Recent results on TMDs from the HERMES experiment

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Abstract. HERMES has taken a wealth of deep-inelastic scattering data using the 27.6 GeV polarized lepton beam at HERA and various pure gas targets, both unpolarized and polarized, which opened the door to several unique results. Among them are the first evidences for the naive-T-odd Sivers and Collins effects. An overview of recent HERMES results on measurement of azimuthal asymmetries in semi-inclusive production of pions, charged kaons and (anti)protons is presented.

1. Introduction
One of the most intriguing puzzles in modern physics is the internal structure of the nucleon. For many years its structure was investigated in deep-inelastic experiments with scattering of leptons by nucleons in inclusive approach. In the last two decades a progress in experimental technique and a rapid theoretical developments in non-perturbative QCD allowed to start more sophisticated study of the nucleon structure.

A formalism of Transverse Momentum Dependent parton distribution functions (TMDs) and of Generalized Parton Distributions (GPDs) was introduced, providing a more comprehensive multi-dimensional description of the nucleon. New distribution functions allow to get complementary descriptions of the nucleon in three dimensions, spanned by the quarks longitudinal momenta and, respectively, by their transverse momenta components and transverse spatial coordinates. They thus may provide, with different approaches, the full phase-space description of the nucleon structure. Experimentally, TMDs and GPDs can be accessed through the analysis of specific azimuthal asymmetries measured, respectively, in semi-inclusive deep-inelastic scattering (SIDIS) and hard exclusive processes.

There are eight leading-twist quark TMDs, which contribute to the SIDIS cross-section in conjunction with a proper fragmentation function (FF). The TMDs depend, in addition to the longitudinal variable $x$, on the transverse momentum of the quark $p_T$. Three TMDs survive after integrating over $p_T$. They are analogs of usual collinear quark distributions $f_1$, $g_1$, and $h_1$. The other five distributions are the Sivers function $f_{T1}^{1T}$, the Boer-Mulders function $h_{1L}^T$, the pretzelosity function $h_{1T}^L$ and two worm-gear functions $h_{1L}^T$ and $g_{1T}^L$. They typically describe a correlation between $p_T$ and the polarization of the nucleon and/or the quark.

In the leading order there are two FFs: the familiar polarization-averaged $D_1$ and the Collins function $H_1^+$ representing a correlation between the transverse polarization of the fragmenting quark and the transverse momentum of the produced hadron.
At the sub-leading order there are many additional TMDs and FFs contributing to the SIDIS cross-section (see e.g. Ref. [1]).

HERMES collaboration has published its results on the one-dimensional Sivers and Collins amplitudes in [2] and [3], respectively. Results on the beam-spin asymmetry (BSA) for pions, obtained with a part of the full statistics, have been presented in [4].

In this talk, a short review of recent HERMES results on azimuthal asymmetries in semi-inclusive processes will be presented.

2. Experiment and extraction of the asymmetry amplitudes

HERMES used the longitudinally polarized lepton beam \( (e^+ \text{ or } e^-) \) of 27.6 GeV scattered off a transversely/longitudinally polarized or unpolarized gas target internal to the HERA storage ring. Scattered leptons and coincident hadrons were detected by the HERMES spectrometer [5]. Leptons were identified with an efficiency exceeding 98% and a hadron contamination of less than 1%. The HERMES dual-radiator ring-imaging Čerenkov detector allows full hadron identification in the momentum range 2–15 GeV. Events were selected subject to the kinematic requirements \( Q^2 > 1 \text{ GeV}^2, 0.023 < z < 0.6, 0.1 < y < 0.95 \) and \( W^2 > 10 \text{ GeV}^2 \), where \( Q^2 \), \( x \), \( y \), and \( W \) are usual DIS variables. Coincident hadrons were accepted in the range \( 0.2 < z < 0.7 \).

Kinematics of SIDIS on a transversely polarized target is depicted at Fig. 1.

