Effects of transversity in deep-inelastic scattering by polarized protons

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Single-spin asymmetries for pions and charged kaons are measured in semi-inclusive deep-inelastic scattering of positrons and electrons off a transversely nuclear-polarized hydrogen target. The dependence of the cross section on the azimuthal angles of the target polarization ($\phi_T$) and the produced hadron ($\phi$) is found to have a substantial $\sin(\phi + \phi_T)$ modulation for the production of
\[ \pi^+, \pi^- \text{ and } K^+ \]. This Fourier component can be interpreted in terms of non-zero transverse distribution functions and non-zero favored and disfavored Collins fragmentation functions with opposite sign. Its amplitude is found to be consistent with zero for \( \pi^+ \) and \( K^+ \) production.

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Most of our knowledge about the internal structure of nucleons comes from deep-inelastic scattering (DIS) experiments. The dominant process in DIS of charged leptons by nucleons is the exchange of a single space-like structure function in inclusive DIS because it is odd unpolarized with a squared four-momentum \(-Q^2\) much larger than the typical hadronic scale, for which the squared term in the nucleon is chosen. The cross section can be decomposed into a model-based on quantum chromodynamics (QCD) allow the independent way in terms of structure functions. Factorization theorems (see [1, 2] and references therein) formation on the transversity distribution was available based on quantum chromodynamics (QCD) allow the interpretation of these structure functions in terms of parton distribution functions (PDFs), which ultimately describe DIS (SIDIS), where it can appear in combination with the chiral-odd Collins fragmentation function [7]. This letter presents a measurement of the associated signal.

Polarized inclusive DIS of charged leptons on nucleons, \( lN \to l'hX \), where \( lN \to l'TX \) (where \( X \) denotes the undetected hadronic final state), can be described by four structure functions with the scattered lepton, the cross section depends on functions (see, e.g., [3]) which can be interpreted using among other variables, the hadron transverse momentum collinear factorization theorems (see, e.g., [4] and references therein). Three of the structure functions contain scattering plane and about the virtual-photon direction. Contributions already at leading order in an expansion If the polarization of the final state is not measured, the in \( M/Q \) (twist expansion). They include the leading- SIDIS cross section can be decomposed in terms of 18 twist (twist-2) parton distribution functions \( f_2^q(x) \), also semi-inclusive structure functions (see, e.g., [8]), denoted as \( g(x) \), and \( g_1^q(x) \), also denoted as \( \Delta q(x) \) [3] (for). When the transverse momentum of the produced simplicity, the dependence on the factorization scale has hadron is small compared to the hard scale \( Q \), been dropped). The variable \( x \) represents the fraction of semi-inclusive DIS can be described using transverse-the nucleon momentum carried by the parton in a frame momentum-dependent factorization [9, 10]. The semi-nucleon moves fast in the direction opposite inclusive structure functions can be interpreted in to the probe (e.g., in the Breit frame). The presence of terms of convolutions involving transverse-momentum-hard probe is essential to defining a specific direction (TMD) parton distribution and fragmentation (\( q \) in Fig. 1), which is usually denoted as longitudinal, functions [11]. The former encode information about the and a plane perpendicular to it, which is usually denoted distribution of partons in a three-dimensional momentum space. Hence, spectively. In a parton-model picture, \( f_2^q(x) \) describes the study of semi-inclusive DIS not only opens the way the number density of quarks of flavor \( q \) in a fast-moving to the measurement of transversity, but also probes new nucleon without regard to their polarization. The PDF dimensions of the structure of the nucleons and of the describes the difference between the number densities of quarks with helicity equal or opposite to the nucleon if the nucleon is longitudinally polarized.

