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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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Abstract

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.

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1 Introduction

More than half a century has been spent to extensively study 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. Only during the second half of this period, the focus has shifted to a more comprehensive picture of the internal structure. One such extension is the inclusion of the parton's momentum components 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[1] requires eight such TMDs [2], which are summarized

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[1] A comprehensive discussion of twist in this context can be found in Ref. [1].

Table 1: Leading-twist TMD distribution and fragmentation functions and their key symmetry properties. Only the first three TMD PDFs and the D_1 fragmentation function survive integration over transverse momentum. Only the transversity, the Sivers, pretzelosity, and the worm-gear (II) TMDs are easily accessible in this measurement.

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

in Table 1. Three of these survive integration over transverse momentum and comprise 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 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 about it for the helicity and transversity distributions. The HERMES experiment [3] at the HERA facility in Hamburg (Germany) 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]. Here, a selection of HERMES results of the latest comprehensive analysis [7] of TMD signals in semi-inclusive deep-inelastic scattering of electrons or 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 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 in magnitude 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 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]. More details on the experiment and the experimental signatures 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 ϕ and ϕ_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]. The first two modulations originate from the leading-twist transversity and Sivers TMDs (denoted as Collins and Sivers modulations, respectively), while the last modulation is a subleading-twist contribution to the cross section.

Table 2: 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.

Azimuthal modulation		**Significant non-vanishing Fourier amplitude**						
		π^+	π^-	K^+	K^-	p	π^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]	✓	(✓)	(✓)				
$\cos(\phi+\phi_S)$								
$\cos(\phi_S)$				✓				
$\cos(2\phi-\phi_S)$								

3 Results and discussion

An overview of the results of all ten allowed modulations is given in Table 2. 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 from separate 1D projections, and allows for more detailed studies of particular phase-space regions. As an example, Fig. 1 shows the 3D presentation of the π^+ Sivers results, where the values clearly exceed 0.1 at large x, z, and $P_{h\perp}$, while staying below in the separate 1D projections of these data shown in Fig. 2, where they are also compared to the results for K^+ as well as to those for protons and antiprotons. The inclusion of the latter two in the analysis is another novelty, in particular as so far only mesons as final-state hadrons were considered. It is intriguing that the proton results are rather similar to those of the π^+. 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. 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^+.

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

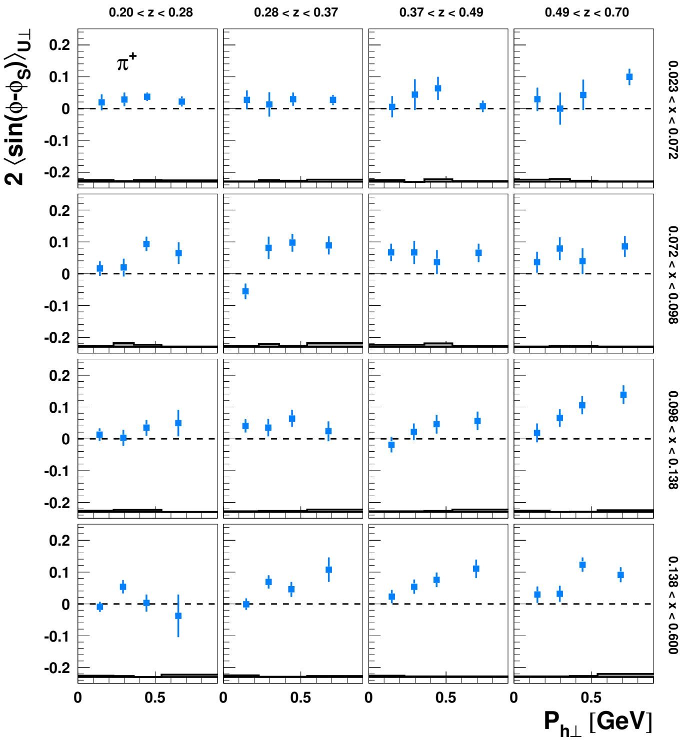

Figure 1: Three-dimensional presentation of the Sivers modulation for π^+.

transverse-momentum direction of hadrons produced in the fragmentation of transversely polarized quarks. Earlier HERMES data [4] 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 seen for also negative pions. This is visible in 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 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.

The last result to be highlighted here are the subleading-twist $\sin\phi_S$ modulations, shown in Fig. 4. Their interpretation is less straight-forward due to being of subleading twist (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 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. There is some reminiscence of the earlier discussed 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.

