Azimuthal Asymmetries: 
Access to Novel Structure Functions \(^1\)

K. A. Oganessyan \(^\dagger\), L. S. Asilyan, E. De Sanctis and V. Muccifora

INFN-Laboratori Nazionali di Frascati, Enrico Fermi 40, I-00044 Frascati, Italy
\(^\dagger\)DESY, Notkestrasse 85, 22603 Hamburg, Germany

Abstract. One of the most interesting consequence of non-zero intrinsic transverse momentum of partons in the nucleon is the nontrivial azimuthal dependence of the cross section of hard scattering processes. Many of the observable asymmetries contain unknown functions which provide essential information on the quark and gluon structure. Several of them have been studied in the last few years; we discuss their qualitative and quantitative features in semi-inclusive DIS.

Introduction

The study of the structure of hadrons, bound states of quarks and gluons, in the context of quantum chromodynamics (QCD), is one of the challenges of elementary particle physics requiring new nonperturbative approaches in the field theory.

This talk focuses on a discussion of correlations between the spins of hadron or quark and the momentum of the quark with respect of that of the hadron in polarized hard scattering processes. Signatures of these correlations appear in high-energy scattering processes as correlations between the azimuthal angles of the (transverse) spin and the (transverse) momentum vectors.

In particular, we discuss single-spin (transversely polarized target or longitudinally polarized beam) and double-spin (longitudinally polarized beam and transversely polarized target) azimuthal asymmetries in single hadron electroproduction in DIS.

The general form of the factorized cross sections of hard scattering process is written as [1]

\[
\frac{d\sigma}{d^3q} = H^0 \ f_2 \ f_2^0 + \frac{1}{Q^n} H^1 \ f_2 \ f_{2+n}^0 + \frac{1}{Q^{n+1}} ;
\]

with \( n = 1 \) and 2 for the polarized and unpolarized case, respectively. The perturbatively calculable coefficient functions are denoted \( H^0, H^1 \) and are convoluted with the non-perturbative soft parts \( f_i \ f_i^0 \), where \( i \) denotes the twist. The cross section is related to helicity-dependent amplitudes \( \Lambda_{\Lambda \lambda}^\Lambda \Lambda_0 \) [2], which describes a process where a target of helicity \( \Lambda \) emits a parton of helicity \( \lambda \), and the scattered parton with helicity \( \lambda^0 \) is reabsorbed by a hadron of helicity \( \Lambda^0 \). In the spin-1/2 case, due to helicity conserva-

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FIGURE 1. The kinematics of semi-inclusive DIS: $k_1 (k_2)$ is the 4-momentum of the incoming (outgoing) charged lepton, $Q^2 = q^2$, where $q = k_1 - k_2$, is the 4-momentum of the virtual photon. The momentum $P (P_h)$ is the momentum of the target (observed) hadron. The scaling variables are $x = Q^2=2 (P \cdot q)$, $y = (P \cdot q)/(P \cdot k)$ and $z = (P \cdot P_h)/(P \cdot q)$. The momentum $k_{1T} (P_{hT})$ is the incoming lepton (observed hadron) momentum component perpendicular to the virtual photon momentum direction, and $\phi$ is the azimuthal angle between $P_{hT}$ and $k_{1T}$, $S_T$ is the target spin vector and $\phi_5$ is its azimuthal angle.

Transverse target single-spin azimuthal asymmetry

To access the transversity distribution function, $h_1$ (also commonly denoted $\delta q$), in semi-inclusive DIS off transversely polarized nucleons (see the relevant kinematics in Fig.1), one can measure the azimuthal angular dependences in the production of leading spin-0 or (on average) unpolarized hadrons from transversely polarized quarks with nonzero transverse momentum. This production is described by the intrinsic transverse momentum dependent fragmentation function $H_T^z$ ($z$), which is chiral-odd and also T-odd, i.e., non-vanishing only due to final state interactions [3]. Due to its chiral-odd structure it is a natural partner to isolate chiral-odd distribution functions, such as $h_1$.

2 The asterisk indicates bad component of quark/gluon field.
\( h_{L}, \) and \( e. \) It is worthy to note that a clean separation of current and target fragmentation effects in the data is required \([4, 5]\).

The observable moment is defined as the appropriately weighted integral over \( \phi \) of the cross section asymmetry \( f \):

\[
A_{UT}^{\sin (\phi + \phi_{S})} \frac{R}{L} \frac{d\phi}{d\sigma} \sin (\phi + \phi_{S}) \frac{d\sigma^{*}}{d\sigma + d\sigma^{+}};
\]

(2)

where \( * \) (\( + \)) denotes the up (down) transverse polarization of the target in the virtual-photon frame. This asymmetry is given by \([3, 6, 7]\):

\[
A_{UT}^{\sin (\phi + \phi_{S})} \propto \frac{h_{1}(x)}{f_{1}(x)} \frac{H_{1}^{(1)u}(\zeta)}{D_{1}(\zeta)};
\]

(3)

An indication of a non-zero \( H_{1}^{(1)u}(\zeta) \) comes from the single spin asymmetry measured for pions produced in semi-inclusive DIS of leptons off a longitudinally polarized target at HERMES \([8]\).

