PROCEEDINGS OF SCIENCE

Beam-helicity asymmetries in semi-inclusive deep-inelastic single-hadron production from unpolarized hydrogen and deuterium targets

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A measurement of beam-helicity asymmetries for single-hadron production in deep-inelastic scattering is presented. Data from the scattering of 27.6 GeV electrons and positrons off gaseous hydrogen and deuterium targets were collected by the HERMES experiment. The asymmetries for charged pions and kaons as well as for protons and anti-protons are presented binned in the Bjorken scaling variable, the hadron transverse momentum, and the fractional energy.

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1. Introduction

Semi-inclusive deep-inelastic scattering (DIS) of leptons by nucleons, where hadrons are detected in coincidence with the scattered lepton, probes both the structure of the target nucleon and details of the hadronization process of the struck quark and/or the target remnant. For instance, longitudinal double-spin asymmetries [1] reveal information on the helicity of quarks inside a longitudinally polarized nucleon and hadron multiplicities [2] are crucial for a quark-flavor separation of fragmentation functions (FFs). Single-spin asymmetries in semi-inclusive DIS are sensitive to more intricate details of the strong interaction as they involve interference effects of contributions with different angular momenta. One prominent example is the Sivers asymmetry, basically a left-right asymmetry with respect to the nucleon spin in the distribution of hadrons produced in scattering by a transversely polarized nucleon. It is bound to an explicit transverse-momentum dependence of parton distributions, it vanishes when integrating the hadronic tensor over transverse momenta. While one of the most studied single-spin asymmetries, it is not the only one possible. One of the first ones observed in semi-inclusive DIS is the longitudinal target-spin asymmetry A_{UL} (here and in the following, the first subscript denotes beam and the second target polarization) [3]. Unlike the Sivers asymmetry it is a higher-twist observable. The contributing higher-twist parton distribution functions (PDFs) and FFs have no probabilistic interpretation, albeit some of them can be related to leading-twist versions by Wandzura–Wilczek-type (WW-type) approximations [4]. The single-spin asymmetry presented here [5], the beam-helicity asymmetry A_{LU} in semi-inclusive DIS, is again a higher-twist observable. As such it receives various contributions involving either twist-3 PDFs or FFs, which will be discussed later on. An intriguing facet of this asymmetry is that no WW-type approximation exists for any of the contributing terms and that the asymmetry thus vanishes when systematically ignoring interaction dependent and quark-mass suppressed terms [4].

In the one-photon approximation, the fully differential cross section for producing a hadron h in semi-inclusive DIS of an electron by nucleons is given by [6, 7]

$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x_B\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{x_B y Q^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x_B}\right)\Big\{F_{UU,T}^h + \varepsilon F_{UU,L}^h + \sqrt{2\varepsilon(1+\varepsilon)}\,F_{UU}^{h,\cos\phi}\cos\phi$$
$$+\,\varepsilon\,F_{UU}^{h,\cos 2\phi}\cos 2\phi + \lambda\sqrt{2\varepsilon(1-\varepsilon)}\,F_{LU}^{h,\sin\phi}\sin\phi + \,\dots\Big\}, \tag{1.1}$$

where only terms involving unpolarized nucleons are included. The cross section is differential in the usual DIS Lorentz invariants x_B, y, Q^2, and z as well as in the azimuthal angle ϕ of the hadron transverse-momentum vector $P_{h\perp}$ around the virtual-photon direction as given by the *Trento Conventions* [8]. The beam helicity in the lepton-nucleon center of mass is given by λ. Furthermore, the "photon polarization parameter" $\varepsilon = \frac{1-y-\frac{1}{4}\gamma^2 y^2}{1-y+\frac{1}{4}y^2(\gamma^2+2)}$ is the ratio of longitudinal-to-transverse photon flux, where $\gamma = Q/\nu$, with ν the photon energy in the target rest frame, and α is the fine-structure constant. The various $F_{XY,Z}^{h,\mathrm{mod}}$ represent structure functions whose subscripts denote the polarization of the beam, of the target (with respect to the virtual-photon direction), and—if applicable—of the virtual photon. The superscript indicates the dependence on the hadron type and the azimuthal modulation parametrized. Each of these structure functions is a function of x_B, Q^2, z, and $P_{h\perp}$ and embody information about the three-dimensional nucleon structure and the hadronization of the struck quark into hadron h. The structure function of interest here, the beam-

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helicity dependent sine modulation $F_{LU}^{h,\sin\phi}(x_B, Q^2, z, P_{h\perp})$, can be expressed in the limit of small hadron transverse momentum ($P_{h\perp} \ll zQ$) in terms of four different subleading-twist combinations of parton distribution and fragmentation function [7]:

- The twist-3 PDF e^q [9] and the twist-2 naive-T-odd Collins FF [10]: The Collins FF serves here as the chiral-odd partner of the chiral-odd e^q and leads to the explicit dependence on transverse momentum. The twist-3 e^q itself survives integration over transverse momentum and could thus be probed in the related dihadron beam-helicity asymmetry [11]. The interest in e^q arises partially due to its connection to the πN sigma term [12, 13, 14].

