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Single Spin Asymmetries in Proton-Proton and Proton-Neutron Scattering at 820 GeV [1]

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Abstract

The physics case is summarised for the investigation of high energy spin phenomena by placing an internal polarised target into HERA's unpolarised proton beam. The luminosity and experimental sensitivity are discussed. Estimating the physics reach of single spin asymmetries in different final states reveals a considerable physics potential in testing the spin sector of perturbative QCD.

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1 Introduction

If the HERA proton ring could be operated with polarised particles a host of new experimental possibilities would ensue. At present it is not clear though whether this is a practical possibility. A viable first step, however, towards investigating spin effects in hadron–hadron interactions at HERA could be an experiment scattering unpolarised 820 GeV protons off polarised nucleons utilising a polarised internal gas target. Both proton-proton and proton-neutron spin asymmetries would be readily accessible since modern polarised gas targets can be operated with Hydrogen, Deuterium, or ^{3}He.

Experimentally single spin asymmetries are usually generated by switching the direction of the initial spin vector. In the given situation they can be measured as correlation between the polarisation of the target nucleon on one hand, and the final state polarisations and angular distributions on the other.

In the next section the experimental sensitivity is estimated for two different luminosity scenarios. Then, the physics reach with several interesting final states is discussed in some detail. The magnitude of the gluon spin might be probed with jets or possibly dimuons. It appears feasible to measure (leading) twist-3 contributions with direct photons where theoretical predictions distinguishing between proton and neutron target are of special interest. New pion data at higher transverse momenta could clarify the situation of the non-zero transverse pion asymmetry which appears to be in conflict with pertubative QCD. Analysing dipions from the same jet might allow to access the valence quark transversity distribution.

2 Luminosity and Sensitivity

A realistic estimate for the average HERA proton beam current is $\bar{I}_B = 80$ mA $= 0.5 \cdot 10^{18}\ s^{-1}$ constituting half of the design current. An internal target area desity of $n_T = 10^{12}$ atoms/cm^2, as can be delivered by a standard polarised jet target, would not deteriorate the present HERA proton beam performance. This safe "low luminosity option" would have a luminosity of

$$\mathcal{L}_L = n_T \cdot \bar{I}_B = 0.5 \cdot 10^{30}\ \mathrm{cm}^{-2} s^{-1}\ .$$

In an optimistic scenario the polarised internal target could presumably be operated with an area density of a few 10^{13}, say $n_T = 3 \cdot 10^{13}$ atoms/cm^2. Note that the UA6 unpolarised internal target was successfully run at a comparable density in the CERN $Sp\bar{p}S$ collider. Today's polarised H/D [1] and ^{3}He targets [2] with storage cells are capable of running at those densities with polarisations as high as 80% and 50%, respectively. Hence a "high luminosity option" with

$$\mathcal{L}_H = 1.5 \cdot 10^{31}\ \mathrm{cm}^{-2} s^{-1}$$

appears feasible although still to be proven under actual HERA conditions.

To assess the physics reach of different final states a total running time of $T = 1.6 \cdot 10^7\ s$ with 100% efficiency is assumed. This corresponds to about 3 calendar years of HERA operation with 6 months per year physics running and 33% combined up–time for accelerator and experiment. Hence the integrated luminosities per year for the two discussed running scenarios are

$$\begin{array}{ll} \mathcal{L}_L \cdot T = \ 8\ pb^{-1} & \text{for the low luminosity option and} \\ \mathcal{L}_H \cdot T = 240\ pb^{-1} & \text{for the high luminosity option.} \end{array}$$

The experimental sensitivity in the measured single spin asymmetry A is

$$\delta A = \frac{1}{p_{targ}} \cdot \frac{1}{\sqrt{N}}\ ,$$

where p_{targ} is the degree of target polarisation and $N = \mathcal{L} \cdot T \cdot C \cdot \sigma$ the total number of recorded events. Here σ is the unpolarised cross section and C the combined trigger and reconstruction efficiency. Then

$$\delta A = \frac{1}{p_{targ}} \cdot \frac{1}{\sqrt{\mathcal{L} \cdot T \cdot C}} \cdot \frac{1}{\sqrt{\sigma}}\ ,$$

and with $p_{targ} = 0.8$ and C = 50% one obtains as experimental sensitivities

$$\begin{array}{ll} \delta A_L = 0.6/\sqrt{\sigma\,[pb]} & \text{for the low luminosity option and} \\ \delta A_H = 0.1/\sqrt{\sigma\,[pb]} & \text{for the high luminosity option.} \end{array}$$

