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HERMES Results on Azimuthal Asymmetries related to TMDs and DVCS

Klaus Rith *† **(on behalf of the HERMES collaboration)**
Friedrich-Alexander-Universität Erlangen-Nürnberg and DESY/Hamburg
E-mail: klaus.rith@desy.de

Azimuthal modulations of differential cross sections and asymmetries in semi-inclusive deep-inelastic scattering and hard exclusive electroproduction of mesons and real photons provide informations about transverse-momentum-dependent parton distributions (TMDs) and Generalised Parton Distributions. The HERMES experiment at HERA has performed such measurements using longitudinally polarised electron and positron beams with both helicities, unpolarised and longitudinally polarised hydrogen and deuterium targets, a transversely polarised hydrogen target and various unpolarised nuclear targets, and has determined the amplitudes of the corresponding azimuthal modulations. Some selected amplitudes for pions and charged kaons measured in semi-inclusive deep-inelastic scattering from a transversely polarised hydrogen target and for the hard exclusive electroproduction of real photons related to Deeply-Virtual Compton Scattering (DVCS) are presented.

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*Speaker.

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1. Introduction

Azimuthal modulations of differential cross sections and asymmetries in semi-inclusive deep-inelastic scattering (SIDIS) and hard exclusive electroproduction of mesons and real photons provide informations about transverse-momentum-dependent parton distributions (TMDs) and Generalised Parton Distributions (GPDs). The relevant azimuthal angles are the angles ϕ and ϕ_s around the direction of the exchanged virtual photon between the lepton scattering plane and the hadron production plane and the target spin direction, respectively. The amplitudes of these modulations are usually presented as $A_{XY}^{F.H.}$, where the first subscript refers to the beam charge (C) or the beam polarisation (U: unpolarised, L: longitudinally polarised) and the second subscript to the polarisation of the target (U, L, T: transversely polarised) and F.H. denotes Fourier harmonics of linear combinations of ϕ and ϕ_s. The HERMES experiment at HERA [1] has performed such measurements using longitudinally polarised electron and positron beams with both helicities, unpolarised and longitudinally polarised hydrogen (H) and deuterium (D) targets, a transversely polarised H target and various unpolarised nuclear targets, and has determined the amplitudes of the corresponding azimuthal modulations. In this contribution some selected results are presented.

2. TMDs

The structure of the nucleon can be parameterised in terms of eight leading-twist quark distribution functions (DFs) when including the transverse momentum of quarks in the description [2, 3]. They embody the correlations between the spin of the nucleon, the spin of the quarks and their longitudinal and transverse momentum. Only three of them survive integration over the transverse momenta. These are the unpolarised longitudinal-momentum distribution f_1, the *helicity* distribution g_1 and the *transversity* distribution h_1. The other five DFs are the *Sivers* DF $f_{1T}^{\perp}$, that describes the distribution of unpolarised quarks in a transversely polarised nucleon and can be related to orbital angular momenta of quarks, the *Boer-Mulders* DF $h_1^{\perp}$ (transversely polarised quarks in an unpolarised nucleon), the *Kotzinian-Mulders* DF $h_{1L}^{\perp}$ (transversely polarised quarks in a longitudinally polarised nucleon), the *pretzelosity* DF $h_{1T}^{\perp}$ (sideways transversely polarised quarks in a transversely polarised nucleon) and the *worm-gear* DF $g_{1T}^{\perp}$ (longitudinally polarised quarks in a transversely polarised nucleon). (The dependence of these DFs on the Bjorken variable x, the negative squared four-momentum of the virtual photon Q^2, and the quark transverse momenta has been omitted for brevity). Only f_1 and g_1 can be measured in inclusive DIS, all others can only be accessed in semi-inclusive measurements where in addition to the scattered lepton also a leading hadron is detected. The *Sivers* and *Boer-Mulders* DFs are naive-time-reversal odd, i.e., they are forbidden by time-reversal invariance T and their existence requires initial-state or final-state interactions. The DFs h_1, $h_1^{\perp}$, $h_{1L}^{\perp}$, and $h_{1T}^{\perp}$ are chiral-odd and can only be measured in conjunction with another chiral-odd quantity. In SIDIS this is the polarised *Collins* fragmentation function (FF) $H_{1,q}^{\perp}(z)$, where z is the fraction of the virtual-photon energy carried by the produced hadron.

