Single target-spin asymmetries in semi-inclusive pion electroproduction on longitudinally polarized protons[*]

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We evaluate the single target-spin $sin\,\phi_h$ and $sin\,2\phi_h$ azimuthal asymmetries in the semi-inclusive deep inelastic lepton scattering off longitudinally polarized proton target under HERMES kinematic conditions. A good agreement with the HERMES data can be achieved using only the twist-2 distribution and fragmentation functions.

Significant single-spin asymmetries have been observed in experiments with transversely polarized proton and anti-proton beams [1]. Recently new experimental results on azimuthal asymmetries became available. Specifically, the first measurements of single target-spin azimuthal asymmetries of pion production in semi-inclusive deep inelastic scattering (SIDIS) of leptons off a longitudinally polarized target at HERMES [2] and off a transversely polarized target at SMC [3], and the observation of the azimuthal correlations for particles produced from opposite jets in Z decay at DELPHI [4].

In this note we present estimates of the single spin azimuthal asymmetry in the SIDIS on a longitudinally polarized nucleon target for the HERMES kinematic conditions. Our approach is based on the parton model description of polarized SIDIS [5]. The cross-section contains the $(1/Q)^0$-order terms coming from leading dynamical twist-two distribution and fragmentation functions (DF's and FF's) as well as $(1/Q)$-order kinematic twist-three terms arising due to the intrinsic transverse momentum of the quark in the nucleon. We will neglect the $(1/Q)$-order contributions of the higher twist DF's and FF's obtained in [6]. Thus, our approach is similar to that of [7] in describing the $cos\,\phi_h$ asymmetry in unpolarized SIDIS.

Let k_1 (k_2) be the initial (final) momentum of the incoming (outgoing) charged lepton, $Q^2 = -q^2$, $q = k_1 - k_2$ – the momentum of the virtual photon, P and P_h (M and M_h) – the target and final hadron momentum (mass), $x = q^2/2(Pq)$, $y = (Pq)/(Pk_1)$, $z = (PP_h)/(Pq)$, P_{hT} (k_{1T}) – the hadron (lepton) transverse with respect to virtual photon momentum direction and ϕ_h – the azimuthal angle between P_{hT} and k_{1T} around the virtual photon direction. Note that the azimuthal angle of the transverse (with respect to the virtual photon) component of the target polarization, ϕ_S, is equal to 0 (π) for the

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target polarized parallel (antiparallel) to the beam (Fig. 1).

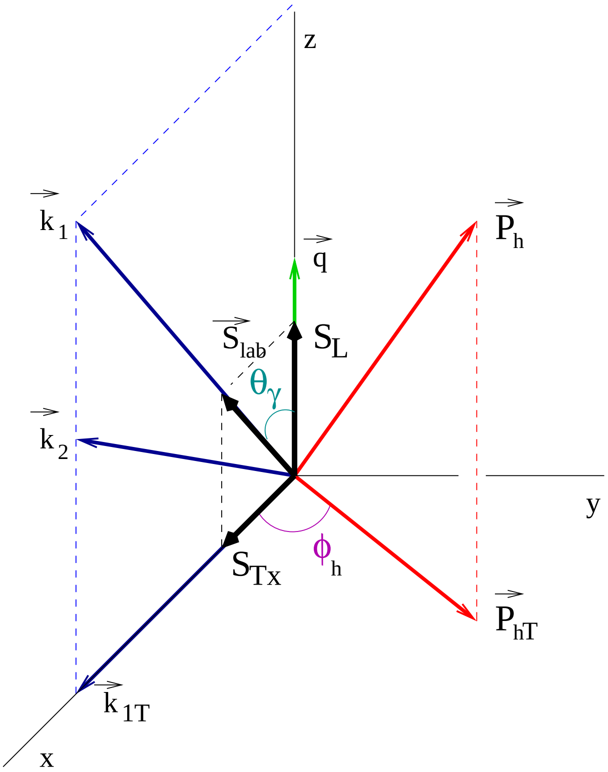

Figure 1. The definition of the azimuthal angle ϕ_h and the target polarization components in virtual photon frame.

