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OVERVIEW OF RECENT RESULTS FROM THE HERMES EXPERIMENT

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HERMES has taken a wealth of deep-inelastic scattering (DIS) data using the 27.6 GeV polarized lepton beam at HERA and various pure gas targets, both unpolarized and polarized, which opened the door to several unique results. Among them are the first evidences for the naive-T-odd Sivers and Collins effects as well as the recent first measurements of azimuthal modulations in the unpolarized semi-inclusive DIS cross section for charged kaons and pions and of beam-helicity asymmetries in exclusive leptoproduction of real photons using recoil-proton detection. An overview of HERMES results is given with emphasis on the exploration of the three-dimensional structure of the nucleon.

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INTRODUCTION

Finding the fundamental and basic constituents of matter has driven humans curiosity for a long time. With the establishment of quantum chromodynamics (QCD) it appeared that physicists were close to understanding what the visible Universe is all about. However, in the late 1980s they were proven wrong when the naive picture of the spin structure of the nucleon fell apart: not the spin of the quarks is responsible for the spin of the proton — they only carry about 1/3 of the proton spin — their orbital angular momentum and also the role of the gluons had to be investigated.

This discovery drove the initiation of several new experiments, among others the HERMES experiment at HERA. Two decades ago it got approved and since then has continued to provide new insights into the structure of the proton. By now it is the only experiment which has published both the spin-independent and also the spin-dependent DIS structure functions F_2, g_1, and g_2 [1–3]. In addition, it was the first one to also measure the tensor structure function b_1 of the deuteron [4] and the possible contribution of two-photon exchange to inclusive DIS from a transversely polarized proton [5] (which was found to be consistent with zero at a level of 10^{-3}).

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In the past decade, the focus moved towards multidimensional images of the proton. New classes of parton distributions became available from the theoretical side: transverse-momentum-dependent distributions (TMDs) and generalized parton distributions (GPDs). Those provide three-dimensional pictures in momentum space and in mixed momentum and transverse position space, respectively. They also required novel techniques. HERMES with its versatile pure gas target, which could run with a series of unpolarized gases and — more importantly — with longitudinally or transversely polarized nucleons, its excellent particle identification with very clean lepton/hadron separation and hadron identification in the momentum range of 2–16 GeV using a dual-radiator ring-imaging Cherenkov counter, and its large acceptance allowed dedicated studies of TMDs, using semi-inclusive DIS, and GPDs, using exclusive reactions. The latter got another boost with the installation of a recoil detector.

1. SEMI-INCLUSIVE DIS

In the collinear parton model, i.e., integrated over transverse momentum of partons in the (fast moving) nucleon, only three parton distributions are required to describe the nucleon structure on twist-2 level: the unpolarized distribution $f_1(x)$*, where x is the longitudinal momentum fraction of the proton carried by the parton, the helicity distribution $g_1(x)$, and the transversity distribution $h_1(x)$. These distributions miss an important aspect of a system of confined partons: the parton's transverse motion in many cases cannot be neglected, and can be correlated with the spin of the partons. This rich structure is parameterized by eight TMDs, of which three yield the above «collinear distributions» upon integration over transverse momentum. Three of the remaining TMDs are chiral-odd, involving transverse quark polarization, among them — the nobel Boer–Mulders (BM) distribution. It describes the distribution of transversely polarized quarks in unpolarized nucleons and thus gives raise to spin effects in collision of unpolarized hadrons. Another rather peculiar TMD is the Sivers function, which correlates the transverse momentum of unpolarized quarks with the transverse spin of the parent hadron. It is strongly linked to orbital angular momentum and to various single-spin asymmetries observed in lepton–nucleon and nucleon–nucleon reactions. Both the BM and Sivers functions are naive-T-odd and thus reverse sign when measured in the Drell–Yan process compared to DIS.

