Observation of the Naive-T-odd Sivers Effect in Deep-Inelastic Scattering

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Azimuthal single-spin asymmetries of lepto-produced pions and charged kaons were measured on a transversely polarized hydrogen target. Evidence for a naive-T-odd, transverse-momentum-dependent parton distribution function is deduced from non-vanishing Sivers effects for π^+, π^0, and $K^\pm$, as well as in the difference of the π^+ and π^- cross sections.

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The ongoing experimental effort in spin-dependent high-energy scattering and attendant theoretical work continue to indicate that the spins of the quarks and gluons are not sufficient to explain the nucleon spin [1]. The investigation of the only remaining contribution, that of orbital angular momentum of the constituents, is clearly essential. Transverse-momentum-dependent parton distribution functions are recognized as a tool to study spin-orbit correlations, hence providing experimental observables for studying orbital angular momentum. One particular example is the Sivers function $f_{1T}^{\perp}$ [2], describing the correlation between the momentum direction of the struck quark and the spin of its parent nucleon. This correlation is commonly defined as the Sivers effect. A non-vanishing $f_{1T}^{\perp}$ contributes to, e.g., single-spin asymmetries (SSAs) in semi-inclusive deep-inelastic scattering (DIS) off transversely polarized protons, $ep^{\uparrow} \rightarrow e'hX$, where h is a hadron detected in coincidence with the scattered lepton e'.

For a long time, transverse SSAs had been assumed to be negligible in hard scattering processes. They are odd under naive time reversal, i.e., time reversal of three-momenta and angular momenta, and thus require interference of amplitudes with different helicities and phases. In QED and perturbative QCD, these ingredients are suppressed [3, 4]. Therefore, in semi-inclusive DIS they must be ascribed to the non-perturbative parts in the cross section, i.e., to specific parton distribution and fragmentation functions, commonly categorized as being naive-T-odd. The idea of a naive-T-odd quark distribution function goes back to an interpretation [2] of large left-right asymmetries observed in pion production in the collision of unpolarized with transversely polarized nucleons [5]. It was argued that such asymmetries could be attributed to a left-right asymmetry in the distribution of unpolarized quarks in transversely polarized nucleons, i.e., an asymmetry that exists before the pion is formed in the fragmentation process, and that does not vanish at high energies. A decade after an initial proof [6] that this distribution function, now termed the Sivers function, must vanish because of time-reversal invariance of QCD, it was realized through the pioneering work in Ref. [7] and subsequently in Refs. [8, 9, 10] that this proof applies only to transverse-momentum-integrated distribution functions. A gauge link, previously neglected in the definition of gauge-invariant distribution functions, invalidates the original proof for the case of transverse-momentum-dependent distribution functions. The gauge link provides the phase for the interference (required for naive-T-oddness), and can be interpreted as an interaction of the struck quark with the color field of the target remnant [11].

The inclusion of the gauge link has profound consequences on factorization proofs and on the concept of universality, which are of fundamental relevance for high-energy hadronic physics. A direct QCD prediction is a Sivers effect in the Drell–Yan process that has the opposite sign compared to the one in semi-inclusive DIS [8]. For hadron production in proton-proton collisions the situation is more intricate [12], leading to a violation of standard factorization and universality, even for the case of unpolarized collisions [13]. Therefore, the study of the Sivers effect in semi-inclusive DIS and other processes is of utmost importance for our understanding of high-energy scattering involving hadrons.

The Sivers effect has been related to the orbital motion of quarks inside a transversely polarized nucleon since the seminal work in Ref. [2]. In the calculation of Ref. [7], it became clear that orbital angular momentum of quarks is needed for a non-vanishing Sivers effect as it arises through overlap integrals of wave-function components with different orbital angular momenta. However, no quantitative relation has yet been found between $f_{1T}^{\perp}$ and the orbital angular momentum of quarks. One faces a similar quandary with the anomalous magnetic moment κ of the nucleon: it also requires wave function components with non-vanishing quark orbital angular momentum without constraining the *net* orbital angular momentum [14]. Indeed, $f_{1T}^{\perp}$ involves overlap integrals between the same wave function components that also appear in the expressions for κ as well as for the total angular momentum in the Ji relation [15] for the nucleon-spin decomposition [7, 14].

An interesting link between κ and $f_{1T}^{\perp}$ was suggested in Ref. [16]: the sign of the quark-flavor contribution to κ determines the sign of $f_{1T}^{\perp}$ for that quark flavor. If the final-state interactions are attractive, as one would assume for the confining color force, a positive flavor contribution to κ leads to a negative $f_{1T}^{\perp}$. (The sign and angle definitions follow the *Trento Conventions* [17].)