We use the approach developed in [8] and consider the cross-section integrated with different weights depending on the final hadron transverse momenta $w_i(P_{hT})$ [4]:

$$\Sigma_i = \frac{Q^2 y}{2\pi\alpha^2} \int d^2 P_{hT}\, w_i(P_{hT})\, d\sigma, \tag{1}$$

with $w_1(P_{hT}) = 1$, $w_2(P_{hT}) = |P_{hT}| \sin\phi_h / M_h$ and $w_3(P_{hT}) = |P_{hT}|^2 \sin 2\phi_h / 2MM_h$. Considering only the twist-two contributions, we have:

$$\Sigma_1 = (1 + (1-y)^2)\, f_1(x) D_1(z), \tag{2}$$

where $f_1(x)$ and $D_1(z)$ are the usual unpolarized DF's and FF's. Moreover

$$\Sigma_2 = \Sigma_{2L} + \Sigma_{2T}, \tag{3}$$

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[4] More details can be found in [9].

where

$$\Sigma_{2L} = -8S_L \frac{M}{Q}\,(2-y)\sqrt{1-y}\, z h_{1L}^{\perp(1)}(x) H_1^{\perp(1)}(z) \tag{4}$$

is the $(1/Q)$-order contribution from twist-two DF $h_{1L}^{\perp(1)}(x)$ and FF $H_1^{\perp(1)}(z)$ arising due to intrinsic transverse momentum and

$$\Sigma_{2T} = 2S_{T\,x}\,(1-y)\, z h_1(x) H_1^{\perp(1)}(z) \tag{5}$$

is arising due to the small ($\sim (1/Q)$) transverse component of the target polarization ($S_{T\,x}$) [5,9]. Finally

$$\Sigma_3 = 8S_L(1-y)\, z^2 h_{1L}^{\perp(1)}(x) H_1^{\perp(1)}(z). \tag{6}$$

The weighted cross sections involve the p_T^2 (k_T^2) moment of the DF's (FF's), defined as

$$h_{1L}^{\perp(1)}(x) \equiv \int d^2p_T \left(\frac{p_T^2}{2M^2}\right) h_{1L}^{\perp}(x, p_T^2), \tag{7}$$

$$H_1^{\perp(1)}(z) \equiv z^2 \int d^2k_T \left(\frac{k_T^2}{2M_h^2}\right) H_1^{\perp}(z, z^2k_T^2). \tag{8}$$

We note that $h_{1L}^{\perp}(x)$ and $h_1(x)$ describe the quark transverse spin distribution in the longitudinally and transversely polarized nucleon respectively, while $H_1^{\perp}(z)$ describes the analyzing power of transversely polarized quark fragmentation (Collins effect) [10].

The single target-spin asymmetries for SIDIS on a longitudinally polarized target are defined as

$$\langle\frac{|P_{hT}|}{M_h}\sin\phi_h\rangle \equiv \frac{\int d^2P_{hT}\frac{|P_{hT}|}{M_h}\sin\phi_h\,(d\sigma^+ - d\sigma^-)}{\int d^2P_{hT}\,(d\sigma^+ + d\sigma^-)}, \tag{9}$$

$$\langle\frac{|P_{hT}|^2}{MM_h}\sin 2\phi_h\rangle \equiv \frac{\int d^2P_{hT}\frac{|P_{hT}|^2}{MM_h}\sin 2\phi_h\,(d\sigma^+ - d\sigma^-)}{\int d^2P_{hT}\,(d\sigma^+ + d\sigma^-)}, \tag{10}$$

where $+(-)$ denotes positive (negative) longitudinal polarization of the target. Using $\Sigma_{1,2,3}$ one can see that for both polarized and unpolarized lepton these asymmetries are given by

$$\langle\frac{|P_{hT}|}{M_h}\sin\phi_h\rangle(x,y,z) = \frac{\Sigma_2(x,y,z)}{\Sigma_1(x,y,z)} \tag{11}$$

$$\langle\frac{|P_{hT}|^2}{MM_h}\sin 2\phi_h\rangle(x,y,z) = \frac{\Sigma_3(x,y,z)}{\Sigma_1(x,y,z)}. \tag{12}$$

