Recent Measurements of the $\cos(n\phi_h)$ Azimuthal Modulations of the Unpolarized Deep Inelastic Scattering Cross-section at HERMES

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Abstract. The cross section for hadron production in deep-inelastic lepton scattering contains azimuthal modulations which can be related to transverse momentum dependent (TMD) distribution and fragmentation functions. The former provide a picture of how the quarks are moving within nucleons. Specifically, the $\cos\phi_h$ and $\cos 2\phi_h$ modulations of the unpolarized cross section relate quark spin and quark transverse momentum. These moments have been carefully measured at the HERMES experiment in a fully differential way, as a function of x, y, z, and $P_{h\perp}$ for positive and negative hadrons produced from hydrogen and deuterium targets. These measurements give new access to the flavor dependent TMDs via their charge and target dependence. These data must be compared to comprehensive models to determine which terms contribute significantly to the $\cos\phi_h$ and $\cos 2\phi_h$ moments and allow access to the underlying structure functions.

Keywords: Semi-Inclusive DIS; Azimuthal asymmetries; Intrinsic transverse momentum, spin
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INTRODUCTION

In semi-inclusive deep-inelastic scattering (SIDIS) the incident lepton with momentum k emits a virtual photon which interacts with the target nucleon to produce a hadron with momentum P_h and transverse momentum $P_{h\perp}$. This process is depicted in Figure 1 where additionally the ϕ_h angle is defined as the angle between the lepton scattering plane and the hadron production plane.

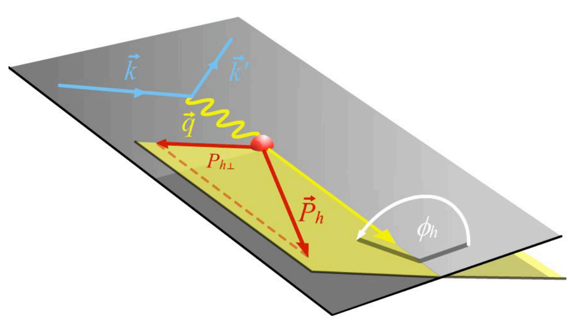

FIGURE 1. Schematic of SIDIS indicating the lepton ($\vec{k}$, $\vec{k}'$) scattering plane and the hadron ($\vec{P}_h$) production plane, with hadron transverse momentum $\vec{P}_{h\perp}$ and azimuthal angle ϕ_h

As the unpolarized semi-inclusive cross section can depend on five independent variables, the measurements in this work were made as a function of four kinematic variables in addition to the ϕ_h angle. The kinematic variables used are the Bjorken scaling variable x and the fractional energy of the virtual photon y, along with the semi-inclusive variables describing the fractional energy of the observed hadron z and its transverse momentum $P_{h\perp}$.

At leading order and next-to-leading twist, the unpolarized (UU) cross-section is [1]:

$$\frac{d^5\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi_h} = \Big\{ C[R\,f_1 D_1] + \cos 2\phi_h C\Big[S\,h_1^\perp H_1^\perp\Big] \\ + \cos\phi_h \frac{2M}{Q}\, C\Big[T\,h_1^\perp H_1^\perp + U\,f_1 D_1 + \ldots\Big]\Big\} \tag{1}$$

where R, S, T and U are kinematic factors and C denotes a convolution integral.

We define the moments $2\langle\cos n\phi_h\rangle_{UU} \equiv \int \cos n\phi_h d^5\sigma / \int d^5\sigma$.

The $\cos\phi_h$ moment contains the "Cahn" term, proportional to the unpolarized distribution and fragmentation functions, $f_1 D_1$; it is a kinematic effect arising from non-zero transverse quark momentum and was first discussed by Cahn [2, 3]. Observations of the Cahn term can provide information on the quarks' intrinsic transverse momentum distributions. A second term contains the unmeasured Boer-Mulders distribution function $h_1^\perp$ and the measured Collins fragmentation function $H_1^\perp$ [4]. The sign and magnitude of $h_{1,q}^\perp$ reflects the correlation between the spin $\vec{S}_q$ and orbital angular momentum $\vec{L}_q$ of a quark of flavor q within the nucleon.

The $\cos 2\phi_h$ modulation arises solely from a Boer-Mulders $\otimes$ Collins term at twist-2, providing direct access to $h_1^\perp$. However, at twist-4 the Cahn term appears again.

RESULTS AND INTERPRETATION

Determining the $\cos\phi_h$ and $\cos 2\phi_h$ moments of the unpolarized SIDIS cross section requires a careful treatment of experimental effects. The finite acceptance of the spectrometer, detector smearing, and QED radiative effects can cause false moments and distort the measured distributions via bin migration. To correct for these kinematic-dependent effects, the data were analyzed in a 5-dimensional grid of 4800 bins in the variables x, y, z, $P_{h\perp}$, and ϕ_h. A 10-dimensional smearing matrix was populated by Monte Carlo simulation and incorporated into the fitting procedure (see Ref. [5] for further details). Monte Carlo tests have shown that this procedure is able to accurately reproduce input moments, which is not possible when the data is analyzed in only one dimension. The final moments presented are one dimensional projections of the moments in which the other four variables have been integrated over. The analysis presented here is based on data collected during 2000, 2005, and the 2006 electron beam period.

