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The Physics Case for Polarised Proton-Nucleon Scattering at HERA[1]

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Abstract: The physics case for a possible fixed target polarized nucleon-nucleon collision experiment at HERA is described. The experiment named *HERA–*$\vec{N}$ could be realized using an internal polarized gas target in the HERA polarized/unpolarized proton beam. A wide spectrum of nucleon spin structure problems could be investigated and the experiment would constitute a fixed target complement to the RHIC spin physics program with competitive statistical accuracy.

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1 Introduction

For more than 4 years *HERMES* at DESY has been studying the spin structure of the nucleon using a polarized internal gas target in HERA's polarized electron/positron storage ring. In a similar approach, the installation of such a target in HERA's *proton* storage ring would open a new chapter in the study of high energy nucleon-nucleon spin physics in a fixed-target environmnent at $\sqrt{s} \simeq 40$ GeV [1, 2]. An internal polarized nucleon target offering a polarization above 80% and no or small dilution, can be safely operated in a high energy proton ring at high densities up to 10^{14} atoms/cm^2. As long as the polarized target is used in conjunction with the unpolarized proton beam, the physics scope would be focused onto 'phase I', i.e. measurements of single spin asymmetries. Once polarized protons should be available, a variety of double spin asymmetries could be investigated. These 'phase II' measurements would then constitute an alternative – fixed target – approach to similar physics which soon will be accessible to the collider experiments at the low end of the RHIC energy scale ($\sqrt{s} \simeq 50$ GeV). Altogether, a rich spin physics program would emerge at DESY; it has been called *HERA–*$\vec{N}$ [1] to allow for easier reference.

The estimate of the integrated luminosity which could be accumulated in the experiment 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 rather conservative values for both the average HERA proton beam current ($\bar{I}_B = 80$ mA $= 0.5 \cdot 10^{18}\ s^{-1}$) and for the polarized target density ($n_T = 3 \cdot 10^{13}$ atoms/cm^2) the projected integrated luminosity becomes $\mathcal{L} \cdot T = 240$ pb^{-1} when for the total running time T an equivalent of $T = 1.6 \cdot 10^7\ s$ is assumed. This corresponds to about 3 real years under *present* HERA conditions. One may argue, however, that at the time the experiment would run even 500 pb^{-1} *per year* might presumably become a realistic figure and the luminosity to be accumulated over the lifetime of the experiment might be considerably higher.

[1] Invited talk at the workshop 'Polarized Protons at High Energies - Accelerator Challenges and Physics Opportunities, DESY Hamburg, 17-20 May 1999.

2 Single Spin Asymmetries

Single (transverse) spin asymmetries in inclusive particle production at large p_T are forbidden in leading-twist pQCD, reflecting the fact that single spin asymmetries are zero at the partonic level and that collinear parton configurations inside hadrons do not allow for single spin dependences. The earlier naive expectation that they should generally be zero in pQCD has been proven to be false. Several models and theoretical analyses suggest possible higher twist effects: there might be twist-3 dynamical contributions (hard scattering higher twists); there might also be intrinsic $k_\perp$ effects, both in the quark fragmentation process [3] (Collins effect) and in the quark distribution functions [4] (Sivers effect). It has been shown that models based on both of the latter effects [5, 6] are capable to describe the existing experimental data.

Qiu and Sterman recently presented a detailed discussion of single spin asymmetries in pion production [7] in the context of twist-3 matrix elements. At moderate x_F, a rather mild decrease with p_T is predicted already for transverse momenta above 2 GeV; this is the region where the perturbative calculations are expected to be reliable.

There exists a variety of alternative approaches to the above mentioned twist-3 based explanations of single spin asymmetries. As an example, one model derives the asymmetry from the orbital momenta of the current quarks within the constituent quark [8]. Sign and size of the asymmetry are then proportional to the polarization of the constituent quark in the polarized nucleon. Above 2 GeV an $\mathcal{O}(0.3)$ and almost p_T-independent asymmetry is predicted even at the highest RHIC energy, $\sqrt{s} = 500$ GeV. In a totally different approach, based on the contribution of instantons to the hadron production processes, the single spin asymmetry is predicted [9] in qualitative agreement with existing experimental data.

In the following the capabilities of *HERA–*$\vec{N}$ are discussed to investigate single spin asymmetries with a transversely polarized target in the unpolarized HERA proton beam ('phase I'). It is worth noting that once polarization of the proton beam should have been achieved ('phase II'), single spin asymmetries may be measured with significantly higher precision using an unpolarized target whose density is only limited by beam life time deterioration.

Inclusive pion and kaon production. The reaction $p^\uparrow p \to \pi^{0\pm} X$ exhibits surprisingly large single spin asymmetries, as was measured a few years ago by the *E704* Collaboration at Fermilab using a 200 GeV transversely polarized proton beam [10]. 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 (see fig. 1). It is positive for both π^+ and π^0 mesons, while it has the opposite sign for π^- mesons. The same tendency was observed recently by the *E925* Collaboration at BNL scattering a 21.6 GeV proton beam on a carbon target [11]. Their data are shown in fig. 1 together with the older *E704* data. At large x_F ($\gtrsim 0.6$) the measured asymmetries are compatible in both experiments, while at $x_F \lesssim 0.5$ the asymmetries measured by *E925* are compatible with zero. This difference may be induced not only by the different beam energies but also by different acceptances in p_T and different target nuclei used. The charged pion data of *E704* taken in the range $0.2 < p_T < 2$ GeV were split into two samples at $p_T = 0.7$ GeV/c; the observed rise is stronger for the high p_T sample. New results on the asymmetry in η meson production were presented recently by *E704* [12]. The asymmetry is positive and the behaviour is compatible with the one observed in π^0 and π^+ production. A variety of asymmetry measurements exists in inclusive particle production at smaller energies (see e.g. a recent review in ref. [13]).

The p_T values accessible with *HERA–*$\vec{N}$ would be significantly larger than those reached in all experiments performed up to now. The sensitivity δA_N of the asymmetry measurement in inclusive production of different particles at *HERA–*$\vec{N}$ was calculated [14] using the inclusive differential cross-sections obtained with the Monte-Carlo program PYTHIA 5.6 [15]. The results are shown in fig. 2 in the (x_F, p_T) plane as contours characterizing the sensitivity level $\delta A_N = 0.05$ in bins of $\Delta p_L \times \Delta p_T = 2 \times 2$ (GeV/c)^2. For produced particles lines of constant polar angle in the laboratory system are shown.

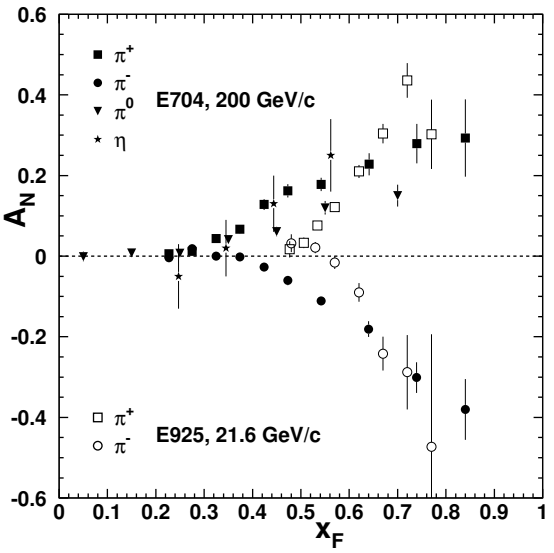

Figure 1: *Single spin asymmetry in inclusive pion and eta production as measured by the E704 [10] and E925 [11] Collaborations.*

Experimentally, it is not a simple task to measure single spin asymmetries in the fragmentation region of the polarized nucleon in a fixed target experiment at 820 GeV. This region lies either at negative x_F, i.e. at very large laboratory angles (a few tens of degrees), if a combination of polarized target and unpolarized beam is used, or at positive x_F, i.e. at very small angles (a few mrad) for the other combination, unpolarized target and polarized beam (cf. fig. 2). The question, how close to the HERA proton beam particles can be measured, deserves a special study.