3 Physics Objectives

3.1 Probing the Gluon Spin with Inclusive Jets

At $\sqrt{s} = 40$ GeV and $p_t = 5$ GeV the huge unpolarised cross section for inclusive jet production allows for sensitivities of 0.0001 [0.0006] in the high [low] luminosity option. At $p_t = 10$ GeV the sensitivities are still 0.003 [0.018], always meant for 1 GeV bins. Stratmann and Vogelsang [3] calculated the corresponding hard scattering cross sections for both *transverse* and *longitudinal* singly polarised proton–proton scattering including all underlying pQCD $2 \to 2$ subprocesses. The *transverse* asymmetry is shown in fig. 1, at $p_t = 10$ GeV ($x_t = 0.5$) is $A_T \simeq 12\%$, unfortunately with insignificant dependence on the transverse polarisation of the sea.

Fig. 1 Transverse asymmetry on the parton level for inclusive jet production at $\sqrt{s}$ = 40 GeV. The solid line was obtained using the scale $Q^2 = p_t^2/4$, the dashed one corresponds to the fixed scale Q^2 = 10 GeV^2.

The *longitudinal* asymmetry A_L is very sensitive to the size of ΔG, as can be seen from fig. 2. Over the accessible p_t range $5 \div 10$ GeV A_L rises smoothly from 5 to 25% if $\Delta G = 0$, whereas it stays approximately constant at 25% when a very large gluon spin is assumed.

In the given kinematical situation the c.m. backward jet will emerge under a few hundred milliradian in the laboratory system. Anticipating that the three fastest particles in the jet can be isolated a handedness [5, 6] analysis is believed to measure the spin of the fragmenting parton. The supposedly process independent handedness parameter could possibly be about 0.05 [7]. This, together with dilutions from the internal target polarisation (0.8) and an anticipated average parton spin (0.25), would result in a total dilution factor of about 100. Hence the 25% parton level asymmetry would be reduced to a 2.5 per mille, i.e. 0.0025 hadronic level asymmetry. This, at $p_t = 5$ GeV, is a 4 σ effect even in the low luminosity option. Obviously, the systematic error has to be kept on the permille level as well.

3.2 Probing the Gluon Spin with Dimuons

Carlitz and Willey [8] calculated the *longitudinal* single spin asymmetry A_L for dimuon production in proton-proton collisions. It is non-zero if the axial vector built from the muon momenta has a longitudinal component. The relevant subprocesses are gluon Compton scattering and quark–antiquark annihilation. Using different assumptions

Fig. 2 Longitudinal asymmetry on the parton level for inclusive jet production at $\sqrt{s}$ = 40 GeV [4], based upon two different sets of polarized parton distributions. Set a) implies a very large gluon spin and a vanishing polarized sea, set b) has a vanishing gluon spin but a large negative polarized sea, cf. [3].

on the total gluon spin this asymmetry was calculated by Nadolsky [9]. As shown in fig. 3, at $Q_\perp^2 = 3\ (GeV)^2$ the asymmetry ranges from $A_L = 0.02$ for ΔG = 1 up to $A_L = 0.08 \div 0.12$ for ΔG = 6, although today ΔG = 3 $\div$ 4 might be more a realistic upper limit. For dimuon masses above 10 GeV this scenario corresponds to an unpolarised cross section below 1 pb. Even in the high luminosity option the expected experimental sensitivity is at best $\delta A \simeq 0.1$ and hence comparable to the whole asymmetry difference.

The steeply rising dimuon cross section suggests to reconsider the case at smaller dimuon masses, e.g. 4 GeV. Here the cross section of about 100 pb leads to $\delta A \simeq 0.01$ in the high luminosity option. However, the actual improvement in the sensitivity to asymmetry ratio remains questionable since in most models a smaller gluon spin is expected when it is probed at smaller dimuon masses.

3.3 Probing Twist-3 Matrix Elements with Direct Photons

Based upon a twist-3 parton distribution involving the correlation between quark fields and the gluonic field strength, the leading single *transverse* spin asymmetry for high p_t direct photon production was estimated by Qiu and Sterman [11]. The essential subprocess is gluon Compton scattering with the gluon carrying the initial polarisation information. The hard scattering asymmetry rises to about 20% for $x_F \simeq$ - 0.8.

