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Latest HERMES results on azimuthal single- and double-spin asymmetries in semi-inclusive deep-inelastic scattering by transversely polarized protons

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Azimuthal single- and double-spin asymmetries measured at HERMES in semi-inclusive leptoproduction of pions, charged kaons, protons, and antiprotons from a transversely polarized hydrogen target are presented. The results of a re-analysis of the previously published Collins and Sivers asymmetries, extended to include protons and antiprotons as well as an extraction in a multi-dimensional binning and enlarged phase space, is reported along with the corresponding results for the remaining single- and double-spin asymmetries associated to the semi-inclusive deep-inelastic scattering process with a transversely polarized target. Among those results, significant non-vanishing $\cos(\phi - \phi_s)$ modulations provide evidence for a sizable worm-gear distribution g_{1T}. Most of the other modulations are found to be consistent with zero with the notable exception of large $\sin(\phi_s)$ modulations for charged pions and positively charged kaons.

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1. Introduction

For decades, deep-inelastic scattering (DIS) experiments, performed with various experimental setups, different collisions systems and complementary kinematic coverages, have allowed to study the nucleon structure with increasing precision. The main goal of these experiments has been to determine the number densities of quarks and gluons (collectively denoted as partons) as a function of the fraction of the nucleon's momentum carried by these partons. This one-dimensional description of the internal structure of nucleons has more recently been extended to include the dependence on the parton's transverse momentum, i.e. perpendicular to the parent-proton momentum direction, and its correlations with the polarization directions of the parton and/or the parent nucleon. Within this new paradigm, the standard collinear Parton Distribution Functions (PDFs) are replaced by a wider family of non-perturbative objects, called TMDs (Transverse Momentum Distributions), which allow to describe the nucleon structure in three dimensions in momentum space. The complete description of the proton structure in terms of TMDs at leading twist requires eight such distribution functions [1], which are summarized in Table 1. Only three of these survive integration over transverse momentum: the rather well-known unpolarized PDF f_1, the less known helicity distribution g_1, and the poorly known transversity h_1. The other five distributions, apart from the Sivers distribution $f_{1T}^{\perp}$, are presently basically unknown. In addition, while some information is available on the transverse-momentum dependence of f_1, very little is known in this respect for the helicity and transversity distributions. The HERMES experiment [2] at the HERA facility in Hamburg (Germany) has played a pioneering role in the investigation of TMDs, observing for the first time unambiguous experimental signals for the transversity, the closely related Collins fragmentation function (FF), as well as the Sivers function [3–5]. In this document, a selection of HERMES results of the latest comprehensive analysis [6] of TMD signals in semi-inclusive deep-inelastic scattering of electrons or positrons by transversely polarized protons is presented.

Name	**TMD PDF/FF**	**Chirality**	**Naive time reversal**
Polarization-averaged	f_1	even	even
Helicity	g_1	even	even
Transversity	h_1	odd	even
Sivers	$f_{1T}^{\perp}$	even	odd
Boer–Mulders	$h_1^{\perp}$	odd	odd
Pretzelosity	$h_{1T}^{\perp}$	odd	even
Worm-gear (I)	$h_{1L}^{\perp}$	odd	even
Worm-gear (II)	g_{1T}	even	even
Polarization-averaged	D_1	even	even
Collins	$H_1^{\perp}$	odd	odd

Table 1: Leading-twist TMD distribution and fragmentation functions and their key symmetry properties. Only the transversity, the Sivers, pretzelosity, and the worm-gear (II) TMDs are easily accessible in this measurement.

