SPIN PHYSICS WITH HERA-$\vec{N}$

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Abstract

The physics aspects of polarized nucleon-nucleon collisions aiming at studying the nucleon spin structure at HERA are considered. A possible experiment, HERA-$\vec{N}$, could be realized using an internal polarized target in the HERA polarized/unpolarized proton beam. Single spin asymmetry measurements could provide unique information on higher twist contributions. Once the HERA proton beam is polarized measurements of the polarized gluon and light sea quark distributions using double longitudinal spin asymmetries might be possible. The experiment would constitute a fixed target complement to the RHIC spin physics program with competitive statistical accuracy.

1 Introduction

Past experiments with colliding polarized particles have reached quite some progress, still the present picture of the nucleon spin structure is essentially incomplete. A number of new experiments at CERN, SLAC, DESY, BNL was proposed to investigate in more detail polarized particle interactions and to measure with good accuracy polarized parton distributions. Up to now polarized deep inelastic scattering exeperiments have measured only the longitudinal twist-2 spin structure function $g_1(x)$ and set an upper limit on the structure function $g_2(x)$ which contains a twist-3 contribution. Polarized hadron-hadron experiments measured large single spin asymmetries expected to be zero in perturbative QCD. No measurements of the polarized gluon distribution, ΔG, and of chiral odd quark distributions have been accomplished up to now.

An experiment ('HERA–$\vec{N}$' [1, 2, 3, 4]) 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 [5]. The estimate of the integrated luminosity which could be achieved 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 $\bar{I}_B = 80$ mA $= 0.5 \cdot 10^{18}\ s^{-1}$ for the average HERA proton beam current and a rather conservative polarized target density of $n_T = 3 \cdot 10^{13}$ 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 $T = 1.6 \cdot 10^7\ s$ at 100 % efficiency is assumed. This corresponds to about 3 real years under present HERA conditions. One may argue, however, that even 500 pb^{-1} *per year* might presumably become a realistic figure [3]. 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 of a possible experiment with an internal polarized target in the (polarized) HERA proton ring. Any discussion of a possible structure of the experiment and its site in the HERA ring is beyond the scope of this paper.

2 Single Spin Asymmetries

A study of single spin asymmetries in inclusive particle production is considered now as a way for investigation of higher twist effects: there might be twist-3 dynamical contributions or hard scattering higher twists; there might also be intrinsic $\boldsymbol{k}_\perp$ effects, both in the quark fragmentation process and in the quark distribution functions. The contributions of the different effects are process dependent and therefore a comparative study of single spin asymmetries in different processes might be a unique way of understanding the origin and the importance of higher twist contributions in large p_T inclusive production.

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

Inclusive pion production $p^\uparrow p \to \pi^{0\pm} X$ 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 [6]. 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 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.

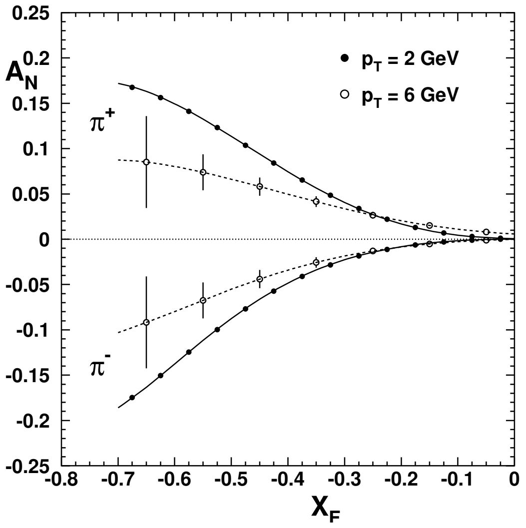

Figure 1: *Capability of HERA-$\vec{N}$ to discriminate predictions [7] for different p_T.*

The accessible p_T values with $HERA-\vec{N}$ could be significantly larger than those E704 had; the combined p_T dependence of all involved higher-twist effects can be measured with good accuracy ($\delta A_N \le 0.05$) 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. The capability of HERA-$\vec{N}$ to really prove a predicted p_T dependence is shown in fig. 1, where the curve was obtained assuming a non–zero quark distribution analysing power, $N_q(\boldsymbol{k}_\perp)$, according to Ref. [7].

The study of polarization asymmetries in **inclusive 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 [8]. 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. 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.

