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 (ϕS) and the produced hadron (ϕ) is found to have a substantial sin(ϕ + ϕS) modulation for the production of...
\( \pi^+, \pi^- \) and \( K^+ \). This Fourier component can be interpreted in terms of non-zero transversity 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 protons 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 under the exchange of a virtual photon and a hadron. In contrast to the nucleon itself, the dependence on the factorization scale has simplicity, the dependence on the factorization scale has been studied. In DIS, the transverse momentum of the virtual photon is larger than the typical hadronic scale, for which the squared hadron mass is much smaller than the typical hadronic scale, for which the squared hadron mass is much smaller. The transversity distribution does not appear in any seminclusive structure functions (see, e.g., [8]) which can be interpreted using momentum-dependent factorization theorems (see, e.g., [9] 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 are the chiral-odd Collins fragmentation function [7]. This letter presents a measurement of the associated signal.

In polarized semi-inclusive DIS, \( lN \rightarrow ll'X \), where \( lN \rightarrow ll'X \) (where \( X \) denotes the undetected hadronic final state), can be described by four structure functions \( h_1(x) \) with the scattered lepton, the cross section depends on, among other variables, the hadron transverse momentum and its azimuthal orientation with respect to the lepton. The semi-inclusive DIS cross section can be decomposed in terms of 18 twist-2 parton distribution functions \( f_2(x) \), also semi-inclusive structure functions (see, e.g., [8]), denoted as \( g(x) \), and \( g_1(x) \), also denoted as \( \Delta g(x) [3] \). The variable \( x \) represents the fraction of the virtual photon that is detected in the final state in coincidence with the hadron \( h \), and also as \( \Delta q(x) [3] \) for denoted also as \( \Delta q(x) [3] \). When the transverse momentum of the produced simplicity, the dependence on the factorization scale has been dropped. The variable \( x \) represents the fraction of semi-inclusive DIS can be described using transverse-momentum-dependent factorization [9, 10]. The semi-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 dependent (TMD) parton distribution and fragmentation (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 as transverse. The three-integrals of \( f_2(x) \) and \( g_2(x) \) are in turn space, whereas the latter describe the hadronization of the vector and axial charge of the nucleon, re- our understanding of QCD. When performing a twist expansion, eight structure functions contain contributions at leading order, related to the eight leading-twist TMD PDFs [8]. One of these structure functions is interpreted as the convolution of the transversity distribution function \( h_2(x, p_T^2) \) (not integrated over the transverse momentum) and the Collins fragmentation function \( H_1^{\perp 1}(z, k_T^2) \), which acts as a polarization of the fragmenting quark and helicity conservation \( h_1^\perp(x) \) does not exist for gluons in case of the nucleon if the nucleon is longitudinally polarized.

In a parton-model picture, \( f_2(x) \) describes the study of semi-inclusive DIS not only opens the way to the measurement of transversity, but also probes new nucleon without regard to their polarization. The PDF of dimensions of the structure of the nucleons and of the hadronization process, thus offering new perspectives to our understanding of QCD. There is a third leading-twist PDF, the function \( h_1^\perp(x) \) (also denoted as \( \Delta q(x) \)), called the transversity distribution (see [5] for a review on the subject). Its x-integral 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 \( \perp \) and parallel or anti-parallel to the transverse polarization of the nucleon. In contrast to \( f_2(x) \) and \( g_2(x) \), due to helicity conservation \( h_1^\perp(x) \) does not exist for gluons in case
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 \( 2 \sin(\phi + \phi_S) \) \( \sigma_{UT} \), where \( \phi \) and \( \phi_S \) 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.](image)

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 GeV HERA polarized positron/electron storage ring at DESY. The two beam helicity states are almost perfectly balanced in the present data, and no effects arising from the residual total net beam polarization were observed. The target cell was immersed in a transversely oriented magnetic holding field. The magnitude of the proton-polarization component perpendicular to the beam direction was 0.725±0.053. Scattered leptons and coincident hadrons with vertical and horizontal scattering angles in the ranges \( 40 < |\theta_L| < 140 \) mrad and \( |\theta_H| < 170 \) mrad, respectively, were detected by the HERMES spectrometer [25]. Leptons were identified with an efficiency exceeding 98% and a contamination of less than 1%. Charged hadrons detected within the momentum range 2–15 GeV were identified using a dual-radiator RICH [26] by means of a hadron-identification algorithm that takes into account the event topology. The detection of the neutral pions is based on the measurements of photon pairs in the calorimeter. These were only accepted if \( E_\gamma > 1 \) GeV and \( 0.10 \) GeV \( < M_{\gamma\gamma} < 0.17 \) GeV, where \( E_\gamma \) and \( M_{\gamma\gamma} \) denote the photon energy and the photon-pair invariant mass, respectively.

Events were selected according to the kinematic requirements \( W^2 > 10 \) GeV\(^2\), \( 0.023 < x < 0.4 \), \( 0.1 < y < 0.95 \), and \( Q^2 > 1 \) GeV\(^2\), where \( W^2 \equiv (P + q)^2 \), \( Q^2 \equiv -q^2 \equiv -(k-k')^2 \), \( y \equiv (P\cdot q)/(P\cdot k) \), and \( x \equiv Q^2/(2P\cdot q) \) are the conventional DIS kinematic variables with \( P \), \( k \) and \( k' \) representing the four-momenta of the initial state target proton, incident and outgoing lepton, respectively. In order to minimize target fragmentation effects as well as to exclude kinematic regions where contributions from exclusive channels become sizable, coincident hadrons were only included if \( 0.2 < z < 0.7 \), where \( z = (P\cdot P_h)/(P\cdot q) \) and \( P_h \) is the four-momentum of the produced hadron.

