STUDIES OF TMDs AT HERMES

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Single-spin asymmetries measured at the HERMES experiment for pions and charged kaons in semi-inclusive deep-inelastic scattering of electrons and positrons off a transversely polarized hydrogen target, are reported. Two of them reveal clear evidences of non-zero leading-twist parton distribution functions, such as the poorly known transversity and Sivers functions, describing crucial aspects of the dynamics of quarks in a transversely polarized nucleon. Evidences of a non-zero favored and disfavored Collins fragmentation function with opposite sign are also observed.

Keywords: Semi-inclusive DIS; Single-spin asymmetries; Transversity, TMDs.

1. Introduction

For decades, inclusive deep-inelastic scattering (DIS) experiments have crucially contributed to the present knowledge on the internal structure of nucleons. In particular, these experiments have provided precise measurements of two fundamental parton distribution functions (PDFs)[1] : the momentum distribution, $f_1(x)$, and the helicity distribution, $g_1(x)$, where x denotes the longitudinal momentum fraction carried by the partons.

A complete description of the nucleon structure at leading order in an expansion in M/Q (twist expansion) requires, after integrating over the quark transverse momentum $\mathbf{p}_T$, the knowledge of a third fundamental PDF, named transversity, which is presently poorly known. It is denoted as $h_1(x)$ and reflects the difference between the number densities of quarks with spin parallel or antiparallel to the spin of the parent nucleon when the latter is transversely polarized (see Ref. [2] for a review on the subject). Differently from $f_1(x)$ and $g_1(x)$, $h_1(x)$ does not couple with gluons for spin-$\frac{1}{2}$ targets due to helicity conservation. As a consequence, although $g_1(x)$ and $h_1(x)$ might be similar at very low scales[2] , they are expected to have a different QCD evolution, and can thus differ significantly at higher scales. Furthermore, it has been shown[3] that any departure from the identity $h_1(x) = g_1(x)$ is a signature of relativistic effects in the nucleon.

Transversity has long remained unmeasured due to its chiral-odd nature, which prevents its measurement in inclusive deep-inelastic scattering. In order to preserve chirality conservation in hard electromagnetic and strong interactions, the transversity distribution can only be measured in conjunction with another chiral-odd object. One possibility is represented by the semi-inclusive deep-inelastic scattering (SIDIS), in which at least one final state hadron is detected in coincidence with the scattered lepton. In this process the transversity distribution can be probed, e.g., in conjunction with the chiral-odd Collins fragmentation function, $H_1^\perp(z)$, which describes the correlation between the transverse polarization of the quarks and the transverse momentum of the produced hadrons $P_{h\perp}$. Here z denotes the fraction of the original virtual photon energy carried by the produced hadron. This correlation, commonly denoted as the Collins effect, produces left-right asymmetries in the direction of the final-state hadrons.

Besides allowing to access transversity, semi-inclusive DIS experiments also opened the way to the extraction of a variety of new PDFs which arise when the transverse momentum $\mathbf{p}_T$ of the quarks is not integrated out. These poorly known PDFs, typically denoted as transverse-momentum-dependent (TMD) PDFs, are increasingly gaining theoretical and experimental interest. Describing correlations between the quark or the nucleon polarization and the quark transverse momentum $\mathbf{p}_T$, i.e. spin-orbit correlations, the TMD distribution functions encode information on the 3-dimensional structure of nucleons. At leading-twist, eight TMD distribution functions, each describing a peculiar aspect of the nucleon structure, enter the SIDIS cross section in conjunction with a fragmentation function[4,5] . When the polarization of the final hadrons is not detected, this can be either the Collins function $H_1^\perp(z)$ or the relatively well known spin-independent fragmentation function $D_1(z)$. Among these PDFs, particularly interesting is the Sivers function[6] , denoted as $f_{1T}^\perp(x)$. It describes the correlation between the transverse momentum $\mathbf{p}_T$ of the quarks and the transverse spin of the parent nucleon, also known as the Sivers effect. Similarly to the Collins effect, the Sivers effect causes left-right (azimuthal) asymmetries in the direction of the final-state hadrons. The Sivers function is naïve T-odd, i.e. odd under a special (naïve) time-reversal operator that does not interchange initial and final states. The interest on this TMD distribution function suddenly increased after it was demonstrated[7] that non-vanishing orbital angular momentum of quarks, the main still unmeasured contribution the nucleon spin, is needed for a non-vanishing Sivers effect, although no direct simple relations can be established between the two, yet.