In semi-inclusive DIS, $f_{1T}^{\perp}$ leads to SSAs in the distribution of hadrons in the azimuthal angle about the virtual-photon direction. In general, azimuthal SSAs provide important information not only about the Sivers function but also about other distribution and fragmentation functions. For example, transversity [18], describing the distribution of transversely polarized quarks in transversely polarized nucleons, combined with the naive-T-odd Collins fragmentation function [6], also leads to SSAs. The keys to extracting different combinations of the various distribution and fragmentation functions are their different dependences on the two azimuthal angles ϕ and ϕ_S of the hadron momentum $\boldsymbol{P}_h$ and of the transverse component $\boldsymbol{S}_T$ of the target-proton spin, respectively, about the virtual-photon direction (cf. [17]). The Sivers effect manifests itself as a $\sin(\phi - \phi_S)$ modulation in the azimuthal distribution [19].

In this Letter clear evidence for a non-vanishing Sivers function is reported. The $\sin(\phi - \phi_S)$ modulations in semi-inclusive DIS are measured for pions and charged kaons, as well as in the difference between the π^+ and π^- cross sections, providing sensitivity to $f_{1T}^{\perp}$ for both valence and sea quarks.

The data reported here were recorded during the 2002–2005 running period of the HERMES experiment using a transversely nuclear-polarized hydrogen gas target internal to the 27.6 GeV HERA lepton (e^+ or e^-) storage ring at DESY. The open-ended target cell was fed by an atomic-beam source [20] based on Stern–Gerlach separation combined with radio-frequency transitions of hyperfine states. The nuclear spin direction was flipped at 1–3 min time intervals, while both nuclear polarization and the atomic fraction inside the target cell were continuously measured [21]. The average magnitude of the proton-polarization component perpendicular to the lepton-beam direction was 0.725 ± 0.053.

Scattered leptons and coincident hadrons were detected by the HERMES spectrometer [22]. Leptons were identified with an efficiency exceeding 98% and a hadron contamination of less than 1%. Charged hadrons with momentum $2\,\mathrm{GeV} < |\boldsymbol{P}_h| < 15\,\mathrm{GeV}$ were identified using a dual-radiator ring-imaging Čerenkov detector (RICH) [23]. For this a hadron-identification algorithm was employed that takes into account the topology of the whole event, in contrast to the track-level algorithm in previous analyses [24]. Events were selected subject to the requirements $Q^2 > 1\,\mathrm{GeV}^2$, $W^2 > 10\,\mathrm{GeV}^2$, $0.1 < y < 0.95$, and $0.023 < x < 0.4$, where $Q^2 \equiv -q^2 \equiv -(k-k')^2$, $W^2 \equiv (P+q)^2$, $y \equiv (P\cdot q)/(P\cdot k)$, and $x \equiv Q^2/(2P\cdot q)$. Here, P, k, and k' represent the four-momenta of the target proton, the incident lepton, and the scattered lepton, respectively. Coincident hadrons were accepted if $0.2 < z < 0.7$, where $z \equiv (P\cdot P_h)/(P\cdot q)$.

The cross section for semi-inclusive production of hadrons using an unpolarized lepton beam on a transversely polarized target can be written as [19, 25, 26]

$$\sigma(\phi,\phi_S) = \sigma_{UU}\{1 + 2\langle\cos\phi\rangle_{UU}\cos\phi + 2\langle\cos 2\phi\rangle_{UU}\cos 2\phi + |\boldsymbol{S}_T|\,[2\langle\sin(\phi-\phi_S)\rangle_{UT}\sin(\phi-\phi_S) + \ldots]\}, \quad (1)$$

where five sine modulations contribute to the polarization-dependent part, but, for convenience, only the $\sin(\phi-\phi_S)$ modulation (the Sivers term), is written out explicitly. Here, the subscript UT denotes unpolarized beam and transverse target polarization (with respect to the virtual-photon direction), while σ_{UU} represents the ϕ-independent part of the polarization-independent cross section. The $\sin(\phi-\phi_S)$ amplitude can be interpreted in the quark-parton model as [19]

$$2\langle\sin(\phi-\phi_S)\rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x,p_T^2) \otimes_{\mathcal{W}} D_1^q(z,K_T^2)}{\sum_q e_q^2 f_1^q(x,p_T^2) \otimes D_1^q(z,K_T^2)}, \quad (2)$$

where the sums run over the quark flavors, the e_q are the quark charges, and f_1 and D_1 are the spin-independent quark distribution and fragmentation functions, respectively. The symbol $\otimes$ ($\otimes_{\mathcal{W}}$) represents a (weighted) convolution integral over intrinsic and fragmentation transverse momenta $\boldsymbol{p}_T$ and $\boldsymbol{K}_T$, respectively.

