Accessing TMDs at HERMES

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Abstract. Transverse Momentum Dependent (TMD) parton distribution functions are being recognized as crucial ingredients for a complete understanding of the nucleon structure. Describing correlations between the quark or the nucleon spin with the quark transverse momentum, they allow for a tridimensional description of the nucleon structure in momentum space and could provide insights into the yet unmeasured quark orbital angular momentum. Eight leading-twist TMDs contribute to the cross-section for lepton-hadron Semi Inclusive Deep Inelastic Scattering (SIDIS) in conjunction with a fragmentation function. At HERMES, TMDs are probed for various hadron types through the analysis of specific azimuthal modulations of the SIDIS cross-section. Three double-spin asymmetries sensitive to the TMD (worm-gear) \( g_{1T} \) recently extracted from data collected with a transversely polarized target and a longitudinally polarized beam, are reported.

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SEMII-INCLUSIVE DIS AND TMDS

In recent years, semi-inclusive deep-inelastic-scattering (SIDIS) processes are being explored by several experiments to investigate the nucleon structure through the measurements of new observables, not accessible in inclusive DIS. The detection of a final-state hadron in coincidence with the scattered lepton has the advantage of providing unique information on the quark flavors involved in the scattering process ("flavor tagging") through the identification of the final state hadrons (e.g. \( \pi, K \), etc), and allows to access new dimensions, such as the transverse-spin and transverse-momentum degrees of freedom of the nucleon. For instance, the recent first extraction of the chiral-odd transversity distribution \( h_1^T(x) \) [1], the least known of the three fundamental leading-twist collinear parton distribution functions (PDFs), required the measurement of specific azimuthal asymmetries (the "Collins asymmetries") in SIDIS of unpolarized leptons off transversely polarized protons [2, 3, 4] and deuterons [5]. Here \( x \) denotes the fraction of the longitudinal momentum of the parent (fast-moving) nucleon carried by the struck quark.

When the transverse momentum \( p_T \) of the quarks is not integrated out, a variety of new PDFs arise, describing correlations between the quark or the nucleon spin with the quark transverse momentum, often referred to as spin-orbit correlations. These poorly known PDFs, typically denoted as transverse-momentum-dependent PDFs (or simply TMDs), encode information on the 3-dimensional structure of nucleons in momentum space ("nucleon tomography") and are increasingly gaining theoretical and experimental interest. At leading-twist, eight TMDs, each with a specific probabilistic interpretation in terms of quark number densities, enter the SIDIS cross section in conjunction with a fragmentation function (FF) (see e.g. [6]). When the polarization of the final hadrons is not regarded, this can be either the chiral-odd Collins function \( H_1^\perp(z, K_T^2) \), describing left-right asymmetries in the fragmentation of transversely polarized quarks, or the relatively well known spin-independent chiral-even Boer-Mulders function \( D_1(z, K_T^2) \) FF. Here \( z \) and \( K_T^2 \) denote the fraction of the energy of the exchanged virtual photon carried by the produced hadron and the transverse momentum of the fragmenting quark with respect to the outgoing hadron direction, respectively.

Of particular interest are the naïve T-odd Sivers [7] and Boer-Mulders [8] functions, denoted as \( f_{1T}^\perp(x, p_T^2) \) and \( h_1^T(x, p_T^2) \), respectively. The first describes the correlation between the transverse momentum of the quarks and the transverse polarization of the parent nucleon, whereas the second describes the correlation between the transverse momentum and the transverse polarization of the quarks in an unpolarized nucleon. Here, naïve T-odd means odd under a special (naïve) time-reversal operator that does not interchange initial and final states. The interest on these TMDs suddenly increased after it was demonstrated [9] that the inclusion of a gauge link in their definition, which can be interpreted as an interaction of the struck quark with the color field of the target remnant, allows for their gauge-invariance and preserves the time-reversal invariance of QCD. While the Sivers function is responsible of single-spin asymmetries in transversely polarized SIDIS (Sivers effect) [2, 4, 5, 10], the Boer-Mulders function generates azimuthal asymmetries in unpolarized processes (Boer-Mulders effect) [11]-[15].
DATA ANALYSIS AND RESULTS

