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# Azimuthal Single- and Double-Spin Asymmetries in Semi-Inclusive Deep-Inelastic Lepton Scattering by Transversely Polarized Protons

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A comprehensive set of azimuthal single-spin and double-spin asymmetries in semi-inclusive leptoproduction of pions, charged kaons, protons, and antiprotons from transversely polarized protons is presented. These asymmetries include the previously published HERMES results on Collins and Sivers asymmetries, the analysis of which has been extended to include protons and antiprotons and also to an extraction in a three-dimensional kinematic binning and enlarged phase space. They are complemented by corresponding results for the remaining single-spin and double-spin asymmetries for transverse target-polarization orientation.

**KEYWORDS:** lepton-nucleon scattering, QCD, polarization, HERMES

## 1. Introduction

More than half a century has been spent on extensive studies of the internal structure of hadrons, in particular of protons. The focus has been mainly on an one-dimensional picture, where the number density of the elementary building blocks—quarks and gluons (collectively denoted as partons)—has been determined as a function of the fraction of the proton's momentum carried by these partons. During the second half of this period, the focus has shifted to creating a multi-dimensional picture of the proton's internal structure. As such one needs to include also the components of the parton momentum that are perpendicular to that of the parent-proton momentum, possibly correlating those with the polarization directions of the parton and/or the parent proton. The complete description of the proton structure in terms of such *transverse momentum distributions* (TMDs) at leading twist (cf. Ref. [1] for a comprehensive discussion of twist in this context) requires eight such TMDs [2]. Not all of them require an explicit dependence on transverse momentum; three of them exist also as collinear version: the rather well-known unpolarized parton distribution function (PDF) $f_1$, the somewhat lesser known helicity distribution $g_1$, and the currently still poorly known transversity $h_1$. The remaining five TMDs require transverse momentum and are, apart from the Sivers distribution $f_{1T}^{\perp}$, presently basically unknown. The HERMES experiment [3], which ran from 1995–2007 at HERA (DESY, Hamburg), has played a pioneering role in the investigation of TMDs, among others observing for the first time unambiguous experimental signals for transversity, the closely related Collins fragmentation function (FF), as well as the Sivers function [4–6]. In this contribution, a small selection of results from the latest comprehensive HERMES analysis [7] of TMDs in semi-inclusive deep-inelastic scattering of electrons/positrons by transversely polarized protons will be presented.

## 2. TMD measurement at HERMES

TMDs can be studied in lepton scattering by polarized or unpolarized protons [2]. At HERMES, the 27.6 GeV electrons/positrons (subsequently denoted as leptons) of HERA scattered by protons in a pure-gas target internal to the lepton storage ring. In this analysis, the target protons had an average transverse polarization of $0.725 \pm 0.053$ in magnitude. Tracking devices in front and behind a 1.6 Tm dipole magnet were used to reconstruct the trajectories of scattered leptons and produced hadrons. They were 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 characteristic angular distributions of the scattered leptons and produced hadrons about the direction of the virtual photon in relation to the target-polarization direction [2]. (Details can be found in the original publication [7].) Here, selected results of the $\sin(\phi + \phi_S)$, $\sin(\phi - \phi_S)$, and the $\sin(\phi_S)$ modulations will be presented, where $\phi$ and $\phi_S$ are the azimuthal angles of the hadron transverse momentum and of the target-polarization direction, respectively, measured with respect to the lepton scattering plane [8]. They originate from the leading-twist transversity and Sivers TMDs (denoted as Collins and Sivers modulations, respectively), as well as from a subleading-twist contribution to the cross section.

