recently received much attention (for references see [19]). The naive expectation that they should be zero in perturbative QCD has been proven to be false, both experimentally and theoretically. It is now clear that higher twist effects are responsible for these asymmetries, which should be zero only in leading twist-2 perturbative QCD. Several models and theoretical analyses suggest possible higher twist effects: there might be twist-3 dynamical contributions, which we shall denote as hard scattering higher twists; there might also be intrinsic k_\perp effects, both in the quark fragmentation process and in the quark distribution functions. The latter are not by themselves higher twist contributions - they are rather non-perturbative universal nucleon properties - but give rise to twist-3 contributions when convoluted with the hard scattering cross sections. The dynamical contributions result from a short distance part calculable in perturbative QCD with slightly modified Feynman rules, combined with a long distance part related to quark-gluon correlations.

An intrinsic k_\perp effect in the quark fragmentation is known as Collins or sheared jet effect; it simply amounts to say that the number of hadrons h (say, pions) resulting from the fragmentation of a transversely polarized quark, with longitudinal momentum fraction z and transverse momentum \mathbf{k}_\perp , depends on the quark spin orientation. That is, one expects the *quark fragmentation analysing power* $A_q(\mathbf{k}_\perp) \equiv (D_{h/q\uparrow}(z, \mathbf{k}_\perp) - D_{h/q\downarrow}(z, \mathbf{k}_\perp)) / (D_{h/q\uparrow}(z, \mathbf{k}_\perp) + D_{h/q\downarrow}(z, \mathbf{k}_\perp))$ to be different from zero, where, by parity invariance, the quark spin should be orthogonal to the $q-h$ plane. Notice also that time reversal invariance does not forbid such quantity to be $\neq 0$ because of the (necessary) soft interactions of the fragmenting quark with external strong fields, i.e. because of final state interactions. This idea has been applied to the computation of the single spin asymmetries observed in $pp^\uparrow \rightarrow \pi X$ [20].

A similar idea applies to the distribution functions, provided soft gluon interactions between initial state partons are present and taken into account, which most certainly is the case for hadron-hadron interactions. That is, one can expect that the number of quarks with longitudinal momentum fraction x and transverse intrinsic motion \mathbf{k}_\perp depends on the transverse spin direction of the parent nucleon, so that the *quark distribution analysing power* $N_q(\mathbf{k}_\perp) \equiv (f_{q/N^\uparrow}(x, \mathbf{k}_\perp) - f_{q/N^\downarrow}(x, \mathbf{k}_\perp)) / (f_{q/N^\uparrow}(x, \mathbf{k}_\perp) + f_{q/N^\downarrow}(x, \mathbf{k}_\perp))$ can be different from zero. This effect also has been used to explain the single spin asymmetries observed in $pp^\uparrow \rightarrow \pi X$ [21].

As mentioned above, both $A_q(\mathbf{k}_\perp)$ and $N_q(\mathbf{k}_\perp)$ are leading twist quantities which, when convoluted with the elementary cross-sections and integrated over \mathbf{k}_\perp , give twist-3 contributions to the single spin asymmetries.

Each of the above mechanisms might be present and important in understanding twist-3 contributions; in particular the quark fragmentation or distribution analysing powers look like new non-perturbative universal quantities, crucial in clarifying the spin structure of nucleons. It is then of great importance to study possible ways of disentangling these different contributions in order to be able to assess the importance of each of them. We propose here to measure the single spin asymmetry, $(d\sigma^{AB^\uparrow \rightarrow CX} - d\sigma^{AB^\downarrow \rightarrow CX}) / (d\sigma^{AB^\uparrow \rightarrow CX} + d\sigma^{AB^\downarrow \rightarrow CX})$ in several different processes $AB^\uparrow \rightarrow CX$ which should allow to fulfil such a task. To obtain a complete picture we need to consider nucleon-nucleon interactions together with other processes, like lepton-nucleon scattering, which might add valuable information. For each of them we discuss the possible sources of higher twist contributions, distinguishing, according to the above discussion, between those originating from the hard scattering and those originating either from the quark fragmentation or distribution analysing power.

- $pN^\uparrow \rightarrow hX$: all kinds of higher twist contributions may be present; this asymmetry *alone* could not help in evaluating the relative importance of the different terms.
- $pN^\uparrow \rightarrow \gamma X$, $pN^\uparrow \rightarrow \mu^+\mu^-X$, $pN^\uparrow \rightarrow jets + X$: no fragmentation process is involved and we remain with possible sources of non-zero single spin asymmetries in the hard scattering or the quark distribution analysing power.
- $lN^\uparrow \rightarrow hX$: a single spin asymmetry can originate either from hard scattering or from k_\perp effects in the fragmentation function, but not in the distribution functions, as soft initial state interactions are suppressed by powers of α_{em} .
- $lN^\uparrow \rightarrow \gamma X$, $\gamma N^\uparrow \rightarrow \gamma X$, $lN^\uparrow \rightarrow \mu^+\mu^-X$, $lN^\uparrow \rightarrow jets + X$: a single spin asymmetry in any of these processes may only be due to higher-twist hard scattering effects.