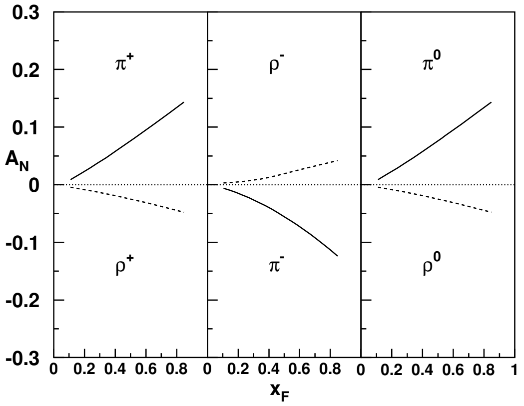

Figure 2: *Asymmetry in inclusive production of π's and ρ's as predicted in model [8].*

Inclusive direct photon production, $pp^{\uparrow} \to \gamma X$, proceeds without fragmentation, i.e. the photon carries directly the information from the hard scattering process. Hence this process measures a combination of initial $\boldsymbol{k}_{\perp}$ effects and hard scattering twist–3 processes. The first and only results up to now were obtained by the E704 Collaboration [9] 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-$\vec{N}$ 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 ($q\bar{q} \to \gamma g$), 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.

There is an interesting possibility [10, 11] to extract the third twist-2 quark distribution function (quark transversity distribution, $\delta q(x)$ or $h_1(x)$) using **inclusive production of two pions** on the transversely polarized nucleon, $p + p^{\uparrow} \to \pi^+ + \pi^- + X$. This structure function describing basically the fraction of transverse polarization of the proton carried by its quarks is absolutely unknown at present. 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 [5, 11, 12]. One should study the asymmetry in two pions production as 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. The statistical sensitivity of HERA-$\vec{N}$ has to be calculated.

The single spin asymmetries in **inclusive J/ψ production** [2] and in **Drell-Yan production**, $p + p^{\uparrow} \to l\bar{l} + X$, at small transverse momenta [13], were calculated for the HERA-$\vec{N}$ energy and shown to be of the order of $0.01 \div 0.02$.

Large spin effects in **proton-proton elastic scattering**, $p + p^{\uparrow} \to p + p$, have been discovered many years ago. The single spin asymmetry A_N was found significantly different from zero. At HERA-$\vec{N}$ energy one can measure the asymmetry in the range of $p_T^2 = 5 \div 12$ (GeV/c)^2 (see ref.[2, 3]).

3 Double Spin Asymmetries

The measurement of double spin asymmetries in certain final states seems to be the most valuable tool to measure polarized gluon and quark distribution functions in the nucleon. The most accurate way to do so is the study of those processes which can be calculated in the framework of perturbative QCD. Production of *direct photon (plus jet)*, *J/ψ (plus jet)*, and *Drell-Yan pair* final states are most suited because there are only small uncertainties due to fragmentation.
In the following we discuss the capabilities of HERA-$\vec{N}$, operated in doubly polarized mode, 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.
In a recent study [14] **inclusive photon production** with HERA-$\vec{N}$ was investigated. Basing on a NLO calculation rather firm predictions were obtained for A_{LL}. In fig.'s 3a and 3b 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.

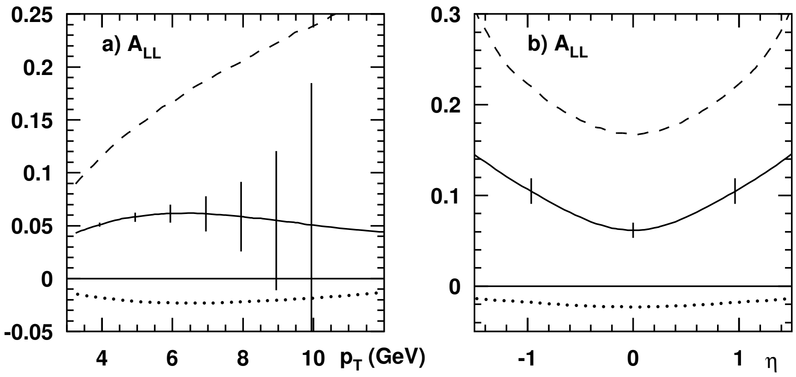

Figure 3: *Double spin asymmetry in inclusive photon production displayed vs. a) p_T and b) η for different polarized gluon distribution functions (see Ref. [14]), shown in conjunction with the projected statistical sensitivity of HERA-$\vec{N}$.*

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

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

Because of the relatively large quark mass the $c\bar{c}$ production cross section and the expected asymmetry are supposed to be calculable perturbatively.