There is a third leading-twist PDF, the function \( h_1^q(x) \) (also denoted as \( \delta q(x) \)), called the transversity distribution (see [5] for a review on the subject). Its \( x \)-integral is interpreted as the convolution of is related to the tensor charge of the nucleon. It can be interpreted [6] as the difference between the densities of quarks with transverse (Pauli-Lubanski) polarization fragmentation function \( H_1^+ \) (not integrated over the transverse momentum) and the Collins function \( H_1^- \), which acts as a parallel or anti-parallel to the transverse polarization of the nucleon. In contrast, \( f_2^q(x) \) and \( g^q_1(x) \), due to helicity conservation \( h_1^q(x) \) does not exist for gluons in case \( k_T \) [7]. Here, \( z \) denotes the fraction of the virtual pho-
ton energy carried by the produced hadron in the laboratory frame, \( p_T \) denotes the transverse momentum of the quark with respect to the parent hadron direction, and \( k_T \) denotes the transverse momentum of the fragmenting quark with respect to the direction of the produced hadron. This structure function manifests itself as a \( \sin(\phi + \phi_S) \) modulation in the SIDIS cross section with a transversely polarized target. Its Fourier amplitude, henceforth named Collins amplitude, is denoted as \( 2\langle \sin(\phi + \phi_S) \rangle_{UT} \), where \( \phi \) (\( \phi_S \)) represents the azimuthal angle of the hadron momentum (of the transverse component of the target spin) with respect to the lepton scattering plane and about the virtual-photon direction, in accordance with the Trento Conventions [12] (see Fig. 1).

The subscript UT denotes unpolarized beam and target polarization transverse with respect to the virtual-photon direction. Other azimuthal modulations have different origins and involve other distribution and fragmentation functions. They can be disentangled through their specific dependence on the two azimuthal angles \( \phi \) and \( \phi_S \) (see, e.g., [13]).

FIG. 1: The definition of the azimuthal angles \( \phi \) and \( \phi_S \) relative to the lepton scattering plane.

Non-zero Collins amplitudes were previously reported for charged pions from a hydrogen target [14], based on a small subset (about 10%) of the data reported here (consisting of about 8.76 million DIS events). Similar amplitudes, albeit consistent with zero, were measured on a deuterium target by the COMPASS Collaboration [15–17].

In this letter, in addition to much improved statistical precision on the charged pion results, the Collins amplitudes for \( K^+, K^−, \) and \( \pi^0 \) are presented for the first time for a proton target. In Refs. [18, 19] the first joint extraction of the transversity distribution function and the Collins fragmentation function was carried out, under simplifying assumptions, using preliminary results from a subset of the present data in combination with SIDIS data from the COMPASS collaboration [15–17] and \( e^+e^- \) annihilation data from the BELLE collaboration [20, 21].

Recently, significant amplitudes for two-hadron production in semi-inclusive DIS, which constitutes an independent process to probe transversity, were measured at the HERMES experiment [22] providing additional evidences for a non-zero transversity distribution function.

The data reported here were recorded during the 2002–2005 running period of the HERMES experiment with a transversely nuclear-polarized hydrogen target stored in an open-ended target cell internal to the 27.6 GeV HERA polarized positron/electron storage ring at DESY. The two beam helicity states are almost perfectly balanced and the present data, and no effects arising from the residual net beam polarization were observed. The target cell was fed by an atomic-beam source [23] which uses Stern–Gerlach separation combined with radio-frequency transitions of hyperfine states. The target cell was immersed in a transversely oriented magnetic holding field. The subscript UT denotes unpolarized beam and target.

The cross section for semi-inclusive production of hadrons using an unpolarized lepton beam and a transversely polarized target includes a polarization-averaged part and a polarization-dependent part. The former contains two cosine modulations and the latter contains a total of five sine modulations [8, 27, 28]:

\[
\sigma(\phi, \phi_S) = \sigma_{UU} \left\{ 1 + \sum_{n=1}^{2} 2\langle \cos(n\phi) \rangle_{UU} \cos(n\phi) + |S_T| \sum_{i=1}^{5} 2\langle \sin \Phi_i \rangle_{UT} \sin \Phi_i \right\}, \tag{1}
\]

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where $S_T$ denotes the transverse (with respect to the virtual photon direction) component of the target proton spin and $\Phi = [\phi + \phi_S, \phi - \phi_S, \phi_S, 2\phi - \phi_S, 3\phi - \phi_S]$. The subscript UU denotes unpolarized beam and unpolarized target, and $\sigma_{UU}$ represents the $\phi$-independent part of the polarization-averaged cross section.