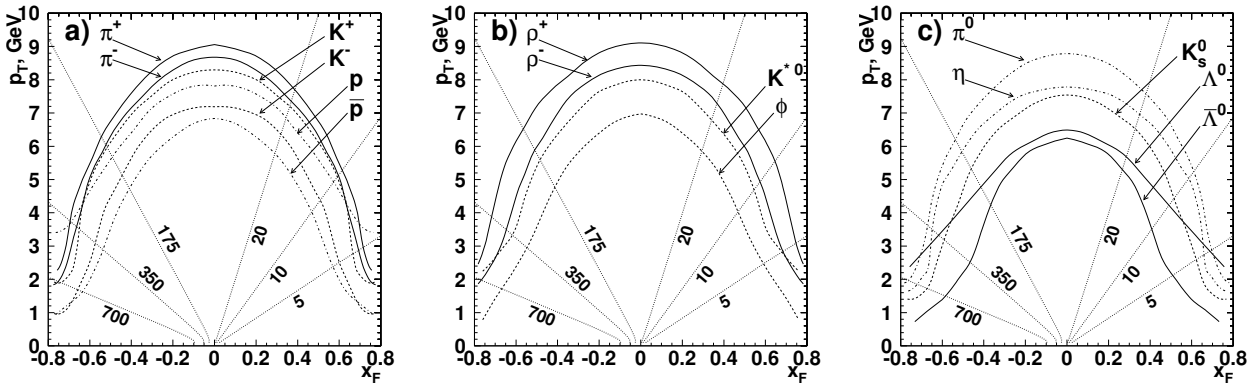

Figure 2: *Contours of the asymmetry sensitivity level for inclusive production of different particles in the* (x_F, p_T) *plane; inside the contour the sensitivity level is* $\delta A_N \leq 0.05$. *Only the following decay modes are taken into account:* $K^{*0} \to K^+\pi^-$, $\phi \to K^+K^-$, $\eta \to \gamma\gamma$, $K^0_s \to \pi^+\pi^-$, $\Lambda^0 \to p\pi^-$, $\bar{\Lambda}^0 \to \bar{p}\pi^+$. *Lines of constant laboratory angles of the particles are shown and marked with their values in units of mrad.*

As can be seen from fig. 2, the combined p_T dependence of all involved effects can be measured with good statistical accuracy ($\delta A_N \leq 0.05$) up to transverse momenta of about $8 \div 10$ GeV/c in the central region $|x_F| < 0.2$ and up to $5 \div 6$ GeV/c in the target or beam fragmentation region, respectively, depending on which nucleon is polarized. Hence the p_T range of a few

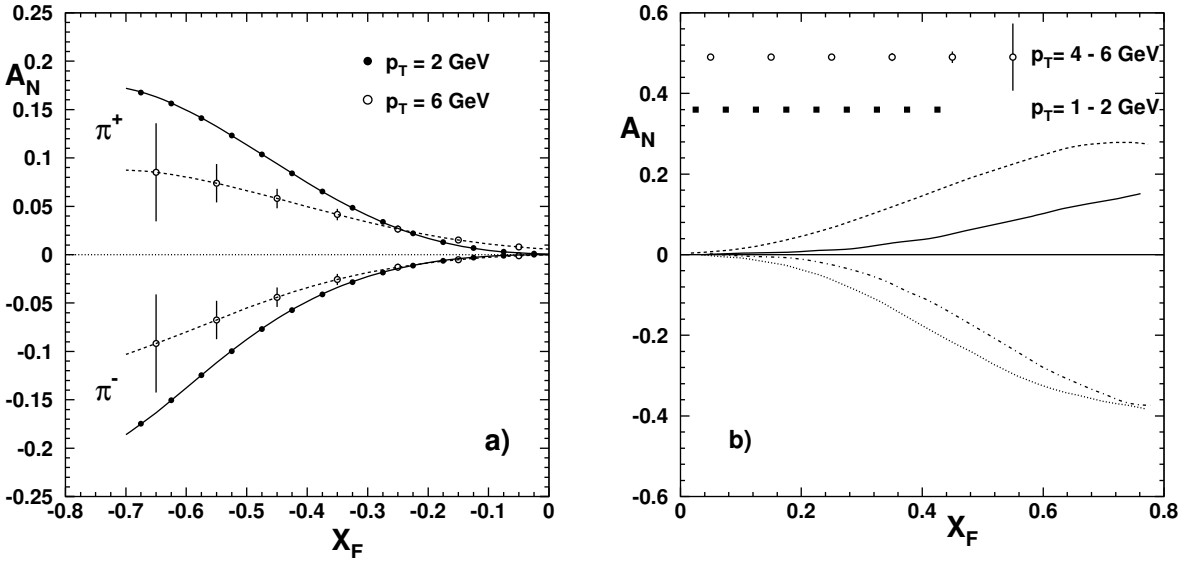

Figure 3: *(a) Capability of HERA–$\vec{N}$ to prove the p_T dependence of A_N in charged pion production, as predicted by the model of ref. [5]. (b) Capability of HERA–$\vec{N}$ to measure a $p_T - x_F$ dependence of the asymmetry in inclusive K^0_s production. The curves correspond to different sets of kaon fragmentation function (see ref. [5]).*

GeV, in which higher twist effects are expected to be essential, would be well covered.

The capability of *HERA–$\vec{N}$* to prove or disprove a predicted p_T dependence in the fragmentation region of the polarized nucleon is shown in fig. 3a for inclusive pion production. The theoretical curve is based on the assumption of a non–zero quark distribution analysing power according to ref. [5]. Note that a somewhat weaker increase with x_F is obtained for the predicted asymmetry value if the model of ref. [7] was used. The curves and the projected statistical errors in fig. 3a are drawn for the combination of unpolarized proton beam and polarized target.

Fig. 3b shows the capability of *HERA–$\vec{N}$* to measure the p_T and x_F dependence of the asymmetry in inclusive K^0_s production, calculated for the case of a polarized beam and an unpolarized target and assuming the K^0_S mesons to be accepted in the range 5 to 170 mrad. The theoretical predictions are taken from ref. [5]. It should be noted that the existing sets of kaon fragmentation functions essentially offer two choices. On the one hand, if the main contribution to the large x_F production of kaons is coming from partonic processes involving only valence quarks from the initial nucleon and the final meson, the single spin asymmetries predicted by the model of ref. [5] are quite similar to the pion case: $A_N(K^+) \sim A_N(\pi^+)$; $A_N(K^0) \sim A_N(\pi^-)$; $A_N(K^-) \sim A_N(\bar{K^0}) \sim 0$. On the other hand, if the used set of kaon fragmentation functions enhances the role of the sea quarks, the situation for charged kaons remains essentially unchanged whereas quite different predictions are obtained for K^0_Ss. Hence the measurement of single spin asymmetries in inclusive neutral kaon production may offer, as a by-product, a tool to possibly discriminate between different sets of kaon fragmentation functions.

Inclusive direct photon production. The reaction $pp^\uparrow \to \gamma X$ proceeds without fragmentation, i.e. this process measures a combination of initial $k_\perp$ effects and hard scattering twist–3

processes. The first and only results up to now were obtained by the *E704* Collaboration [16] showing an asymmetry compatible with zero within large errors for $2.5 < p_T < 3.1$ GeV/c in the central region $|x_F| \lesssim 0.15$.

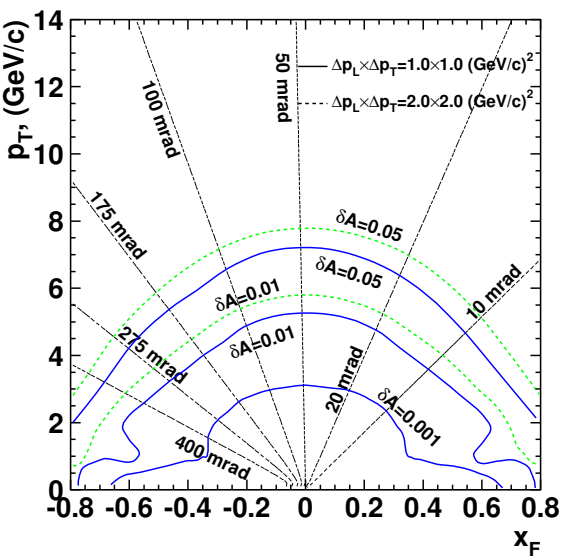

Figure 4: *Asymmetry sensitivity levels for photon production in the (p_T, x_F) plane. Laboratory angles of the photons are shown.*

The experimental sensitivity of *HERA–*$\vec{N}$ (see fig. 4) was determined using cross-section calculations of the two dominant hard subprocesses, i.e. gluon–Compton scattering ($qg \to \gamma q$) and quark–antiquark annihilation ($q\bar{q} \to \gamma g$). Background photons that originate mainly from π^0 and η decays were taken into account, as well. It turns out that a good sensitivity (about 0.05) can be maintained up to $p_T \leq 8$ GeV/c in the central region. For increasing transverse momentum the background photons are becoming less essential; hence in the central region it is expected to be possible to detect a clear dependence of the direct photon single spin asymmetry on p_T. The situation is less favourable concerning its x_F dependence. The theoretical predictions [5] show a rather shallow increase of A_N with x_F.

