Studies of Partonic Transverse Momentum and Spin Structure of the Nucleon at HERMES

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Abstract. The investigation of the partonic degrees of freedom beyond collinear approximation (3D description) has been gained increasing interest in the last decade. At the HERMES experiment, azimuthal single-spin asymmetries of pions and charged kaons produced in semi-inclusive deep-inelastic scattering of electrons and positrons off a transversely (polarized) hydrogen and deuterium target have been measured. Such asymmetries provide new insights on crucial aspects of the parton dynamics. By measuring various hadron types in the initial and final states, flavor sensitivity is achieved. Evidence is reported of the poorly known transversity function and of naive-T-odd transverse-momentum-dependent parton distribution functions related to spin-orbit effects. Evidence of spin-orbit effects in quark fragmentation is also observed, which are opposite in sign for favored and disfavored processes.

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INTRODUCTION

A complete collinear description of the nucleon structure at leading order in an expansion in M/Q (twist expansion), where Q is the photon virtuality and M the nucleon mass, requires the knowledge of three fundamental parton distributions (PDFs): the momentum distribution $f_1(x)$, the helicity distribution $g_1(x)$, and the presently poorly known transversity distribution $h_1(x)$. Here x denotes the longitudinal momentum fraction carried by the partons. The transversity distribution reflects the quark transverse polarization in a transversely polarized nucleon (see Ref. [1] for a review on the subject). Its difference from the quark helicity distribution is a signature of relativistic effects in the nucleon [2]. Differently from $f_1(x)$ and $g_1(x)$, $h_1(x)$ does not couple with gluons for spin-$1/2$ targets due to helicity conservation and thus undergoes peculiar QCD evolution. Transversity has long remained unmeasured due to its chiral-odd nature, which prevents its measurement in inclusive deep-inelastic scattering: 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.

Besides allowing to access transversity, SIDIS experiments open the way to the extraction of transverse-momentum-dependent (TMD) PDFs, which are increasingly gaining theoretical and experimental interest. Describing correlations between the quark or the nucleon polarization and the quark transverse momentum, i.e. spin-orbit correlations, the TMD distribution functions encode information on the 3-dimensional structure of nucleons.

When the hadron transverse momentum $P_{h\perp}$ is not integrated out, the SIDIS cross-section depends on several structure functions [3]. In the limit of $P_{h\perp}$ much smaller than the hard scale Q, the structure functions can be interpreted in terms of convolutions involving TMD parton distribution and fragmentation functions (FFs). At leading order in twist-expansion (twist-2) and neglecting the polarization of the final state hadron, there are eight non-vanishing structure functions, related to the eight twist-2 parton distributions and two twist-2 fragmentation functions. The three PDFs surviving transverse-momentum integration were introduced above. Each TMD brings an independent piece of information on the parton dynamic. They can be all access in SIDIS since associated with specific azimuthal angle dependences of the cross-section, namely the dependence on combinations 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 related to some of these terms are presented for various hadron types h. These Fourier amplitudes were extracted through a maximum-likelihood fit of the SIDIS events, alternately binned in x, (y), z and $P_{h\perp}$, but unbinned in ϕ and ϕ_S.

TRANSVERSITY AND COLLINS FUNCTIONS

In SIDIS process the transversity distribution $h_1(x)$ can be probed in conjunction with the chiral-odd Collins FF $H_1^{\perp}(z)$, which describes the correlation between the transverse polarization of the quarks and the transverse momentum of the produced hadrons $P_{h\perp}$ [4]. Here z denotes the fraction of the virtual photon energy carried by the produced hadron. The related signal is a $\sin(\phi+\phi_\mathrm{S})_\mathrm{UT}$ azimuthal modulation of the SIDIS cross-section for unpolarized beam and transversely polarized target. The HERMES Collaboration published the first evidence of not-zero transversity and Collins functions in 2005 [5]. The final results based on the full statistics collected on proton target [6] are shown in Fig. 1. The signal for charged pions is different from zero and increasing with x, as expected for spin-1/2 target where transversity does not couple with gluons. 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 flavor among struck quarks in conjunction with opposite signs of the favored ($u \to \pi^+$) and unfavored ($u \to \pi^-$) Collins fragmentation functions. This observation is supported by the BELLE [7] and COMPASS [8] results and by the combined fits reported in Refs. [9]. The neutral pion signal is consistent with isospin symmetry. The Collins amplitudes for charged kaons are also shown in Fig. 1. Positive kaons have a signal larger than positive pions, whereas the negative kaons have a signal consistent with zero. The observed differences with respect pion signals can be ascribed, for instance, to the different Collins fragmentation functions involved and, in general, indicates a flavor dependence due to the different valence flavor content of the two mesons.

