HERMES results on azimuthal modulations in the spin-averaged SIDIS cross section

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In unpolarized semi-inclusive deep-inelastic scattering azimuthal $\cos\phi_h$ and $\cos 2\phi_h$ modulations of the hadron distributions originate from quark intrinsic transverse momentum and transverse spin. An extraction of these modulations has been performed at HERMES by means of a multidimensional $(x, y, z, P_{h\perp})$ unfolding procedure to disentangle the physical azimuthal dependence of the cross section from instrumental and radiative contributions.
Results are presented for ^1H and ^2H targets and separately for positively and negatively charged hadrons to access flavor-dependent information about quark intrinsic transverse momenta and spin-orbit correlations.

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 the exchange of one virtual boson. 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):

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

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.

Assuming one-photon exchange, the leptoproduction cross section can be expressed as the contraction of leptonic $(L_{\mu\nu})$ and hadronic $(W^{\mu\nu})$ tensors. The leptonic tensor can exactly be calculated within the Quantum ElectroDynamics (QED) framework, while the hadronic tensor can not be calculated from first principles. However, using symmetry arguments and conservation laws, $W^{\mu\nu}$ can be expressed, in a model-independent way, in terms of structure functions. In case of unpolarized scattering, the cross section reads [2]:

$$\frac{d\sigma}{dx\,dy\,dz} = \frac{\alpha^2}{xyQ^2}\Big(1 + \frac{\gamma^2}{2x}\Big)\{A(y)\,F_{UU,T} + B(y)\,F_{UU,L}\}, \tag{2}$$

where 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, $A(y) \sim (1 - y + 1/2y^2)$ and $B(y) \sim (1 - y)$. 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.

Equation (2) is the well known unpolarized cross section integrated over the outgoing hadron momentum component transverse to the virtual photon direction $P_{h\perp}$ (Fig. 1).

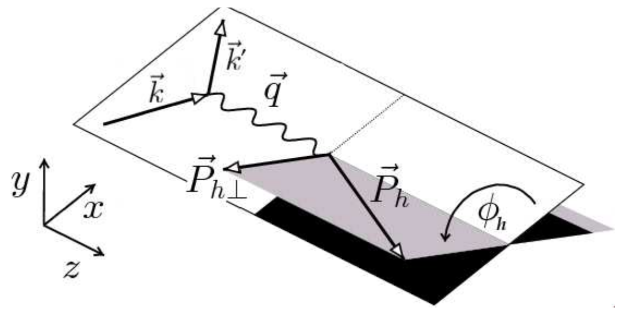

Figure 1: Definition of the azimuthal angle ϕ_h between scattering plane (grey) and hadron production plane (yellow): $\phi_h = \frac{\vec{q}\times\vec{k}\cdot\vec{P}_h}{|\vec{q}\times\vec{k}\cdot\vec{P}_h|} cos^{-1}\left(\frac{\vec{q}\times\vec{k}\cdot\vec{q}\times\vec{P}_h}{|\vec{q}\times\vec{k}||\vec{q}\times\vec{P}_h|}\right)$

If the cross section is unintegrated over $P_{h\perp}$, an azimuthal dependence around the outgoing hadron direction appears [2]:

$$\begin{aligned}\frac{d\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi_h} &= \frac{\alpha^2}{xyQ^2}(1+\frac{\gamma^2}{2x})\{A(y)\,F_{UU,T} + B(y)\,F_{UU,L} + \\ &\quad C(y)\,\cos\phi_h F_{UU}^{\cos\phi_h} + B(y)\,\cos 2\phi_h F_{UU}^{\cos 2\phi_h}\},\end{aligned} \tag{3}$$

where ϕ_h is the azimuthal angle of the hadron production plane around the virtual-photon direction (Fig. 1), $C(y) \sim (2-y)\sqrt{1-y}$, and $F_{UU}^{\cos\phi_h}$, $F_{UU}^{\cos 2\phi_h}$ are new struture functions related to $\cos\phi_h$ and $\cos 2\phi_h$ modulations, respectively.