- The leading-twist f_1^q coupled to the twist-3 chiral-even FF $\tilde{G}^{\perp}$ [15]: While the f_1^q quark distribution is well measured (at least is collinear version), little is known about $\tilde{G}^{\perp}$. The tilde identifies it as an interaction-dependent function, thus vanishing in WW-type approximations. Based on an estimate using the spectator model, this contribution was found to be non-negligible [16].

- The twist-3 PDF $g^{\perp}$ [15] and the ordinary twist-2 D_1 FF: The naive-T-odd $g^{\perp}$ function turns out to be a pure twist-3 function, which vanishes in the WW-type approximation. As it is coupled to the ordinary FF, it can contribute also to semi-inclusive lepto-production of jets where formally one sums over all hadrons and integrates over their kinematics. It thus can be isolated in the corresponding beam-helicity asymmetries of semi-inclusive single-jet production [7], where it is the only term contributing.

- The Boer–Mulders PDF [17] coupled to the twist-3 FF $\tilde{E}$ [18]: The naive-T-odd and chiral-odd Boer–Mulders could be measured in this observable, complementary to the case of the leading-twist cosine modulation $F_{UU}^{h,\cos 2\phi}$ [19], where it is coupled to the leading-twist Collins FF. However, its extraction from $F_{LU}^{h,\sin\phi}$ is hampered by the multitude of contributions. In addition, little is known about the interaction-dependent chiral-odd $\tilde{E}$, which originates from quark-gluon-quark interactions (again vanishing in the WW-type approximation). Originally, it had been foreseen as a probe of the transversity distribution [18].

2. Measurement of beam-helicity asymmetries

Ideally, the structure function of interest is extracted directly from measurements of the semi-inclusive cross section. Experimentally, measurements of spin asymmetries are preferred due to cancellations of various experimental effects. The beam-helicity asymmetries presented here [5] are extracted using the HERMES data set taken between the years 1996 and 2007. 27.6 GeV longitudinally polarized electrons and positrons scattered off pure hydrogen and deuterium gas targets. The helicity of the lepton beam was reversed roughly every two months, with an average beam polarization of 34% to 53% in magnitude.

The beam-helicity asymmetry $A_{LU}^{\sin(\phi)}$ is extracted by minimizing the function

$$-\ln \mathbb{L} = -\sum_i w_i \ln \left[1 + P_{B,i}\sqrt{2\varepsilon_i(1-\varepsilon_i)}\,A_{LU}^{\sin(\phi)}\,\sin(\phi_i)\right], \tag{2.1}$$

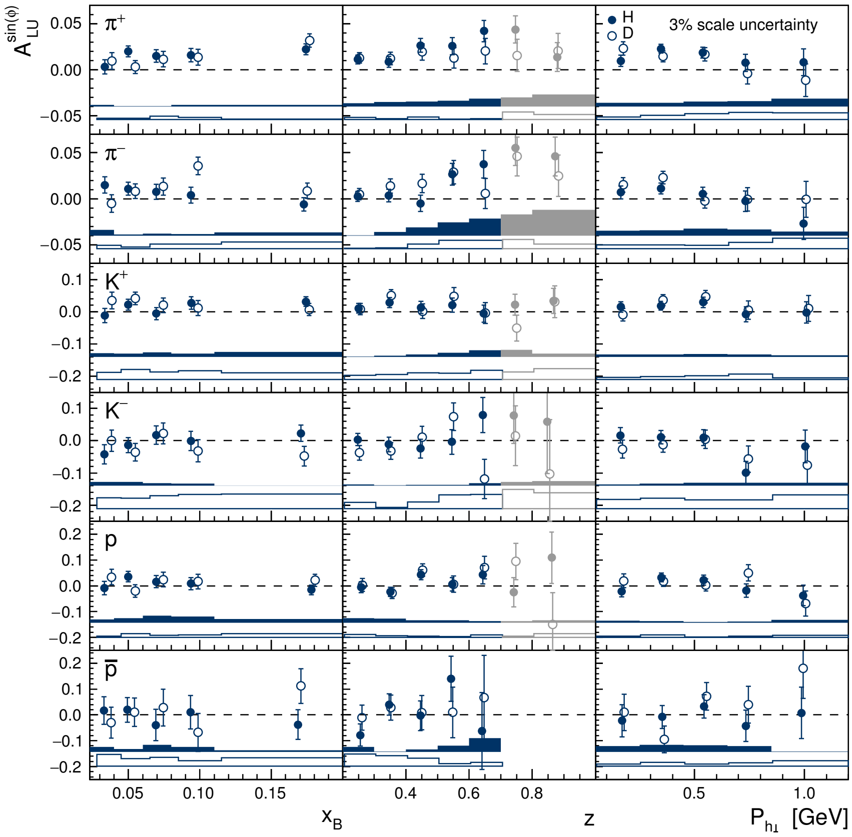

Figure 1: Beam-helicity asymmetries for $\pi^{\pm}$, $K^{\pm}$, protons, and anti-protons, as a function of x_B, z, and $P_{h\perp}$, for data collected on a hydrogen (closed symbols) and deuterium (open symbols) target. Error bars (bands) represent statistical (systematic) uncertainties. An additional systematic scale uncertainty of 3% originates from the measurement of the beam polarization. Grey data points represent the region for which $z > 0.7$, not included in the data used for the x_B and $P_{h\perp}$ projections.

where the sum runs over all the semi-inclusive DIS events. The weight w_i encodes a correction for erroneously identified DIS events, by subtracting events for which the leading lepton is oppositely charged with respect to the beam lepton. Moreover, the weight w_i assigns a probability for each identified hadron in an event to be a pion, a kaon, or a proton [19].