![Figure 1. Definition of azimuthal angles \( \phi \) and \( \phi_S \) and the hadron transverse momentum \( P_{h\perp} \) for semi-inclusive deep inelastic scattering on a transversely polarized target.](image)

The asymmetry amplitudes were extracted in each particular kinematic bin using an unbinned maximum likelihood fit of the selected SIDIS events to proper probability density function (p.d.f.). Proper p.d.f. should follow to structure of the cross-section. The general structure of SIDIS cross-section was developed and presented in [1]. For a case of a transversely polarized target the probability density function is the following:

\[
p.d.f. = 1 + S_\perp (p_1 \cdot \sin(\phi + \phi_S) + p_2 \cdot \sin(\phi - \phi_S) + p_3 \cdot \sin(\phi_S) + p_4 \cdot \sin(2\phi - \phi_S) + p_5 \cdot \sin(3\phi - \phi_S) + p_6 \cdot \sin(2\phi + \phi_S)) + S_L P_L (p_7 \cdot \cos(\phi - \phi_S) + p_8 \cdot \cos(\phi_S) + p_9 \cdot \cos(2\phi - \phi_S) + p_{10} \cdot \cos(\phi + \phi_S)),
\]

where \( S_\perp \) is the transverse target polarization and \( P_L \) is the beam polarization. Note that two additional \( \sin(2\phi + \phi_S) \) and \( \cos(\phi + \phi_S) \) modulation terms, with respect to [1], are included here due to existence of the longitudinal component of the target polarization vector [6]. Parameters \( p_1, \ldots, p_{10} \) correspond to asymmetry amplitudes \( 2\sin(\phi + \phi_S) U_{\perp\perp}, 2\cos(\phi + \phi_S) U_{\perp L} \). The first and second subscript of the asymmetry amplitude indicate the respective polarization of beam and target (“U” – unpolarized, “L” – longitudinal, and “\( \perp \)” – transverse).

For a case of longitudinal beam and an unpolarized target the probability density function is taken to be

\[
p.d.f. = 1 + P_L \cdot p_0 \cdot \sin(\phi),
\]
where parameter \( p_0 \) corresponds to amplitude \( 2\langle \sin(\phi) \rangle_{LU} \).

For three-dimensional study, the amplitudes were evaluated in \((\text{four-}x) \times (\text{four-}z) \times (\text{four-}P_{h\perp})\) bins.

3. Results

The asymmetry amplitudes are known functions [1] of unknown TMDs and FFs.

Leading order amplitudes in a case of the unpolarized beam and the transversely polarized target are the following.

The Sivers amplitude depends on the Sivers distribution function \( f_{1T} \) and familiar FF \( D_1 \):

\[
2\langle \sin(\phi_h - \phi_S) \rangle_{U\perp} \propto C\left[ -\frac{h_{P_T}}{M_h} f_{1T} D_1 \right],
\]

where \( h = P_{h\perp}/|P_{h\perp}| \) and \( C[w D] \) denotes a convolution integral over the quark transverse momenta \( p_T \) and \( k_T \) defined for any combination of a TMD \( f(x, p_T^2) \) and a FF \( D(z, k_T^2) \) multiplied by an arbitrary function \( w(p_T, k_T) \) [1].

The Collins amplitude depends on the transversity distribution \( h_1 \) and the Collins FF \( H_1^T \):

\[
2\langle \sin(\phi_h + \phi_S) \rangle_{U\perp} \propto C\left[ -\frac{h_{1T}}{M_h} h_1 H_1^T \right],
\]

and the Collins FF \( H_1^T \):

\[
2\langle \sin(3\phi_h - \phi_S) \rangle_{U\perp} \propto C\left[ 2\left( \frac{h_{P_T}}{M_h} \right) (p_T k_T) + \frac{p_T^2 (h_{k_T}) - 4(h_{P_T})^2 (h_{k_T})}{2M_h} \right] h_1 H_1^T \]

Other possible amplitudes, \( 2\langle \sin(\phi_h - \phi_S) \rangle_{U\perp} \) and \( 2\langle \sin(2\phi_h - \phi_S) \rangle_{U\perp} \), are at the twist-3 level.

Leading order amplitudes in a case of the longitudinally polarized beam and the transversely polarized target is the following: \( 2\langle \cos(\phi_h - \phi_S) \rangle_{L\perp} \propto C\left[ -\frac{h_{1T}}{M_h} g_{1T} D_1 \right] \). This amplitude depends on the worm-gear function \( g_{1T} \) and familiar FF \( D_1 \).

Other possible asymmetries, \( 2\langle \sin(\phi_S) \rangle_{L\perp} \) and \( 2\langle \sin(2\phi_h - \phi_S) \rangle_{L\perp} \), are at the twist-3 level.

In a case of the longitudinal beam polarization and the unpolarized target the asymmetry amplitude is at the twist-3 level only:

\[
2\langle \sin(\phi) \rangle_{LU} \propto \frac{2M_h}{Q} C\left[ -\frac{h_{k_T}}{M_h} (x e H_1^T + \frac{M_h}{Q} f_1 \hat{G}^\perp) + \frac{h_{P_T}}{M_h} (x g^+ D_1 + \frac{M_h}{Q} h_1 \hat{E}) \right].
\]

It depends on the twist-2 TMDs \( f_1 \) and \( h_1^T \), twist-3 TMDs \( e \) and \( g^+ \), twist-2 FFs \( D_1 \) and \( H_1^T \), and twist-3 FFs \( \hat{G}^\perp \) and \( \hat{E} \).