Inclusive vector meson production. The study of polarization asymmetries in inclusive vector meson production is especially attractive as these particles are produced 'more directly' in comparison to pions and kaons 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 [17]. If the asymmetry is generated only during the fragmentation of polarized quarks, 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.

The statistical sensitivity of *HERA–*$\vec{N}$ for measuring single spin asymmetries in inclusive production of ρ, K^{*0}, and ϕ vector mesons can be seen from fig. 2b. The sensitivity for ρ production is at a level comparable to that for pions (fig. 2a, while for K^{*0} and ϕ mesons the reachable p_T values are lower. On the other hand, a study of the asymmetry in K^{*0} and ϕ production using the decay channels $K^{*0} \to K^\pm \pi^\mp$ and $\phi \to K^+ K^-$ could be easier since the level of the expected combinatorial background is smaller.
It is worth noting that the asymmetry in ϕ meson production could be useful for a study of the strange quark polarization in a nucleon [8].

Inclusive Lambda production. A sizeable asymmetry in the inclusive production of Λ^0 and $\bar{\Lambda}^0$ hyperons would allow to study the asymmetry in their production up to p_T of about 5 to 6 GeV/c, as can be seen from fig. 2c. The measurement of the final state Λ polarization via its decay would allow to study the polarization spin transfer coefficient, D_{NN}. A recent study by *E704* [18] at moderate values of p_T ($0.1 \div 1.5$ GeV/c) showed a sizeable (up to 30%) spin transfer from the incident polarized proton to the outgoing Λ^0.

Drell-Yan production. The single spin asymmetry in the reaction $p + p^{\uparrow} \to l\bar{l} + X$ was calculated at *HERA–*$\vec{N}$ energy and small transverse momenta in the framework of twist-3 pQCD [19, 20]. The resulting asymmetry does not exceed 0.02 in size. It appears to be too small for an experimental verification given the statistical significance for 240 pb^{-1} that can be seen from fig. 11.

Inclusive J/ψ production. The single spin asymmetry in inclusive J/ψ production was calculated in the framework of the colour singlet model. The calculations at *HERA–*$\vec{N}$ energy [21] show an asymmetry less than 0.01 in the region $|x_F| < 0.6$, i.e. the effect is practically unobservable.

Proton-proton elastic scattering. Large spin effects in $p + p^{\uparrow} \to p + p$ have been discovered many years ago. The single spin asymmetry A_N was found to be significantly different from zero as it is shown in fig. 5 in conjunction with the projected *HERA–*$\vec{N}$ statistical errors. At *HERA–*$\vec{N}$ energy the detection of the recoil proton with *squared* transverse momenta between 5 and 12 (GeV/c)^2 requires a very large angular acceptance (up to 40 degrees) [21]. 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 [22]. The predicted asymmetry is about 0.1 for p_T^2 values between 4 and 5 (GeV/c)^2 with a projected statistical error of $0.01 \div 0.02$ for *HERA–*$\vec{N}$ (cf. fig. 5), i.e. already with 240 pb^{-1} a significant measurement of the asymmetry A_N can be performed to test the spin dependence of elastic *pp* scattering at high energies provided the necessary special detector components are available.

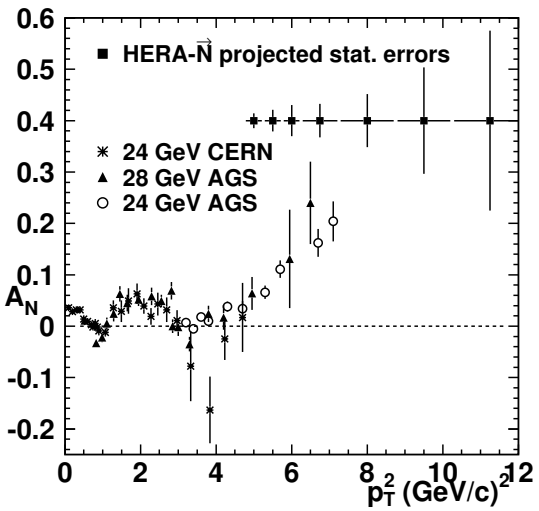

Figure 5: *Single spin asymmetry in polarized proton-proton elastic scattering as a function of* p_T^2.

3 The Polarized Gluon Density $\Delta G(x)$

At present, the experimental information on the polarized gluon density in the nucleon, $\Delta G(x)$, and its moments is completely insufficient. The only direct information comes from a recent measurement of the HERMES Collaboration [23], who found the ratio of $\Delta G/G$ to be positive ($\Delta G/G = 0.41 \pm 0.17(stat.)$) at $x_g \sim 0.17$. However, the relatively small available c.m.s. energy of about 7 GeV implies theoretical uncertainties that potentially are large. In this situation new experiments are required to accomplish both direct and indirect measurements of $\Delta G(x)$.

3.1 $\frac{\Delta G}{G}(x)$ from Inclusive Processes

Direct photon production. The cross section for high p_T direct photon production in NN interactions is dominated by the quark–gluon Compton subprocess, $q(x_1) + g(x_2) \to \gamma + q$; the additional quark–antiquark annihilation subprocess is assumed to be suppressed because of the lower density of antiquarks compared to gluons.
The asymmetry can be described by the following partonic formula for the quark–gluon Compton subprocess:

$$A_{LL}^{\gamma} = \frac{\sum_f \; e_f^2 \, \Delta q_f(x_1) \, \Delta G(x_2) \, d\,\Delta\hat{\sigma}(x_1, x_2) + [x_1 \leftrightarrow x_2]}{\sum_f \; e_f^2 \; q_f(x_1) \, G(x_2) \, d\,\hat{\sigma}(x_1, x_2) + [x_1 \leftrightarrow x_2]}. \tag{1}$$

Here x_1 and x_2 are the fractional momenta of the two incoming partons in the subprocess. As can be seen, the asymmetry A_{LL}^{γ} is directly sensitive to the polarized gluon distribution.

In a recent study [25] inclusive photon production at *HERA–*$\vec{N}$ was investigated. Based upon a NLO calculation, firm predictions were obtained for A_{LL}^{γ} including an assessment of the theoretical uncertainties; the latter turned out to be of rather moderate size. Using three different assumptions for the polarized gluon distribution corresponding predictions for the asymmetry A_{LL}^{γ} were calculated. Their dependence on p_T and pseudorapidity η is shown in fig.'s 6a and 6b in conjunction with the projected statistical uncertainty of *HERA–*$\vec{N}$. As can be seen, there is sufficient statistical accuracy over a wide kinematical region to discriminate between different polarized gluon distribution functions.

However, at present the theoretical interpretation of direct photon production at high energy is not as clear as it might appear. A standard NLO QCD description fails to describe the cross section from the recent Fermilab data of *E706* and requires the introduction of unexpectedly large intrinsic $k_\perp$ effects [24]. It is likely, but still has to be proven, that this unpleasant feature will drop out in spin asymmetries.

Inclusive J/ψ production. Because of the relatively large quark mass ($m_c \gg \Lambda_{QCD}$) the $c\bar{c}$ production processes occur at small distances and the subprocess level cross sections as well as the expected asymmetries can be calculated perturbatively. The underlying mechanism at the parton level is gluon-gluon fusion, $g(x_1) + g(x_2) \to (c\bar{c}) + g$. The asymmetry can be written as

$$A_{LL}^{J/\psi} = \frac{\sum_f \; e_f^2 \, \Delta G(x_1) \, \Delta G(x_2) \, d\,\Delta\hat{\sigma}(x_1, x_2) + [x_1 \leftrightarrow x_2]}{\sum_f \; e_f^2 \; G(x_1) \, G(x_2) \, d\,\hat{\sigma}(x_1, x_2) + [x_1 \leftrightarrow x_2]}, \tag{2}$$

i.e. the asymmetry $A_{LL}^{J/\psi}$ is sensitive to the square of the polarized gluon distribution.