The Collins amplitude $2\langle \sin(\phi + \phi_S) \rangle_{UT}$ can be interpreted in the quark-parton model as [27]

$$
2\langle \sin(\phi + \phi_S) \rangle_{UT}(x, y, z, P_{h\perp}) = \frac{(1 - y) C[-P_{h\perp} \cdot k_T h_1^q(x, p_T^2) M_{1}^q(z, k_T^2)]}{(1 - y + y^2/2) C[f_1^q(x, p_T^2) D_1^q(z, k_T^2)]}
$$

where $P_{h\perp} \equiv |P_h - (P_h \cdot q/q)|$ is the transverse momentum of the produced hadron, and $D_1^q$ is the polarization-averaged quark fragmentation function. The notation $C$ denotes the convolution [8]

$$
C [...] = \sum_q e_q^2 \int d^2p_T d^2k_T \delta(2) \left( p_T - k_T - \frac{P_{h\perp}}{z} \right) ...
$$

where the sum runs over the quark flavors $q$, and $e_q$ are the quark electric charges in units of the elementary charge. Note that, as the quark flavors enter the cross section with the square of their electric charge, the $u$-quarks are likely to provide the dominant contribution for proton targets ($u$-quark dominance). Similar expressions hold for the other azimuthal modulations in eq. (1) [8].

Experimentally, the asymmetry amplitudes for opposite target-spin states $\uparrow, \downarrow$

$$
A_{h\perp}^\uparrow(\phi, \phi_S) \equiv \frac{1}{|S_T|} \frac{\sigma_{h_{1\uparrow}}^\phi - \sigma_{h_{1\downarrow}}^\phi}{\sigma_{h_{1\uparrow}}^\phi + \sigma_{h_{1\downarrow}}^\phi},
$$

were measured, using a maximum-likelihood fit alternately binned in $x$, $z$, and $P_{h\perp}$, but unbinned in $\phi$ and $\phi_S$. The asymmetry amplitudes for neutral pions were corrected for the combinatorial background evaluated in the side-bands of the photon-pair invariant mass spectrum. In addition to the five sine terms in eq. (1), the Collins amplitudes will be addressed in a future paper. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the accuracy in the measurement of the target polarization.

The extracted Collins amplitudes are shown in Fig. 2 as a function of $x$, $z$, or $P_{h\perp}$. They are positive for $\pi^+$ and $K^+$, negative for $\pi^-$, and consistent with zero for $\pi^0$ and $K^-$ at a confidence level of at least 95% based on a Student’s $t$-test including the systematic uncertainty. The fit also included a $\sin(2\phi + \phi_S)$ term, arising from the valence quarks. In general, the non-vanishing amplitudes increase in the small but non-vanishing target-polarization component, mainly receiving contributions from the valence quarks, and this is consistent with the transversity being longitudinal to the virtual-photon direction when the target is polarized perpendicular to the beam direction. A large contribution from the sea quarks, which would be expected to dominate in the low-$x$ region, was indeed not expected from the limited spectrometer acceptance, the six amplitudes were extracted simultaneously. The fit did not include the $\cos(\phi \omega)$ modulations of eq. (1). As a consequence, the Fourier amplitudes extracted from the asymmetry in eq. (4) do not coincide with those of eq. (1).