## 3. Results and discussion

Table I provides an overview of the results of all ten allowed modulations. An important novelty of this new analysis of the HERMES data set compared to previous analyses of the Collins and Sivers modulations [4–6] is the focus on multi-dimensional binning of the data. Results are obtained in a 3D grid in $x$, $z$, and $P_{h\perp}$, i.e., the Bjorken variable, the photon's energy fraction carried by the hadron, as well as the transverse component of the hadron momentum, respectively. This approach reduces systematics arising from the kinematic dependence of detection efficiencies, eliminates statistical correlations of data points

| Azimuthal modulation | | Significant non-vanishing Fourier amplitude | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $\pi^+$ | $\pi^-$ | $K^+$ | $K^-$ | $p$ | $\pi^0$ | $\bar{p}$ |
| $\sin(\phi + \phi_S)$ | [Collins] | ✓ | ✓ | ✓ | | ✓ | | |
| $\sin(\phi - \phi_S)$ | [Sivers] | ✓ | | ✓ | ✓ | ✓ | (✓) | ✓ |
| $\sin(3\phi - \phi_S)$ | [Pretzelosity] | | | | | | | |
| $\sin(\phi_S)$ | | (✓) | ✓ | | ✓ | | | |
| $\sin(2\phi - \phi_S)$ | | | | | | | | (✓) |
| $\sin(2\phi + \phi_S)$ | | | | ✓ | | | | |
| $\cos(\phi - \phi_S)$ | [Worm-gear] | ✓ | (✓) | (✓) | | | | |
| $\cos(\phi + \phi_S)$ | | | | | | | | |
| $\cos(\phi_S)$ | | | | ✓ | | | | |
| $\cos(2\phi - \phi_S)$ | | | | | | | | |

**Table I.** The various azimuthal modulations of the semi-inclusive cross section and those hadron species whose corresponding Fourier amplitudes are incompatible with the NULL hypothesis at 95% (90%) confidence according to the Student's t-test. Antiprotons and neutral pions are given separated in the last two columns to indicate that the statistical test of those is based on the one-dimensional projections and hence restricted to using only seven data points compared to using 64 data points of the three-dimensional projections used for the other hadrons.

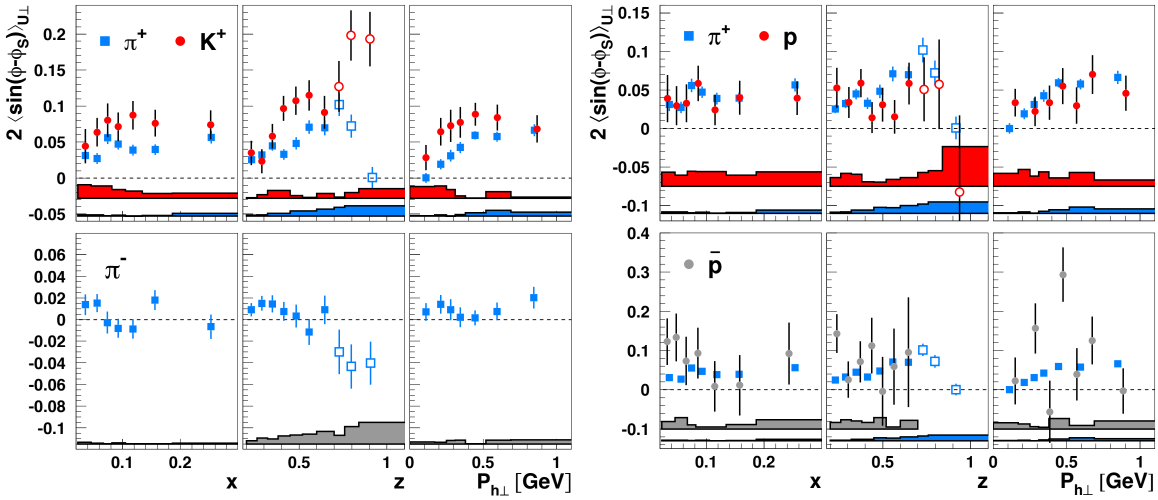

**Fig. 1.** One-dimensional projections in $x$, $z$, and $P_{h\perp}$ of the Sivers modulation for $\pi^{\pm}$, $K^{+}$, $p$, and $\bar{p}$ (as labelled). Open points (only in the $z$ projection) cover the region of large $z$ that is not included in the $x$ and $P_{h\perp}$ projections.