A larger asymmetry with a transversely polarized target is expected \([9, 10]\). However, the existence of the competing mechanism, which, due to asymmetric distribution of quarks transverse momenta in a hadron, also gives a transverse spin asymmetry at leading twist \([11, 12]\), turns the transversity measurement challenging. For distinguishing the different mechanisms and for its complete description (\( x \)-dependence at large \( x \), \( Q^{2} \)-evolution, etc.) results from different scattering processes and different kinematics are required. New data from HERMES and COMPASS measurements on transversely polarized targets will give possibility to measure the transversity \([13]\). Fig.2 show the expected accuracies for the reconstruction of \( h_{1}(x) \) and \( H_{1}^{(1)u}(\zeta) \) at HERMES with transversely polarized proton target \([13, 14]\). In addition, analysis of data from

\[\text{FIGURE 2. a) The transversity distribution } \delta u(x) \text{ and } h_{1}^{u}(x) \text{ and b) the ratio of the fragmentation functions } H_{1}^{(1)u}(\zeta) \text{ over } D_{1}(\zeta) \text{ as they would be measured at HERMES \([13, 14]\). The hatched bands show projected systematic uncertainties.}\]

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\(^{3}\) The first and second subscripts indicate the polarizations of beam and target, respectively. We use \( U \) for unpolarized, \( L \) for longitudinally polarized and \( T \) for transversely polarized particles.
FIGURE 3. The single beam spin $A_{LU}^{\sin \phi}$ and the single target spin $A_{UL}^{\sin 2 \phi}$ asymmetries for $\pi^+$ production as a function of $x$ and $z$. Data are from HERMES experiment [8]. Error bars show the statistical and the systematical uncertainties.

$e^+ e^- \rightarrow \pi^+ \pi^- X$ process, which expected to show a similar azimuthal correlations is under way at the BELLE B-factory at KEK [15].

Beam single-spin azimuthal asymmetry

At order 1=$Q$ a $\sin \phi$ asymmetry was predicted [16] for longitudinally polarized beam and unpolarized target. It probes the interaction-dependent distribution function $\tilde{e}(x)$ ($\tilde{e}(x) = e(x) \frac{m f_1(x)}{x}$) [7, 13] in combination with the above mentioned fragmentation function $H_1^a$. It is important to notice that this asymmetry is related to the left-right asymmetry in the hadron momentum distribution with respect to the electron scattering plane,

$$A_{LU} = \frac{R_0}{R} \frac{\pi}{\pi} \frac{d\phi d\sigma}{d\phi d\sigma} + \frac{R_2}{R} \frac{\pi}{\pi} \frac{d\phi d\sigma}{d\phi d\sigma};$$

which is $2=\pi$ times $A_{LU}^{\sin \phi}$,

$$A_{LU}^{\sin \phi} = \frac{R_0}{R} \frac{\pi}{\pi} \frac{d\phi \sin \phi [d\sigma_1 + d\sigma]}{d\phi [d\sigma_1 + d\sigma]} \propto \sum a e_a^2 \tilde{e}_a^2 (x) H_1^2 \frac{d\sigma_1}{d\sigma};$$

$$\sum a e_a^2 f_1^a (x) D_1^a (x);$$
To evaluate this asymmetry as well as the single target-spin sin2φ asymmetry, $A_{UL}^{sin2φ}$ \[7, 17\], we use the MIT bag model \[18\] as input.

For the weighted T-odd fragmentation function, $H^T (1)$, we use the Collins ansatz \[3\] for the analyzing power with the factor $h = 1$; \[9\]. The x- and z-dependences of the $A_{UL}^{sinφ}$ and $A_{UL}^{sin2φ}$ for π⁺ are shown in Fig.3. The asymmetry $A_{UL}^{sinφ}$ amounts to about 3%, while $A_{UL}^{sin2φ}$ is larger (about 6%). This is in disagreement with the asymmetries measured by HERMES \[8\], which, as shown in the figure, are consistent with zero within the errors. This clearly indicate the necessity of a serious improvement of MIT bag model.

### Double-spin azimuthal asymmetry

The double spin azimuthal asymmetry is related to the $g_T (x) \langle g_2 (κ) \rangle$ distribution function.

Accounting for transverse momenta of the quarks, a longitudinal quark spin asymmetry exists in a transversely polarized nucleon target. The relevant leading twist distribution $g_{1T} (κp_T^2)$ can be determined from the measurement of this asymmetry in semi-inclusive DIS \[7, 19, 20\] in the case of longitudinally polarized beam and transversely polarized target.

The observable cos (φ $\phi_S$) moment in the cross section is defined in the following way

$$A_{LT}^{cos φ \phi_S} \approx \frac{\sum a_{αβ}^{2 (1)} (κ) zD_1 (ξ)}{\sum a_{αβ}^{2 (1)} (κ) D_1 (ξ)} :$$

The x-dependence of $A_{LT}^{cos φ \phi_S}$ calculated for π⁺ production is shown in Fig.4 \[19, 20\]: as seen it is a sizable asymmetry that may provide an alternative way to measure $g_2 (κ)$.
Conclusion

We have discussed the qualitative and quantitative features of nontrivial azimuthal
dependence of the cross section of the semi-inclusive DIS which provided essential
information on nucleon spin structure.

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