We use the non-relativistic approximation $h_1(x) = g_1(x)$, the upper limit from Soffer's inequality [11] $h_1(x) = (f_1(x) + g_1(x))/2$, and the relation between $h_{1L}^{\perp(1)}(x)$ and $h_1(x)$

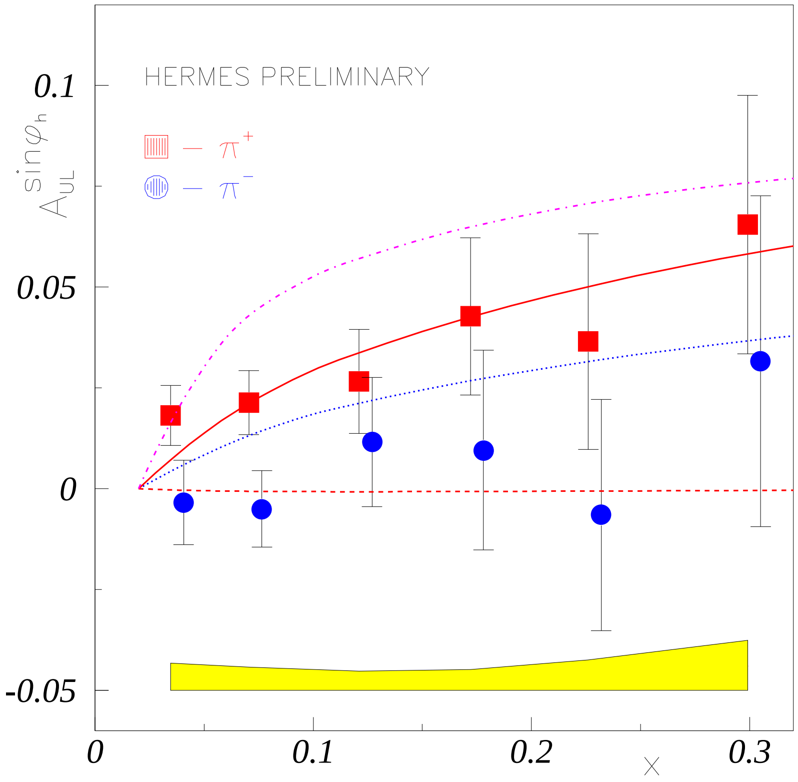

Figure 2. The $A_{UL}^{\sin\phi_h}(x)$ asymmetry of $\pi^{\pm}$ production. The continuous (π^+) and dashed (π^-) curves correspond to $M_C = 0.7$ GeV, $h_1 = g_1$; dotted (π^+) and dot-dashed (π^+) to $M_C = 0.3$ GeV, $h_1 = g_1$ and $M_C = 0.7$GeV $h_1 = (f_1 + g_1)/2$, respectively.

[6] obtained by neglecting the interaction dependent twist-three part of the DF and the term proportional to the current quark's mass:

$$h_{1L}^{\perp(1)}(x) = -x^2 \int_x^1 dy \frac{h_1(y)}{y^2}. \tag{13}$$

We took the parameterisations of DF's $f_1(x)$ and $g_1(x)$ from Ref. [12]. To calculate the T-odd FF $H_1^{\perp(1)}(z)$ we adopt the Collins parameterisation [10] for the analyzing power of transversely polarized quark fragmentation

$$A_C(z,k_T) \equiv \frac{|k_T|}{M_h} \frac{H_1^{\perp}(z,k_T^2)}{D_1(z,k_T^2)} = \frac{M_C\,|k_T|}{M_C^2 + k_T^2} \tag{14}$$

and assume a Gaussian parameterisation of the unpolarized FF [8] with $\langle z^2 k_T^2 \rangle = b^2$ (in the numerical calculations we use $b = 0.5$ GeV [13]). For $D_1^{\pi^{\pm}}(z)$ we use the parameterisation from Ref. [14].