HERMES has been the first to measure a clear signal of the Sivers function using transversely polarized protons [6]. The corresponding Fourier amplitudes

*The dependence on the 4-momentum transfer Q^2, which is only weak, is omitted here for brevity.

of the single-spin asymmetry were found to be positive for positively charged mesons (π^+ and K^+) while consistent with zero for the negative ones [7]. This can be explained with Sivers up and down quark distributions that are opposite in sign. The large amplitudes for K^+ vs. π^+ hints at a nontrivial role of sea quarks. Using the same data set, the Fourier amplitudes attributed to transversity coupled to the Collins fragmentation function, a spin-dependent fragmentation function that leads to left–right asymmetries in the direction of the outgoing hadron when fragmenting from a transversely polarized quark, were extracted [8]. Those amplitudes were found to be nonzero for both positive and negative pions, but with opposite sign and larger magnitude for π^-. This points at favored Collins fragmentation that has an analyzing power opposite to the one of the unfavored case, but of similar magnitude. Also, the expected picture of transversity valence distributions was confirmed, e.g., positive transversity for up quarks and negative for down quarks.

More recently, the HERMES analyses of TMDs for unpolarized nucleons have become available. A vital ingredient to the interpretation of all the available TMD-related asymmetries is the knowledge of the transverse-momentum behavior of the spin-independent cross section (integrated over azimuthal angles). In Fig. 1, the charged pion and kaon multiplicities, i.e., hadron yields normalized to the inclusive DIS cross section, are presented as a function of the meson's transverse momentum $P_{h\perp}$ in slices of their energy fraction z for scattering from protons and deuterons (only for pions), and as a function of z in comparison to various theoretical curves (for details, see [9]).

The transverse quark-momentum can lead to azimuthal modulations in the hadron distribution about the virtual-photon direction (expressed in cosines of the angle ϕ between the scattering and the hadron production plane (cf. [10]). This spin-independent Cahn effect was predicted some 30 years ago, but has been studied only vaguely in experiments. In actual measurements, the Cahn effect, which is subleading twist, has to compete with modulations induced by the BM TMD. The latter, in combination with the Collins fragmentation function, results at leading twist in a $\cos(2\phi)$ modulation, and at subleading twist in a $\cos\phi$ modulation. The HERMES results [10] on the $\cos\phi$ and the $\cos(2\phi)$ modulations for charged pions and kaons as well as for unidentified hadrons on proton and deuterons have been obtained in a fully differential analysis, where acceptance and smearing due QED radiative corrections have been corrected for in a five-dimensional unfolding procedure. In Fig. 2, the results for the $\cos(2\phi)$ Fourier amplitudes are shown as a function of x, the fractional energy transfer y, z, and $P_{h\perp}$ for the case of a proton target. There is a strong flavor and hadron-charge dependence. When interpreted in terms of the BM distribution, the results are consistent with the picture of a BM distribution that is rather similar (e.g., same sign) for the valence quarks and of a Collins fragmentation function that has opposite signs for favored and disfavored fragmentation

