Flavor dependent azimuthal cosine modulations in SIDIS unpolarized cross section

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The azimuthal $\cos\phi$ and $\cos 2\phi$ modulations of the distribution of hadrons produced in unpolarized semi-inclusive deep-inelastic scattering of electrons and positrons off hydrogen and deuterium targets have been measuread at the HERMES experiment. For the first time these modulations were determined in a four-dimensional kinematic space for positively and negatively charged pions and kaons separately, as well as for unidentified hadrons. These azimuthal dependences are sensitive to the transverse motion and polarization of the quarks within the nucleon via, e.g., the Cahn, Boer-Mulders and Collins effects.

1 Introduction

In lepton-nucleon deep-inelastic scattering (DIS), the structure of the nucleon is probed by the interaction of a high energy lepton with a target nucleon, via, at HERMES kinematics, the exchange of one virtual photon. If at least one of the produced hadrons is detected in coincidence with the scattered lepton, the reaction is called semi-inclusive deep-inelastic scattering (SIDIS):

$$l(\mathbf{k}) + N(\mathbf{P}) \to l'(\mathbf{k'}) + h(\mathbf{P}_h) + X(\mathbf{P}_X), \tag{1}$$

where l (l') is the incident (scattered) lepton, N is the target nucleon, h is a detected hadron, X is the target remnant and the quantities in parentheses in equation (1) are the corresponding four-momenta.

If unintegrated over the hadron momentum component transverse to the virtual photon direction $P_{h\perp}$ (Fig. 1), the cross section can be written as [1]:

$$d\sigma \equiv \frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi_h} = \frac{\alpha^2}{xyQ^2}(1+\frac{\gamma^2}{2x})\{A(y)\,F_{UU,T} + B(y)\,F_{UU,L} + C(y)\,\cos\phi_h F_{UU}^{\cos\phi_h} + B(y)\,\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\}, \tag{2}$$

where $F_{UU}^{\cos\phi_h}$, $F_{UU}^{\cos 2\phi_h}$, are azimuthally dependent structure functions, and are related respectively to $\cos\phi_h$ and $\cos 2\phi_h$ modulations, with ϕ_h the azimuthal angle of the hadron production plane around the virtual-photon direction (Fig. 1). In equation 2, the subscripts UU stand for unpolarized beam and target, T (L) indicates the transverse (longitudinal) polarization of the virtual photon, α is the electromagnetic coupling constant, $\gamma = 2Mx/Q$ with M the target mass, $A(y) \sim (1 - y + 1/2y^2)$, $B(y) \sim (1 - y)$, and $C(y) \sim (2 - y)\sqrt{1-y}$.

Here Q^2 and y are respectively the negative squared four-momentum and the fractional energy of the virtual photon, x the Bjorken scaling variable and z the fractional energy of the produced hadron.

Among possible mechanisms, two are expected to give important contributions to the azimuthal dependence of the unpolarized cross section in the hadron transverse momentum range accessible at HERMES. The first one is called the *Cahn effect* [2, 3], a pure kinematic effect where the azimuthal modulations are generated by the non-zero intrinsic transverse motion of quarks. In the second mechanism, the *Boer-Mulders effect* [4], $\cos\phi_h$ and $\cos 2\phi_h$ modulations originate from the coupling of the quark intrinsic transverse momentum and intrinsic transverse spin, a kind of spin-orbit effect.

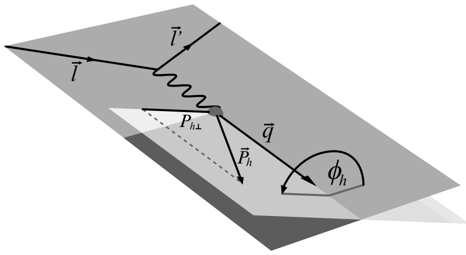

Figure 1: Definition of the azimuthal angle ϕ_h between scattering plane, spanned by the in- and out-going lepton three-momenta ($\vec{l}$, $\vec{l}'$), and the hadron production plane, defined by the three-momenta of the virtual photon ($\vec{q}$) and produced hadron ($\vec{P}_h$).

2 Multi-dimensional unfolding

In order to study the new structure functions $F_{UU}^{\cos\phi_h}$ and $F_{UU}^{\cos 2\phi_h}$ defined in Eq. (2), a measure of the azimuthal modulation of the unpolarized cross section is needed, which can be extracted via the so-called $\langle\cos n\phi_h\rangle$-moments:

$$\langle\cos n\phi_h\rangle = \frac{\int \cos n\phi_h \, d\sigma \, d\phi_h}{\int d\sigma \, d\phi_h} \tag{3}$$

with $n = 1, 2$ and $d\sigma$ defined in equation 2.

The extraction of these cosine moments from data is challenging because they couple to a number of *experimental sources* of azimuthal modulations, *e.g.* detector geometrical acceptance and higher-order QED effects (*radiative effects*). Moreover, in the typical case, the event sample is binned only in one variable (1-dimensional analysis), and integrated over the full range of all the other ones, but the mentioned structure functions and the instrumental spurious contributions depend on all the kinematic variables x, y, z and $P_{h\perp}$ simultaneously. Therefore a 4-dimensional analysis is needed to take into account the correlations between the physical modulations and those spurious contributions, where the event sample is binned simultaneously in all the relevant variables [1]. Therefore, a detailed Monte Carlo simulation of the experimental apparatus including radiative effects is used to define a 4-D unfolding procedure [6] that corrects the extracted cosine moments for radiative and instrumenthal effects.