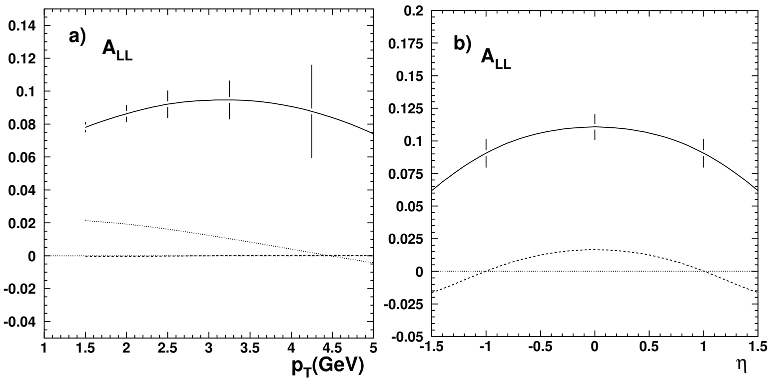

Figure 4: *Double spin asymmetry in inclusive J/ψ production displayed vs. a) p_T and b) η for NLO set A (full line) and set C (dashed line) of Ref. [16], shown in conjunction with the projected statistical sensitivity of HERA-$\vec{N}$.*

In fig.'s 4a and 4b the expected asymmetry [15] is presented versus p_T and η for two different polarized gluon distributions from ref.[16]; apparently a very good discrimination between different sets is possible over the HERA-$\vec{N}$ kinematical range.

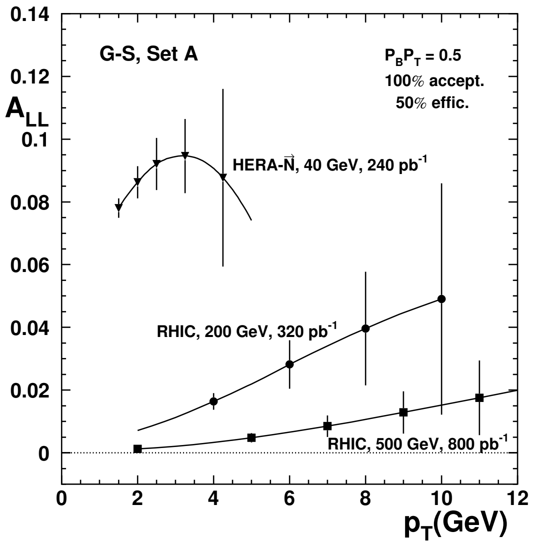

Figure 5: *The asymmetry and projected statistical errors for J/ψ production at HERA-$\vec{N}$ and two different energies at RHIC as a function of p_T.*

For comparison the expected double spin asymmetries for J/ψ production at RHIC energies were calculated [15, 17]. In fig. 5 predictions at HERA-$\vec{N}$ and two different RHIC energies are shown with projected statistical errors. In the statistically accessible p_T interval the asymmetry ranges between 0.08 and 0.10 at HERA-$\vec{N}$, but only between 0.01 and 0.03 at RHIC energies. It is likely that the fixed target experiment at HERA might accomplish a more significant measurement of the charmonium production asymmetry.

One may consider also a possibility to extract $\Delta G/G$ using the inclusive **two jet production**. Several hard subprocesses (gg, gq, qq scattering) contribute to the production and a good knowledge of polarized quark distributions would be essential. At HERA-$\vec{N}$ there is an additional difficulty - the jet reconstruction at small $\sqrt{s}$. One may probably replace the jet reconstruction by a registration of two correlated high p_T hadrons opposite in azimuth. This possibility still needs careful investigation.

Photon or J/ψ Production Associated with Jets. The complete kinematics of the 2→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. [2]).

Using this approach **photon plus jet** production was discussed in Ref. [3] as a tool to directly measure ΔG/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. 6 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 [18]. 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.