The data analysed was recorded during the 2003–2005 running period of the HERMES experiment using a longitudinally polarized 27.6 GeV positron/electron beam and a transversely nuclear-polarized hydrogen gas target internal to the HERA storage ring at DESY. The open-ended target cell was fed by a polarized atomic-beam source [23] based on Stern-Gerlach separation and RF transitions of hyperfine states. The nuclear polarization of the atoms was flipped in the HERA storage ring at DESY. The open-ended target cell was fed by a polarized atomic-beam source [23] based on Stern-Gerlach separation and RF transitions of hyperfine states. The nuclear polarization of the atoms was flipped.

Another very interesting TMD is the so-called pretzelosity or Mulders-Tangerman distribution. It is denoted as $h_{LT}^{\perp}(x, p_F^2)$ and describes the correlation between the transverse momentum and the transverse polarization of the quarks in a transversely polarized nucleon. In various models, such as the bag or spectator models, it appears as the difference between the helicity and the transversity distributions, thus encoding pure relativistic effects in the quark motion within the nucleon. As the name pretzelosity suggests, non-zero values of this function could indicate that the shape of the nucleon is non-spherical [16, 17].

Among the leading-twist TMDs, the ‘worm-gears’ $h_{LT}^{\perp}(x, p_F^2)$ and $g_{LT}^{\perp}(x, p_F^2)$ are those that have received the least attention so far. They are, nevertheless, very intriguing objects: $g_{LT}^{\perp}(x, p_F^2)$ describes the probability of finding a longitudinally (transversely) polarized quark inside a transversely (longitudinally) polarized nucleon. Interestingly, they are the only two leading-twist TMDs whose corresponding Generalized Parton Distributions vanish in light-cone quark models [18], and are found to be one the opposite of the other ($g_{LT}^{\perp}(x, p_F^2) = -h_{LT}^{\perp}(x, p_F^2)$) in various quark models [19, 20, 21, 22]. Despite their similarities, these two TMDs have a different behaviour under chiral transformations: $h_{LT}^{\perp}(x, p_F^2)$ is chiral-odd and can be probed in SIDIS in combination with the Collins FF, while $g_{LT}^{\perp}(x, p_F^2)$ is chiral-even and can thus be accessed in SIDIS combined with the unpolarized FF. Another important difference, especially from the experimental point of view, is that $h_{LT}^{\perp}(x, p_F^2)$ can be accessed in longitudinal target $A_{UL}$ single-spin asymmetries (SSAs), whereas in the case of $g_{LT}^{\perp}(x, p_F^2)$ the longitudinal polarization of the quarks leads to $A_{LT}$ double-spin asymmetries (DSAs), requiring both a longitudinally polarized beam and a transversely polarized target [6].

At leading-twist, the term of the SIDIS cross section that accounts for this DSA exhibits a $\cos(\phi - \phi_s)$ modulation in the azimuthal angles $\phi$ and $\phi_s$, respectively of the detected hadron and of the target transverse polarization with respect to the lepton scattering plane and about the virtual-photon direction. In SIDIS experiments the worm-gear $g_{LT}^{\perp}(x, p_F^2)$ can be accessed at leading-twist through the measurement of the DSA:

\[ 2\langle \cos(\phi - \phi_s) \rangle_{L,T}^h = \frac{\int d^2d\phi_{\perp} d\phi_{\parallel} \cos(\phi - \phi_s) \sigma_{LT}}{\int d^2d\phi_{\parallel} d\phi_{\perp} \sigma_{UU}} = \frac{C \left[ -P_{L,T}g_{LT}^{\perp}(x, p_F^2) D_{T,h}^{\perp}(z, K_F^2) \right]}{C \left[ f_1^{\perp}(x, p_F^2) D_{T,h}^{\perp}(z, K_F^2) \right]}, \]