The HERMES result for the $\cos\phi_h$ moment on both hydrogen and deuterium (Figure 2) is near zero for negative hadrons and significantly negative for positive hadrons. The difference between the $\langle\cos\phi_h\rangle_{UU}$ moments for positive and negative hadrons, if it is the result of the Cahn term, may indicate that the average quark transverse momentum changes with quark flavor. However, while the observed sign for positive hadrons

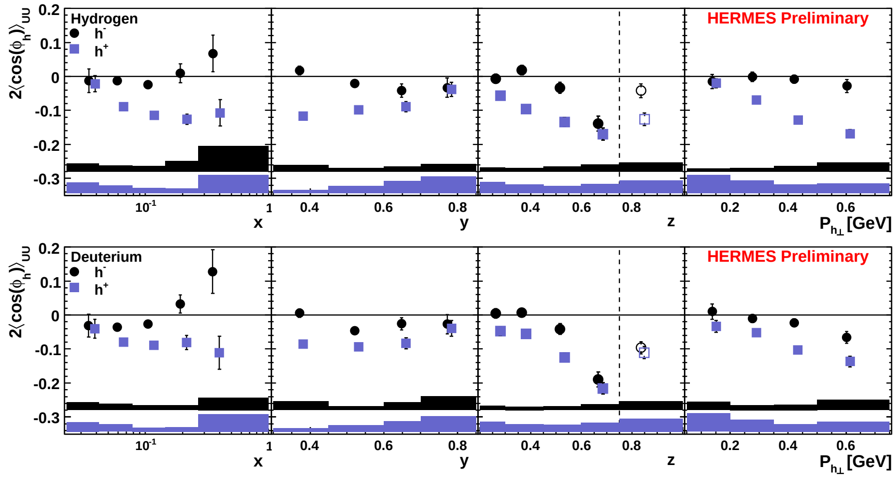

FIGURE 2. HERMES Preliminary $\langle \cos\phi_h \rangle_{UU}$ for negative (circles) and positive (squares) hadrons on a hydrogen (top) and deuterium (bottom) target. The error bars represent the statistical error while the bands represent the systematic error. The open points at high z are not included in the projections over the other variables.

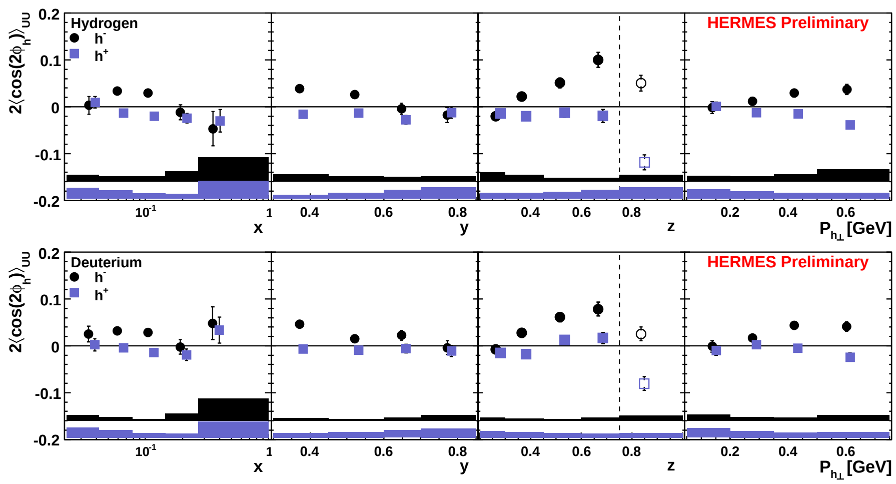

FIGURE 3. Same as Figure 2 but for $\langle \cos 2\phi_h \rangle_{UU}$

is in agreement with the Cahn-only model predictions of Anselmino et al. [6, 7] the magnitude of the prediction is larger than the data. This could indicate that the assumed average transverse momentum of quarks in Anselmino's calculation is not consistent with the data or that the Boer-Mulders term (and additional terms) make a significant contribution to the moment.

The HERMES result for the $\cos 2\phi_h$ moment (Figure 3) is significantly positive for negative hadrons and near zero for positive hadrons on both targets. Predictions made with a di-quark spectator model of only the Boer-Mulders term [8, 9] do well in describing the hydrogen data. The calculations of Barone et al. [10], which use a scaled version of the measured Sivers function, also show a Boer-Mulders term close to the data, but including the Cahn contribution results in moments larger than those observed in the data. This seems to indicate that the twist-4 Cahn term is small in HERMES kinematics, but this should be studied to be better understood. Work is currently in progress in this area [11].

While both of the above models assume that the Boer-Mulders functions for u and d quarks have the same sign, Zhang fit two parameter sets to Boer-Mulders Drell-Yan data [12], one that assumes the same sign and one that assumes opposite signs for $h_{1,u}^{\perp}$ and $h_{1,d}^{\perp}$. Both parameter sets give similar results that compare well with the hydrogen target data. However, simple calculations making use of these parameter sets were done by the author for a deuterium target and showed that while the same-sign parameter set gave results consistent with the shape of the data, the opposite-sign parameter set gave results near zero for both charges and not in agreement with the data. This highlights the need for more sophisticated calculations in all models for a deuterium target and also seems to indicate that u and d quarks have a spin-orbit coupling, and thus a Boer-Mulders function, of the same sign.

CONCLUSIONS

HERMES measurements of the $\langle\cos\phi_h\rangle_{UU}$ and $\langle\cos 2\phi_h\rangle_{UU}$ moments for positive and negative hadron production from hydrogen and deuterium targets have been presented. The results have been compared to several model predictions and seem to indicate that u and d quarks have non-zero spin-orbit correlations of the same sign. Additionally, the average transverse momenta for u and d quarks may differ, but at this time are not yet well described by the models. There is urgent need for comprehensive model calculations that present results for both hydrogen and deuterium targets and include both the Cahn and Boer-Mulders terms in both the $\cos\phi_h$ and the $\cos 2\phi_h$ moments. Only by using the full data set provided by HERMES can we definitively conclude something about the spin-orbit correlation implied by the Boer-Mulders function or the intrinsic transverse momentum of quarks implied by the Cahn term.

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