TRANSVERSE SPIN EFFECTS IN SINGLE AND DOUBLE HADRON ELECTROPRODUCTION AT HERMES

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In the first phase of the HERA II running period the HERMES collaboration is taking data with a transversely polarized Hydrogen target. It was installed during the HERA shutdown in the fall of 2000. The transverse target extends the spin physics program of HERMES to the topic of transversity. It allows to investigate the distribution of transversely polarized quarks in a transversely polarized nucleon. In the data evidence is found not only for a non-zero signal on transversity but also on the Sivers mechanism that can be related to non-zero orbital angular momenta of the quarks in a transversely polarized nucleon.

1. Introduction

Deep inelastic scattering (DIS) of leptons off a nucleon is an excellent tool to investigate the structure of the nucleon. The HERMES experiment uses the 27.6 GeV electron or positron beam from the HERA machine. In combination with a fixed gaseous transversely polarized Hydrogen target[1] the center of mass energy is about $\sqrt{s} = 7$ GeV. The scattered lepton is detected together with some of the produced hadrons in the DIS process in the HERMES spectrometer [2]. The tracking detectors in combination with the spectrometer magnet allow the momentum determination with a resolution between 1.5% and 2.6% depending on the momentum of the particle. For particle identification (PID) four different detectors are available. A lead-glass calorimeter, a pre-shower scintillator hodoscope, a transition radiation detector (TRD) and a dual radiator ring imaging Cherenkov detector (RICH). The latter is a mandatory prerequisite for a clear separation of the different hadronic particle types pions, kaons and protons[3].

2. Helicity amplitudes

In the handbag diagram, shown on the left hand side in fig.1, the DIS process is factorized into a hard part and a soft part. The hard scattering of the photon-quark vertex can be calculated accurately in QED while the soft part retains the unknown information about the structure of the target and has to be parameterized. This lower part of the handbag diagram can be represented in terms of helicity amplitudes dependent on the helicities of the quark and proton propagators. The amplitude is then given in the helicity basis as $A_{\Lambda\lambda,\Lambda'\lambda'}$ where $\Lambda,\ \lambda,\ \Lambda'$ and λ' are the nucleon and quark helicity in the initial and final state, respectively. Out of the 16 possible

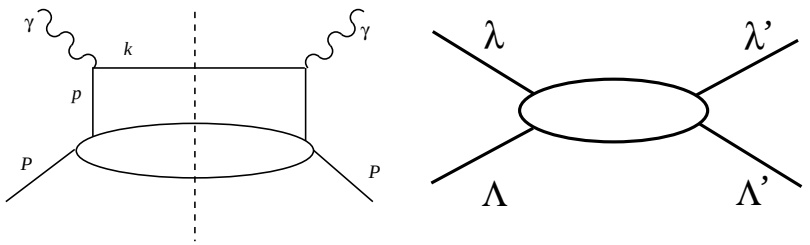

Figure 1. Handbag diagram left and quark-nucleon helicity amplitude right

helicity amplitudes only three are independent and possibly non-zero after applying helicity conservation ($\Lambda + \lambda = \Lambda' + \lambda'$) and parity conservation ($A_{\Lambda\lambda,\Lambda'\lambda'} = A_{-\Lambda-\lambda,-\Lambda'-\lambda'}$). These three amplitudes are:

$$A_{++,++};\ A_{+-,+-};\ A_{+-,-+}\ .$$

The first two of these amplitudes conserve the helicity of the nucleon and quark lines where in the last one $A_{+-,-+}$ the helicity of the quark is flipped as $\lambda \to -\lambda'$ and hence the proton helicity $\Lambda \to -\Lambda'$ in order to conserve the total helicity of the system. These amplitudes can be related to quark distributions with the following relation:

