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Longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering of electrons and positrons by protons and deuterons

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A comprehensive collection of results on longitudinal double-spin asymmetries is presented for charged pions and kaons produced in semi-inclusive deep-inelastic scattering of electrons and positrons on the proton and deuteron, based on the full HERMES data set. The dependence of the asymmetries on hadron transverse momentum and azimuthal angle extends the sensitivity to the flavor structure of the nucleon beyond the distribution functions accessible in the collinear framework. No strong dependence on those variables is observed. In addition, the hadron charge-difference asymmetry is presented, which under certain model assumptions provides access to the helicity distributions of valence quarks.

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1. Introduction

Double-spin asymmetries involving longitudinal polarization of both projectile and target have served as a powerful tool to study the spin structure of nucleons for a long time. Measurements of asymmetries in inclusive deep-inelastic scattering (DIS) revealed that only a fraction of the nucleon spin originates in the spin of the quarks that make up the nucleon [1, 2], while data from proton-proton collision indicate that also the gluons are polarized [3]. Semi-inclusive DIS allows one to further discriminate between quark flavors due to the correlation between the hadron produced and the flavor of the struck quark [4, 5]. The detection of the final-state hadron in DIS also opened the avenue to the investigation of the multidimensional structure of the nucleon cast in terms of transverse-momentum distributions, or short TMDs. Here, a reanalysis [6] of the complete HERMES data on semi-inclusive DIS by longitudinally polarized protons and deuterons is presented that goes beyond the previous one [5] by improving several analysis details and—more importantly—by including the dependence on the full hadron kinematics.

The fully differential cross section for producing a hadron h in semi-inclusive DIS of an electron by nucleons is given by [7]

$$\frac{\mathrm{d}\sigma^h}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}P_{h\perp}^2\,\mathrm{d}\phi} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}^h+\varepsilon F_{UU,L}^h \\ +\lambda\Lambda\left[\sqrt{1-\varepsilon^2}F_{LL}^h+\sqrt{2\varepsilon(1-\varepsilon)}\,F_{LL}^{h,\cos\phi}\cos\phi\right]+\ \dots\Bigg\}, \tag{1.1}$$

where only terms involving no polarization at all or longitudinal polarization of both electron and nucleon are included (denoted by their helicities in the lepton-nucleon center of mass, λ and Λ, respectively). The cross section is differential in the usual DIS Lorentz invariants x, 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]. 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, 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. In particular, the azimuthally uniform $F_{LL}^h(x,Q^2,z,P_{h\perp})$ can be expressed, in the limit of small hadron transverse momentum ($P_{h\perp} \ll zQ$), in terms of a leading-twist distribution and fragmentation function:

$$F_{LL}^h \propto \sum_q e_q^2\left[\,g_{1L}^q(x,p_T^2)\otimes_{\mathscr{W}_1} D_1^{q\to h}(z,k_T^2)\right]. \tag{1.2}$$

Here, “$\otimes_{\mathscr{W}_1}$” represents a convolution of the distribution and fragmentation functions over the intrinsic transverse momentum p_T of the parton q (with fractional charge e_q) and the transverse-momentum contribution k_T from the fragmentation process with a kinematic “weight” $\mathscr{W}_1$. The function $\mathscr{W}_1$ [and $\mathscr{W}_2$ from Eq. (1.3)] is given explicitly, e.g., in Ref. [7]. In the collinear limit, F_{LL}^h

reduces to the well-known product of the collinear helicity distribution $g_1^q(x)$ and the collinear fragmentation function $D_1^{q\to h}(z)$. At subleading twist, a cosine modulation arises, which in a Wandzura–Wilczek-type approximation [9] can again be written as a convolution of g_{1L}^q with $D_1^{q\to h}$:

$$F_{LL}^{h,\cos\phi} \propto \frac{M}{Q}\sum_q e_q^2 \left[\, g_{1L}^q(x,p_T^2) \otimes_{\mathscr{W}_2} D_1^{q\to h}(z,k_T^2) \,\right]. \tag{1.3}$$

2. HERMES measurement of longitudinal double-spin asymmetries

Ideally, the structure functions of interest are extracted directly from measurements of the semi-inclusive cross section. Experimentally, measurements of spin asymmetries are preferred due to cancellations of several experimental effects, e.g., the luminosity calibration. The lepton-nucleon asymmetries presented here are computed using basically the same data set and procedure presented in prior HERMES publications on longitudinal double-spin asymmetries [10, 5, 2] (differences from previous analyses are discussed below):

$$A_\parallel^h \equiv \frac{C_\phi^h}{f_D}\left[\frac{L_{\rightrightarrows} N^h_{\rightleftarrows} - L_{\rightleftarrows} N^h_{\rightrightarrows}}{L_{P,\rightrightarrows} N^h_{\rightleftarrows} + L_{P,\rightleftarrows} N^h_{\rightrightarrows}}\right]_{\mathrm{B}} . \tag{2.1}$$