from separate 1D projections, and allows for more detailed studies of particular phase-space regions. As an example, the 3D presentation of the $\pi^{+}$ Sivers modulation [7] reveal regions where the magnitude of the those clearly exceed 0.1 at large $x$, $z$, and $P_{h\perp}$, while staying below in the separate 1D projections of these data shown here in Fig. 1. The $\pi^{+}$ results are also compared to the results for $K^{+}$ as well as to those for protons and antiprotons, which were measured here for the first time. It is intriguing that the proton results are rather similar to those of the $\pi^{+}$. It might be a reflection of the nature of the Sivers effect: it is not so much the fragmentation process (where clear differences for pions and protons are expected) but already an intrinsic transverse-momentum left-right asymmetry for unpolarized quarks in an transversely polarized proton that characterizes the Sivers effect. 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. Another important addition in this analysis is the extension of the kinematic region to large values of $z$ in the 1D representation. This region is more sensitive to the flavor of the struck quark, however, it also receives larger contributions from the decay of exclusively produced $\rho^{0}$ 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 $\pi^{+}$.

The Collins modulation provides information about both the transversity distribution and the novel Collins fragmentation function. The latter describes a left-right preferences in the transverse-momentum direction of hadrons produced in the fragmentation of transversely polarized quarks. It had been known already from earlier HERMES data [4] that hadrons produced in disfavored fragmentation (e.g., up-quarks into negative pions) prefer to go to the opposite direction than hadrons produced in favored fragmentation (e.g., up-quarks into positive pions). This results in large $\pi^{-}$ Collins modulations, which is visible in Fig. 2, where 1D projections of the Collins modulations are shown for charged pions and kaons. Strikingly, the $K^{+}$ results are similar in shape to the $\pi^{+}$ data, but about twice as large in magnitude. The $K^{-}$, not sharing any of its valence quarks with those of the proton, exhibits vanishing modulation. The vanishing Collins modulation for protons and antiprotons are not shown here but can be found in Ref. [7]. However, unlike the $K^{-}$ case, up-quark scattering does

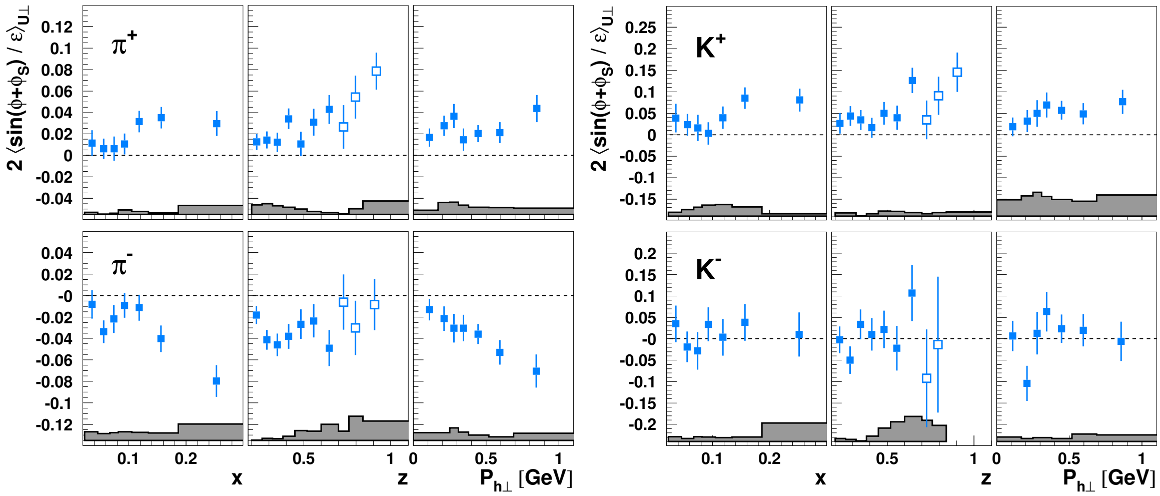


**Fig. 2.** One-dimensional projections in $x$, $z$, and $P_{h\perp}$ of the Collins modulation for charged pions and kaons (as labelled). Open points (only in the $z$ projection) cover the region of large $z$ that is not included in the $x$ and $P_{h\perp}$ projections.