$$f(x) = f_+(x) + f_-(x) \sim Im(A_{++,++} + A_{+-,+-}), \tag{1}$$

$$\Delta f(x) = f_+(x) - f_-(x) \sim Im(A_{++,++} - A_{+-,+-}), \tag{2}$$

$$\delta f(x)\ = f_\uparrow(x) - f_\downarrow(x)\ \sim Im(A_{+-,-+}). \tag{3}$$

$f(x)$ is the well known momentum distribution of quarks in the nucleon and $\Delta f(x)$ is the difference of parallel to anti-parallel longitudinally polarized quarks with respect to the longitudinally polarized nucleon. $\delta f(x)$

describes the distribution difference of transversely polarized quarks parallel minus anti-parallel to the parent transversely polarized nucleon. $f_+(x)$ is the distribution of quarks which are polarized parallel to the parent nucleon and $f_-(x)$ is the distribution of quarks which are polarized opposite to the parent nucleon. In the third distribution $\delta f(x)$ the transversity basis ($|\uparrow\rangle$ and $|\downarrow\rangle$) is used for the quark distributions. This is necessary to obtain a probabilistic interpretation of the quark distributions. Using the relations $|\uparrow\rangle = \frac{1}{\sqrt{2}}(|+\rangle + i\,|-\rangle)$ and $|\downarrow\rangle = \frac{1}{\sqrt{2}}(|+\rangle - i\,|-\rangle)$ the helicity flip amplitude can be expressed in this transversity basis and the quark transversity distribution becomes

$$\delta f(x) = f_\uparrow(x) - f_\downarrow(x) \sim Im(A_{\uparrow\uparrow,\uparrow\uparrow} - A_{\uparrow\downarrow,\uparrow\downarrow}). \tag{4}$$

In the case of a gluon-nucleon helicity amplitude a helicity flip amplitude cannot exist due to helicity conservation. The change of the gluon helicity by two units can not be compensated by a helicity change of the nucleon. As a consequence there is no gluonic contribution to $\delta f(x)$ in the spin 1/2 nucleon.

3. Transversity in lepton scattering

In DIS the virtual photon couples to the quark in the nucleon thereby probing its structure. This process conserves helicity. Hence the inclusive DIS process where only the scattered lepton is detected is not suitable to measure transversity. In the handbag diagram this is equivalent to the fact that the helicity of the quark line coupling to the photons does not change. An additional process is needed to take care of a quark helicity flip. Such a possible process is described by the Collins fragmentation function $H_1^\perp(z, (-z\mathbf{k_T})^2)$ [4]. This chiral odd function is the difference of the probability density of a transversely polarized struck quark with its initial spin parallel to the parent nucleon minus anti-parallel to the parent nucleon. The detected final state hadron is a given type. k_T is the transverse momentum of the struck quark. Consequently one has to measure semi-inclusive deep inelastic scattering (SIDIS) processes to get access transversity. Consequently one measures the convolution of the transversity distribution function times the Collins fragmentation function.

3.1. *Single spin azimuthal asymmetry*

In SIDIS the observable that allows to access the product of this distribution function (DF) times the fragmentation function (FF) is a single

spin azimuthal asymmetry (SSA). This asymmetry is formed between the SIDIS cross section on the two transverse target polarization states. It is calculated as a function of two angles, the azimuthal angle ϕ between the lepton scattering plane and the hadron production plane and the angle ϕ_S between the lepton scattering plane and the nucleon polarization axis. The kinematics of this process is shown in fig. 2. The signature of the Collins