The $A_{UL}^{\sin\phi_h}(x)$ asymmetry for $\pi^{\pm}$ production on the proton target is obtained from the defined asymmetry (Eq.(11)) by the relation $A_{UL}^{\sin\phi_h} \approx \frac{2M_h}{\langle P_{hT}\rangle}\langle\frac{|P_{hT}|}{M_h}\sin\phi_h\rangle$ and is presented in Fig. 2 in comparison with preliminary HERMES data [2]. The data corresponds to $Q^2 \geq 1$ GeV^2, $E_\pi \geq 4$ GeV, and the ranges $0.2 \leq z \leq 0.7$, $0.2 \leq y \leq 0.8$. The theoretical curves are calculated by integrating over the same ranges with $\langle P_{hT}\rangle = 0.52$ GeV, $\langle P_{hT}^2\rangle = 0.35$ GeV^2. These average values of P_{hT}, P_{hT}^2 are obtained in mentioned kinematics assuming a Gaussian parameterisation of DF's and FF's with $a = 0.7$ GeV ($\langle p_T^2\rangle = a^2$) [13]. From Fig. 2 one can see that a good agreement with HERMES data [2] can be achieved by varying $h_1(x)$ and M_C. Note that the main effect comes from the Σ_{2L} term, the contribution of Σ_{2T} is about $20 \div 25\%$.

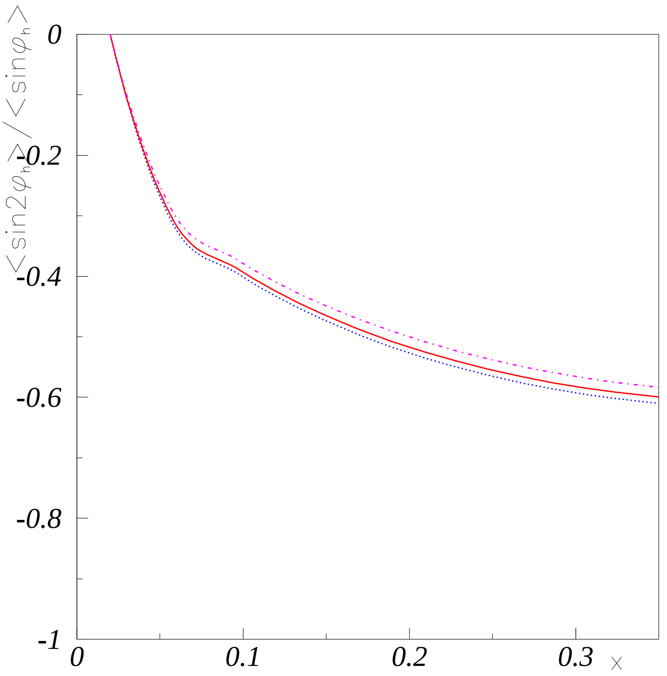

Figure 3. The ratio of the amplitudes of the $\sin 2\phi_h$ and $\sin\phi_h$ single target-spin asymmetries for π^+ production. The curves have the same notations as in the Fig. 2.

We calculate the $sin2\phi_h$-weighted asymmetry in the same manner as well and show that the amplitude of the $sin2\phi_h$ modulation is about a factor of 2-3 smaller than that of the $sin\phi_h$ modulation (see Fig. 3) in the HERMES kinematics. Note that the ratio of these asymmetries is almost independent of the choice of $h_1(x)$ and M_C.

In conclusion, the $sin\,\phi_h$ and $sin\,2\phi_h$ single target-spin asymmetries of SIDIS off longitudinally polarized protons related to the time reversal odd FF was investigated. It was shown that the main $(1/Q)$-order contribution to the spin asymmetry arises from intrinsic

k_T effects similar to the $cos\phi_h$ asymmetry in unpolarized SIDIS. A good agreement with the HERMES data can be achieved using only the twist-2 DF's and FF's. The $(1/Q)^0$-order $sin2\phi_h$ asymmetry, in contrast to the naive expectations, is suppressed comparing to the $(1/Q)$-order $sin\phi_h$ asymmetry at HERMES kinematics.

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