However, in the following they will be considered to be equivalent because inclusion in the fit of estimates [30] for the $\cos(\phi)$ and $\cos(2\phi)$ amplitudes of the unpolarized

FIG. 2: Collins amplitudes for pions and charged kaons as a function of $x$, $z$, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the accuracy in the measurement of the target polarization. Cross section resulted in negligible effects on the extracted amplitudes.
A possible explanation is dominance of u flavor among the fragmentation functions, which can be different for different mesons. The asymmetry amplitude is dominated by the decay of vector mesons, updating previously reported [29, 27] results on the 

\[ \langle \sin(\phi + \phi_S) \rangle_U^T + C(\sin(\phi + \phi_S))_{\pi} - (1 + C)\langle \sin(\phi + \phi_S) \rangle_U^T = 0 , \]

where \( C \) denotes the polarization-averaged cross section ratio for semi-inclusive negative and positive pion production. The extracted pion amplitudes are found to fulfill eq. (5) within the experimental uncertainty. Despite the expectation of similar magnitudes for the single-spin asymmetries for longitudinally polarized protons [35, 36], the resulting relatively small effect was included in the systematic uncertainty.

A Monte Carlo simulation was used to estimate the fraction of pions and kaons originating from the decay of exclusive produced vector mesons, updating previous results reported in Ref. [37]. For charged pions, this fraction is dominated by the decay of \( \rho^0 \) mesons, and in the latter is consistent with zero in the whole kinematic region covered by the present analysis, is of the order of 6-7%. The vector-meson fractions for neutral pions and charged kaons are of the order of 2-3%. The \( \pi^- \) mesons from the decay of exclusively produced vector mesons, and in particular the differences between the two kinematic regions, are in reasonable agreement with the two-body model. Among the various features of the extracted amplitudes stemming from the decay of exclusively produced vector mesons, and in particular the differences between the two kinematic regions, are in reasonable agreement with the two-body model. Among the various features of the extracted amplitudes stemming from the decay of exclusively produced vector mesons, and in particular the differences between the two kinematic regions, are in reasonable agreement with the two-body model.
hadrons and can have an effect on the extracted amplitudes through the convolution of eqs. (2) and (3).

The above discussion is based on eq. (2) and is thus valid up to twist-3. It is therefore interesting to investigate the presence of possible twist-4 contributions. To this end, the $Q^2$ dependence of the extracted amplitudes was studied in some detail. To minimize effects arising from the strong correlation between $x$ and $Q^2$ in the data, the events in each $x$ bin were divided into two sub-bins, with $Q^2$ below and above the mean value $\langle Q^2(x_i) \rangle$ for the original bin (see Fig. 3). However, due to the limited statistics it was not possible to exclude nor support the presence of twist-4 contributions by fitting the data in Fig. 3 with different $Q^2$ dependencies.

![FIG. 3: Collins amplitudes for charged pions as functions of $x$. The $Q^2$ range for each $i$-bin in $x$ was divided into two regions above and below the average $Q^2$ of that bin ($\langle Q^2(x_i) \rangle$). The bottom panels show the $x$-dependence of the average $Q^2$.](image)

In summary, non-zero Collins amplitudes in semi-inclusive DIS are measured for charged pions and positive kaons. These amplitudes arise from the transverse polarization of quarks in the target, revealed by its influence on the fragmentation of the struck quark, and thus support the existence of a non-zero transversity distribution function in the proton. They also support the existence of a non-zero Collins fragmentation functions. In particular, by comparing the Collins amplitudes of $\pi^+$ and $\pi^-$, it appears that fragmentation that is disfavored in terms of quark flavor has a surprising importance, and enters with a sign opposite to that of the favored one. In contrast to the expectation that the $\pi^+$ and the $K^+$ Collins amplitudes should have similar magnitudes, based on the common $u$-quark dominance, the amplitude for $\pi^+$ is found to be significantly larger than that for $\pi^-$. This could be an indication, e.g., of an important role of the sea quarks in conjunction with possibly large fragmentation function. Collins amplitudes consistent with zero are measured for $\pi^0$ and $K^-$. These data should considerably improve the precision of transversity extractions from future global fits.

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