It is clear from the above discussion that a careful and complete study of single spin asymmetries in several processes might be a unique way of understanding the origin and importance of higher twist contributions in inclusive hadronic interactions; not only, but it might also allow a determination of fundamental non-perturbative properties of quarks inside polarized nucleons and of polarized quark fragmentations. Such properties should be of universal value and applicability and their knowledge might be as important as the knowledge of unpolarized distribution and fragmentation functions.

In the following we discuss the capability of HERA- \vec{N} to investigate single spin asymmetries.

Inclusive pion production $p^\uparrow p \rightarrow \pi^{0\pm} X$ at 200 GeV exhibits surprisingly large single spin asymmetries, as it was measured a few years ago by the E704 Collaboration using a transversely polarized beam [22]. For any kind of pions the asymmetry A_N shows a considerable rise above $x_F > 0.3$, i.e. in the fragmentation region of the polarized nucleon. It is positive for both π^+ and π^0 mesons, while it has the opposite sign for π^- mesons. The charged pion data taken in the $0.2 < p_T < 2$ GeV range were split into two samples at $p_T = 0.7$ GeV/c; the observed rise is stronger for the high p_T sample, as can be seen from fig. 1.

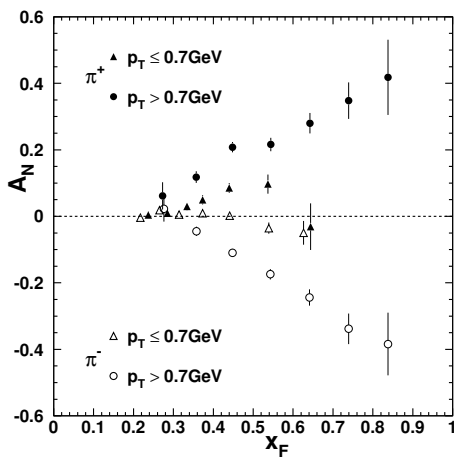


Fig. 1. Single spin asymmetry in inclusive pion production $p^\uparrow + p \rightarrow \pi^{0\pm} + X$ measured by the E704 Collaboration [22] and shown for two subregions of p_T .

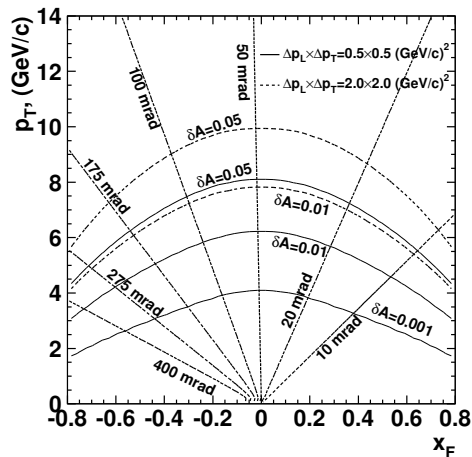


Fig. 2. Asymmetry sensitivity levels for π^+ production in the (p_T, x_F) plane. Laboratory angles of the pions are shown.

Contours characterizing different HERA- \vec{N} sensitivity levels ($\delta A_N = 0.001, 0.01$ and 0.05) for an asymmetry measurements in the reaction $pp^\uparrow \rightarrow \pi^+ X$ are shown in fig. 2. Note that in the large p_T region the contours calculated with big $\Delta p_L \times \Delta p_T$ bins are appropriate, since usually a larger bin size is chosen where the statistics starts to decrease. We can conclude that the ac-

cessible p_T values are significantly larger than those E704 had; the combined p_T dependence of all involved higher-twist effects can be measured with good accuracy ($\delta A_N \leq 0.05$) up to transverse momenta of about 10 GeV/c in the central region $|x_F| < 0.2$ and up to 6 GeV/c in the target fragmentation region. This corresponds to an almost one order of magnitude extension in the p_T range in comparison to E704. The capability of HERA- \vec{N} to really prove a predicted p_T dependence is shown in fig. 3, where the curve was obtained assuming a non-zero quark distribution analysing power, $N_q(\mathbf{k}_\perp)$, according to Ref. [21].

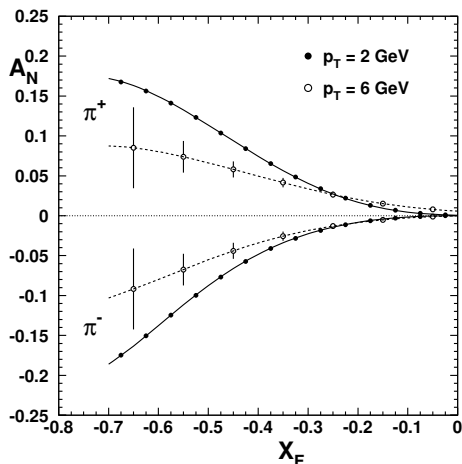


Fig. 3. Capability of HERA- \vec{N} to discriminate predictions for different p_T .