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]:

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

(1)
where $S_T$ denotes the transverse (with respect to the virtual photon direction) component of the target proton spin and $\Phi = [\phi + \phi_S, \phi - \phi_S, 2\phi - \phi_S, 3\phi - \phi_S]$. 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]

$$2\langle \sin(\phi + \phi_S) \rangle_{UT}(x, y, z, P_{h\perp}) = \frac{(1 - y)}{(1 - y + y^2/2)} \frac{C[f_2^U(x, p_T^2)D^T(z, k_T^2)]}{C[f_2^U(x, p_T^2)D^T(z, k_T^2)]} \int d^2 p_T d^2 k_T \delta^{(2)} \left( p_T - k_T - \frac{P_{h\perp}}{z} \right),$$

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

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

where the sum runs over the quark flavors $q$, and $c_q$ 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 $u$- and $d$-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 $\uparrow, \downarrow$

$$A_{h\perp}^\uparrow(\phi, \phi_S) \equiv \frac{1}{|S_T|} \frac{\sigma_{U\uparrow}^h - \sigma_{U\downarrow}^h}{\sigma_{U\uparrow}^h + \sigma_{U\downarrow}^h}, \quad (4)$$

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 included a $\sin(2\phi + \phi_S)$ term, arising from the mainly receiving contributions from the valence quarks. The target is polarized perpendicular to the beam direction $[29]$. In order to avoid cross contamination arising mainly 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 $\cos(\phi)$ 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 Collins fragmentation function from the BELLE experiment [20, 21] Note that the $x$, $z$, and $P_{h\perp}$ dependencies in Fig. 2 are three projections of the same data and are thus fully correlated. A multidimensional extraction of the Collins amplitudes will be addressed in a future pa-
A possible explanation is dominance of $u$ flavor among the 220 struck quarks, in conjunction with a substantial magnitude of opposite sign of the disfavored Collins fragmentation function describing, e.g., the fragmentation of $u$ quarks into $\pi^-$ mesons, as already suggested in Ref. [14]. Opposite signs for the favored and disfavored Collins fragmentation functions are not in contradiction to the BELLE results [20, 21] and are supported by the combined fits reported in [18]. They can be understood in the light of the string model of fragmentation [38] (and also of the Schäfer–Teryaev sum rule [39]). If a favored pion is created on fragmentation parameters tuned to HERMES hadron reaction, the order of 6-7%. The vector-meson fractions for neutral mesons are shown in [13] for the two kinematic regions stemming from the decay of exclusively produced vector mesons, updating previous measurements of single-spin asymmetries for longitudinally polarized protons [35, 36]. The resulting relatively small effect was accounted for in the systematic uncertainties. The impact on the extracted amplitudes of contributions [29] are found to fulfill eq. (5) within the experimental uncertainty from the non-vanishing longitudinal target-spin component was estimated based on previous measurements of 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 exclusively 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 265 the latter is consistent with zero in the whole kinematic range. Here however, one should keep in mind that, in the order of 6-7%. The vector-meson fractions for neutral pions and charged kaons are of the order of 2-3%. The $z$ with the target proton and $P_{h\perp}$ dependences of the fraction of pions and kaons are indicated in the systematic uncertainty.

In interpreting the various features of the extracted stemming from the decay of exclusively produced vector amplitudes, and in particular the differences between mesons are shown in [13] for the two kinematic regions, those of pions and kaons, the largely unknown role of $Q^2 < 4$ GeV$^2$ and $Q^2 > 4$ GeV$^2$ (the $x$ dependence was not reported due to the strong correlation between $x$ and $Q^2$ in the data). They exhibit maxima at high $z$ and with possibly large fragmentation functions, (ii) the following $P_{h\perp}$ dependences from decay of semi-inclusively produced signal and were not used to correct the pion and kaon yields analysed in the present work.

The results of Fig. 2 show that the $\pi^-$ amplitude is of opposite sign to that of $\pi^+$ and larger in magnitude, respectively; (iii) the $k_T$ dependences of the fragmentations, which can be different for different
amplitudes should have similar magnitudes, based on the
with a sign opposite to that of the favored one. In con-
of quark flavor has a surprising importance, and enters
it appears that fragmentation that is disfavored in terms
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 $\langle Q^2(x) \rangle$ 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 $x$-bin in $x$ was divided into the two
regions above and below the average $Q^2$ of that bin ($\langle Q^2(x) \rangle$).
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 polar-
ization of quarks in the target, revealed by its influence
on the fragmentation of the struck quark, and thus sup-
port 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 partic-
ular, 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 con-
trast 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 $K^+$ 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 fragmenta-
tion functions. Collins amplitudes consistent with zero
are measured for $\pi^0$ and $K^-$. These data should consid-
erably improve the precision of transversity extractions
from future global fits.

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