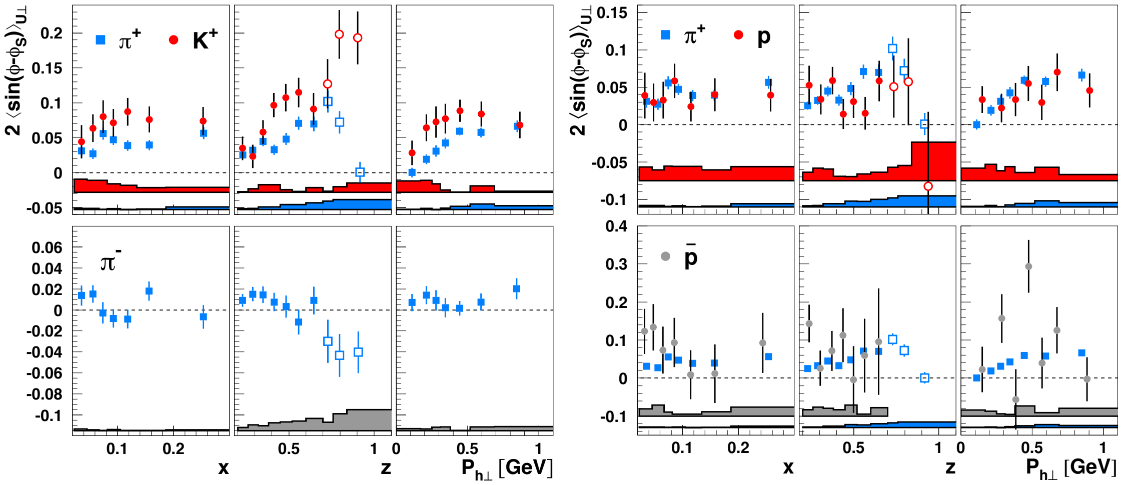

Figure 2: One-dimensional projections in x, z, and $P_{h\perp}$ of the Sivers modulation for charged pions, K^+, protons, and antiprotons (as labelled). The open points in the z projection cover the region of large z that is not included in the other projections.

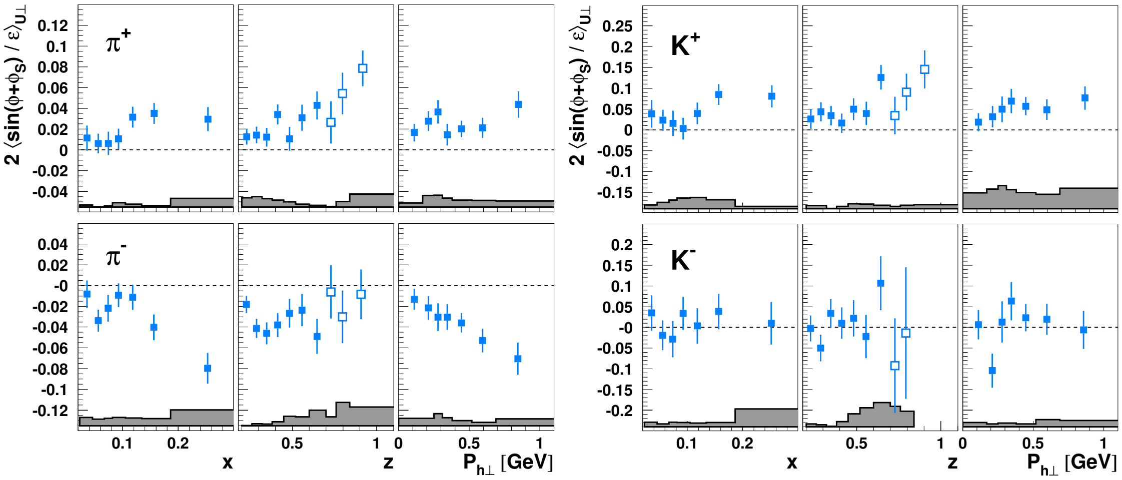

Figure 3: One-dimensional projections in x, z, and $P_{h\perp}$ of the Collins modulation for charged pions and kaons (as labelled). The open points in the z projection cover the region of large z that is not included in the other projections.

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.

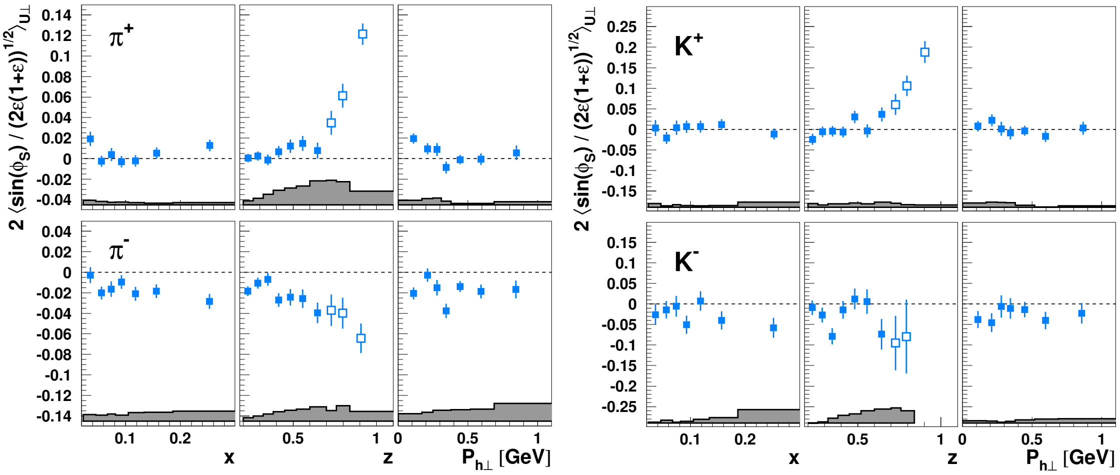

Figure 4: One-dimensional projections in x, z, and $P_{h\perp}$ of the subleading-twist $\sin\phi_S$ modulation for charged pions and kaons (as labelled). The open points in the z projection cover the region of large z that is not included in the other projections.

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