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

A.M. Kotzinian[a] †‡, K.A. Oganessyan[b]†, H.R. Avakian[b]†, E. De Sanctis[b]

[a]CERN, CH-1211, Geneva 23, Switzerland

[b]INFN-Laboratori Nazionali di Frascati, I-00040, Enrico Fermi 40, Frascati, Italy

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

*talk presented by K. Oganessyan at the Workshop on the structure ot the Nucleon (N^{99}), Frascati, June 7-9, 1999.

†On leave of absence from Yerevan Physics Institute, Alikhanian Br.2, AM-375036 Yerevan, Armenia

‡JINR, RU-141980 Dubna, Russia

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

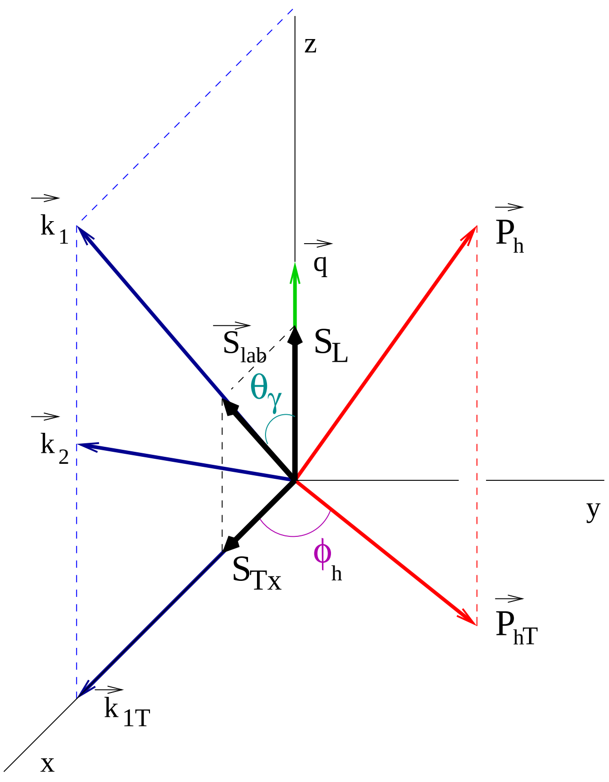

Figure 1. The definition of the azimuthal angle ϕ_h and the target polarization components in virtual photon frame.

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

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

[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

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

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

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 $h_1(x)$

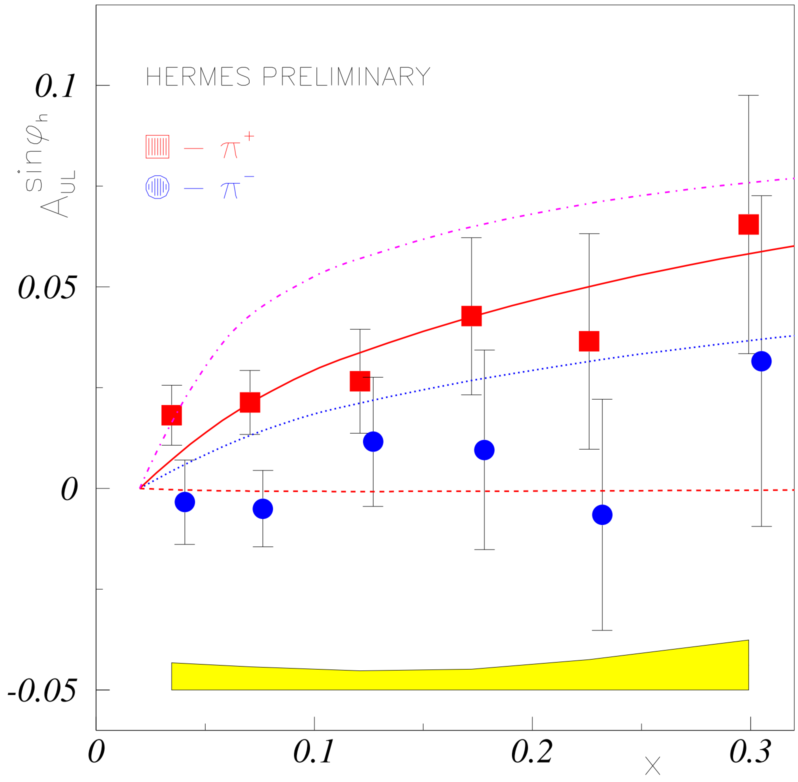

Figure 2. The $A_{UL}^{\sin\phi_h}(x)$ asymmetry of $\pi^{\pm}$ production. The continuous (π^+) and dashed (π^-) curves correspond to $M_C = 0.7$ GeV, $h_1 = g_1$; dotted (π^+) and dot-dashed (π^+) to $M_C = 0.3$ GeV, $h_1 = g_1$ and $M_C = 0.7$GeV $h_1 = (f_1 + g_1)/2$, respectively.

[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 $20 \div 25\%$.

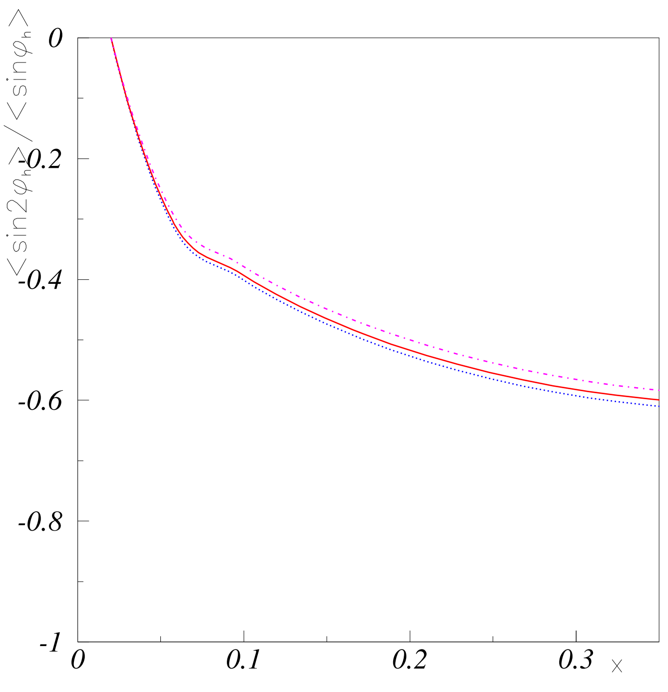

Figure 3. The ratio of the amplitudes of the $\sin 2\phi_h$ and $\sin\phi_h$ single target-spin asymmetries for π^+ production. The curves have the same notations as in the Fig. 2.

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 $sin2\phi_h$ 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.

The authors would like to thank D. Boer, R. Jakob, and P. Mulders for useful discussions. The work of (K.O) and (H.A) was in part supported by the INTAS contributions (contract number 93-1827) from the European Union.

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