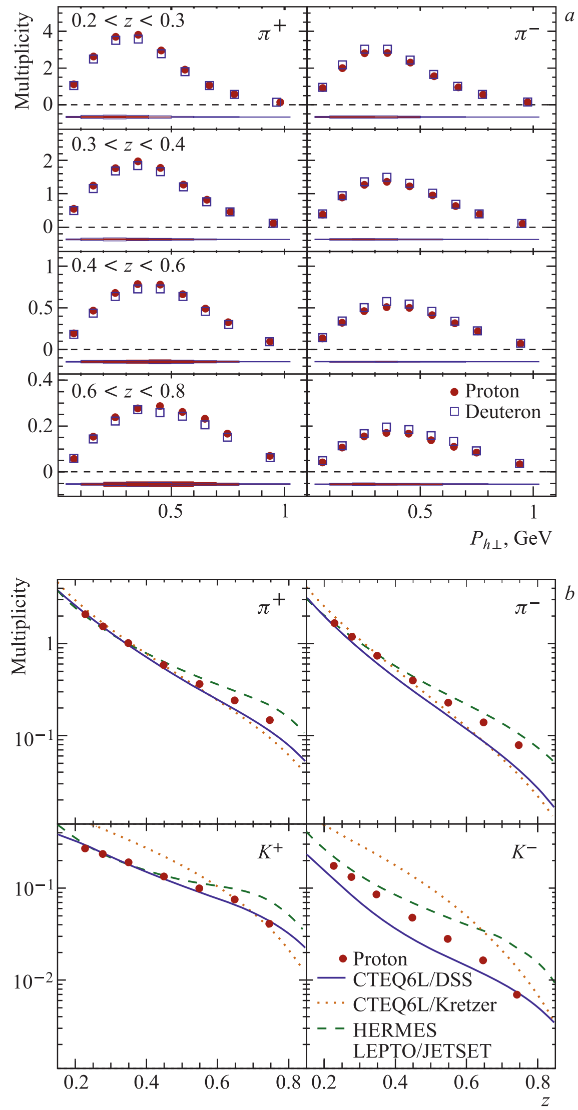

Fig. 1. *a*) Pion multiplicities as a function of transverse momentum in slices of z for both proton and deuteron targets. *b*) Pion and kaon multiplicities from protons and deuterons as a function of z compared to various theoretical predictions. (Figure taken from [9])

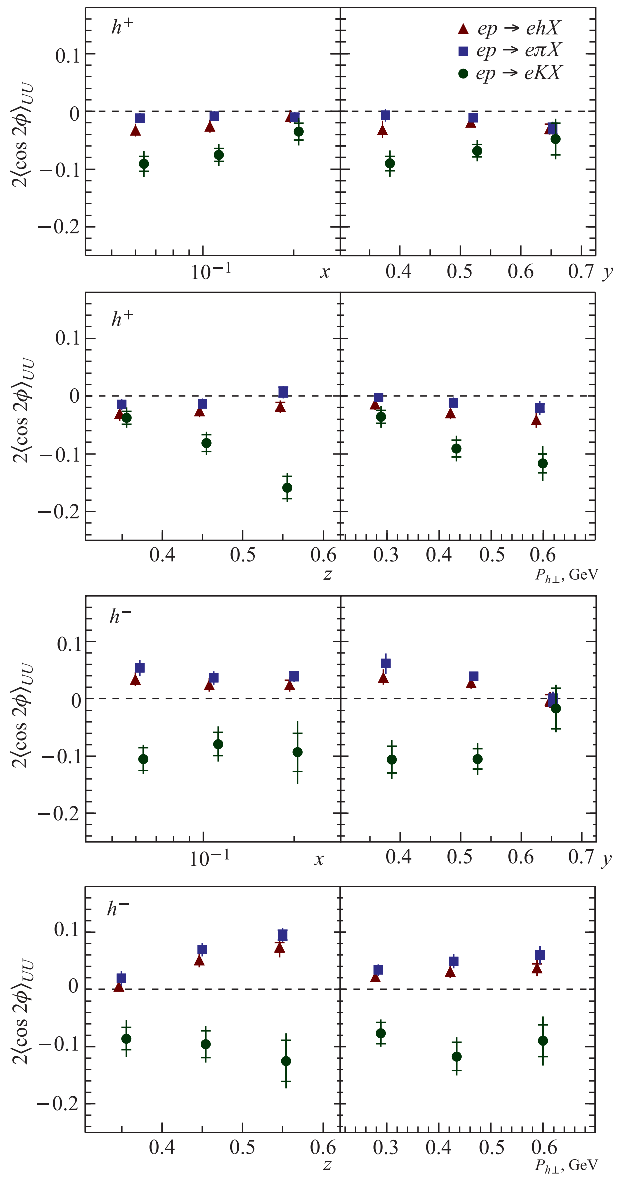

Fig. 2. The $\cos(2\phi)$ Fourier amplitudes in the production from unpolarized protons of charged pions, kaons, as well as unidentified hadrons, shown as a function of x, y, z, and $P_{h\perp}$. (Figure taken from [10])