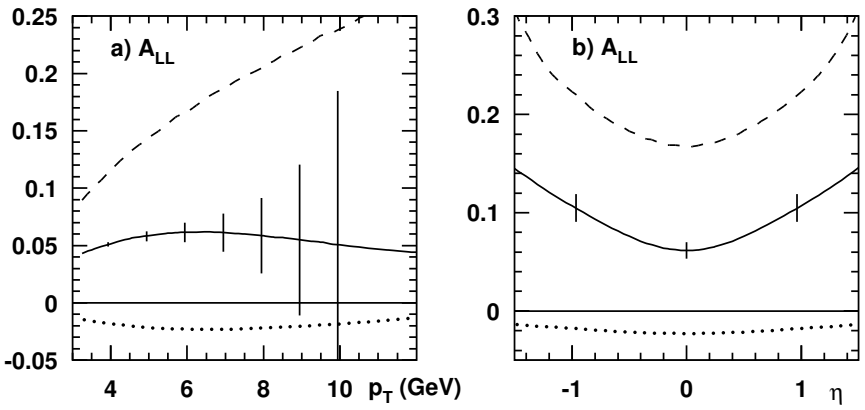

Figure 6: *Double spin asymmetry in inclusive photon production displayed vs. a p_T and b η for different polarized gluon distribution functions (see ref. [25]), shown in conjunction with the projected statistical sensitivity of HERA–$\vec{N}$.*

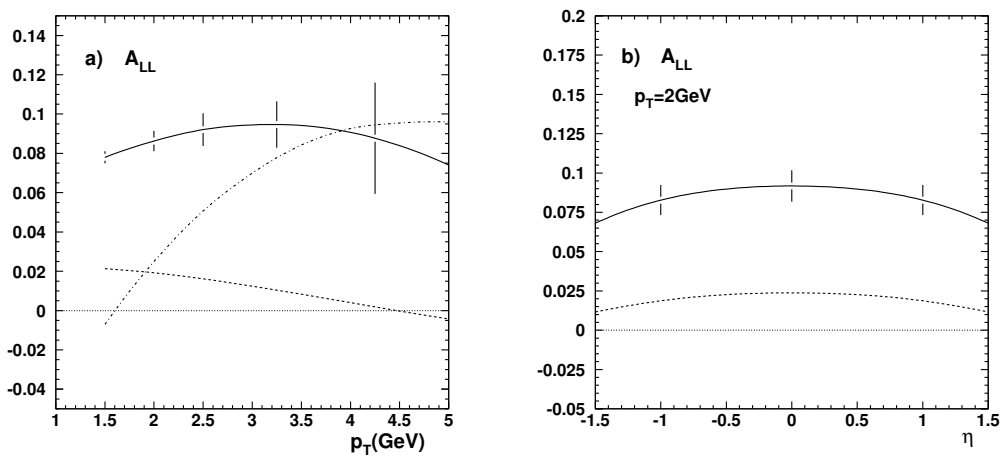

Figure 7: *Double spin asymmetry in inclusive J/ψ production displayed vs. (a) p_T for NLO set A (full line) and set B (dashed line) of ref. [26]; (b) η for NLO set A (full line) and set C (dashed line) of ref. [26], shown in conjunction with the projected statistical sensitivity of HERA–$\vec{N}$. The dash-dotted line in (a) represents the color singlet contribution to the asymmetry.*

Nevertheless, also this channel is not free of theoretical problems. The knowledge of the production mechanism is a necessary pre-requisite for the extraction of ΔG. Experimental studies of the unpolarized production of J/ψ in various reactions have shown that two possible mechanisms should be considered to describe the existing data. The J/ψ can be produced directly through the color singlet mechanism (CSM) or in a two-step procedure through the color octet mechanism (COM). However, both of them are not able to describe the available data in a consistent way.

Recently, the longitudinal double spin asymmetry in inclusive J/ψ hadroproduction was calculated [27] taking into account both the color singlet and the color octet states of the $c\bar{c}$-pair. In fig.'s 7a and 7b the expected asymmetry is presented versus p_T and pseudorapidity η, calculated utilizing NLO polarized gluon distributions from ref.[26]. Apparently a very good discrimina-

tion between both sets is possible over the whole kinematical range of *HERA–$\vec{N}$*; both electron and muon decay channels of the J/ψ are included. It is interesting to observe from fig. 7a that for $p_T \gtrsim 3$ GeV the asymmetry originating from the total CSM contribution is about as large as the asymmetry caused by the COM. More details can be found in ref. [28].

For comparison the expected double spin asymmetries for inclusive J/ψ production at RHIC energies were calculated [29]. In fig. 8 predictions at *HERA–$\vec{N}$* and two different RHIC energies are shown in conjunction with the projected statistical uncertainties. In the statistically accessible p_T interval the asymmetry ranges between 0.08 and 0.09 at *HERA–$\vec{N}$*, but does not exceed 0.04 at RHIC energies. Comparing both ranges and taking into account unavoidable limitations by systematic errors it is likely that the fixed target experiment might accomplish a more significant measurement of the charmonium production asymmetry. Additionally, the background to the J/ψ signal from b-hadron decays is expected to be essential at RHIC energies.

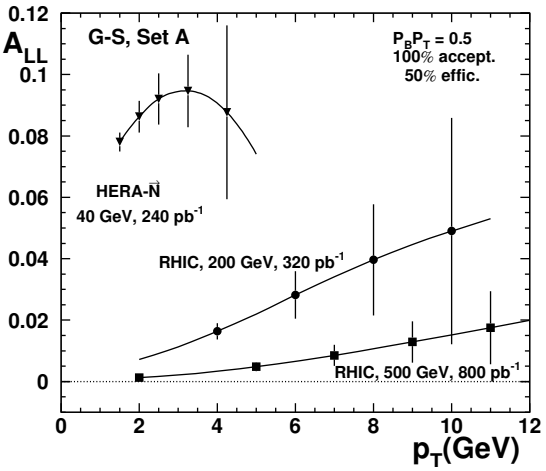

Figure 8: *Transverse momentum dependence of the expected asymmetries and projected statistical errors for J/ψ production at HERA–$\vec{N}$ and for two different energies at RHIC, calculated with the NLO set A of ref. [26].*

Inclusive $\chi_{c1,c2}$ production. The two P-wave charmonium states $\chi_{c1}(3510)$, $\chi_{c2}(3556)$ have rather large radiative $\chi_{c1,c2} \to J/\psi + \gamma$ branching ratios. Hence optimizing the *HERA–$\vec{N}$* apparatus for both J/ψ and photon detection may deliver good conditions for $\chi_{c1,c2}$ detection, as well. A separation of both states requires a very good effective mass resolution of the spectrometer lying between 10 and 20 MeV which seems not excluded at the given stage of knowledge about a possible future apparatus.

The above discussion of the theoretical uncertainties in the description of J/ψ production fully applies also to P-wave charmonium production.

Recently, double spin asymmetries in P-wave charmonium production at *non-zero* transverse momentum ($p_t > 1.5$ GeV) were calculated [30] taking into account both possible mechanisms, CSM and COM. The asymmetries for the production of χ_{c1} and χ_{c2} states exhibit different signs in the transverse momentum range $1.5 < p_t < 3$ GeV. The transverse momentum dependence of $A_{LL}^{\chi_{c2}}$ is shown, as an example, in fig. 9 for certain parameterizations of the polarized gluon distribution. Additionally, projected statistical errors were calculated for both *HERA–$\vec{N}$* and RHIC.

A measurement of $A_{LL}^{\chi_{c2}}$ for $1.5 < p_t < 2.5$ GeV would clearly identify a polarized gluon distribution if it is sufficiently large at $x_{gluon} \simeq 0.1$ (see fig. 9a). Additionally, a differentiation between color singlet and color octet contributions may be possible in this case.