play an important role, but fragmentation into baryons is expected to be quite different from fragmentation into spin-zero mesons, especially when spin effects do play a role as is the case for the Collins FF. For both, the $\pi^+$ and $K^+$, the magnitude of the Collins effect increases with increasing $z$ while the $\pi^-$ remains at the same level or even decreases in magnitude. A possible explanation could be an increased role of down-quark fragmentation in the production, with down-quark transversity being smaller than up-quark transversity.

Unlike the Sivers and Collins modulations, the $\sin\phi_S$ modulations shown in Fig. 3 are subleading in twist. As such heir interpretation is less straight-forward (for instance, they do not have a 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 $Q$ being the hard scale of the process (here, $-Q^2$ being the squared invariant mass of the virtual photon). Surprisingly enough, the modulations are found to be sizable, also in comparison to the leading-twist Sivers and Collins modulations. Striking is also the strong increase in magnitude at large $z$. In general, there is some similarity in behavior with the Collins modulation. Indeed, some of the literature [9, 10] suggest a stringent relation between at least some terms contributing to the $\sin\phi_S$ modulation and the Collins effect.

## 4. Conclusion

The latest HERMES publication on transverse single- and double-spin asymmetries in deep-inelastic scattering by transversely polarized protons [7] goes substantially beyond earlier publications that focussed on only the Sivers and Collins modulations for mesons and on only 1D projections of those. This new analysis provides for the very first time results on the complete set of modulations, for pions, charged kaons as well as for protons and antiprotons, as well as a simultaneous 3D extraction and presentation. 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.

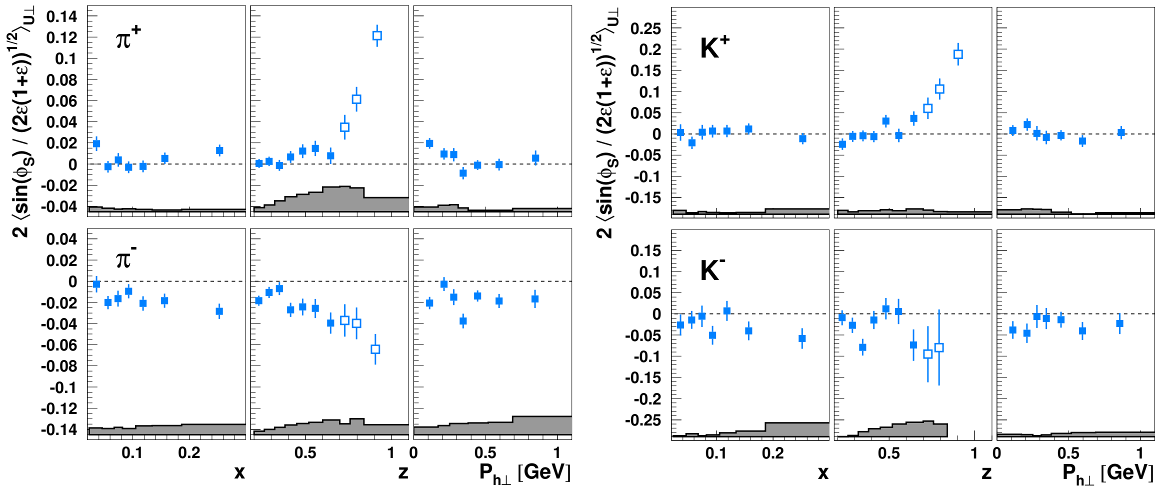


**Fig. 3.** One-dimensional projections in $x$, $z$, and $P_{h\perp}$ of the subleading-twist $\sin\phi_S$ modulation for charged pions and kaons (as labelled). Open points (only in the $z$ projection) cover the region of large $z$ that is not included in the $x$ and $P_{h\perp}$ projections.

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