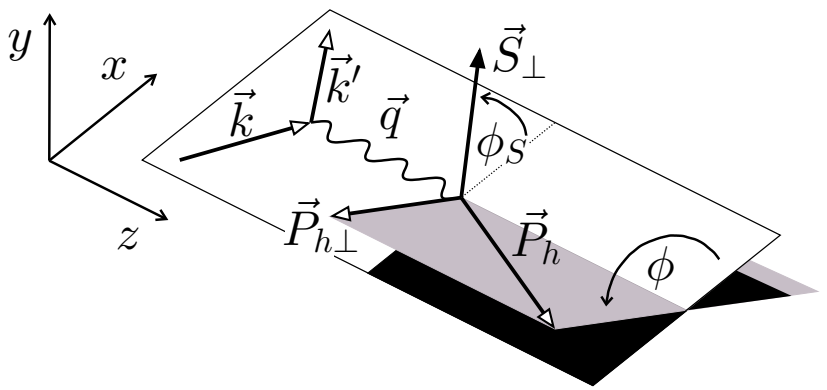

Figure 2. SIDIS on a transversely polarized nucleon target. ϕ_S is the angle between the nucleon polarization axis and the lepton scattering plane (LSP). The angle ϕ is between the LSP and the hadron production plane

mechanism is a $\sin(\phi+\phi_S)$ modulation of the cross section which enters the SSA. There is another combination of DF and FF on leading twist that can generate a SSA in SIDIS. This is the so called Sivers mechanism [5] where the Sivers DF $f_{1T}^{\perp}(x)$ describes the transverse momentum distribution of quarks in a transversely polarized nucleon. It appears in the cross section in combination with the unpolarized FF. The signature of this contribution to the cross section is a $\sin(\phi - \phi_S)$ modulation. The Collins and Sivers mechanism can be extracted from SSA when using a transversely polarized Hydrogen target. In this case the full angular range of ϕ_S from 0 and 2π is covered by the experimental setup. The SSA of an unpolarized lepton

beam with a transversely polarized Hydrogen target is given as

$$\begin{aligned} A_{UT}(\phi,\phi_S) &= \frac{1}{S_\perp}\frac{N^\uparrow(\phi,\phi_S)-N^\downarrow(\phi,\phi_S)}{N^\uparrow(\phi,\phi_S)+N^\downarrow(\phi,\phi_S)} \\ &\propto \sin(\phi+\phi_S)\frac{\sum_q e_q^2\cdot\delta q(x)\otimes H_1^{\perp q}(z,(zk_T)^2)}{\sum_q e_q^2\cdot q(x)D_1^q(z)} \\ &\quad +\sin(\phi-\phi_S)\frac{\sum_q e_q^2\cdot f_{1T}^{\perp q}(x,p_T^2)\otimes D_1^q(z)}{\sum_q e_q^2\cdot q(x)D_1^q(z)} \\ &\quad +\ldots \quad . \end{aligned} \tag{5}$$

Here $N^{\uparrow(\downarrow)}(\phi,\phi_S)$ are the yields of SIDIS events with upward and downward polarized protons, respectively. These values are calculated as function of the two azimuthal angles ϕ and ϕ_S. The sums are over all quark flavors weighted by their charge squared. The product of the DF and FF functions indicated by the symbol $\otimes$ are convolution integrals over the intrinsic transverse momenta of the quarks before (p_T) and after (k_T) the absorption of the virtual photon. In order to obtain the Collins and Sivers moments in an unbiased way the two sine modulations are extracted simultaneously from the data by fitting the asymmetries in a two dimensional grid of the two azimuthal angles ϕ and ϕ_S.

3.2. *Extracting Collins and Sivers*

The current available statistics obtained with the HERMES detector using the 27.6 GeV lepton beam from HERA and the transversely polarized Hydrogen target allows us to calculate the asymmetry A_{UT} in a grid of 12 times 12 bins in ϕ and ϕ_S ranging from 0 to 2π. These asymmetries are then fitted with the form

$$\begin{aligned} A_{UT}^{\pi^\pm}(\phi,\phi_S) &= 2\cdot\langle\sin(\phi+\phi_S)\rangle_{UT}^{\pi^\pm}\cdot\frac{B(\langle y\rangle)}{A(\langle x\rangle,\langle y\rangle)}\cdot\sin(\phi+\phi_S) \\ &\quad +2\cdot\langle\sin(\phi-\phi_S)\rangle_{UT}^{\pi^\pm}\cdot\sin(\phi-\phi_S) \\ &\quad +c_3\cdot\sin(2\phi-\phi_S)+c_4\cdot\sin(\phi_S)+c_5. \end{aligned} \tag{6}$$