With increasing c.m.s. energy the discrimination power of $\chi_{c1,c2}$ production decreases, as can be seen from fig. 9b showing the double spin asymmetry at $\sqrt{s} = 200$ GeV. With the presently

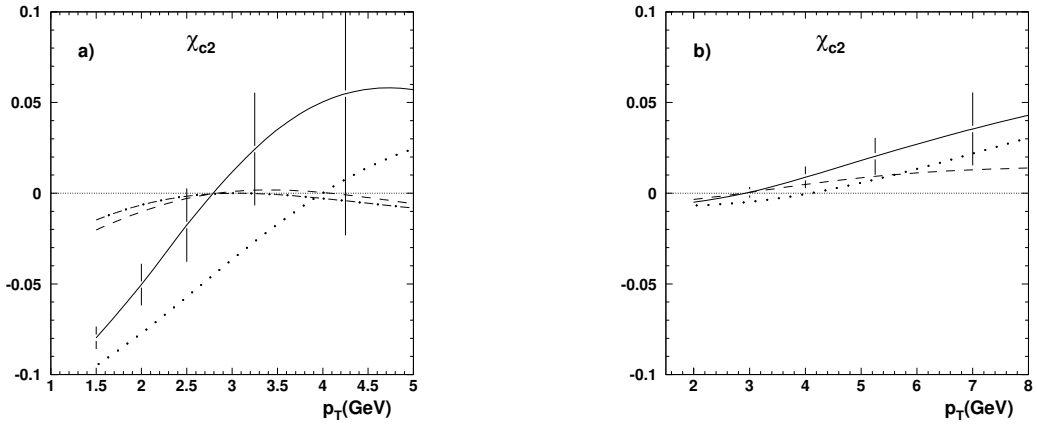

Figure 9: *Double spin asymmetry in inclusive χ_{c2} production as a function of transverse momentum p_T at (a) HERA–$\vec{N}$ and (b) RHIC ($\sqrt{s}$ = 200 GeV). The solid (dashed) line corresponds to set A (B) of the NLO GS parameterization [26] and the dash-dotted line to the LO set A [26]. The dotted line represents the expected asymmetry calculated only in the CSM for the NLO set A [26]. The projected statistical sensitivities are also shown. The figures are taken from ref. [30].*

envisaged integrated *RHIC* luminosity of 320 pb^{-1} assuming 100% efficiency and $P_B P_T \simeq 0.5$ it will be very hard to draw any conclusion in the discussed context.

Very recently χ_{c2} production at small transverse momenta was considered based upon the ideas of QCD multipole expansion [31]. It is argued that a measurement of the angular distribution in the radiative decay of χ_{c2} produced in *unpolarized* proton-proton collisions is supposed to yield the ratio between the amplitudes of color octet and color singlet states. Knowing this ratio a measurement of the angular distribution of the double spin asymmetry in *polarized* proton-proton is then supposed to allow access to $\frac{\Delta G}{G}$.

It seems appropriate here to underline that the inclusive photon and charmonium final states discussed above correspond to different ranges of validity of pQCD. When measuring photon production with transverse momenta between 2 GeV and 6 GeV the lower momentum region can not be considered as a safe working ground for pQCD. In contrast, charmonium production is safe even at vanishing transverse momentum since the large mass of the charm quark guarantees the necessary hard scale.

3.2 Photon or J/ψ Production Associated with Jets

In contrast to inclusive production the final state 'photon (J/ψ) plus jet' offers *direct* access to the polarized gluon distribution. Since the underlying partonic subprocess is of the type $2 \to 2$, the kinematics of the back-to-back parton emission is completely known, at least in principle, if the emerging products on the hadron level are fully detected. This is an essential advantage compared to inclusive production discussed in the previous section.

Photon plus jet production. The complete kinematics of the underlying hard 2→2 subprocess allows to establish a simple relation between $A_{LL}^{\gamma+jet}$ and $\frac{\Delta G}{G}$ [21]:

$$\frac{\Delta G}{G}(x_{gluon}) = \frac{A_{LL}^{\gamma+jet}}{A_{DIS} \cdot \hat{a}_{LL}}, \tag{3}$$

where the partonic level asymmetry $\hat{a}_{LL}$ and $A_{DIS} = g_1/F_1$ should be taken at appropriate values of the kinematical variables calculated from the measured kinematics of the registered photon and jet.

This approach was used in ref. [32] to estimate the projected statistical sensitivity of *HERA–*$\vec{N}$ for a $\frac{\Delta G}{G}(x_{gluon})$ measurement. The corresponding results, including the acceptance of a possible detector, are shown in fig. 10 vs. x_g in conjunction with predicted errors for *STAR* running at RHIC at 200 GeV c.m. energy [33]. The errors demonstrate clearly that in the region $0.1 \leq x_{gluon} \leq 0.4$ a significant result from photon plus jet production can be expected from *HERA–*$\vec{N}$. As can be seen, the measurement of $\frac{\Delta G}{G}$ from photon plus jet production in doubly polarized nucleon-nucleon collisions at HERA can presumably be performed with an accuracy that is competitive to RHIC.

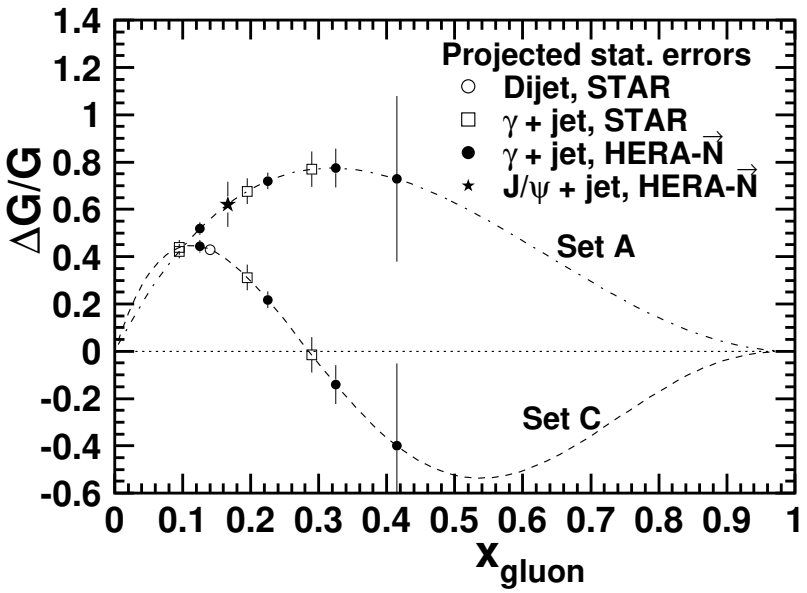

Figure 10: *Typical predictions for the polarized gluon distribution (LO calculations from ref. [34]) confronted to the projected statistical errors expected for HERA–*$\vec{N}$ *and RHIC experiments.*

It seems here appropriate to underline that the interesting x_{gluon}-range (0.1 ... 0.3) will be accessed with *STAR* at 200 GeV in the deep perturbative transverse momentum region (10 ... 30 GeV), whereas at *HERA–*$\vec{N}$ the transverse momenta lie in the pQCD onset region (2 ... 6 GeV); hence both approaches are complementary with respect to the validity of pQCD.

It is important to note that the *HERA–*$\vec{N}$ fixed-target kinematics causes additional problems for jet reconstruction in comparison to a collider experiment (for more details see ref. [21]). A forward oriented detector with good granularity down to scattering angles of $10 \div 20$ mrad is required. From preliminary Monte Carlo studies [21] it was seen that the number of photon events accompanied by a successfully reconstructed jet decreases considerably for lower values of p_T and, correspondingly, of x_{gluon}. Appropriate preliminary jet reconstruction efficiencies were included to arrive at realistic projected error bars for the *HERA–*$\vec{N}$ points in fig. 10.