Fig. 3 Longitudinal asymmetry on the parton level for dimuon production at 400 GeV incoming energy [10] versus virtual photon energy for different assumptions on the gluon spin. At 820 GeV the asymmetries will be slightly smaller.

Estimating the same matrix element differently Ehrnsperger et al. [12] reconsidered the case with special emphasis to differences between proton and neutron target. Only a small negative proton asymmetry but a rather large positive neutron asymmetry of several 10% is predicted. According to Korotkiyan and Teryaev [13] the contribution due to gluonic poles should vanish and all asymmetry is due to fermionic poles,only. Nevertheless, a sizeable parton level asymmetry remains, as can be seen from fig. 4.

In another paper Ji [14] considered the variety of relevant three–gluon–correlations. Many different structure functions appear in the cross section making any selection impossible when considering the full kinematic region. At large negative x_F however, as for the measurements at HERA, the pure gluon correlations are expected to become dominant compared to quark–gluon correlations.

The dilution of the asymmetry on going from the parton to the hadron level amounts to a factor of 5, since there is no fragmentation. Hence the above discussed neutron asymmetry requires $\delta A \leq 0.005$, i.e. it can be studied up to $p_t \simeq 4.5$ GeV in the high luminosity option. Note that the gaseous H/D target considered is a good tool to minimise systematic errors in the study of proton–neutron differences.

Fig. 4 Transverse asymmetry on the parton level for inclusive direct photon production.

3.4 New Physics from Transverse Pion Asymmetries ?

The only significant data on single spin asymmetries are from E704 who have measured the reactions $p^{\uparrow} + p \rightarrow \pi^{0\pm} + X$ in a *transversely* polarised beam at 200 GeV [15]. In strong contradiction to pQCD predictions, significant non–zero asymmetries were found, as is shown in fig. 5. With increasing x_F the charged pion asymmetry is smoothly rising to 40%, opposite in sign for the different pion charges. Years after publication this data still constitutes a challenge to perturbative QCD. Confirmation by an independent experiment at twice as high transverse momenta would certainly be worthwile.

An example of heretic ideas on this subject is provided by the model of orbiting valence quarks proposed by Boros et al. [16]. Within a semi–classical approach the constituents of a polarised hadron are assumed to perform an orbital motion about the polarisation axis and left/right asymmetries are expected to arise from annihilations of these valence quarks. The model is able to give a fair description of the inclusive pion data and of the dimuon data as well.

In a very recent QCD based approach [17] is argued that in high p_t inclusive pion production the gluon–quark asymmetry on the parton level dominates over the gluon–gluon one. As a consequence the flavor–dependent valence quark polarization leads to a mirror symmetry in the sign of charged pion asymmetries and explains qualitatively the behaviour of the π^0 asymmetry as well.

Fig. 5 Transverse asymmetries measured by E704 in inclusive pion production at 200 GeV.

3.5 Accessing the Valence Quark Transversity with Dipions

The measurement of two–pion correlations within the same jet, in a scattering of *transversely* polarised hadrons off unpolarised ones, is proposed by Collins et al. [18]. To measure the transversity distribution on the twist-2 level they propose to jointly probe the transversity of two quarks participating in the hard scattering. The underlying pQCD subprocess is quark gluon scattering with the outgoing polarised quark fragmenting into a jet which is then supposed to carry spin information from the transversely polarised target valence quark. It is expected that for low–mass pion pairs the azimuthal dependence of the two–pion plane about the jet axis reverses sign when the spin of the incoming hadron is reversed.

The reconstruction of the hard scattering would require to measure c.m. opposite jets associated with pion pairs. Obviously, in the given fixed target environment the feasibility of pion identification in the forward jet deserves further study. The experimental sensitivity was already discussed above. The spin transfer in the hard subprocess is possibly large hence a large asymmetry in the overall process might occur. More theoretical work would is needed to arrive at numerical predictions.

4 Conclusions

There is reason for optimism that interesting and important, and even completely new fundamental information on the nucleon spin could be accessed by placing an internal polarised target into the unpolarised HERA proton beam. A rather broad physics programme aiming at testing the spin sector of perturbative QCD and beyond, can be based upon measurements of single spin asymmetries in several final states. However, for most of the accessible processes better theoretical predictions are necessary in order to justify a serious experimental effort.

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