Here, $N^h_{\rightrightarrows(\rightleftarrows)}$ represents the hadron yield, and $L_{\rightrightarrows(\rightleftarrows)}$ and $L_{P,\rightrightarrows(\rightleftarrows)}$ represent the luminosity and polarization-weighted luminosity in the parallel (antiparallel) experimental beam/target helicity configuration. The square brackets, $[\,]_{\mathrm{B}}$, indicate that the enclosed quantity is corrected to Born level, i.e., unfolded for radiative and detector smearing, using Born and smeared Monte Carlo simulations according to the essentially model-independent procedure described in Ref. [5]. The factor f_D represents the dilution of the polarization of the nucleon with respect to that of the nucleus, and C_ϕ^h is a correction that compensates for any distortion caused by the convolution of the azimuthal moments of the polarization-independent cross section with the non-uniform detector acceptance.

The closely related virtual-photon–nucleon asymmetry A_1^h can be calculated from $A_\parallel^h$ as

$$A_1^h = \frac{1}{D(1+\eta\gamma)} A_\parallel^h, \tag{2.2}$$

where the contributions from the spin structure function g_2 and, in case of a deuterium target, from the tensor structure function b_1 are negligible [11]. The exact expression of the kinematic factor η can be found, e.g., in Ref. [6], and

$$D = \frac{1-(1-y)\varepsilon}{1+\varepsilon R} \tag{2.3}$$

accounts for the limited degree of polarization transfer at the electron–virtual-photon vertex, including the ratio R of longitudinal-to-transverse cross sections which—strictly speaking—is available so far only for inclusive DIS measurements.

The analysis has much in common with those in prior HERMES publications, although several changes are made in this analysis, which increase statistical precision and reduce systematic uncertainties. They are listed here and more details can be found in Ref. [6]:

1. The primary result are the lepton-nucleon asymmetries as derived from Eq. 2.1. While containing all the physics of Eq. 1.1, this approach avoids employing a parametrization for R that is only known for inclusive DIS but needed for the calculation of A_1^h.

2. The nucleon-polarization correction factor f_D in Eq. (2.1) is the ratio of the polarization of the target nucleon to that of the host nucleus. It is unity for protons and 0.926 for deuterons and is applied directly to the asymmetries in this analysis.

3. An additional low-z bin ($0.1 < z < 0.2$) is added for the data binned in x and z simultaneously.

4. The hydrogen data used here makes use of a threshold Cherenkov counter that required a minimum hadron momentum of 4 GeV in order to distinguish charged pions from heavier hadrons. The dual-radiator ring-imaging Cherenkov detector (RICH) [12] used for the deuterium data allows lowering the minimum momentum requirement to 2 GeV, in contrast to what was done before.

5. The RICH hadron identification algorithm was improved to reconstruct better multi-hadron events [13] using an event-level algorithm.

6. Event migration due to radiative and detector smearing is corrected for in a multidimensional unfolding procedure, i.e., not only in x but also in the other variables under study.

7. An azimuthal-acceptance correction, the factor C_{ϕ}^{h} in Eq. (2.1), is applied to the semi-inclusive asymmetries that compensates for the influence of the azimuthal spectrometer acceptance in the implicit integration over kinematic variables in the semi-inclusive yields.

Only a small selection of the results presented in Ref. [6] can be shown here. For the first time, the three-dimensional dependence of the double-spin asymmetry has become available and is presented for charged pions from protons in Fig. 1. Within the precision of the measurements, the asymmetries display no obvious dependence on the hadron variables. There is possibly an indication that the non-vanishing asymmetry for π^- from protons observed in the one-dimensional

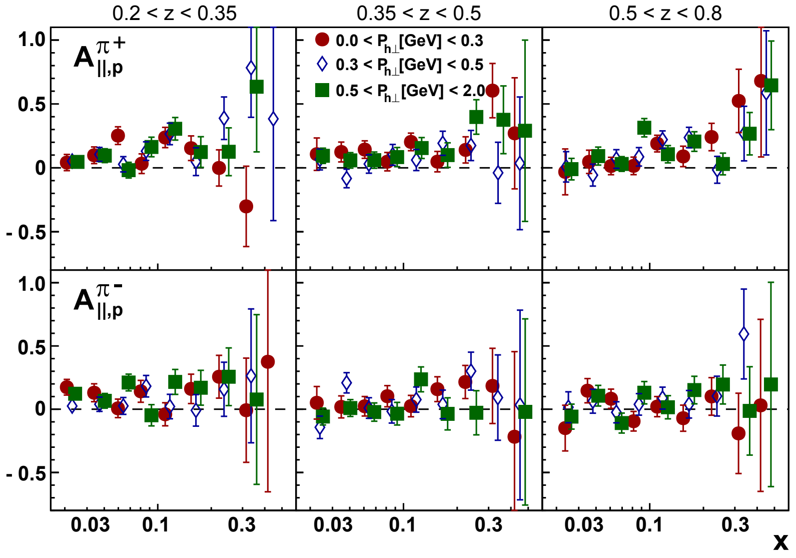

Figure 1: $A^{h}_{\parallel,N}(x,z,P_{h\perp})$ as a function of x in three different z ranges and three different $P_{h\perp}$ ranges as labeled, with $N = p,d$ denoting the target nucleus and $h = \pi^{\pm},K^{\pm}$ the final-state hadron detected.