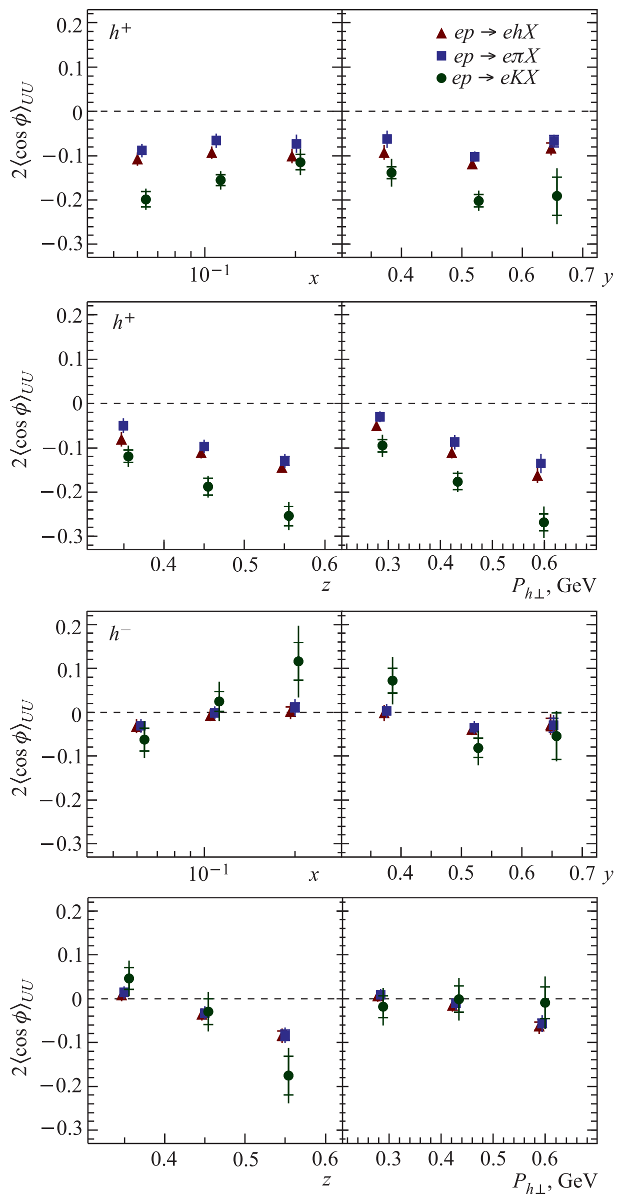

Fig. 3. The same as in Fig. 2, but for the cos ϕ Fourier amplitudes. (Figure taken from [10])

(as already concluded from the Collins amplitude results). The surprising discrepancy between nonstrange and strange mesons again hints at the important role of sea quarks in kaon production. The subleading-twist $\cos\phi$ modulation is shown in Fig. 3, again for charged pions, kaons, and unidentified hadrons, produced from a proton target. Similar to the $\cos(2\phi)$ modulation it exhibits a strong flavor dependence, which may get attributed to the BM contribution. However, this modulation receives several other (unknown) contributions, which hampers a clean interpretation.

2. EXCLUSIVE REACTIONS

The latest since the realization that GPDs, accessible, e.g., in exclusive reactions, can be used to decompose the nucleon spin in terms of the angular momenta of quarks and gluons [11], GPDs have gained in importance in the investigation of the nucleon structure. While it has become clear that in praxis it is rather difficult to use experimental results to determine the terms in that nucleon–spin decomposition, GPDs have not lost their attraction. One reason is the possibility of providing nucleon tomography via the impact-parameter interpretation of GPDs [12].