SIVERS FUNCTION

The Sivers function $f_{1T}^{\perp}(x)$ describes the correlation between the transverse momentum of the quarks and the transverse spin of the parent nucleon [10]. In conjunction with the

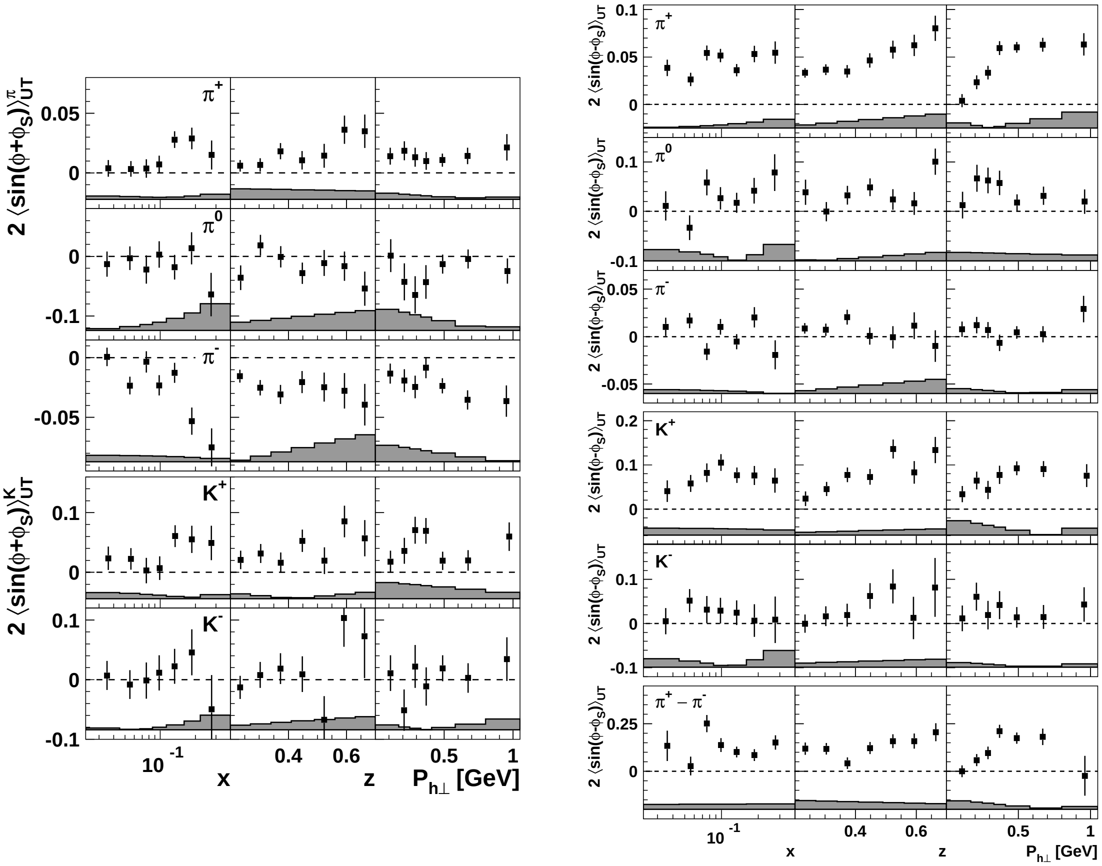

FIGURE 1. Collins $2\langle sin(\phi+\phi_S)\rangle^h_{UT}$ (left) and Sivers $2\langle sin(\phi-\phi_S)\rangle^h_{UT}$ (right) amplitudes for identified hadron h and scattering on a proton target as a function of x, z, or $P_{h\perp}$. A 7.3% scale uncertainty, not shown, arises from the accuracy in the measurement of the target polarization.

known unpolarized FFs $\mathrm{D}_1(\mathrm{x})$, it generates a $\sin(\phi-\phi_\mathrm{S})_\mathrm{UT}$ azimuthal modulations of the SIDIS cross-section. The interest on this TMD distribution function suddenly increased after it was demonstrated that non-vanishing orbital angular momentum of quarks is needed for a non-vanishing Sivers effect, although no model independent relation could be established between the two yet. The Sivers function is naively T-odd, i.e. odd under a special naive time-reversal operator that does not interchange initial and final states. This reflects in peculiar universality properties. A sign change between SIDIS and Drell-Yan reactions is predicted on the basis of basic principles of QCD, like color flow and gauge invariance. A major experimental effort is ongoing to validate such a prediction and, as a consequence, the general TMD theoretical framework. Following the first evidence for a non-zero Sivers function published in 2005 [5], the HERMES final results for the Sivers amplitudes on proton target [11] are shown for pions and charged kaons in Fig. 1. 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 and are consistent with the predicted linear decrease in the limit of $P_{h\perp}$ going to zero. The amplitudes for K^+ are found to be significantly larger than those for π^+. This difference may be due to a non-negligible role of the sea quark flavors. Assuming that scattering from u-quarks is the dominant process, the positive Sivers amplitudes for π^+ and K^+ 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. This hypothesis is in agreement with phenomenological analyses [12] of the Sivers function based on HERMES data. It is also supported by the COMPASS measurements of a vanishing amplitude on a deuteron target [13] and of a non-zero amplitude for positive hadrons on a proton target [8].