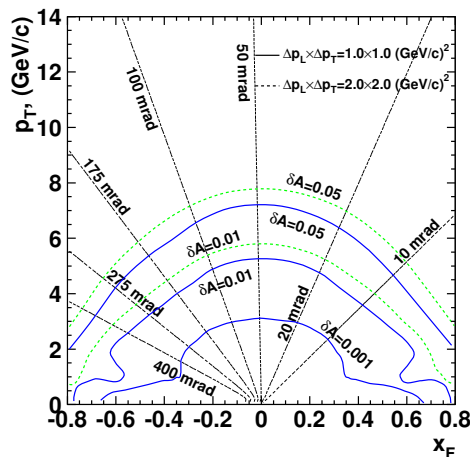


Fig. 4. Asymmetry sensitivity levels for photon production in the (p_T, x_F) plane. Laboratory angles of the photons are shown.

The study of polarization asymmetries in **vector meson production** is especially attractive as these particles are produced ‘more directly’ in comparison to pions which are mainly decay products of heavier particles. Comparing asymmetries in vector and pseudoscalar meson production can provide information on the magnitude of the asymmetry in quark scattering [23]. If the asymmetry is generated only during the fragmentation of polarized quarks [20], the asymmetry of ρ mesons is expected to be opposite in sign to that of pions, $R_{\rho/\pi} = A_N^\rho/A_N^\pi \simeq -\frac{1}{3}$. On the contrary, if the quark scattering asymmetry were the dominating one, the asymmetries of pseudoscalar and vector mesons would not differ substantially. Note that $R_{\rho/\pi} \neq -\frac{1}{3}$ could also mean a violation of the non-relativistic quark model, which was assumed in the calculation of the asymmetry. Although HERA- \vec{N} specific projected errors remain to be calculated, significant results can be expected over a wide kinematical region due to abundant production of vector mesons.

Inclusive direct photon production, $pp^\dagger \rightarrow \gamma X$, proceeds without fragmentation, i.e. the photon carries directly the information from the hard scattering process. Hence this process measures a combination of initial \mathbf{k}_\perp effects and hard scattering twist-3 processes. The first and only results up to now were obtained by E704 Collaboration [24] showing an asymmetry compatible with zero within large errors for $2.5 < p_T < 3.1$ GeV/c in the central region $|x_F| \lesssim 0.15$.

The experimental sensitivity of HERA- \vec{N} (see fig. 4) was determined using cross-section calculations of the two dominant hard subprocesses contributing to direct photon production, i.e. gluon-Compton scattering ($qg \rightarrow \gamma q$) and quark-antiquark annihilation ($q\bar{q} \rightarrow \gamma g$), and of background photons that originate mainly from π^0 and η decays. It turns out that a good sensitivity (about 0.05) can be maintained up to $p_T \leq 8$ GeV/c. For increasing transverse momentum the annihilation subprocess and the background photons are becoming less essential; we expect to be able to detect a clear dependence on p_T , of the direct photon single spin asymmetry.

The single spin asymmetry in **Drell-Yan production**, $p + p^\dagger \rightarrow l\bar{l} + X$, at small transverse momenta was calculated [25] in the framework of twist-3 pQCD at HERA- \vec{N} energy. The resulting asymmetry which does not exceed 2% depends strongly on the kinematical domain; in fig. 5 it is shown as a function of one of the lepton's polar angle for a particular kinematical situation, where the momentum fraction of the scattered quark was chosen as $x = 0.5$ and the dilepton mass was fixed at $M^2 = 10$ GeV².

Inclusive J/ψ production was calculated in the framework of the colour singlet model [26]. The calculations at HERA- \vec{N} energy [19] show an asymmetry less than 0.01 in the region $|x_F| < 0.6$, i.e. the effect is practically unobservable.

Summarizing the prospects for the measurement of single spin asymmetries in inclusive reactions we conclude that an asymmetry size of a few percent seems to be a 'canonical' order of magnitude for single spin asymmetries calculable in present twist-3 pQCD rather independent on the specific final state [27]. Nevertheless, one may expect larger predictions when combining the pure pQCD effects with non-zero transverse momenta in both the distribution and the fragmentation functions. We note that asymmetries on the few percent level are difficult to measure, even with sufficiently small statistical errors, since the systematic error originating mainly from beam and target polarization measurements constitutes a severe limit.

Large spin effects in **proton-proton elastic scattering**, $p + p^\dagger \rightarrow p + p$, have been discovered many years ago. The single spin asymmetry A_N was found significantly different from zero as it is shown in fig. 6 in conjunction with the projected HERA- \vec{N} statistical errors. At HERA- \vec{N} energy the detection

of the recoil proton for p_T^2 values in the range $5 \div 12$ (GeV/c)² requires a very large angular acceptance (up to 40 degrees) [19]. The forward protons for the same interval in p_T^2 have laboratory angles of the order of a few milliradians and require a dedicated forward detector very close to the beam pipe.