where $\sigma_{LT}$ denotes the cross-section difference for opposite target polarization states, $P_{L,T}$ is the transverse momentum of the produced hadron, $f_1^{\perp}(x, p_F^2)$ is the unpolarized distribution function and $C$ denotes a convolution integral over the intrinsic transverse momenta. Other Fourier components of $\sigma_{LT}$ are the sub-leading twist contributions $\cos(\phi_s)$ and $\cos(2\phi - \phi_s)$, where the worm-gear $g_{LT}^{\perp}(x, p_F^2)$ appears in convolution with the higher-twist $D^{\perp}(z, K_F^2)$ FF besides several other contributions of PDFs and FFs.

In this work, preliminary results for the Fourier components of the $A_{LT}$ DSAs, measured at HERMES with a longitudinally polarized beam and transversely polarized protons, are presented for identified pions and charged kaons.
where $P_T$ ($P_B$) denotes the target (beam) polarization, also included six previously measured $A_{UT}$ SSAs: the Collins term $2\langle \sin(\phi + \phi_S) \rangle_{LL}$, sensitive to the transversity distribution [3], the Sivers term $2\langle \sin(\phi - \phi_S) \rangle_{UL}$, sensitive to the Sivers function [10], plus the four terms $2\langle \sin(3\phi - \phi_S) \rangle_{UL}$, $2\langle \sin(2\phi - \phi_S) \rangle_{UL}$, $2\langle \sin(2\phi + \phi_S) \rangle_{UL}$ (denoted with "..." in eq. 2), sensitive, among others, to the pretzelosity and the two worm-gear TMDs [25].

The systematic uncertainty, including contributions from acceptance effects, instrumental smearing, QED radiation and hadron misidentification, was evaluated as described in [3]. An additional 8.0% scale uncertainty, arising from the uncertainty on the beam and target polarization measurements, has to be considered.

The preliminary results for the $2\langle \cos(\phi - \phi_S) \rangle_{LL}$, asymmetry amplitudes are reported in Fig. 1 for pions and charged kaons as a function of $x$, $z$ or $P_{h\perp}$. The results show a positive amplitude for $\pi^-$ and a hint of a positive signal also for $\pi^+$ and $K^+$, whereas amplitudes consistent with zero are observed for $\pi^0$ and $K^-$. The positive amplitude for $\pi^-$ reported here is similar to that recently measured at Jefferson Lab (E06010 experiment in Hall-A) but on a transversely polarized $^3$He (i.e. neutron) target [26]. The amplitudes for the sub-leading twist DSA $2\langle \cos(\phi) \rangle_{LL}$ and $2\langle \cos(2\phi - \phi_S) \rangle_{LL}$, shown in Figs 2-3, are found to be both consistent with zero for all measured mesons.

In summary, semi-inclusive DIS measurements at HERMES allowed the extraction of several observables sensitive to the leading-twist TMDs, such as the Boer-Mulders, the Sivers and the Mulders-Tangerman (pretzelosity) functions. Recently, the analysis of data based on the joint use of a transversely polarized target and a longitudinally polarized beam yielded to the extraction of $A_{LT}$ DSAs sensitive to the unmeasured $g_{1T}^T$ ‘worm-gear’ TMD.
FIGURE 2. Preliminary results for the $2 \langle \cos(\phi_S) \rangle_{T \perp}$ DSA amplitudes for pions and charged kaons as a function of $x$, $z$ or $P_{h \perp}$. The shaded bands represent the systematic uncertainty. A common 8.0% scale uncertainty arises from the precision of the beam and target polarization measurements.

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FIGURE 3. Preliminary results for the $2\langle \cos(2\phi - \phi_5) \rangle_{L_L}^b$ DSA amplitudes for pions and charged kaons as a function of $x$, $z$ or $P_{h_L}$. The shaded bands represent the systematic uncertainty. A common 8.0% scale uncertainty arises from the precision of the beam and target polarization measurements.