In addition to the two different angular dependences of Sivers and Collins moments this fit also takes into account possible contributions from subleading twist cross section terms indicated by $\sin(2\phi-\phi_S)$ and $\sin(\phi_S)$. The factors $A(\langle x\rangle,\langle y\rangle)$ and $B(\langle y\rangle)$ take into account the different y dependence of the Collins and Sivers moments. Here $\langle x\rangle$ is the average Bjorken scaling variable and $\langle y\rangle$ is the average fractional energy of the virtual photon

within a given angular bin. The factor 2 is added to be consistent with the "Trento convention" [6].
As indicated by the index $\pi^{\pm}$ the extraction of the moments is done independently for positive and negative pions in the final state, respectively. Due to the quite different physical meaning of the Collins and Sivers mechanisms the results on their moments are discussed in the following separately.

3.3. *Collins moment*

The results for the Collins moment which is proportional to the product of the transversity distribution function and the Collins fragmentation function is shown in figure 3. The amplitude of the $\sin(\phi+\phi_S)$ moment is plotted

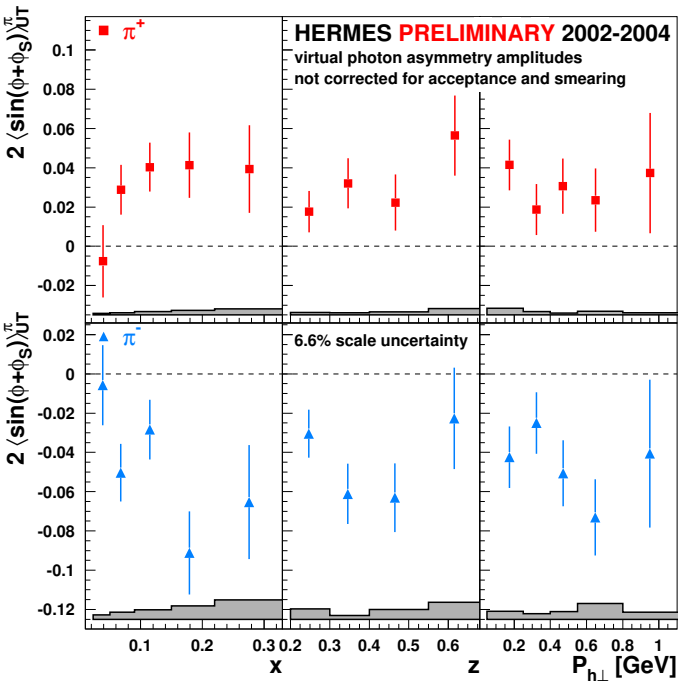

Figure 3. Virtual photon Collins moments as a function of x, z and $P_{h\perp}$. The 6.6% scale uncertainty is due to the target polarization.

as a function of the Bjorken scaling variable x, the fractional hadron energy z and the transverse momentum of the pion. We find a clear positive

signal for the Collins moment in the case of a positive pion in the final state. Having negative pions in the final state we find a signal of opposite sign to that of positive pions. The absolute value is as large or even larger. This large value is somewhat surprising as one would expect, due to u-quark dominance, that the negative pions are suppressed similarly as in the longitudinal case. This behavior could imply that the unfavored FF where $u \to \pi^-$ is of similar magnitude as the favored FF. In order to extract from these moments the transversity distribution $\delta f(x)$ the Collins FF is needed. This FF can be measured at the Belle experiment, an e^-e^+ collider experiment. First results of the azimuthal asymmetries have been reported by the Belle collaboration [7]. This is the first step towards the extraction of the Collins FF.
First estimates to describe the HERMES data on the Collins moment are done using parameterizations for transversity and Collins functions in [8]. This study is based on the QCD factorization approach. They find that the unfavored Collins function has the same size as the favored one with opposite sign. However, higher-statistics data is needed to establish this.