The transverse single spin asymmetry A_N in elastic pp scattering at HERA- \vec{N} and RHIC energies has been calculated in a dynamical model that leads to spin-dependent pomeron couplings [28]. The predicted asymmetry is about 0.1 for $p_T^2 = 4 \div 5$ (GeV/c)² with a projected statistical error of $0.01 \div 0.02$ for HERA- \vec{N} (cf. fig. 6), i.e. a significant measurement of the asymmetry A_N can be performed to test the spin dependence of elastic pp scattering at high energies.

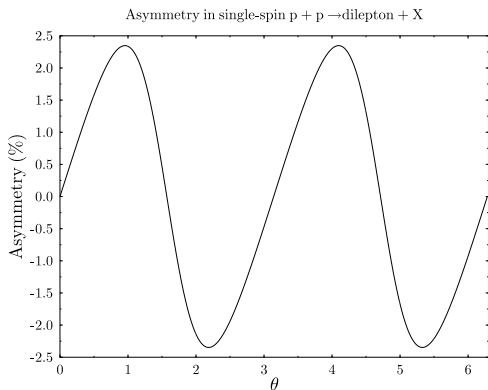


Fig. 5. *Single spin asymmetry in Drell-Yan pair production at HERA- \vec{N} energy, $x = 0.5$ and $M^2 = 10$ GeV².*

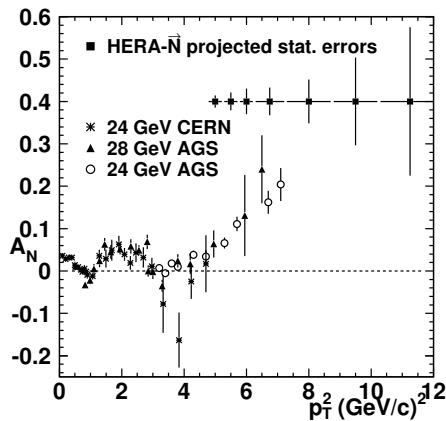


Fig. 6. *Single spin asymmetry in polarized proton-proton elastic scattering as a function of p_T^2 .*

3 Double Spin Asymmetries

Perturbative QCD allows for a simple calculation of Born double spin asymmetries for various $2 \rightarrow 2$ subprocesses at the partonic level. The one-loop radiative corrections to various subprocesses have now been calculated [29], they produce only small changes in the asymmetry in comparison with the leading order. Relying on factorization a rich spectrum of hadronic level asymmetries is predicted which constitutes the backbone of the RHIC spin physics program.

Still, the insufficient knowledge of the polarized parton distributions makes the predictions for double spin asymmetries to a large extent uncertain. Conversely, the measurement of double spin asymmetries in certain final states seems to be among the most valuable tools to eventually determine the polar-

ized parton distribution functions in the nucleon. The presently most accurate way to do so is the study of those processes which can be calculated in the framework of perturbative QCD, i.e. for which the involved production cross sections and subprocess asymmetries can be predicted. Production of *direct photon (plus jet)*, *J/ψ (plus jet)* and *Drell-Yan pairs* are most suited because there are only small uncertainties due to fragmentation.

Once having available a polarized proton beam at HERA, all possible combinations of beam and target polarization (*LL*, *TT*, *LT*) could be investigated at HERA- \vec{N} . This is especially interesting since it would open access to polarized parton distributions which cannot be studied in inclusive lepton DIS. In the following we discuss the capabilities of HERA- \vec{N} , operated in doubly polarized mode ('Phase II'), to perform such measurements.

Direct photon production in *pp* interactions is dominated by the quark-gluon Compton subprocess, $q(x_1) + g(x_2) \rightarrow \gamma + q$. Ignoring the integration over the kinematical domain the longitudinal double spin asymmetry can be written schematically in the simple form

$$A_{LL} = \frac{\sum_i e_i^2 [\Delta q_i(x_1) \Delta G(x_2) + (1 \leftrightarrow 2)]}{\sum_i e_i^2 [q_i(x_1) G(x_2) + (1 \leftrightarrow 2)]} \hat{a}_{LL}, \quad (1)$$

where \hat{a}_{LL} is the partonic asymmetry in the gluon Compton subprocess. The hadron level asymmetry A_{LL} is directly sensitive to the polarized gluon distribution. We note that in (any) *inclusive* production no direct relation can be established between the measured asymmetry A_{LL} and $\frac{\Delta G}{G}$.