Each of these distributions causes distinctive signatures in the hadron's azimuthal angular distribution. For example, the amplitudes of the $\sin(\phi - \phi_s)$ [$\sin(\phi + \phi_s)$] modulation of the transverse-target single-spin asymmetry for an unpolarised beam and a transversely polarised target are proportional to a convolution of the *Sivers* DF $f_{1T}^{\perp}$ and the unpolarised FF $D_{1,q}$ [the *transversity* DF

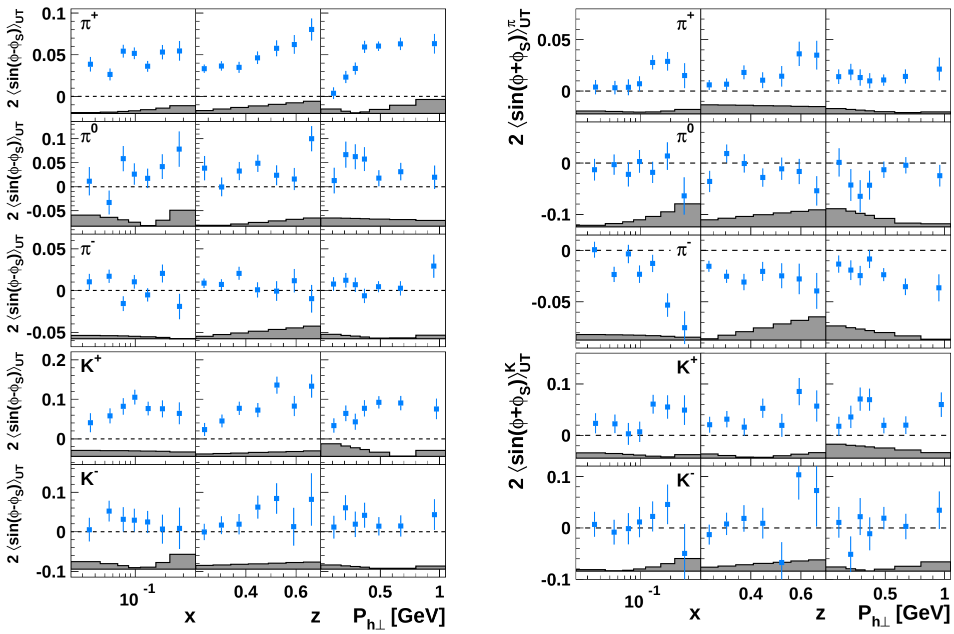

Figure 1: HERMES results for the *Sivers* moments (left panel) and the *Collins* moments (right panel) for pions and charged kaons obtained with a transversely polarised hydrogen target.

h_1 and the *Collins* FF $\mathrm{H}_{1,q}^{\perp}$]. The measured moments for pions and charged kaons [4] are shown in Fig. 1 as a function of x, z and the hadron momentum component transverse to the virtual photon direction, $P_{h\perp}$. The results for the π^+ and K^+ *Sivers* asymmetries (left panel) are significantly positive, providing the first evidence for a T-odd DF appearing in electroproduction. Consequently one has to conclude that the orbital angular momenta of quarks are non-zero. At present it is, however, not yet possible to quantitatively relate the magnitude of this asymmetry to the fraction of nucleon spin which can be attributed to orbital angular momenta of quarks. The measured Collins asymmetries (right panel) for π^+, π^- and K^+ are different from zero providing evidence for the existence of both h_1 and $\mathrm{H}_{1,q}^{\perp}$. The large π^- moment indicates that the unfavored *Collins* FF has similar magnitude as the favored one, but opposite sign. In both cases the amplitudes for K^+ appear to be larger than those for π^+.

If the semi-inclusive unpolarised DIS cross section is unintegrated over $P_{h\perp}$, an azimuthal dependence around the virtual-photon direction exists which has a $cos\phi$ and a $cos2\phi$ component. At leading-twist the amplitude of the $cos2\phi$ modulation is expected to be proportional to a convolution of $\mathrm{H}_{1,q}^{\perp}$ and the *Boer-Mulders* DF $\mathrm{h}_1^{\perp}$ which originates from a coupling between quark transverse momentum and quark transverse spin. Two mechanisms are expected to contribute to the $cos\phi$ modulation: $\mathrm{h}_1^{\perp}$ and the *Cahn* effect, a pure kinematic effect, generated by the non-zero intrinsic transverse motion of quarks. The preliminary $cos\phi$ and a $cos2\phi$ moments [5] for unpolarised beam and unpolarised H target measured for π^+ and π^- are shown in Fig. 2 as a function of x, y, z and $P_{h\perp}$. The $cos\phi$ amplitudes for π^+ and π^- are rather different. Since the *Cahn* effect should be flavour blind, this behaviour indicates a substantial contribution from $\mathrm{h}_1^{\perp}$, which is expected to have opposite sign for up- and down-quarks. This is supported by the $cos2\phi$ amplitudes that are positive (negative) for π^+ (π^-) over most of the kinematic range. The other leading-twist