The amplitudes of the five sine modulations in Eq. (1) were extracted simultaneously to avoid cross contamination. For this a maximum-likelihood fit was used [27], with the data alternately binned in x, z, and $P_{h\perp} \equiv |\boldsymbol{P}_h - \frac{(\boldsymbol{P}_h\cdot\boldsymbol{q})\boldsymbol{q}}{|\boldsymbol{q}|^2}|$, but unbinned in ϕ and ϕ_S. A sixth term, arising from the small but non-vanishing target-spin component that is longitudinal to the virtual-photon direction when the target is polarized perpendicular to the beam direction [28], was also included in the fit.

A scale uncertainty of 7.3% on the extracted Sivers amplitudes arises from the accuracy of the target-polarization determination. Inclusion in the fit of estimates [29] for the $\cos\phi$ and $\cos 2\phi$ amplitudes of the unpolarized cross section had negligible effects on the amplitudes extracted. Possible contributions [28] to the amplitudes from the non-vanishing longitudinal target-spin component were estimated based on measurements of SSAs on longitudinally polarized protons [30, 31] and included in the systematic uncertainty. Effects from the hadron identification using the RICH, the geometric acceptance, smearing due to detector resolution, and radiative effects are not corrected for in the data. Rather, the size of all these effects was estimated using a simulation tuned to the data, which involved a fully differential polynomial fit to the measured azimuthal amplitudes [32]. The result was included in the systematic uncertainty and constitutes the largest contribution.

Based on a PYTHIA6 Monte Carlo simulation [33] tuned to HERMES data, the fraction of charged pions (kaons) stemming from the decay of exclusive vector-meson channels was estimated to be about 6–7% (2–3%). Among the contributions of all the vector mesons to the pion samples, that of the ρ^0 is dominant. A different observable, for which the contributions from exclusive ρ^0 mesons cancels, is the *pion-difference asymmetry*

$$A_{UT}^{\pi^+-\pi^-}(\phi,\phi_S) \equiv \frac{1}{|\boldsymbol{S}_T|}\frac{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-}) - (\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}{(\sigma_{U\uparrow}^{\pi^+}-\sigma_{U\uparrow}^{\pi^-}) + (\sigma_{U\downarrow}^{\pi^+}-\sigma_{U\downarrow}^{\pi^-})}, \quad (3)$$

the SSA in the difference in the π^+ and π^- cross sections for opposite target-spin states $\uparrow,\downarrow$. In addition, this asymmetry helps to isolate the valence-quark Sivers functions: under some assumptions, such as charge-conjugation and isospin symmetry among pion fragmentation functions, one can deduce from Eq. (2) that this SSA stems mainly from the difference $(f_{1T}^{\perp,d_v} - 4f_{1T}^{\perp,u_v})$ in the Sivers functions for valence down and up quarks.

The resulting Sivers amplitudes for pions, charged kaons, and for the pion-difference asymmetry are shown in Fig. 1 as functions of x, z, or $P_{h\perp}$. They are positive and increase with increasing z, except for π^-, for which they are consistent with zero. In the case of π^+, K^+, and the pion-difference asymmetry, the data suggest a saturation of the amplitudes for $P_{h\perp} \gtrsim 0.4$ GeV and are consistent with the predicted linear decrease in the limit of $P_{h\perp}$ going to zero.