In a recent study [30] **inclusive photon production** with HERA- \vec{N} was investigated. Basing on a NLO calculation rather firm predictions were obtained for A_{LL} including an assessment of the theoretical uncertainties; the latter turned out to be of rather moderate size. In fig.'s 7a and 7b three different predictions for the asymmetry are shown in dependence on p_T and pseudorapidity η , in conjunction with the projected statistical uncertainty of HERA- \vec{N} . As can be seen, there is sufficient statistical accuracy in a wide kinematical region to discriminate between different polarized gluon distribution functions.

Compared to direct photon production the production of $c\bar{c}$ quarkonium states, in particular **inclusive J/ψ production**, is a similarly clean tool to measure the polarized gluon distribution. For the production of quarkonia with p_T above 1.5 GeV the $2 \rightarrow 2$ subprocess $g(x_1) + g(x_2) \rightarrow (c\bar{c}) + g$ provides the main contribution. Consequently the asymmetry can be written as

$$A_{LL} = \frac{\Delta G(x_1)}{G(x_1)} \frac{\Delta G(x_2)}{G(x_2)} \hat{a}_{LL}. \quad (2)$$

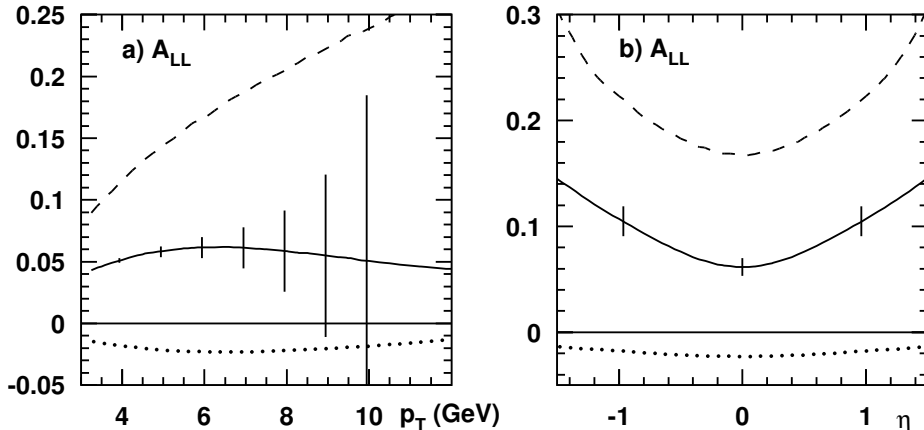


Fig. 7. Double spin asymmetry in inclusive photon production displayed vs. a) p_T and b) η for different polarized gluon distribution functions (see Ref. [30]), shown in conjunction with the projected statistical sensitivity of HERA- \vec{N} .

Because of the relatively large quark mass the $c\bar{c}$ production cross section and the expected asymmetry are supposed to be calculable perturbatively. The calculation of the longitudinal double spin asymmetry in ref. [31] takes into account both the color singlet and the color octet states of the $(c\bar{c})$ -pair. The long distance matrix elements responsible for evolving the color octet $(c\bar{c})$ state into a charmonium were extracted from experimental data.

In fig.'s 8a and 8b the expected asymmetry is presented versus p_T and η for two different polarized gluon distributions from ref.[32]; apparently a very good discrimination between different sets is possible over the HERA- \vec{N} kinematical range. Fig. 8a shows also that the color octet mechanism gives the main contribution to the J/ψ production asymmetry at HERA- \vec{N} energy.

For comparison the expected double spin asymmetries for J/ψ production at RHIC energies were calculated [33]. In fig. 9 predictions at HERA- \vec{N} and two different RHIC energies are shown in conjunction with the projected statistical errors calculated by integration of the differential cross sections over p_T with bins of $\Delta p_T = 0.5$ GeV. In the statistically accessible p_T interval the asymmetry ranges between 0.08 and 0.04 at HERA- \vec{N} , but only between 0.01 and 0.03 at RHIC energies. Comparing both ranges and taking into account the above mentioned limitations by systematic errors it is likely that the fixed target experiment might accomplish a more significant measurement of the charmonium production asymmetry.