The lepton-hadron SIDIS cross section can be written as a superposition of spin-averaged and spin-dependent terms with various polarization states of target and beam[4,5] . Each of these terms is modulated by a specific combination of the azimuthal angle of the target polarization, ϕ_S, and of the produced hadron, ϕ, both referred to the lepton scattering plane. In the present work, a selection of Fourier amplitudes $2\langle\sin(m\phi \pm n\phi_S)\rangle^h_{\mathrm{UT}}$, related to some of these terms, are presented for various hadron types h. Here m and n are integers, and the subscript UT denotes unpolarized beam and transversely polarized target. These Fourier amplitudes were extracted through a maximum-likelihood fit of the SIDIS events, alternately binned in x, z and $P_{h\perp}$, but unbinned in ϕ and ϕ_S.

2. The Collins and Sivers amplitudes

Preliminary HERMES results for the Collins amplitudes for pions are shown in Fig. 1 as a function of x, z, or $P_{h\perp}$ (see Ref. [8] for the final results). They are positive for π^+ and negative for π^-. The amplitudes of π^+ and π^- are observed to increase in magnitude with x. This is consistent with the expectation that transversity mainly receives contributions from the valence quarks. A large contribution from the sea quarks, which would dominate in the low-x region, is indeed not expected due to the fact that transversity can not be generated in gluon splitting in a proton target. A possible explanation for the π^- amplitude, observed to be of opposite sign to that of π^+ and of similar magnitude, can be the dominance of the u-quark flavour among struck quarks in conjunction with a substantial magnitude with opposite sign of the unfavored Collins fragmentation function, describing, *e.g.* the fragmentation of u quarks into π^- mesons: $H_{1,\mathrm{unfav}}^{\perp,u\rightarrow\pi^-} \approx -H_{1,\mathrm{fav}}^{\perp,u\rightarrow\pi^+}$. This observation is supported by the BELLE results[9] and by the combined fits reported in Refs. [10,11]. The Collins amplitudes for charged kaons are also shown in Fig. 1. Due to the common u-quark dominance, *i.e.* the dominant contribution to π^+ and K^+ production from scattering off u-quarks, one would naïvely expect similar amplitudes for these two mesons. The observed differences can be ascribed, for instance, to the the different Collins fragmentation functions involved. On the other hand, the amplitudes for π^- and K^-, which also exhibit a very different behavior, are not expected to be similar not only because of the different fragmentation functions involved, but also because, in contrast to π^-, a K^- has no valence quarks in common with the target proton.

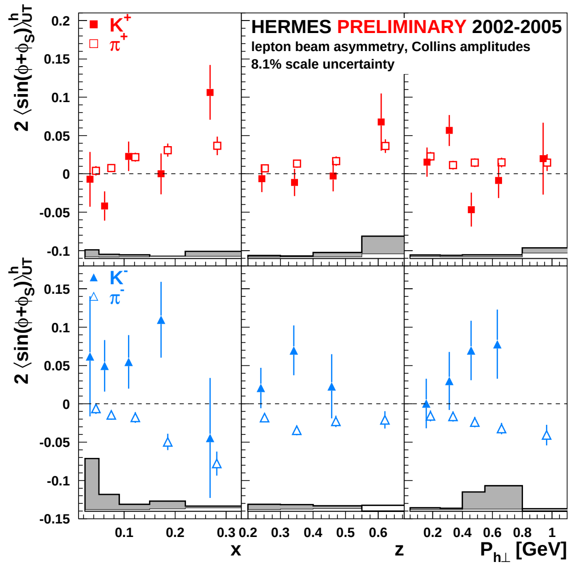

Fig. 1. Collins amplitudes for charged pions (open dots) and charged kaons (full dots) as a function of x, z, or $P_{h\perp}$. A 7.3% scale uncertainty, not shown, arises from the accuracy in the measurement of the target polarization.

The HERMES results for the Sivers amplitudes[12] , are shown for pions and charged kaons in Fig. 2 as a function of x, z, or $P_{h\perp}$. They are positive for all hadrons except for π^-, for which they are consistent with zero, and in general are found to increase with increasing z. In the cases of π^+ and K^+, the amplitudes show a saturation for $P_{h\perp} \geq 0.4$ GeV and are consistent with the predicted linear decrease in the limit of $P_{h\perp}$ going to zero. Despite the expectation of similar magnitudes for the π^+ and K^+ amplitudes, based on the common u-quark dominance, the amplitudes for K^+ are found to be significantly larger than those for π^+. This difference may be due to a significant role of other quark flavors, e.g. the sea quarks, in conjunction with possible higher-twist contributions in kaon production. Assuming that scattering from u-quarks is the dominant process, the positive Sivers amplitudes for π^+ and $K^\pm$ are compatible with a large negative Sivers function for u-quarks. The vanishing amplitudes for π^- then require cancellation effects, e.g. from a d-quark Sivers function opposite in sign to the u-quark Sivers function: $f_{1T}^{\perp,u}(x) \approx -f_{1T}^{\perp,d}(x)$. This hypothesis is in agreement with previous extractions[13–15] of the Sivers function based on earlier HERMES data and with QCD predictions in the large-N_c limit.[16,17]

It is also supported by the vanishing COMPASS Sivers amplitudes measured on a deuteron target[18] .