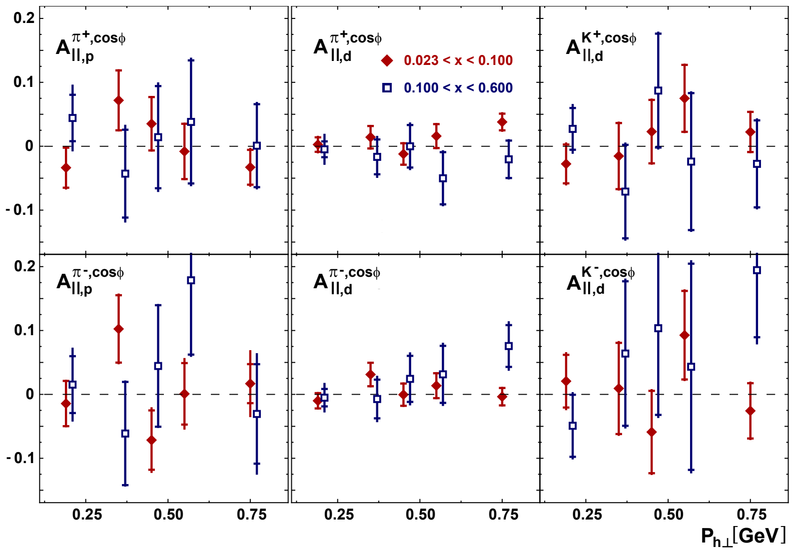

Figure 2: $A_{\parallel}^{h,\cos\phi}(P_{h\perp})$ in two x ranges for charged pions (and kaons) from protons (deuterons) as labelled.

binning in x (cf. Fig. 2 of Ref. [6]) is caused to a large extent by low-z pions. This is in line with expectation considering that disfavored fragmentation, e.g., fragmentation of quark flavors that are not part of the valence structure of the hadron produced, is sizable in that region. As such, π^- production from up quarks—which carry a large positive asymmetry—may still play a dominant role in that kinematic region compared to larger values of z, where disfavored fragmentation will be more and more suppressed.

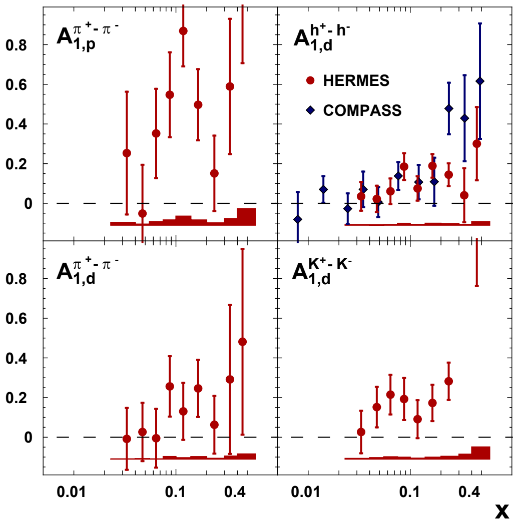

Figure 3: Hadron charge-difference asymmetries for pions from protons, and pions, kaons, and all hadrons from deuterons. Error bars are statistical uncertainties. Systematic uncertainties are given as bands. COMPASS data for undifferentiated hadrons from a ^{6}LiD target are also shown.

The azimuthal dependence of the longitudinal double-spin asymmetry is presented in Fig. 2 as a function of the hadron transverse momentum in two ranges in x. These cosine modulation are of subleading twist and thus suppressed. Indeed, no significant deviation from the dominance of leading twist is visible, the cosine modulations being consistent with zero, albeit within still large uncertainties.

Hadron charge-difference asymmetries are presented in Fig. 3. Under certain model assumptions they provide access to the helicity distributions of valence quarks [6], and are found to be consistent with data from COMPASS [14] for undifferentiated hadrons using a ^{6}LiD target.

Altogether, a comprehensive data

set on longitudinal double-spin asymmetries in semi-inclusive deep-inelastic scattering has been presented. It extends the analysis of the previous HERMES publications to include also transverse-momentum dependence. These data are expected to provide an essentially model-independent constraint for theory and parameterization as they provide the first ever longitudinal double-spin semi-inclusive dataset binned in as many as three kinematic variables simultaneously.

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