2. TMD measurement at HERMES

TMDs can be studied in semi-inclusive lepton scattering by polarized or unpolarized protons [1]. At HERMES, the 27.6 GeV HERA electron/positron beam (subsequently denoted as leptons) traversed a pure-gas target internal to the lepton storage ring. For the measurement presented here, target protons with an average transverse polarization of 0.725 ± 0.053 were used. Scattered leptons and hadrons produced were reconstructed with a series of tracking devices in front and behind a 1.6 Tm dipole magnet, and identified using responses from a dual-radiator ring-imaging Cherenkov detector, a transition-radiation detector, a pre-shower scintillation counter, and an electromagnetic calorimeter. The various TMDs are accessible through a Fourier decomposition of the Semi-Inclusive DIS (SIDIS) cross-section [1] in terms of the azimuthal angles ϕ and ϕ_s of the hadron's transverse momentum and of the target-polarization direction, respectively, measured with respect to the lepton scattering plane [7]. More details on the experiment and the experimental signatures can be found in the original publication [6]. Here, selected results of the $\sin(\phi + \phi_S)$, $\sin(\phi - \phi_S)$, and the $\sin(\phi_S)$ modulations will be presented. The first two modulations originate from the leading-twist transversity and Sivers TMDs (denoted as Collins and Sivers modulations, respectively), while the last one corresponds to a subleading-twist contribution to the cross section. An important novelty of this new analysis of the HERMES data set compared to previous analyses of the Collins and Sivers modulations [3–5] is the focus on multi-dimensional binning of the data. Results are provided in a 3D grid in the Bjorken variable x, the photon's energy fraction carried by the hadron z, and the transverse component of the hadron momentum $P_{h\perp}$. This approach reduces systematics arising from the kinematic dependence of detection efficiencies, eliminates statistical correlations of data points from separate 1D projections, and allows for more detailed studies of particular phase-space regions.

3. Results and discussion

A 3D representation of the π^+ Sivers results is shown in Fig. 1. The amplitude is observed to exceed 0.1 at large x, z, and $P_{h\perp}$, while staying below 0.1 in the separate 1D projections of these data, as shown in Fig. 2, where the π^+ amplitude is also compared to that for K^+ as well as to those for protons and antiprotons. The inclusion of the latter two in the analysis is another novelty (so far only mesons as final-state hadrons were considered). It is intriguing that the proton Sivers amplitude is rather similar to that of the π^+, both in magnitude and in kinematic dependence. This similarity might be a reflection of the nature of the Sivers effect, which arises from an intrinsic transverse-momentum left-right asymmetry for unpolarized quarks in an transversely polarized proton, rather than from a fragmentation process, which would clearly differ for pions and protons. The similar behavior for protons and positive pions might thus hint at the same up-quark dominance in their production for lepton scattering at these kinematics. One more noteworthy novelty in this analysis is the extension of the kinematic region to large values of z (only for the 1D representation), a region that is generally more sensitive to the flavor of the struck quark, but also with larger contributions from the decay of exclusively produced ρ^0 in the case of charged pions, which dilutes the sensitivity to the flavor of the struck quark. This might be visible in the pion-kaon comparison:

while the Sivers effect continues to rise with z for K^+, possibly due to the increased role of up-quark scattering, it drops in the case of π^+.