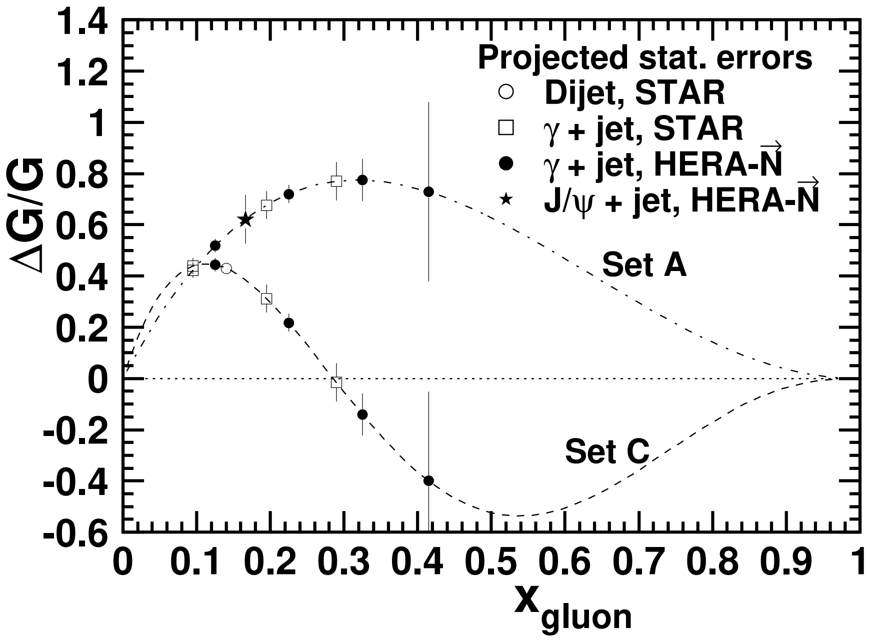

Figure 6: *Typical predictions for the polarized gluon distribution (LO calculations from Ref. [19]) confronted to the projected statistical errors expected for HERA-$\vec{N}$ and RHIC experiments.*

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. 6. 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. 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 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 polarized nucleon-nucleon collisions can provide information on a variety of polarized structure functions in dependence on the relation of the beam and the target polarization directions.

The **longitudinal** double spin asymmetry turns out to be well suited to extract the polarized light sea-quark distribution

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

The prospects for such a measurement with HERA-$\vec{N}$ were calculated in ref. [20] at next-to-leading order QCD. The spread of the predictions (see fig. 7) 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 u sea quark polarization.

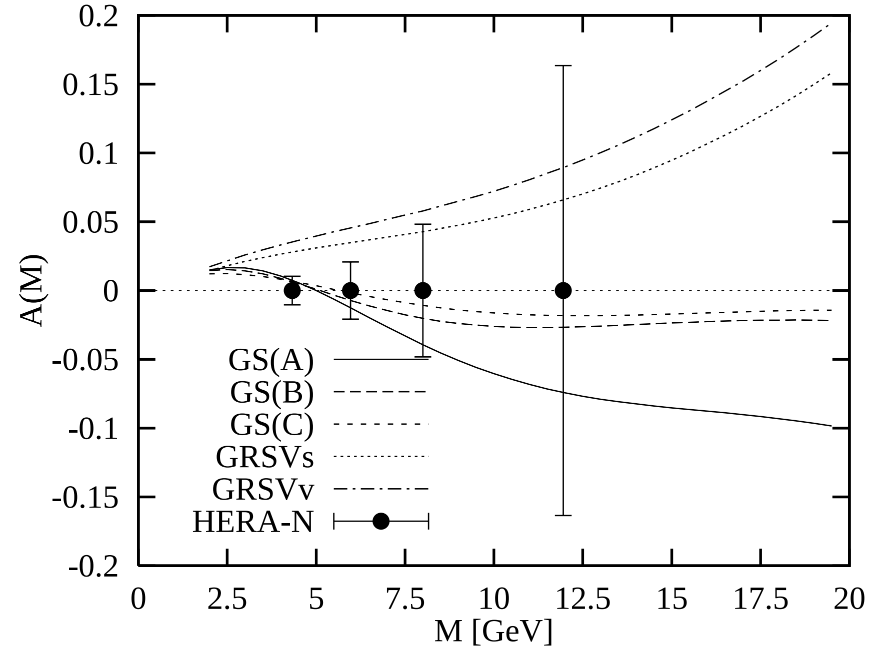

Figure 7: *Expected longitudinal double spin asymmetries in the polarized Drell-Yan process from Ref. [20]) confronted to the projected statistical errors expected for HERA-$\vec{N}$.*