3.4. *Sivers moment*

In case of the Sivers mechanism we look for a $\sin(\phi - \phi_S)$ moment in the SSA. It turns out that the amplitude for the $\sin(\phi - \phi_S)$ moments for positive pions are significantly different from zero and positive. This can be seen in figure 4 as a function of x, z and the transverse momentum the pion $P_{h\perp}$. The amplitude is of similar size as for the Collins moment. Since the Sivers mechanism involves the transverse momentum of unpolarized quarks in a polarized nucleon a non-zero signal implies non-vanishing orbital angular momenta of the quarks. While for the positive pions we observe a clear positive signal of the order of 0.045 the results for the negative pions are very small and compatible with zero. It was pointed out in ref. [9] that a non-vanishing SSA caused by a T-odd distribution function, such as the Sivers function, is related to final state interactions. This means that after the hard scattering process the struck quark interacts with the target remnant. In addition it was shown in ref. [10] that this T-odd function changes sign in hadron induced interactions like Drell-Yan. In such a case initial state interactions are taking place, such that the initial quark from one nucleon interacts with the spectator part of the opposite nucleon before it interacts with the quark of that nucleon.
The HERMES results for the Sivers moments were fitted using parame-

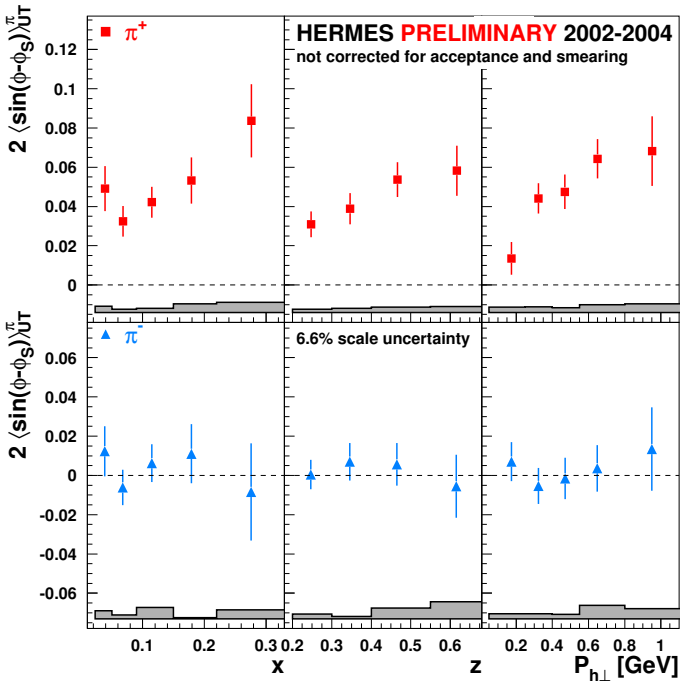

Figure 4. Virtual photon Sivers moments as a function of x, z and $P_{h\perp}$.

terizations for the distribution functions for the u and d quarks taking a Gaussian Ansatz for the p_T and k_T momentum distributions [11]. The conclusion therein is that the Sivers distribution functions for u and d quarks are of the same magnitude but with opposite sign. Such a behavior could explain the very small asymmetries measured in the COMPASS experiment using a transversely polarized deuterium target.

4. Two hadron SSA

Another way to access transversity is to measure SSA with two oppositely charged hadrons in the final state [12]. Assuming that the two hadrons inherit the dependence on the transverse momentum from the same initial struck quark, in relative quantities of the two hadrons like momentum and angle this dependence will cancel[13]. As a consequence the SSA will have no Sivers type contribution but only receive a contribution from transversity. However, the price to pay is - apart from the introduction of a new un-

known FF, the interference fragmentation function (IFF) - the much lower statistics available. At leading twist the asymmetry with unpolarized beam and transversely polarized proton target is

$$A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin(\theta) \delta q(x) H_1^{\sphericalangle}(z, M_{\pi\pi}) \tag{7}$$