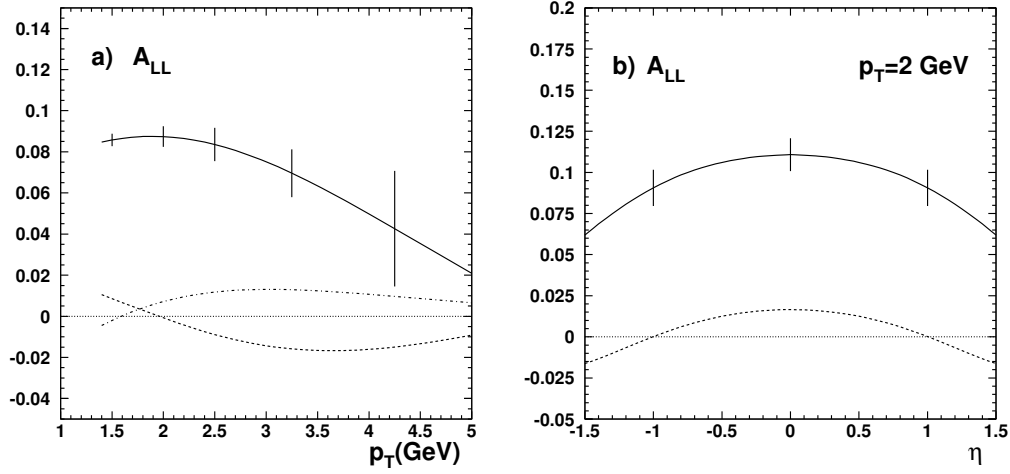


Fig. 8. Double spin asymmetry in inclusive J/ψ production displayed vs. a) p_T and b) η for LO set A (full line) and set C (dashed line) of Ref. [32], shown in conjunction with the projected statistical sensitivity of HERA- \vec{N} . The dash-dotted line in a) represents the color singlet contribution to the asymmetry.

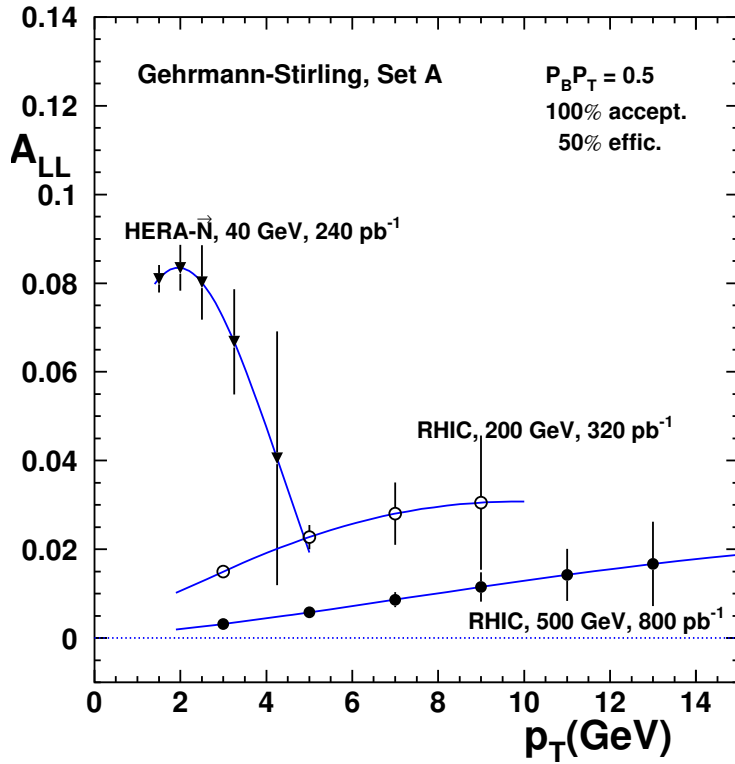


Fig. 9. Transverse momentum dependence of the expected asymmetries and projected statistical errors for J/ψ production at HERA- \vec{N} and for two different energies at RHIC.

Photon or J/ψ Production Associated with Jets. The complete kinematics of the $2 \rightarrow 2$ subprocess can be reconstructed if the away-side jet in the production of photon or J/ψ is measured as well. In this case the asymmetry A_{LL} can be directly related to the polarized gluon distribution if a certain subprocess can be selected (for more details see Ref. [19]).

The measurement of double spin asymmetries in *photon (or J/ψ) plus jet* production requires rather similar scattering angles for both emerging ‘partons’ in the laboratory system. Especially the jet must not escape under too small angles, otherwise it can not be detected efficiently under the given fixed target conditions (for more details see Ref. [19]). Hence a rather forward oriented detector with good granularity down to scattering angles of $10 \div 20$ mrad is required.

Using this approach **photon plus jet** production was discussed in Ref. [34] as a tool to directly measure $\Delta G/G$. The quark–antiquark annihilation subprocess is suppressed relatively to quark-gluon Compton scattering because of the lower density of antiquarks (of the polarized sea) compared to gluons (polarized gluons). In fig. 10 the projected statistical sensitivity of HERA- \vec{N} for the $\Delta G(x)/G(x)$ measurement, on the present level of understanding, is shown vs. x_{gluon} in conjunction with predicted errors for STAR running at RHIC at 200 GeV c.m. energy [35]. The errors demonstrate clearly that in the region $0.1 \leq x_g \leq 0.4$ a significant result from *photon plus jet production* can be expected from HERA- \vec{N} with an accuracy being about competitive to that predicted for RHIC.

In J/ψ **plus jet** production the quark-gluon subprocess contributes only about 10% to the asymmetry compared to the gluon-gluon fusion subprocess. Here the measurement of $\Delta G(x)/G(x)$ is feasible only for $x_{gluon} = 0.1 \div 0.2$, i.e. for J/ψ transverse momenta of about 2.5 GeV/c, being a perturbatively safe value in quarkonium production. This prediction is shown as an additional entry in fig. 10. Although being one point only, this is an important measurement because the lowest lying point from *photon plus jet* production at HERA- \vec{N} is obtained for rather small values of p_T where pQCD is not expected to give reliable predictions in this channel. We note that the nature of the gluon-gluon subprocess has similar consequences for *dijet* production at RHIC; there is [35] only one point at a similar value of x_{gluon} , as well (cf. fig. 10).