3.1. One-dimensional amplitudes for protons and antiprotons

One-dimensional amplitudes for pions and charged pions were published by the HERMES Collaboration a few years ago [2, 3]. In a new study the one-dimensional amplitudes for protons and antiprotons were extracted using (1). The results for the Collins and Sivers amplitudes are presented in Fig. 2. The Collins asymmetry amplitudes for protons show slightly negative values. The Sivers amplitudes for protons are positive. Available statistics of the antiprotons is rather low but the behaviour of the amplitudes have the same tendency as for protons. All other kinds of the asymmetry amplitudes for protons and antiprotons are found to be consistent with zero.

3.2. Three-dimensional amplitudes \( A_{U\perp} \)

A study of the one-dimensional Sivers amplitudes [2] showed that a magnitude of the \( K^+ \) amplitude is larger than a magnitude of the \( \pi^+ \) amplitude. Three-dimensional Sivers amplitudes for \( \pi^+ \) (left panel) and \( K^+ \) (right panel) are presented at Fig. 3.

A comparison of the three-dimensional Collins amplitudes for \( \pi^+ \) (left panel) and \( \pi^- \) (right panel) is presented at Fig. 4.

A comparison of the three-dimensional \( 2\langle \sin(3\phi_h - \phi_S) \rangle_{U\perp} \) amplitudes for \( \pi^+ \) (left panel) and \( \pi^- \) (right panel) is presented at Fig. 5.

Such multi-dimensional data can be very useful for phenomenological analysis of the TMD models.
Figure 2. Collins (left panel) and Sivers (right panel) asymmetry amplitudes for protons and antiprotons as a function of $x$, $z$ or $P_{h\perp}$.

Figure 3. Three-dimensional Sivers asymmetry amplitudes $2\langle \sin(\phi - \phi_S) \rangle_{U\perp}$ for $\pi^+$ mesons (left panel) and $K^+$ mesons (right panel) as a function of $x$, $P_{h\perp}$, and $z$.

3.3. Three-dimensional amplitudes $A_{L\perp}$

Three-dimensional $2\langle \cos(\phi - \phi_S) \rangle_{L\perp}$ amplitudes for $\pi^+$ (left panel) and $\pi^-$ (right panel) is presented at Fig. 6.

3.4. Three-dimensional BSAs

Three-dimensional beam-spin asymmetry amplitudes $2\langle \sin \phi \rangle_{LU}$ for $\pi^+$ (left panel) and $\pi^-$ mesons (right panel) are presented at Fig. 7.
Figure 4. Three-dimensional Collins asymmetry amplitudes $2 \langle \sin(\phi + \phi_S) \rangle_{U \perp}$ for $\pi^+$ mesons (left panel) and $\pi^-$ mesons (right panel) as a function of $x$, $P_{h \perp}$, and $z$.

Figure 5. Three-dimensional asymmetry amplitudes $2 \langle \sin(3\phi - \phi_S) \rangle_{U \perp}$ for $\pi^+$ mesons (left panel) and $\pi^-$ mesons (right panel) as a function of $x$, $P_{h \perp}$, and $z$.

To conclude, HERMES Collaboration continues its study of the azimuthal asymmetries in SIDIS. Various asymmetries for protons and antiprotons were evaluated. Three-dimensional asymmetry amplitudes as a function of $x$, $z$, and $P_{h \perp}$ were evaluated. It is expected that the three-dimensional amplitudes could be much more useful for a phenomenological analysis with a goal to constrain the TMDs.
Figure 6. Three-dimensional asymmetry amplitudes $2 \langle \cos(\phi - \phi_S) \rangle_{L \perp}$ for $\pi^+$ mesons (left panel) and $\pi^-$ mesons (right panel) as a function of $x$, $P_{h \perp}$, and $z$.

Figure 7. Three-dimensional asymmetry amplitudes $2 \langle \sin \phi \rangle_{LU}$ for $\pi^+$ mesons (left panel) and $\pi^-$ mesons (right panel) as a function of $x$, $P_{h \perp}$, and $z$. Data obtained with hydrogen (filled circles) and deuterium (empty circles) targets are presented.

References

[1] Bacchetta A et al. 2007 JHEP 0702 093