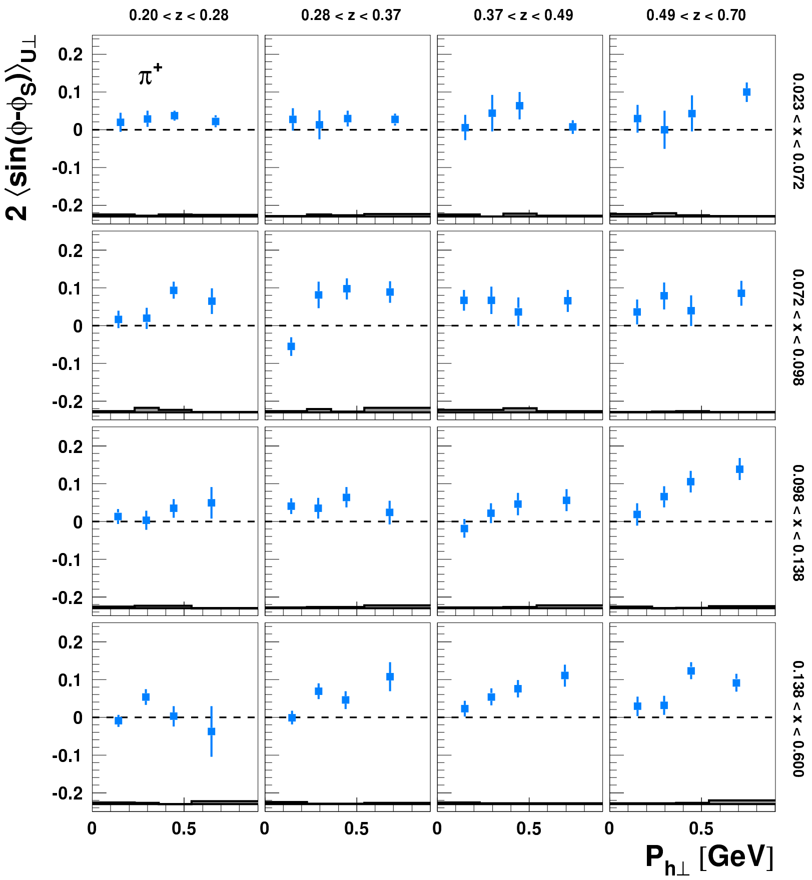

Figure 1: Three-dimensional presentation of the Sivers modulation for π^+.

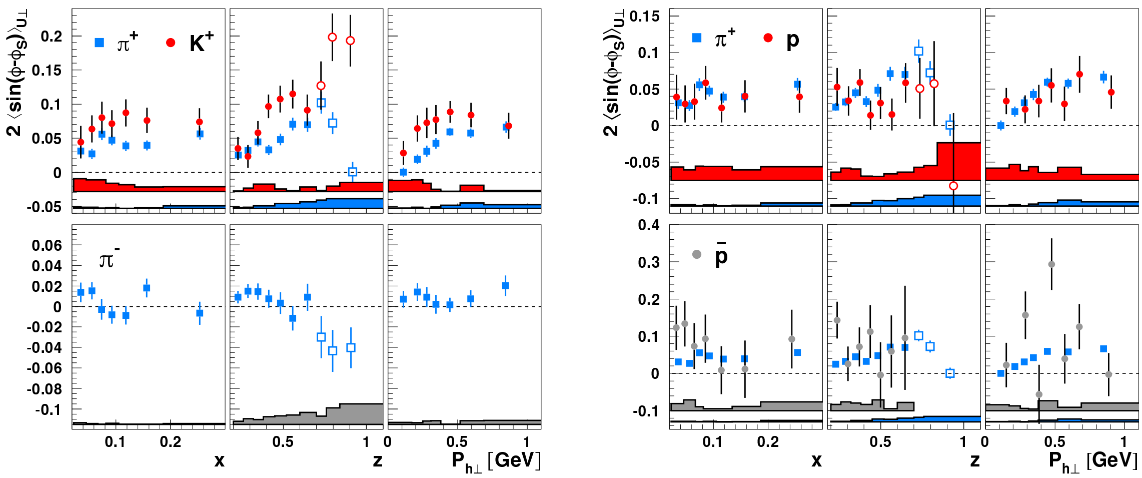

Figure 2: One-dimensional projections in x, z, and $P_{h\perp}$ of the Sivers modulation for charged pions, K^+, protons, and antiprotons (as labelled). The open points in the z projection cover the region of large z that is not included in the other projections.

The Collins modulation provides information about both the transversity distribution and the novel Collins FF. The latter describes a left-right preferences in the transverse-momentum direction of hadrons produced in the fragmentation of transversely polarized quarks. Earlier HERMES data [3] already led to the conclusion that hadrons produced in an disfavored transition (e.g., up-quarks into negative pions) prefer to go to the opposite direction than hadrons produced in a favored transition (e.g., up-quarks into positive pions). Consequently, large Collins effects were also seen for negative pions. This is visible in the upper plots of Fig. 3, where 1D projections of the Collins modulations are shown for charged pions and kaons. Especially noteworthy are the K^+ results, which are similar in shape to the π^+ data, but about twice as large. The K^-, not sharing any of its valence quarks with those of the proton, exhibits vanishing modulation. The latter statement also applies to protons and antiprotons (not shown here); the reason, however, must be a different one and could lie in the fact that fragmentation into baryons is quite different from fragmentation into spin-zero mesons, especially when spin effects do play a role as is the case for the Collins FF. Clearly visible in Fig. 3 (upper plots) is also a rise in magnitude of the Collins effect with increasing z, now both for π^+ and K^+. The π^-, in contrast, remains at the same level or even diminishes in magnitude. This could be due to the increased role of down-quark fragmentation in the production, with down-quark transversity being smaller than up-quark transversity.