At this point we note that the HERA- \vec{N} fixed target kinematics causes additional problems for the jet reconstruction when compared to a collider experiment. The number of photon events accompanied by a successfully reconstructed jet decreases considerably when approaching lower values of p_T and, correspondingly, of x_{gluon} . Preliminary jet reconstruction efficiencies were calculated and taken into account for the results in fig. 10.

Although the x_{gluon} interval ($0.1 \div 0.4$) explored by both HERA- \vec{N} and RHIC is quite comparable, the different transverse momentum ranges accessed (2...8

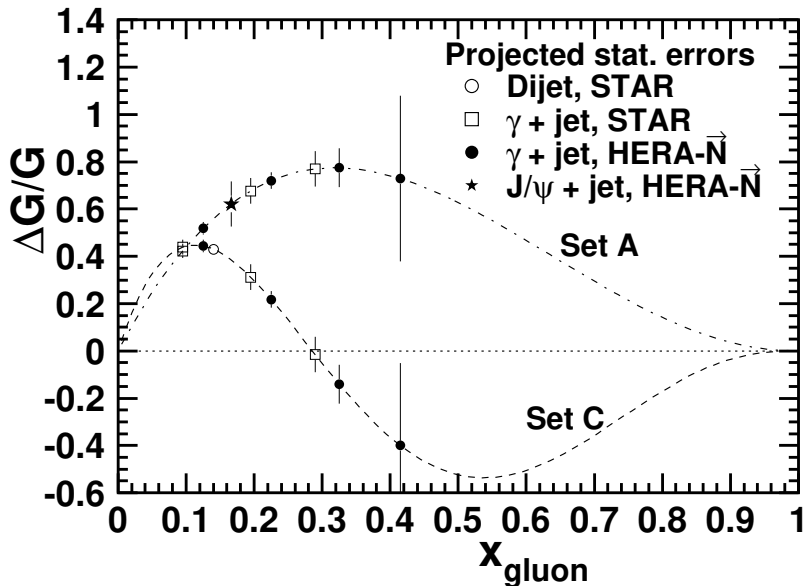


Fig. 10. Typical predictions for the polarized gluon distribution (LO calculations from Ref. [32]) confronted to the projected statistical errors expected for HERA- \vec{N} and RHIC experiments.

GeV at HERA- \vec{N} ; 10...40 GeV at RHIC) make both measurements indeed complementary; $\frac{\Delta G}{G}$ would be studied by HERA- \vec{N} in the pQCD onset region whereas the RHIC experiments will explore $\frac{\Delta G}{G}$ in the deep perturbative region.

The production of **Drell-Yan pairs** in nucleon-nucleon collisions proceeds via quark-antiquark annihilation into a massive off-shell photon which subsequently decays into a lepton pair, $q(x_1) + \bar{q}(x_2) \rightarrow \gamma^* \rightarrow l^+l^-$. The **longitudinal** double spin asymmetry turns out to be well suited to extract the polarized light sea-quark distribution, since schematically

$$A_{LL}^{DY} = \frac{\sum_i e_i^2 [\Delta q_i(x_1) \Delta \bar{q}_i(x_2) + (1 \leftrightarrow 2)]}{\sum_i e_i^2 [q_i(x_1) \bar{q}_i(x_2) + (1 \leftrightarrow 2)]} \hat{a}_{LL} \quad (3)$$

with $\hat{a}_{LL} = -1$. An experimental study of this asymmetry can be performed with the HERA- \vec{N} experiment; the prospects for such a measurement were calculated in ref. [36] at next-to-leading order QCD. The asymmetries expected for different parametrizations of the polarized NLO parton distributions are shown in fig. 11 in conjunction with the statistical accuracy achievable at HERA- \vec{N} . The spread of the predictions reflects the insufficient present knowledge on the polarized sea quark distributions in the region $x > 0.1$; not even the sign of the asymmetry at large M is predicted. Since the asymmetry is the weighted sum of $\Delta \bar{u}$ and $\Delta \bar{d}$ quarks with the strange quark contribution assumed to be small and the weight of $\Delta \bar{u}$ is higher than that of $\Delta \bar{d}$ due to

its abundance in the proton and the electric charge, the measured asymmetry provides mainly information on $\Delta\bar{u}$, i.e. on the light u quark polarization.