Among the possible ones, two mechanisms 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* [3, 4], 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* [5], $\cos\phi_h$ and $\cos 2\phi_h$ modulations originate from the coupling of the quark intrinsic transverse momentum and intrinsic transverse spin, a sort of spin-orbit effect.

2 The HERMES experiment

The results presented here are extracted from data collected at HERMES in the 2000, 2005 and 2006 data taking periods. The fixed-target HERMES experiment ran for more than 10 years until 2007 at the electron-positron storage ring of HERA at DESY. The HERMES spectrometer [6] was a forward-angle instrument consisting of two symmetric (top, bottom) halves above and below the horizontal plane defined by the lepton beam pipe. It was characterized by very high efficiency (about $98-99\%$) in electron-hadron separation, provided by a transition radiation detector, a preshower scintillation counter and an electromagnetic calorimeter. In addition, a dual-radiator Ring-Imaging CHerenkov (RICH) detector provided hadron identification for momenta above 2 GeV/c.

3 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. (3), 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:

$$\langle \cos n\phi_h \rangle \;=\; \frac{\int \cos n\phi_h \, \sigma \, d\phi_h}{\int \sigma \, d\phi_h} \tag{4}$$

with $n = 1, 2$.

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 multi-dimensional analysis is needed to take into account the correlations between the physical modulations and these spurious contributions, where the event sample is binned simultaneously in all the relevant variables [a].

The unfolding procedure [8] described below is used to correct the extracted cosine moments for radiative and detector smearing. A detailed Monte Carlo simulation of the experimental apparatus is used to define the *Smearing matrix* $S(i, j)$, which provides the probability that an event originally in the *Born* bin j, corresponding to the original kinematics (*i.e.* free from experimental distortions), is actually observed in a different *measured* bin i. The unfolding algorithm relates the unknown *Born* yield distribution $n_B(j)$ to the *measured* yield distribution $n(i)$ via the *Smearing matrix* $S(i, j)$:

$$n(i) = \sum_{j=1}^{n_b} S(i,j) n_B(j) + n_{bg}(i), \tag{5}$$

where n_b is the total number of bins and $n_{bg}(i)$ is a vector that contains the events smeared into the measured sample from outside the acceptance.

Assuming a non-singular $S(i, j)$ matrix, Eq. (5) directly provides the *Born* yields:

$$n_B(j) = \sum_{i=1}^{n_b} S^{-1}(j,i) \big[n(i) - n_{bg}(i) \big]. \tag{6}$$

Like $S(i, j)$, also the background $n_{bg}(i)$ is evaluated from a Monte Carlo simulation. While $S(i, j)$, which depends only on the well known description of detectors and radiative effects, is model independent, the definition of $n_{bg}(i)$ can introduce some model dependence in the extraction as it is strictly related to the model for the unpolarized cross section used in the MC.

Since the unfolding mixes different bins contents, the unfolded *Born* yields are statistically correlated, and the extraction of cosine moments from them requires a generalized least-squares fit which takes into account the non-diagonal covariance matrix. A linear

[a] For a more detailed discussion about one- and multi-dimensional analysis see [7].

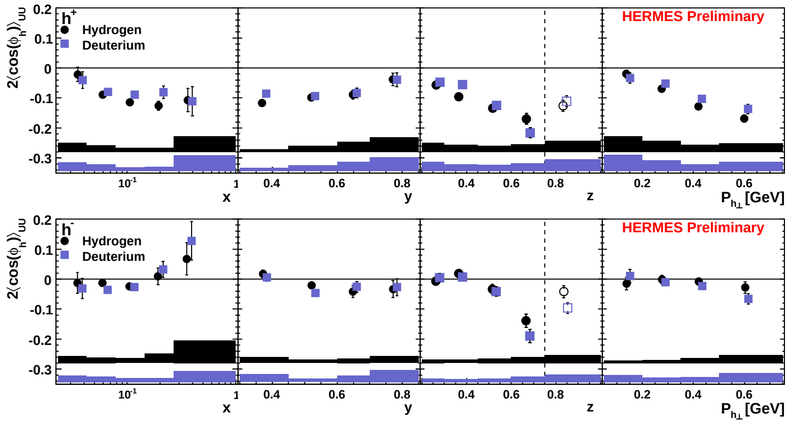

Figure 2: $\cos\phi_h$ moments for positive (upper panel) and negative (lower panel) hadrons, extracted with ^1H (circles) and ^2H (squares) targets, projected versus the kinematic variables x, y, z and $P_{h\perp}$.

regression can then be performed to linearize the problem and extract one moment pair ($\langle\cos\phi_h\rangle$, $\langle\cos 2\phi_h\rangle$) for each kinematic bin, which represents fully differential results.