J/ψ plus jet production. Once the mechanism of J/ψ production is established (see discussion in the previous section), a measurement of the double spin asymmetry $A_{LL}^{J/\psi+jet}$ would allow to access the polarized gluon distribution function directly, in a similar manner as in case of photon plus jet production discussed above. The absolute statistical error of $\frac{\Delta G}{G}(x_{gluon})$ can be expressed as:

$$\delta[\frac{\Delta G}{G}(x_{gluon})] = \frac{\delta A_{LL}^{J/\psi+jet}}{[\Delta G/G] \cdot \hat{a}_{LL}}. \tag{4}$$

In the case of J/ψ plus jet production the cross section decreases more rapidly with x_{gluon}. Following the same principle of analysis as ref. [21], it turns out that the measurement of $\frac{\Delta G}{G}$ in J/ψ plus jet production is feasible only for $x_{gluon} = 0.1 \div 0.2$, i.e. for J/ψ transverse momenta of about 2.5 GeV/c. This prediction is shown as an additional entry in fig. 10. Although it is only a single point, this is a very important measurement, because the lowest point from photon plus jet production is obtained for small transverse momentum where perturbative QCD is not expected to give very reliable predictions. It is worth noting that the nature of the gluon-gluon subprocess has similar consequences for process of jet plus jet production at RHIC. The prediction [33] consists of only one point at a comparable value of x_{gluon} (see fig. 10).

3.3 Other Processes

As just mentioned, also the possibility to extract $\Delta G/G$ from inclusive **two-jet production** may be considered. Several hard subprocesses (gg, gq, qq scattering) contribute to the two-jet final state and a good knowledge of polarized quark distributions would be essential. Note that at *HERA–*$\vec{N}$ the above mentioned additional difficulty of jet reconstruction must be addressed. A potential solution of the problem consists in replacing the reconstruction of the two jets by the registration of two correlated high-p_T hadrons opposite in azimuth.

Another, still unexplored possibility is **open charm production**. Interesting results might be obtained using a high p_T single muon or electron-muon pairs from charm decays as a tag. Both possibilities still need careful investigation.

4 Anti-Quark Helicity Distributions $\Delta\bar{q}(x)$

The production of Drell-Yan pairs in nucleon-nucleon collisions proceeds via quark-antiquark annihilation, $q(x_1) + \bar{q}(x_2) \rightarrow \gamma^* \rightarrow l^+l^-$. The *longitudinal* double spin asymmetry turns out to be well suited to extract the polarized light sea-quark distribution; the asymmetry can be written as

$$A_{LL}^{DY} = \frac{\sum_f \; e_f^2 \; \Delta q_f(x_1) \; \Delta\bar{q}_f(x_2) \; d\,\Delta\hat{\sigma}(x_1, x_2) + [x_1 \leftrightarrow x_2]}{\sum_f \; e_f^2 \; q_f(x_1) \; \bar{q}_f(x_2) \; d\,\hat{\sigma}(x_1, x_2) + [x_1 \leftrightarrow x_2]}. \tag{5}$$

Note that the parton level asymmetry in Drell-Yan production is maximal, $\hat{a}_{LL} = -1$.

The prospects for the A_{LL}^{DY} measurement at *HERA–*$\vec{N}$ were calculated [35] in next-to-leading order QCD. The spread of the predictions (see fig. 11a,b) reflects the insufficient present knowledge on the polarized sea quark distributions in the region $x > 0.1$; not even the sign of the asymmetry is predicted at large mass M of the pair. The asymmetry is obtained from the

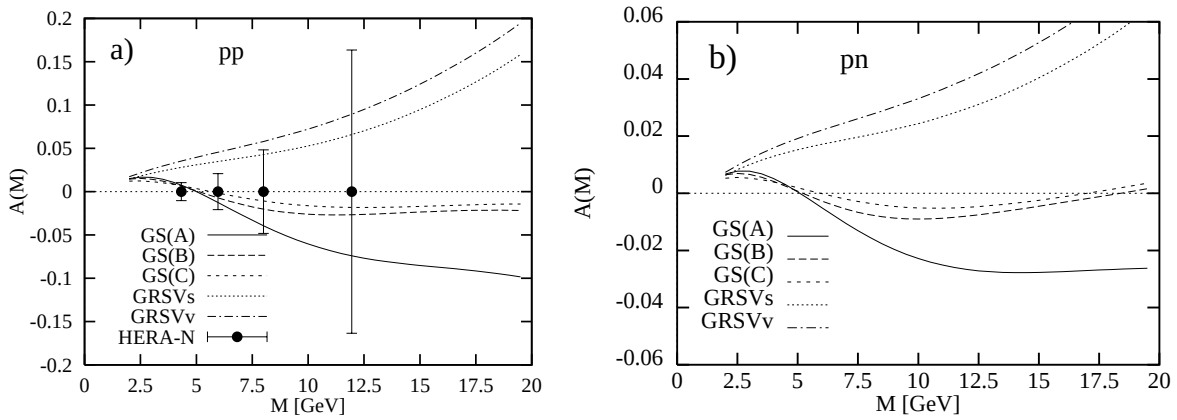

Figure 11: *Longitudinal double spin asymmetries in the polarized Drell-Yan process [35] for (a) pp and (b) pn collisions ($\sqrt{s}$ = 40 GeV) confronted to the projected HERA–$\vec{N}$ statistical errors.*

weighted sum of $\Delta\bar{u}$ and $\Delta\bar{d}$ quarks; the strange quark contribution is assumed to be small. In the case of a proton target 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). Hence the asymmetry expected in *pp* collisions (fig. 11a) provides mainly information on $\Delta\bar{u}$, i.e. on the sea u quark polarization. The flavor contributions are different for *pn* collisions; this results in a much smaller asymmetry (fig. 11b) than in the *pp* case (note the different vertical scales in fig.'s 11a and b). The projected statistical uncertainties for *HERA–*$\vec{N}$, as shown in fig. 11a, have to be enlarged by a factor of $\sqrt{2}$ since preliminary acceptance calculations based upon a *HERA–B* like detector resulted in a value of about 0.5 [14]. Then, with a proton target, a statistically significant measurement of A_{LL}^{DY} would require an integrated luminosity about twice as large as the anticipated 240 pb^{-1}, which appears not unrealistic. Suggestions to extract more detailed physics information by measuring the differential lepton pair distributions in dependence on x_F or η [35, 36] would require even higher luminosities. This applies as well to studies of Drell-Yan production on a neutron target where asymmetries smaller by about a factor of three compared to the proton case had to be probed, as can be seen by comparing the scales of fig.'s 11a and b.

5 Transversity distribution $\delta q(x)$

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 (quark transversity distribution, $\delta q(x)$) which is absolutely unknown at present. It essentially describes the fraction of transverse polarization of the proton carried by its quarks. In inclusive DIS a contribution from this function is suppressed by a factor containing the quark mass whereas it is in principle accessible in semi-inclusive DIS.
The asymmetry A_{TT}^{DY} can be written in the form [37]

$$A_{TT}^{DY} = \frac{\sin^2\theta\cos 2\phi}{1+\cos^2\theta} \quad \frac{\sum_f e_f^2\,\delta q_f(x_1)\,\delta\bar{q}_f(x_2) + [x_1 \leftrightarrow x_2]}{\sum_f e_f^2\,q_f(x_1)\,\bar{q}_f(x_2) + [x_1 \leftrightarrow x_2]}, \tag{6}$$

where θ is the polar angle of one of the leptons in the virtual photon rest frame and ϕ is the angle between the direction of the nucleon polarization and the normal to the dilepton decay