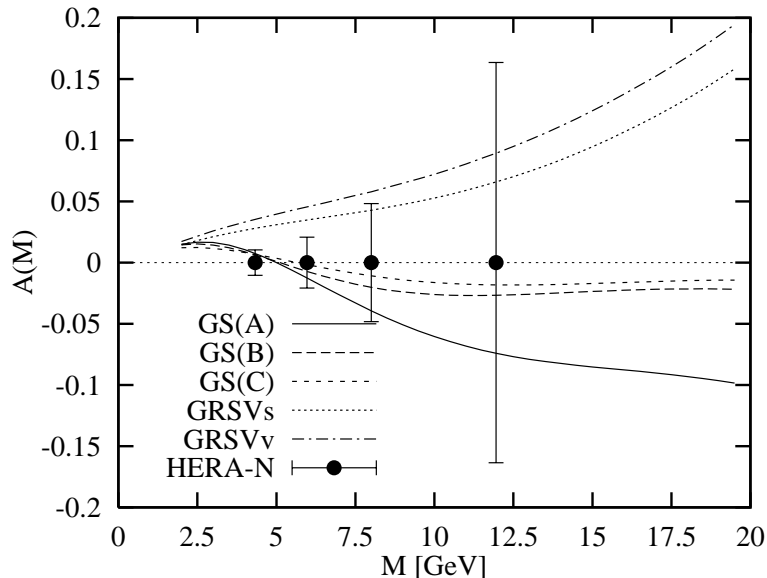


Fig. 11. *Expected asymmetries in the polarized Drell-Yan process from Ref. [36] confronted to the projected statistical errors expected for HERA-N.*

Drell-Yan pair production with transverse polarization of both beam and target can provide a qualitatively new insight into the spin structure of the nucleon by measuring the third twist-2 quark distribution function (often called quark transversity distribution, $\delta q(x)$ or $h_1(x)$) which is absolutely unknown at the present time. It basically describes the fraction of transverse polarization of the proton carried by its quarks. In inclusive lepton DIS a contribution of this function is suppressed by a quark mass whereas it is in principle accessible in semi-inclusive DIS [8,37]. The transverse double spin asymmetry in nucleon-nucleon Drell-Yan production can be schematically written in the form [38]

$$A_{TT}^{DY} = \frac{\sin^2 \theta \cos 2\phi \sum_i e_i^2 [\delta q_i(x_1) \delta \bar{q}_i(x_2) + (1 \leftrightarrow 2)]}{1 + \cos^2 \theta \sum_i e_i^2 [q_i(x_1) \bar{q}_i(x_2) + (1 \leftrightarrow 2)]}, \quad (4)$$

where θ is the polar angle of one lepton in the virtual photon rest frame and ϕ is the angle between the direction of polarization and the normal to the dilepton decay plane. The asymmetry vanishes if one integrates over the azimuthal angle. An estimate given in ref. [39] yields an asymmetry of the order of only one percent. One should stress, however, that the asymmetry level strongly depends on the structure function values, which are unknown at present. Although in the non-relativistic quark model the relation $\delta q(x) = \Delta q(x)$ holds, in reality differences between both distributions are expected to be caused by dynamical effects. For the quoted estimate the somewhat

arbitrary relation $\delta q(x, Q^2 = 4 \text{ GeV}^2) = \Delta q(x, Q^2 = 4 \text{ GeV}^2)$ was assumed and the Q^2 -evolution equation for $\delta q(x, Q^2)$ was used to calculate the function at other values of Q^2 .

We note that there exist another potentially interesting possibility, the study of the **longitudinal-transverse** double spin asymmetry, A_{LT}^{DY} . This asymmetry was calculated in ref.'s [38,40] and depends in a rather complicated fashion on both twist-2 ($\Delta q(x)$ and $\delta q(x)$) and twist-3 ($g_T(x)$ and $h_L(x)$) polarized structure functions. In contrast to A_{LL}^{DY} and A_{TT}^{DY} the asymmetry A_{LT}^{DY} decreases as M/Q .

The HERA- \vec{N} statistical reach has not been calculated yet for neither A_{TT}^{DY} nor A_{LT}^{DY} .

4 Conclusions

The physics scope for the measurement of polarized nucleon-nucleon collisions originating from an internal target in the 820 GeV HERA proton beam has been summarized. Single spin asymmetries, accessible already with the existing unpolarized beam, are found to be an almost unique and powerful tool to study the nature and physical origin of twist-3 effects; even more so when taken in conjunction with results of other experiments. When measuring the polarized gluon distribution through double spin asymmetries in *photon (plus jet)* and *J/ψ (plus jet)* production – requiring a polarized HERA proton beam – the projected statistical accuracies are found to be comparable to those predicted for the spin physics program at RHIC. Although both measurements explore the same x_{gluon} range they are complementary due to the different p_T ranges accessible. A measurement of Drell-Yan pair production with both beam and target longitudinally polarized can improve our knowledge on the polarized light sea quark distributions. A study of the double transverse and/or longitudinal-transverse Drell-Yan spin asymmetries might open first access to the quark transversity distribution. In addition, there is a potential to obtain significant results on the long-standing unexplained spin asymmetries in elastic scattering.

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