The moment dependence of a single variable can be obtained projecting the fully differential results onto the variable under study by weighting the moment in each bin with the corresponding 4π cross section $\sigma^{4\pi}$, obtained from a Monte Carlo calculation, for instance in case of x: $\langle\cos\phi_h\rangle(x_j) = \sum_i \sigma^{4\pi}(x_j)\langle\cos\phi_h\rangle_i / \sum_i \sigma^{4\pi}(x_j)$.

4 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. Because they are experimentally challenging, very few measurements have been performed to date. The results available average out a possible flavor dependence, except the very recent results from COMPASS [9].

At HERMES, the extraction of the unpolarized modulations was performed using a multi-dimensional unfolding procedure from ^1H and ^2H data, and separately for positive and negative hadrons.

The $\cos\phi_h$ moments projected in the relevant kinematic variables are shown in figure 2 for positive (upper panel) and negative (lower panel) hadrons. Both ^1H and ^2H data show similar behavior: the $\langle\cos\phi_h\rangle$ moments are found to be sizable and negative for positive hadrons. The signal increases with $P_{h\perp}$ and with the hadron energy fraction z, except in the very high z range, where the partonic interpretation of the cross section is no longer valid[b]. The negatively charged hadrons exhibit similar features as the positively charged hadrons, but the signal size is significantly lower.

[b]The highest z-bin is shown for completeness but it is not used in the projection of moments in the other variables.

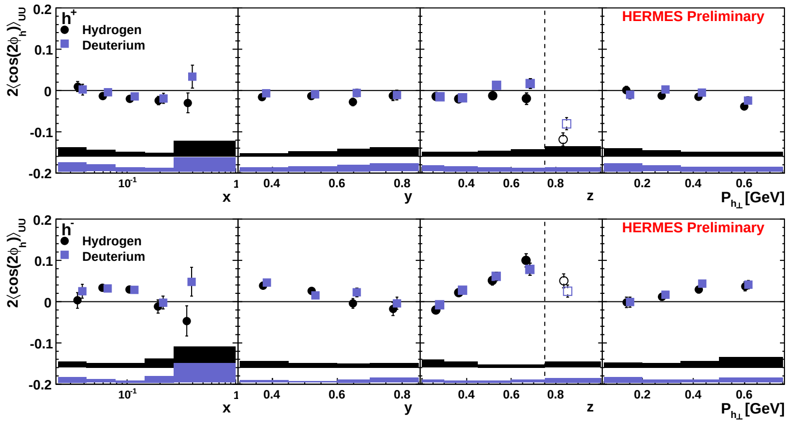

Figure 3: $\cos 2\phi_h$ moments for positive (upper panel) and negative (lower panel) hadrons, extracted with ^1H (circles) and ^2H (squares) targets, projected versus the kinematic variables x, y, z and $P_{h\perp}$.

Figure 3 shows the $\cos 2\phi_h$ moments extracted from ^1H and ^2H data for positive (upper panel) and negative (lower panel) hadrons. The $\langle\cos 2\phi_h\rangle$ moments are found to be slightly negative for positive hadrons, while the $\langle\cos 2\phi_h\rangle$ moments for negative hadrons are slightly positive.

Although there exist still no theoretical model that can fully describes the $\cos\phi_h$ and $\cos 2\phi_h$ modulations measured at HERMES, different results for positive and negative hadrons, in particular an opposite sign in the $\langle\cos 2\phi_h\rangle$ moments, can be considered an evidence of a non-zero Boer-Mulders effect [10, 11, 12].

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