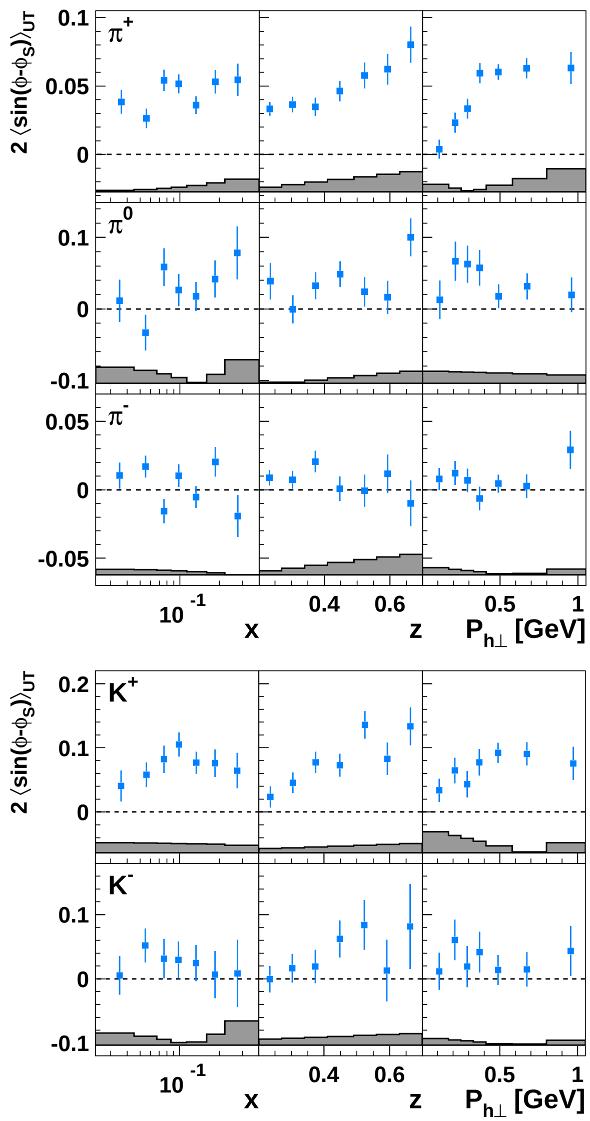

Fig. 2. Sivers amplitudes for pions (upper plot) and charged kaons (lower plot) as a function of x, z, or $P_{h\perp}$. A 7.3% scale uncertainty, not shown, arises from the accuracy in the measurement of the target polarization.

3. The other sine asymmetry amplitudes

The Collins and Sivers amplitudes were extracted together with other four sine azimuthal asymmetries, related to other terms of the SIDIS cross section. These Fourier amplitudes are all consistent with zero for all hadron types, with the only exception of subleading-twist $2\langle\sin(\phi_S)\rangle^h_{UT}$ amplitude, which exhibits a large negative signal for π^-, similar to the corresponding Collins amplitude. Preliminary HERMES results for this Fourier component and for the leading twist $2\langle\sin(3\phi-\phi_S)\rangle^h_{UT}$ amplitude, are shown in Fig. 3 and Fig. 4, respectively. In particular, the latter is related to the chiral-odd $h^{\perp}_{1T}$ TMD distribution function, also known as *pretzelosity*, describing the correlation between the quark transverse momentum $\mathbf{p}_T$ and the transverse polarization of the quarks in a transversely polarized nucleon[19] . This function has recently been linked to a measure of the deviation of the nucleon shape from a sphere[20] .

4. Conclusions

The data collected by the HERMES experiment with a transversely polarized hydrogen target was analysed to extract several azimuthal asymmetry amplitudes. These amplitudes can be interpreted in the framework of the parton model in terms of parton distribution functions and fragmentation functions. Among them are the non-vanishing Collins and Sivers amplitudes, carrying precious information on two leading-twist parton distribution functions: the transversity distribution and the Sivers function, respectively. Significant positive (negative) Collins amplitudes were measured for π^+ (π^-), indicating that both the transversity and the Collins function are non-zero. Significantly positive Sivers amplitudes were observed for both positive pions and kaons. This result clearly indicates that the Sivers function is non-zero and, indirectly, that also the yet unmeasured quark orbital angular momentum is non-zero. In particular, the Sivers amplitude for K^+ was found to be significantly larger than that for π^+, suggesting, e.g., a significant Sivers function for the sea quarks. The additional azimuthal asymmetries, extracted together with the Collins and Sivers amplitudes, are all consistent with zero, with the only exception of $2\langle\sin(\phi_S)\rangle^h_{UT}$, which exhibits a large negative amplitude for π^-, similar to the Collins one. Future plans at HERMES include the extraction of the $2\langle\cos(\mathrm{m}\phi\pm\mathrm{n}\phi_\mathrm{S})\rangle^\mathrm{h}_\mathrm{LT}$ Fourier amplitudes, related to the *worm-gear* $g^{\perp}_{1T}$ TMD distribution function, and of several yet unmeasured dihadron structures of the SIDIS cross seciton.