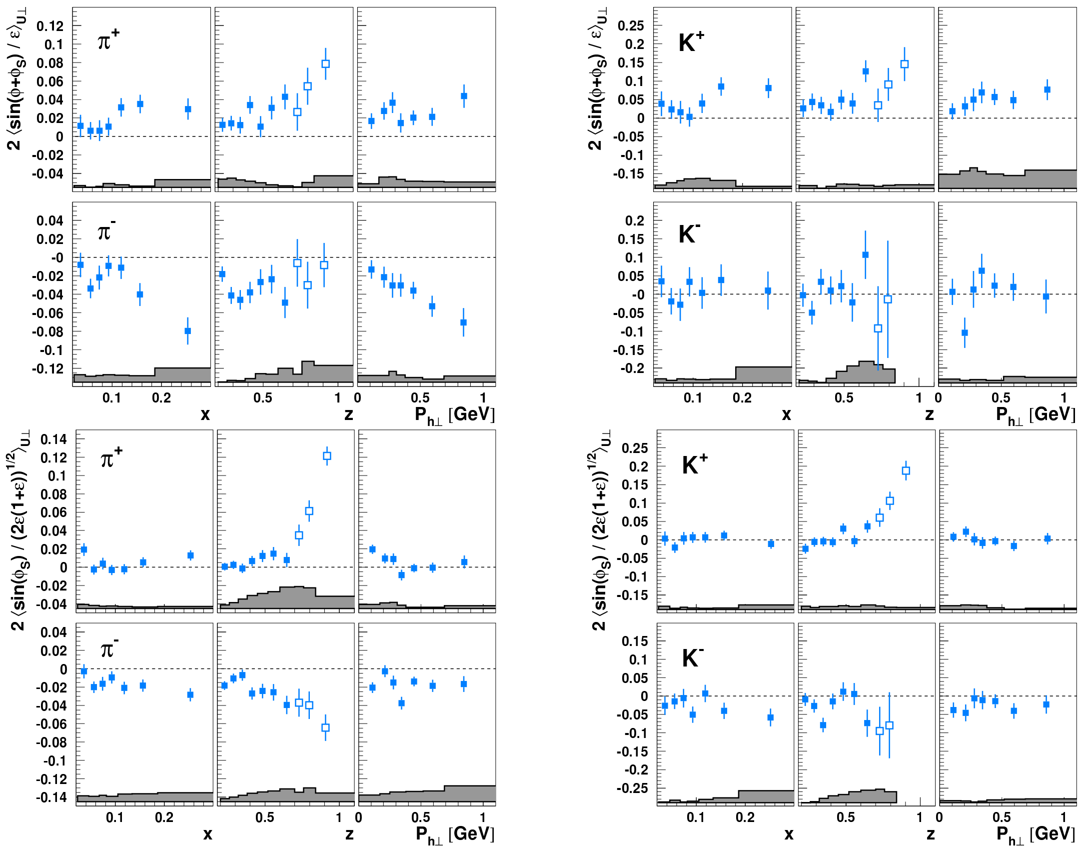

Figure 3: One-dimensional projections in x, z, and $P_{h\perp}$ of the Collins modulation (upper plots) and the subleading-twist $\sin\phi_S$ modulation (lower plots) for charged pions and kaons (as labelled). The open points in the z projection cover the region of large z that is not included in the other projections.

The last results highlighted here are the subleading-twist $\sin\phi_S$ modulations, shown in the lower plots of Fig. 3 Their interpretation is less straight-forward due to their subleading-twist nature (e.g., not having a direct probabilistic interpretation). On the other hand, they must be suppressed by one power in M/Q, with M being a typical mass scale (e.g., the proton mass) and Q the hard scale of the process (here, $-Q^2$ being the squared invariant mass of the virtual photon). Surprisingly, these modulations are found to be sizable, also in comparison to the leading-twist Sivers and Collins modulations.

4. Conclusion

The analysis discussed here provides for the very first time 1D and 3D results on the complete set of modulations for pions, charged kaons as well as for protons and antiprotons. Significant modulations are found for six out of the ten modulations, providing in particular evidence for non-vanishing transversity, Sivers, and worm-gear distributions (as well as the Collins FF), but also for surprisingly large subleading-twist effects.

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