Drell-Yan pair production with **transverse polarization** of both beam and target can provide a measurement of the transversity distribution, $\delta q(x)$. The transverse double spin asymmetry in nucleon-nucleon Drell-Yan production can be schematically written in the form [21]

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

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. An estimate of the asymmetry for HERA-$\vec{N}$ energy was given recently in ref. [22] from both LO and NLO calculations. One should stress, however, that the anticipated asymmetry level strongly depends on the actual size of the transversity distributions, 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. Due to the lack of any information on the transversity distribution, the maximally possible value of the asymmetry was estimated [22]; the corresponding results on LO and NLO DY cross-section and asymmetry are presented at fig. 8. The expected statistical errors for a measurement of A_{TT} with HERA-$\vec{N}$ are also shown. The maximal value of A_{TT} at an invariant mass of $M = 4$ GeV was found to be approximately 4% with an expected statistical error of about 1%. The expected value of the asymmetry at RHIC energies is smaller but the statistical errors become relatively smaller at $\sqrt{s} = 500$ GeV due to the higher luminosity of $\mathcal{L} = 800\text{pb}^{-1}$ [22].

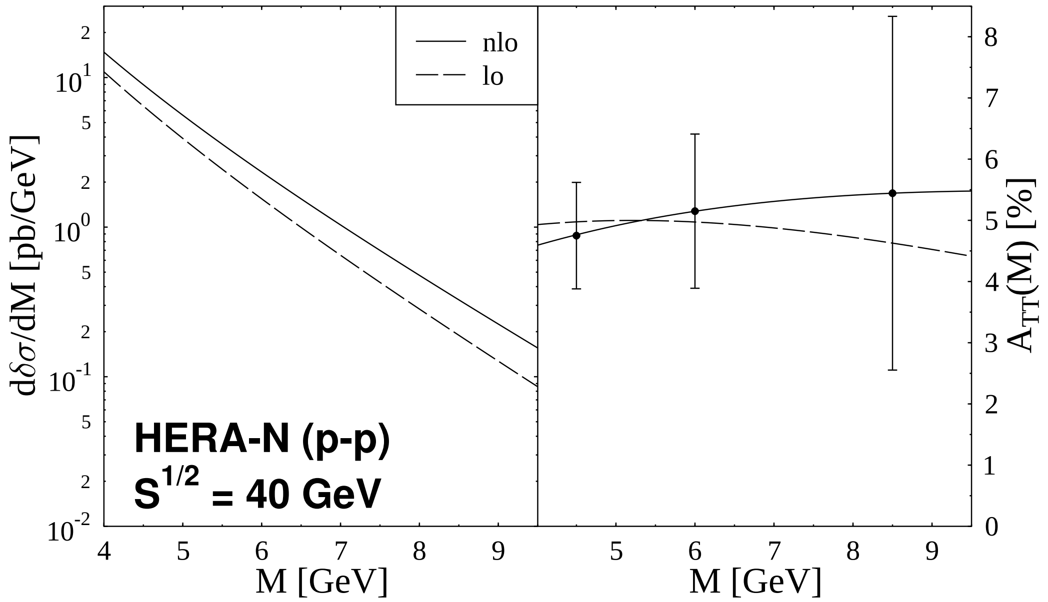

Figure 8: *Maximal polarized Drell-Yan cross-section (left figure) and the asymmetry (right figure) in double transverse polarized collisions as a function of the invariant mass. The results are shown for both LO and NLO calculations. The projected statistical errors for HERA-$\vec{N}$ are presented also. The results are taken from Ref. [22]).*

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 [21, 23] 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 $M/\sqrt{Q^2}$.
The HERA-$\vec{N}$ statistical reach for A_{LT}^{DY} has not been calculated yet.

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 as well as a study of the two pion correlations in the single transverse spin collisions might open first access to the quark transversity distribution. Also, the existence of the polarized internal target in HERA-$\vec{N}$ provides access to study the polarized pn and $pA(D,^3He,...)$ collisions, which are harder to be realized at RHIC. In addition, there is a potential to obtain significant results on the long-standing unexplained spin asymmetries in elastic scattering.

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