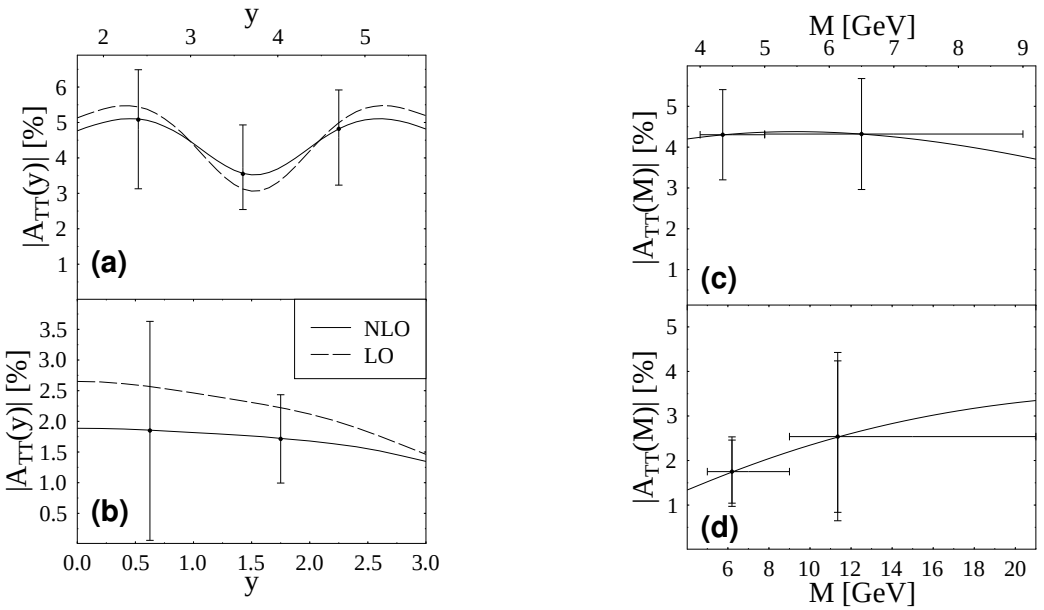

Figure 12: *Predictions [39] for the rapidity dependence of A_{TT} for (a) HERA–$\vec{N}$ ($E_{\rm beam}$ = 820 GeV, $M = 4 - 9$ GeV) and (b) PHENIX at RHIC ($\sqrt{S}$ = 200 GeV, $M = 5 - 9$ GeV). Predictions [39] of $A_{TT}(M)$ for (c) HERA–$\vec{N}$ and (d) RHIC.*

plane. The asymmetry vanishes on integration over the azimuthal angle.
Due to the lack of any information on the transversity distribution, the largest possible value of the asymmetry was estimated [39], based on a saturation of Soffer's inequality [38]. The resulting LO and NLO asymmetries are presented in fig. 12a and b for *HERA–*$\vec{N}$ and RHIC kinematics, respectively. Fig. 12 also shows the projected statistical errors for a measurement of A_{TT} including detector acceptance effects. The maximal value of A_{TT} at an invariant mass of $M = 4$ GeV was found to be approximately 0.04 with a projected statistical error of about 0.01. The expected value of the asymmetry at RHIC energies is smaller as is the expected statistical significance of the measurement.

The **longitudinal-transverse** double spin asymmetry, A_{LT}^{DY}, is sensitive to the transversity distribution, although the asymmetry receives additionally contributions from the twist-3 distributions g_T and h_L. However, calculations [40] show that A_{LT}^{DY} is clearly expected to be much smaller than A_{TT}^{DY} while the absolute predictions still suffer from the limited accuracy of the involved parton distributions.

Two-meson production. Recently it has been proposed to probe the nucleon's transversity distribution through the final state interaction between two mesons ($\pi^+\pi^-, \pi K$, or $K\bar{K}$) inclusively produced on a transversely polarised nucleon, $p + p^\uparrow \to \pi^+ + \pi^- + X$ [41, 42]. It has been shown that the interference effect between the s- and p-wave of the two-meson system around the ρ (for pions), K^* (for πK), or ϕ (for kaons) provides an asymmetry which may be sensitive to the quark transversity distribution in the nucleon. The asymmetry is a function of the angle of the normal of the two-pion plane $\vec{k}_+ \times \vec{k}_-$ with respect to the polarization vector $\vec{S}_\perp$ of the nucleon.
An asymmetry as large as 0.15 has been predicted [42] for jet energies of about 100 GeV at RHIC. No estimates are available yet for *HERA–*$\vec{N}$ where a corresponding measurement could be done already in 'Phase-I', i.e. with an *un*polarized beam.

6 Polarized Fragmentation Functions

When studying the spin transfer from a *longitudinally* polarized nucleon to the Λ hyperon in the process $p\vec{p} \to \vec{\Lambda} X$ at large Λ transverse momentum, the relevant spin asymmetry is defined as

$$A^{\Lambda} = \frac{d\Delta\sigma^{p\vec{p}\to\vec{\Lambda}X}/d\eta}{d\sigma^{pp\to\Lambda X}/d\eta}. \tag{7}$$

Here $d\sigma^{pp\to\Lambda X}/d\eta$ is the unpolarized cross-section and $d\Delta\sigma^{p\vec{p}\to\vec{\Lambda}X}/d\eta$ is given by

$$d\Delta\sigma^{p\vec{p}\to\vec{\Lambda}X}/d\eta = d\sigma^{pp_+\to\Lambda_+ X}/d\eta - d\sigma^{pp_-\to\Lambda_+ X}/d\eta. \tag{8}$$

The subscripts " + "," − " denote particle helicities.

An attempt to determine the spin-dependent Λ fragmentation functions showed [43] that the available LEP data cannot sufficiently constrain the valence fragmentation functions for all flavors. Rather different scenarios adopted for the input valence distributions appear to describe the data equally well. The LO calculation [44] shows that a measurement of the asymmetry (7) at *HERA–*$\vec{N}$ may allow to discriminate among different possible alternatives (see fig. 13).

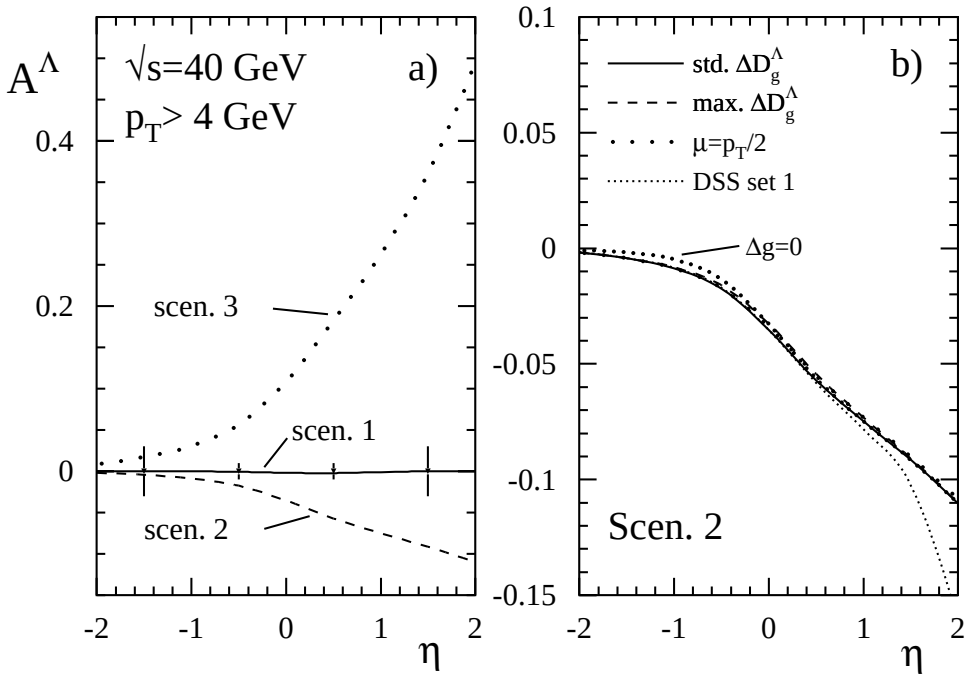

Figure 13: *The asymmetry A^{Λ} as defined in Eq. (7) as a function of Λ rapidity at HERA–*$\vec{N}$ *energy for various sets of spin-dependent fragmentation functions together with the projected statistical errors. A discussion of the different scenarios and curves can be found in ref. [44].*

7 Deuteron and Helium Targets

A fixed-target experiment like *HERA–*$\vec{N}$ offers a unique possibility to study polarized *pn* and *pd* collisions which are harder or even impossible to realize in collider experiments at RHIC. Using a polarized ^3He target would allow to investigate polarized *pn* collisions and in particular a measurement of the polarized sea quark distributions via Drell-Yan pair production (see section 4). Moreover, it is very likely that a fixed-target environment offers the only chance to investigate *pd* collisions with longitudinally polarized deuterons since it presently appears rather difficult to attain longitudinal polarization for deuterons in a collider due to their small magnetic moment.