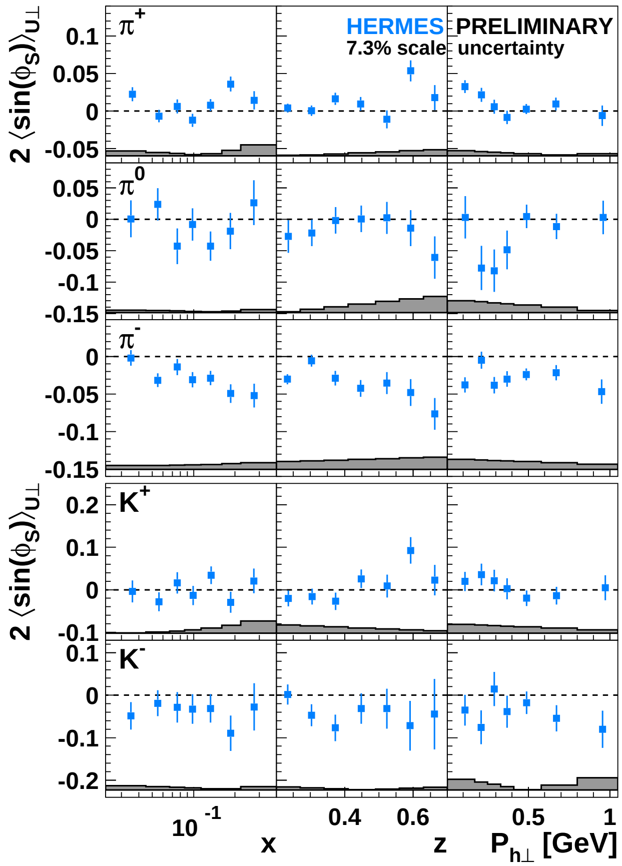

Fig. 3. $2\langle\sin(\phi_S)\rangle_{UT}^h$ amplitudes for pions and charged kaons as a function of x, z, or $P_{h\perp}$. A 7.3% scale uncertainty, not shown, arises from the accuracy in the measurement of the target polarization.

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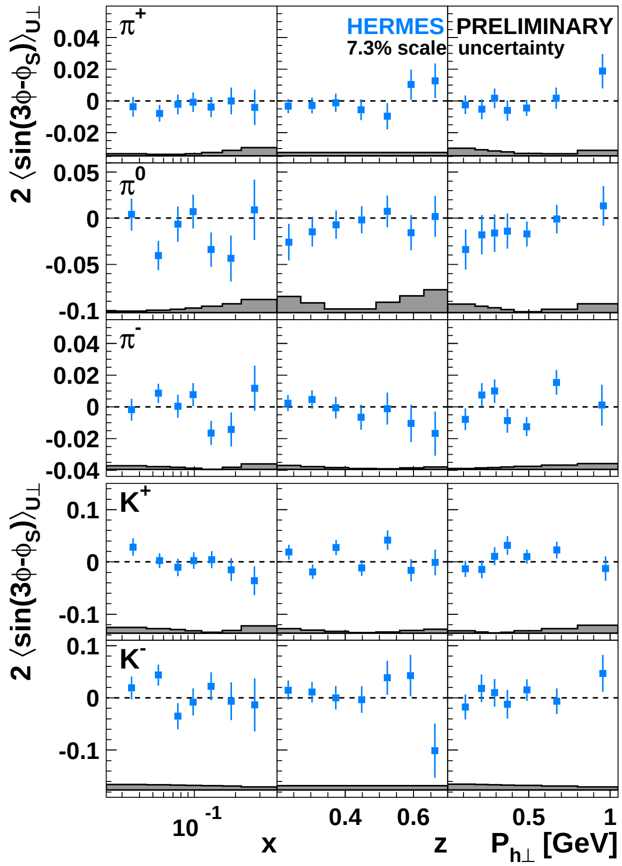

Fig. 4. $2\langle\sin(3\phi - \phi_S)\rangle^h_{UT}$ amplitudes for pions and charged kaons as a function of x, z, or $P_{h\perp}$. A 7.3% scale uncertainty, not shown, arises from the accuracy in the measurement of the target polarization.

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