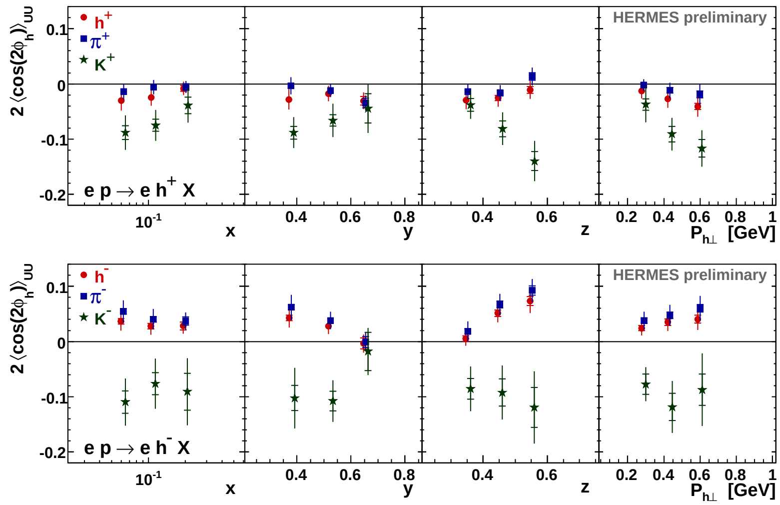

FIGURE 2. The $2\langle cos(2\phi)\rangle^h_{UU}$ amplitudes for identified hadron h and scattering on a proton target as a function of x, y, z, or $P_{h\perp}$.

BOER-MULDERS FUNCTION

The naive-T-odd Boer-Mulders function originates from the coupling of the quark intrinsic transverse momentum and intrinsic transverse spin, a kind of spin-orbit effect [14]. It is chirally-odd, and in conjunction with Collins FFs $H_1^\perp(z)$ generates cosine azimuthal modulations in unpolarized SIDIS reactions. When integrating over some kinematical variable, i.e. in one-dimensional analysis, the unpolarized cosine moments fold with a number of experimental sources of azimuthal modulations, e.g. detector geometrical acceptance and higher-order QED effects (radiative effects). Therefore a 4-D (in x, y, z and $P_{h\perp}$ simultaneously) unfolding procedure was used to correct the extracted moment and obtain fully-differential results in all the relevant kinematical variables at once. To date, the HERMES analysis represents the most complete data set on the subject, and allows access to flavor dependent information on the nucleon internal transverse degrees of freedom. Identified-hadron moments projected in the relevant kinematic variables are shown in Fig. 2 for scattering on a proton target. The moments show opposite sign for positive and negative pions. This clear charge dependence is taken as an indication of a non-zero Boer-Mulders effect [15], being on top of the non-negligible contribution of pure kinematical origin expected at subleading twist (twist-4). The kaon modulations are found to be larger in magnitude than pions ones and negative for both kaon charges. This peculiar behaviour resembles the one already discussed in relation to Collins FFs coupled to transversity and likely reflects the different flavor content of the produced meson. In general the hadrons have a similar trend as the pions but are shifted to lower values than the pions, consistently with the observed kaon moments. The cosine modulations have been extracted also for data collected with deuterium target, and they are found to be compatible with hydrogen results for all hadron types. This suggests that similar contributions arise from up and down quarks to the cosine modulations.

CONCLUSIONS

HERMES is a precursor experiment in the study of the partonic transverse degrees of freedom in the nucleon. The polarized gaseous target internal the HERA beam line has no dilution of polarization (only pure polarizable material) and is free from unwanted nuclear effects (no rescattering). Flavor sensitivity is achieved thanks to different targets (Hydrogen and Deuterium) and to hadron identification in the final state. HERMES published the first evidence for a non-zero transversity distribution, the missing leading-twist quark distribution function required for a complete collinear description of the quark nucleon structure. It published the first evidence for non-zero transverse spin and momentum correlations in quark fragmentation (Collins function) and distribution (Sivers function). A full-differential analysis was applied for the first time to the azimuthal modulations of the unpolarized SIDIS cross-section, and the preliminary results support the presence of a non-zero Boer-Mulders spin-orbit effect.

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