Experimentally, the cleanest realizable process to constrain GPDs is deeply virtual Compton scattering (DVCS), contributing to the exclusive leptoproduction of real photons. The DVCS amplitude interferes with that of the Bethe–Heitler (BH) process, in which a photon is emitted by the incoming or outgoing lepton and not from the nucleon. At HERMES, the BH process dominates the cross section for exclusive leptoproduction of real photons, however, its interference with DVCS allows the study of DVCS on the amplitude level. The interference leads to several, beam-charge-dependent, azimuthal asymmetries that depend on the polarization state of both the beam and the target. The availability of both lepton charges and beam polarization at HERA in conjunction with a gas target made HERMES an ideal laboratory for DVCS related asymmetries. HERMES provided basically a complete set of asymmetry amplitudes. A summary of those results is presented in Fig. 4, where the overall amplitudes (e.g., integrated over the phase space accepted by the HERMES spectrometer) of the more important asymmetries are shown [13]. The «hydrogen pure» results were obtained tagging the recoiling proton with a dedicated recoil detector, while all others established «exclusivity» by a constraint on the missing mass of the system with only the scattered lepton and the real photon observed.

These studies of exclusive production of real photons are complemented by the analysis of exclusive meson production, not covered here.

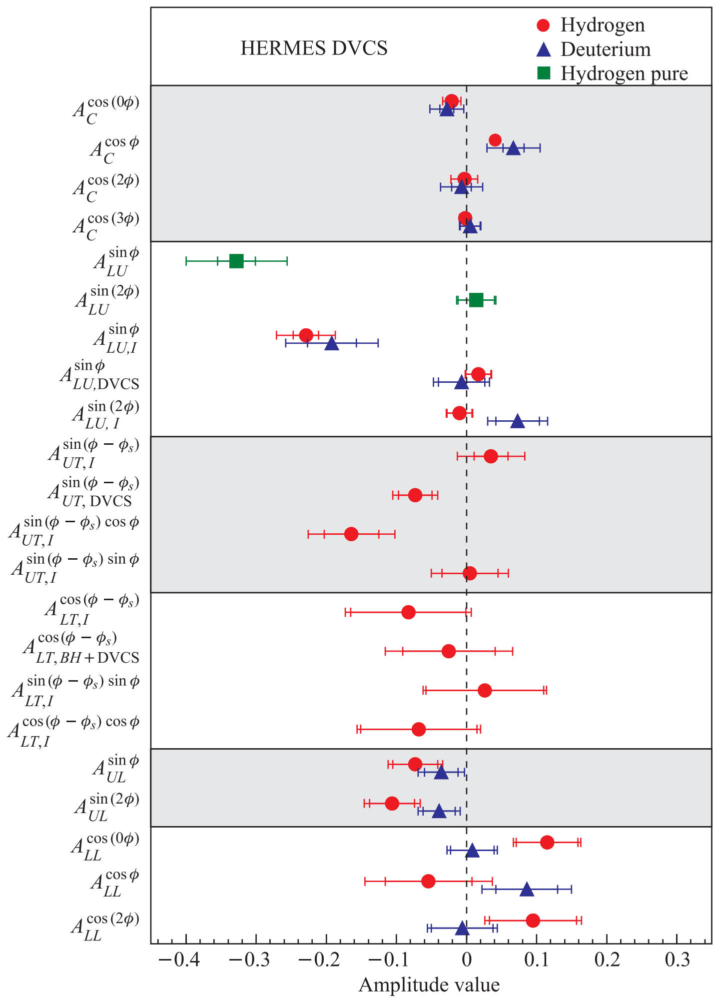

Fig. 4. The Fourier amplitudes of various DVCS related asymmetries in the exclusive lepto-production of real photons from protons (circles and squares) or deuterons (triangles). The upper two panels are mainly sensitive to the GPD H, while the middle two panels — involving transverse target polarization — give sensitivity to the GPD E. The lower two panels are dominated by the GPD $\tilde{H}$

3. SUMMARY

Over the past 20 years, HERMES has provided and is continuing providing a wealth of information on the inner structure of the nucleon. Many of the results have changed our view of the proton, be it the Sivers asymmetries in the field of TMDs or the set of DVCS asymmetry amplitudes in the quest of nucleon tomography.

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