The beam-helicity asymmetries for charged pions and kaons as well as (anti)protons are presented in Fig. 1 as a function of x_B, z, and $P_{h\perp}$. They are positive for pions, increasing in size with z and also slightly increasing as a function of x_B (the latter is less pronounced for π^-). An increase of the asymmetry as a function of $P_{h\perp}$ for low values of $P_{h\perp}$, followed by a decrease at higher $P_{h\perp}$ values is hinted by the data. A positive asymmetry is also seen for K^+, but without any pronounced kinematic dependence. For negative kaons, protons, and anti-protons the asymmetries are compatible with zero. No significant difference between data from hydrogen and deuterium targets is seen.

Similar asymmetries were measured by CLAS [20]. The HERMES hydrogen data for charged pions are compared to those in Fig. 2, where the asymmetry $A_{LU}^{Q,\sin(\phi)}$ is plotted. The latter is

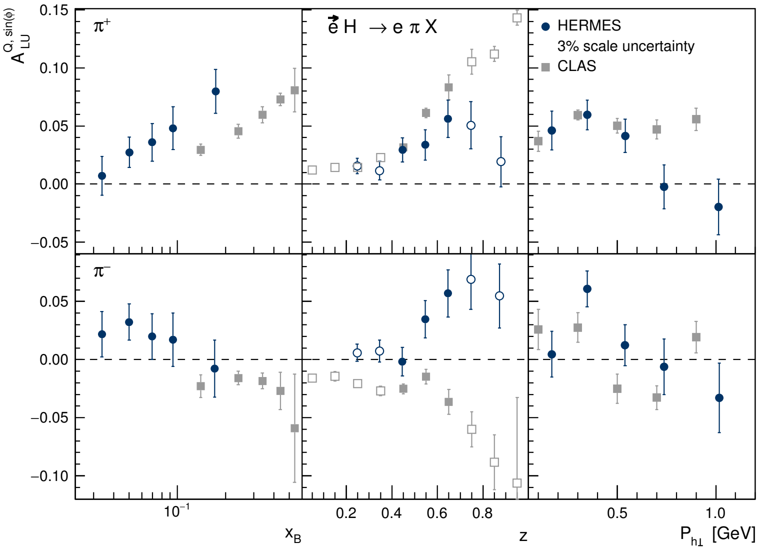

Figure 2: Scaled beam-helicity asymmetries for $\pi^{\pm}$ measured by HERMES (blue circles) and CLAS (grey squares) [20] on a hydrogen target, as a function of x_B, z, and $P_{h\perp}$. The data corresponding to the intervals in z indicated by the open symbols are not included in the projections as a function of x_B and $P_{h\perp}$.

similar to $A_{LU}^{\sin(\phi)}$ but scaled by Q in order to compensate the $1/Q$ suppression inherent to twist-3 observables. An opposite sign of the asymmetries for π^- as a function of z is seen by the two experiments. The contributions to $F_{LU}^{\sin(\phi)}$ from $eH_1^{\perp}$ and $g^{\perp}D_1$ are weighted with x_B, and thus suppressed at smaller x_B values. The CLAS data are instead located at larger x_B. The Collins FFs for up quarks were found to be positive for π^+ and negative for π^-. If $eH_1^{\perp}$ forms the dominant contribution to $F_{LU}^{\sin(\phi)}$ and scattering takes predominantly place off up quarks, opposite signs can be expected for the π^+ and π^- asymmetries. Positive (negative) asymmetries are indeed observed at CLAS for π^+ (π^-). On the other hand, the asymmetries from this analysis, sensitive to lower values of x_B, are positive for both pion charges. This could hint at the dominance of contributions from other combinations of PDFs and FFs to $F_{LU}^{\sin(\phi)}$.

In summary, beam-helicity asymmetries in semi-inclusive leptoproduction of pions, kaons, as well as protons and antiprotons were presented based on an analysis of the HERMES data set using hydrogen and deuterium targets. They are found to be non-vanishing for charged pions and positively charged kaons, while consistent with zero for the others. Comparison to CLASS data at larger values of x_B hint at the dominance of different contributions to $F_{LU}^{\sin(\phi)}$ at the different regions of x_B. For the first time, also the three-dimensional dependence (x_B, z, and $P_{h\perp}$) of the beam-helicity asymmetry has been extracted. It can be found together with a comparison of the one-dimensional projections to existing COMPASS data in Ref. [5].

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