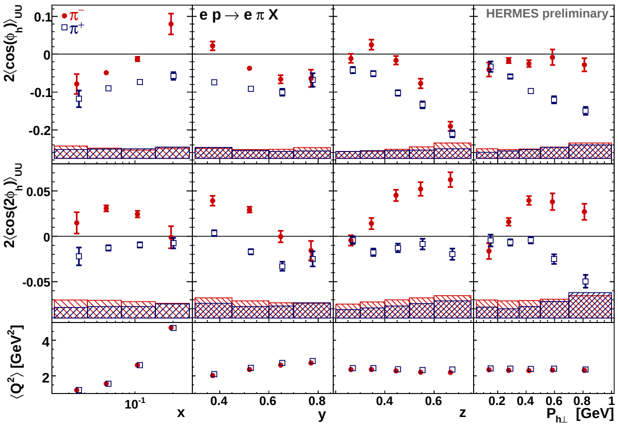

Figure 2: Preliminary HERMES results for the $cos(n\phi)$ moments for charged pions measured with an unpolarised beam and an unpolarised hydrogen target.

amplitudes related to the DFs $g_{1T}^{\perp}$, $h_{1L}^{\perp}$, and $h_{1T}^{\perp}$ and also some higher-twist amplitudes have been found to be very small and in most cases compatible with zero [6].

3. GPDs and DVCS

GPDs provide a framework for describing the multidimensional structure of the nucleon [7]. They encompass parton distribution functions and elastic nucleon form factors as limiting cases and moments, respectively, and provide correlated information on transverse spatial and longitudinal momentum distributions of partons. Furthermore, access to the total parton angular momentum contribution to the nucleon spin may be provided by GPDs through the Ji relation [8]. GPDs can be constrained through measurements of cross sections and asymmetries in exclusive processes. In this contribution some HERMES results are presented on Deeply-Virtual Compton Scattering (DVCS), i.e., the hard exclusive electroproduction of real photons. The asymmetries arise from the DVCS process, where the photon is radiated by the struck quark, and its interference with the Bethe-Heitler process, where the photon is radiated by the initial or final state lepton. The variety of experimental setups used by HERMES enabled the extraction of many asymmetry amplitudes. These are related to Compton Form Factors (CFFs) which are convolutions of the corresponding GPDs with the hard scattering coefficient functions. These asymmetries can be written as Fourier series in linear combinations of the angles ϕ and ϕ_S. HERMES has studied the dependence of such amplitudes on x, Q^2 and t, the squared four-momentum transfer to the target. Details can be found in Refs. [9].

Fig. 3 presents an overview of the extracted azimuthal-asymmetry amplitudes integrated over the entire HERMES kinematic range using the data taken in the years 1996-2007 with the H and D targets. In general the amplitudes for H and D are very similar. The leading-twist amplitudes are sizeable while the suppressed higher-twist amplitudes are compatible with zero. In the upper panel various amplitudes for beam-charge asymmetries are shown. The amplitudes $A_C^{cos(0\phi)}$ and $A_C^{cos\phi}$ which are sensitive to $\Re e(\mathscr{H})$, the real part of the CFF $\mathscr{H}$, are significantly different from zero. In the second panel amplitudes for the beam-helicity asymmetries are shown. Here especially

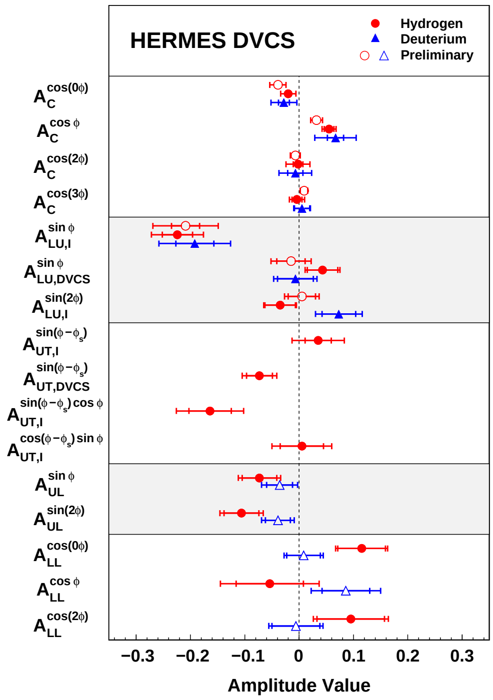

Figure 3: HERMES results for various DVCS amplitudes.

the non-zero amplitude $A_{LU,I}^{sin\phi}$ is of interest since it is sensitive to $\Im m(\mathscr{H})$. The transverse target-spin asymmetries in the middle panel are of special importance since they are sensitive to the GPD E. Here the amplitude $A_{UT,I}^{sin(\phi-\phi_s)cos\phi}$ which is proportional to the imaginary part of a linear combination of the CFFs $\mathscr{H}$ and $\mathscr{E}$ is significantly different from zero. The amplitudes of the longitudinal target-spin asymmetries in the second panel from below are sensitive to $\Im m(\widetilde{\mathscr{H}})$ and the longitudinal double-spin asymmetries in the bottom panel to $\Re e(\widetilde{\mathscr{H}})$. These results will be an important input for global fits of GPDs.

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