Compared to the proton target, the deuteron, as a spin-1 hadron, has additional twist-2 parton distributions, in particular a tensor-polarized quark distribution, $b_1(x)$. It could be measured using Drell-Yan pair production in scattering *unpolarized* protons on the *tensor-polarized* deuteron. The corresponding asymmetry can be written as [45]

$$A_{UQ_0}^{DY} = \frac{\sum_f \; e_f^2 \, [q_f(x_1) \, \bar{b}_{1f}(x_2) \; + \; \bar{q}_f(x_2) \, b_{1f}(x1)]}{\sum_f \; e_f^2 \, [q_f(x_1) \, \bar{q}_f(x_2) \; + \; \bar{q}_f(x_2) \, q_f(x_1)]}. \tag{9}$$

No quantitative estimates for the asymmetry are available yet.

8 Summary and Conclusions

The physics case for a possible fixed target polarized nucleon-nucleon collision experiment utilizing an internal target in the 820 GeV HERA proton beam has been presented. A wide spectrum of nucleon spin structure problems could be investigated. Single (transverse) spin asymmetries, accessible already with the existing unpolarized beam, are found to be a powerful tool to study the nature and physical origin of higher twist effects and a possible manifestation of non-perturbative dynamics. Their measurement requires a sufficiently large p_T-range; *HERA–*$\vec{N}$ would be able to provide data up to p_T =10 GeV/c in the central region and up to 5$\div$6 GeV/c in the fragmentation region of the polarized nucleon. 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 approaches explore the same x_{gluon} range they are complementary due to the different accessible p_T ranges. 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 double transverse and/or longitudinal-transverse Drell-Yan spin asymmetries as well as a study of the single (transverse) spin asymmetry in inclusive two-pion production may open an access to the quark transversity distribution(s). A study of the spin transfer in the reaction $p\vec{p} \to \vec{\Lambda} X$ is capable of providing essential constraints on the polarized Λ hyperon fragmentation functions. The existence of a polarized internal gas target in *HERA–*$\vec{N}$ would allow to study also polarized *pn* and $pA(D,^3He, ...)$ collisions which are harder or even impossible to realize in collider experiments at RHIC. In addition, there is a potential to obtain significant results on the long-standing unexplained spin asymmetries in elastic scattering.

Acknowledgments

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References

[1] W.–D. Nowak, Proc. of the Adriatico Research Conf. *Trends in Collider Spin Physics*, ICTP Trieste, 1995, ed. by Y. Onel, N. Paver, A. Penzo, p.169; hep-ph/9605411. http://www.ifh.de/HERA-N/

[2] V.A. Korotkov, W.–D. Nowak, *Nucl. Phys.* A **622**, 78c (1997)

[3] J.C. Collins, *Nucl. Phys.* B **396**, 161 (1993)

[4] D. Sivers, *Phys. Rev.* D **41**, 83 (1990); ibid. **43**, 261 (1991)

[5] M. Anselmino, M. Boglione, F. Murgia, *Phys. Lett.* B **362**, 164 (1995); M. Anselmino, F. Murgia, *Phys. Lett.* B **442**, 470 (1998).

[6] M. Anselmino, M. Boglione, F. Murgia, DFTT 04/99, hep-ph/9901442, to be published in *Phys. Rev.* D.

[7] J.W. Qiu, G. Sterman, *Phys. Rev.* D **59**, 014004 (1998)).

[8] S.M. Troshin, N.E. Tyurin, *Phys. Rev.* D **52**, 3862 (1995); ibid. **54**, 838 (1996).

[9] N.I. Kochelev, these Proceedings and hep-ph/9905497.

[10] E704 Coll., D.L. Adams et al., *Phys. Lett.* B **264**, 462 (1991)

[11] C. Allgower et al., IHEP 99-14, Protvino, March 1999.

[12] E704 Coll., D.L. Adams et al., *Nucl. Phys.* B **510**, 3 (1998)

[13] A. Bravar, to be publ. in Proc. of 13th Int. Symp. SPIN98, Protvino, Russia, September 8-12, 1998.

[14] V.A. Korotkov, W.–D. Nowak, Proc. of the Workshop *Deep Inelastic Scattering off Polarized Targets: Theory Meets Experiment*, Zeuthen, 1997, DESY 97–200, ed. by J. Blümlein, A. De Roeck, T. Gehrmann, W.–D. Nowak, p.706.

[15] T. Sjöstrand, *Comp. Phys. Comm.* **82**, 74 (1994).

[16] E704 Coll., D.L. Adams et al., *Phys. Lett.* B **345**, 569 (1995)

[17] J. Czyzewski, *Acta Phys. Polon.* **27**, 1759 (1996).

[18] E704 Coll., A. Bravar et al., *Phys. Rev. Lett.* **78**, 4003 (1997)

[19] N. Hammon, O. Teryaev, A. Schäfer, *Phys. Lett.* B **390**, 409 (1997).

[20] D. Boer, P.J. Mulders, O.V. Teryaev, *Phys. Rev.* D **57**, 3057 (1998)

[21] M. Anselmino et al., On Possible Future Polarized Nucleon–Nucleon Collisions at HERA, Internal Report, *DESY–Zeuthen 96–04*, May 1996 (unpublished).

[22] S.V.Goloskokov, O.V. Selyugin, *Phys. Atom. Nucl.* **58**, 1894 (1995).

[23] A. Airapetian et al., DESY 99-071, July 1999; hep-ex/9907020.

[24] L. Apanasevich et al., *Phys. Rev. Lett.* **81**, 2642 (1998)

[25] L.E. Gordon, W. Vogelsang, *Phys. Lett.* B **387**, 629 (1996)

[26] T.K. Gehrmann and W.J. Stirling, *Phys. Rev.* D **53**, 6100 (1996)

[27] A. Tkabladze, O. Teryaev, *Phys. Rev.* D **56**, 7331 (1997)

[28] W.–D. Nowak, O. Teryaev, A. Tkabladze, same Proc. as in ref. [14], p.330. DESY 97-224, hep-ph/9711290.

[29] V.A. Korotkov, W.–D. Nowak, A. Tkabladze, Proc. of the *3rd Meeting on the Prospects of Nucleon-Nucleon Spin Physics at HERA*, Dubna, 1996, JINR preprint E2-96-40, DESY-Zeuthen Internal Report 96-09, ed. by W.–D. Nowak and O.V. Selyugin, p.153.

[30] W.-D. Nowak, A. Tkabladze, *Phys. Lett.* B **443**, 379 (1998)

[31] R.L. Jaffe, D. Kharzeev, *Phys. Lett.* B **455**, 306 (1999)

[32] M. Anselmino et al., Proceedings 'Future Physics at HERA', Eds. G. Ingelman, A. De Roeck, R. Klanner, p.837. DESY 96-128, hep-ph/9608393.

[33] A. Yokosawa, same Proc. as in ref. [1], p.148.

[34] T.K. Gehrmann, W.J. Stirling, *Z. Phys.* C **65**, 461 (1994)

[35] T. Gehrmann, W.J. Stirling, same Proc. as in ref. [32], p.847.

[36] T. Gehrmann, *Nucl. Phys.* B **498**, 245 (1997)

[37] R. L. Jaffe, X. Ji, *Nucl. Phys.* B **375**, 527 (1992)

[38] J. Soffer, *Phys. Rev. Lett.* **74**, 1292 (1995)

[39] O. Martin et al., preprint CERN-TH/98-366, February 1999;
O. Martin, Proc. of 7th Int. Workshop on Deep Inelastic Scattering and QCD, DIS-99, DESY Zeuthen, April 1999; to appear in *Nucl. Phys.* B *Proc. Suppl.*.

[40] Y. Kanazawa, Y. Koike, N. Nishiyama, *Phys. Lett.* B **430**, 195 (1998)

[41] R.L. Jaffe, X. Jin, J. Tang, *Phys. Rev. Lett.* **80**, 1166 (1998)

[42] J. Tang, preprint MIT-CTP-2769, July 1998, hep-ph/9807560.

[43] D. de Florian, M. Stratmann, W. Vogelsang, *Phys. Rev.* D **57**, 5811 (1998)

[44] D. de Florian, M. Stratmann, W. Vogelsang, *Phys. Rev. Lett.* **81**, 530 (1998);
D. de Florian, hep-ph/9905531.

[45] S. Hino, S. Kumano, *Phys. Rev.* D **59**, 094026 (1999);
S. Hino, S. Kumano, SAGA-HE-139-98, hep-ph/9902258, *Phys. Rev.* D in press.