Here the angle $\phi_{R\perp}$ is the azimuthal angle between the lepton scattering plane and the plane defined by the two hadrons (see fig. 5). The third angle θ is the angle between the positively charged hadron and the direction of the sum of the two hadron momenta in the center of mass system of the two hadrons. In order to gain some understanding about the unknown IFF

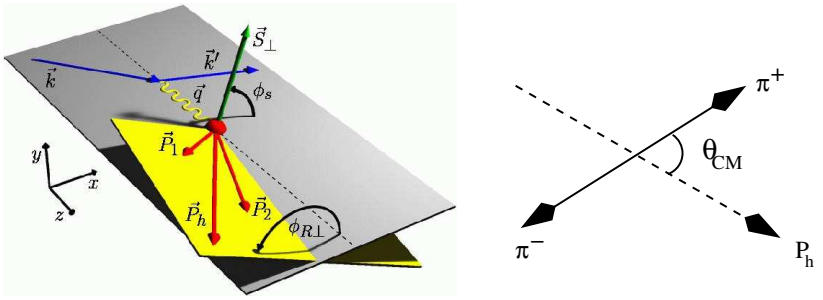

Figure 5. Two-hadron kinematics.

$H_1^{\sphericalangle}$ its dependence on the invariant mass of the two hadrons in the final state is investigated using two different theoretical approaches. In a first approach [14] the dependence is estimated using the results from the pion-pion interaction phase shift analysis. The IFF is expanded using Legendre polynomials to separate the s-p and p-p wave interference of the two pions. Another approach uses a spectator model describing the unobserved part of the string break when the quark fragments into hadrons [15]. In this model the number of FF's reduces as the flavor dependence vanishes.

With the HERMES detector we observe a clear signal in the asymmetry A_{UT} with two hadrons in the final state as shown in figure 6. Also shown is the amplitude of the $\sin(\phi_{R\perp} + \phi_S)$ moment as a function of the invariant mass of the two pions in the final state. The signal is positive over the whole measured range. The mass of the ρ^0 meson is indicated by the dashed vertical line. No sign change is observed in this mass region.

The HERMES program with a transversely polarized Hydrogen target has just finished data taking. We recorded in the order of 10 million DIS events

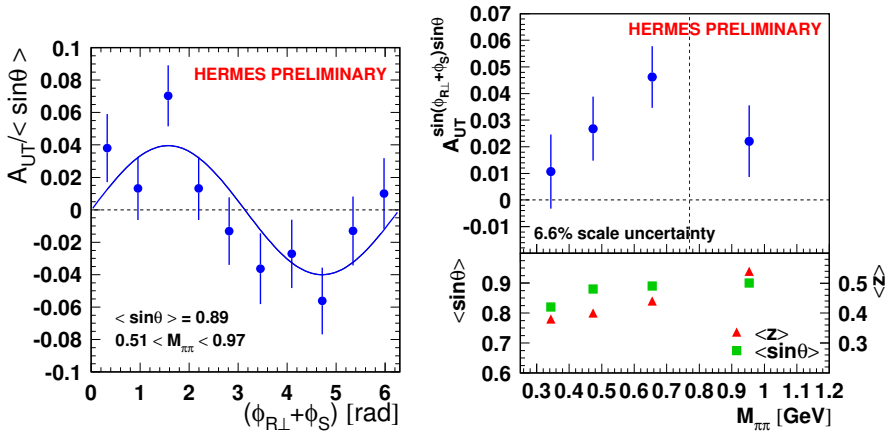

Figure 6. SSA for two hadrons in the final state integrated over the invariant mass range of 0.51 GeV to 0.97 GeV(left) and the extracted $\sin(\phi_{R\perp} + \phi_S)$ moment as a function of the invariant mass of the two pions

in total before data quality cuts. This represents more than double the statistics of the sample on which the results in this report are based.

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