The 4-D unfolded yields are fit to the functional form:

$$\mathcal{A}(1 + \mathcal{B}\cos\phi_h + \mathcal{C}\cos 2\phi_h) \tag{4}$$

where $\mathcal{B} = 2\langle\cos\phi_h\rangle$ and $\mathcal{C} = 2\langle\cos 2\phi_h\rangle$ represent the desired moments. One moment pair $(2\langle\cos\phi_h\rangle, 2\langle\cos 2\phi_h\rangle)$ for each of the 4-D kinematic bins is extracted, and the moment dependences on a single kinematic variable is obtained projecting the 4-D results onto the variable

[1] For a more detailed discussion about one- and multi-dimensional analysis see [5].

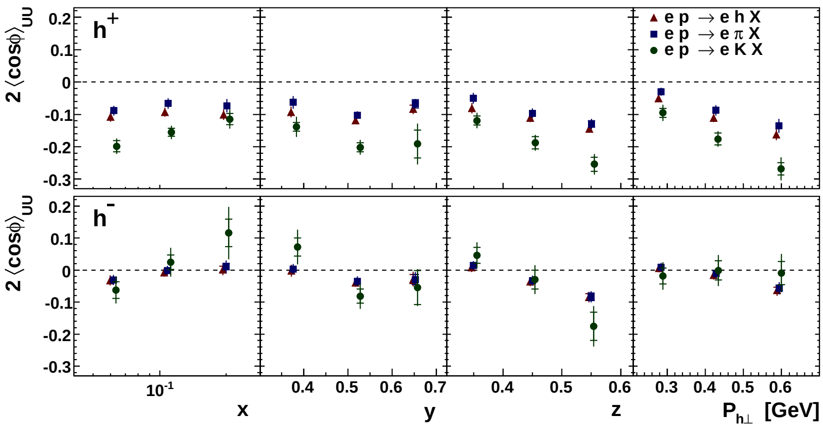

Figure 2: $\langle \cos\phi_h \rangle$ moments for positive (upper panel) and negative (lower panel) hadrons, extracted from hydrogen data projected versus the kinematic variables x, y, z and $P_{h\perp}$.

under study by weighting the moment in each bin with the corresponding 4π cross section obtained from a Monte Carlo calculation [2].

3 Results

The cross section unintegrated over hadron transverse momentum gives access to new exciting aspects of the nucleon structure, which are currently under intense theoretical investigations. To date, HERMES results [8] represents the most complete data set on the subject, and allows access to flavor dependent information on the nucleon internal transverse degrees of freedom.

The projected moments for pions (blue squares), kaons (green circles) and unidentified hadrons (red triangles) are shown projected in the relevant kinematic variables in figures 2 and 3 for $\langle \cos\phi_h \rangle$ (upper panel) and $\langle \cos 2\phi_h \rangle$ (middle panel) moments, respectively.

The $\langle \cos\phi_h \rangle$ moments are found to be negative for all positively charged hadron types, with a significative larger magnitude in the kaon case. All negative hadrons types present moments slightly negative, with a magnitude smaller than for the positive hadron case.

The $\langle \cos 2\phi_h \rangle$ moments show a different behavior in pions with respect to kaons. For pions, the $\langle \cos 2\phi_h \rangle$ moments have opposite sign for positive and negative pions: both modulations are clearly charge dependent, and this feature is considered as an evidence of a non-zero Boer-Mulders effect [9, 10, 11, 12].

The absolute value of kaon $\cos 2\phi_h$ modulations are found to be larger in magnitude than pions ones. Furthermore, while pion $\cos 2\phi_h$ modulations change sign between differently charged pions, kaon modulations are negative for both kaon charges.

The unidentified hadrons present similar trends as the pions but, particularly for the $\langle \cos 2\phi_h \rangle$ moments, the hadrons are shifted to lower values than the pions. The discrepancy between hadrons and pions is consistent with the observed kaon moments.

[2]Details on the full 4-D unfolding and extraction procedure as well as on the projection versus the single variable can be found in [7].

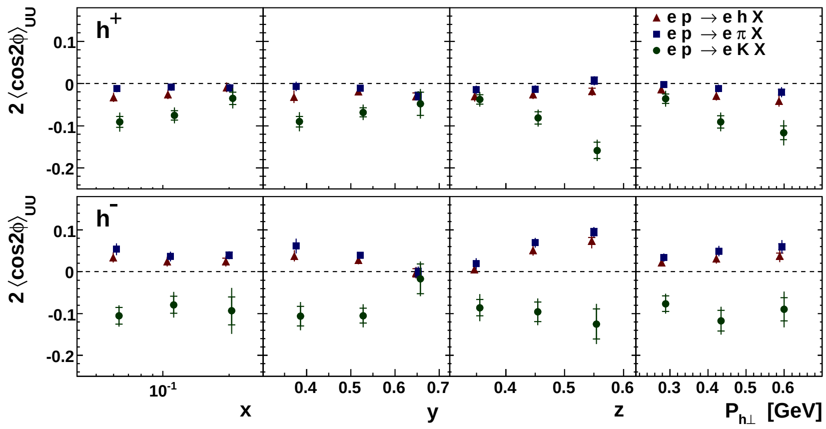

Figure 3: $\langle \cos 2\phi_h \rangle$ moments for positive (upper panel) and negative (lower panel) hadrons, extracted from hydrogen data projected versus the kinematic variables x, y, z and $P_{h\perp}$.

The cosine modulations have been extracted also for data collected with deuterium target, and they are found to be compatible with hydrogen results, both for unidentified hadrons, pions and kaons. This suggests that similar contributions arise from *up* and *down* quarks to the cosine modulations.

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