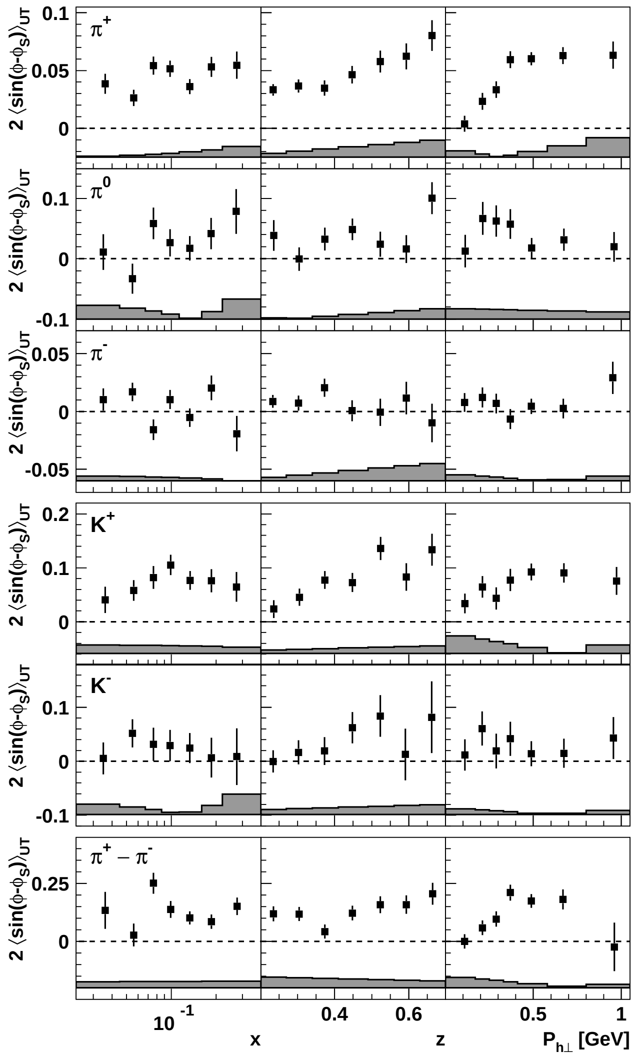

FIG. 1: Sivers amplitudes for pions, charged kaons, and the pion-difference asymmetry (as denoted in the panels) as functions of x, z, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the target-polarization measurement.

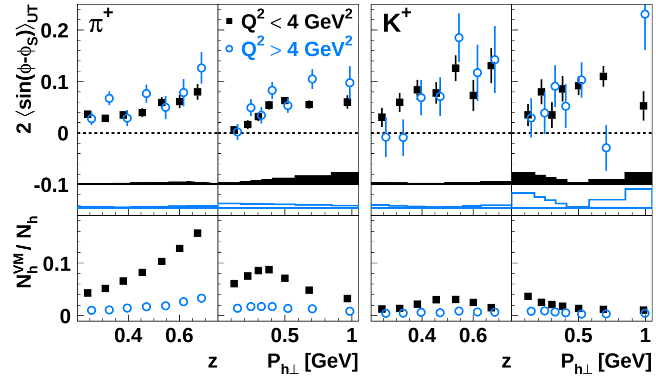

FIG. 2: Sivers amplitudes for π^+ (left) and K^+ (right) as functions of z or $P_{h\perp}$, compared for two different ranges in Q^2 (high-Q^2 points are slightly shifted horizontally). The corresponding fraction of pions and kaons stemming from exclusive vector mesons, extracted from a Monte Carlo simulation, is provided in the bottom panels.

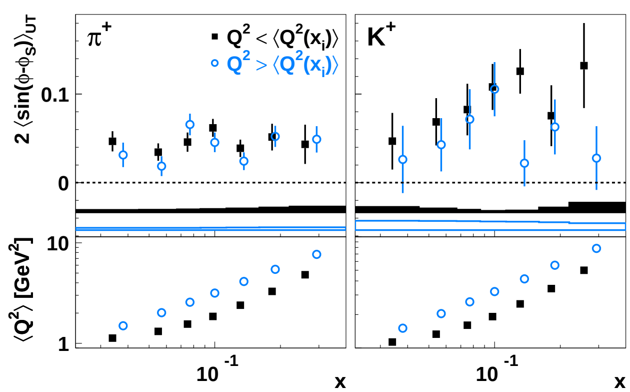

FIG. 3: Sivers amplitudes for π^+ (left) and K^+ (right) as functions of x. The Q^2 range for each bin was divided into the two regions above and below $\langle Q^2(x_i)\rangle$ of that bin. In the bottom the average Q^2 values are given for the two Q^2 ranges.

In order to further examine the influence of exclusive vector-meson decay and other possible $\frac{1}{Q^2}$-suppressed contributions, several studies were performed. Raising the lower limit of Q^2 to 4 GeV^2 eliminates a large part of the vector-meson contribution. Because of strong correlations between x and Q^2 in the data, this is presented only for the z and $P_{h\perp}$ dependences. No influence of the vector-meson fraction on the asymmetries is visible as shown in Fig. 2. For the x dependence shown in Fig. 3, each bin was divided into two Q^2 regions below and above the corresponding average Q^2 ($\langle Q^2(x_i)\rangle$) for that x bin. While the averages of the kinematics integrated over in those x bins do not differ significantly, the $\langle Q^2\rangle$ values for the two Q^2 ranges change by a factor of about 1.7. The asymmetries do not change by as much as would have been expected for a sizable $\frac{1}{Q^2}$-suppressed contribution, e.g., the one from longitudinal photons to the spin-(in)dependent cross section. However, while the π^+ asymmetries for the two Q^2 regions are fully consistent, there is a hint of systematically smaller K^+ asymmetries in the large-Q^2 region.

An interesting facet of the data is the difference in the π^+ and K^+ amplitudes shown in Fig. 4. On the basis of u-quark dominance, i.e., the dominant contribution to π^+ and K^+ production from scattering off u-quarks, one might naively expect that the π^+ and K^+ amplitudes should be similar. The difference in the π^+ and K^+ amplitudes may thus point to a significant role of other quark flavors, e.g., sea quarks. Strictly speaking, even in the case of scattering solely off u-quarks, the fragmentation function D_1, contained in both the numerator and denominator in Eq. (2), does not cancel in general as it appears in convolution integrals. This can lead not only

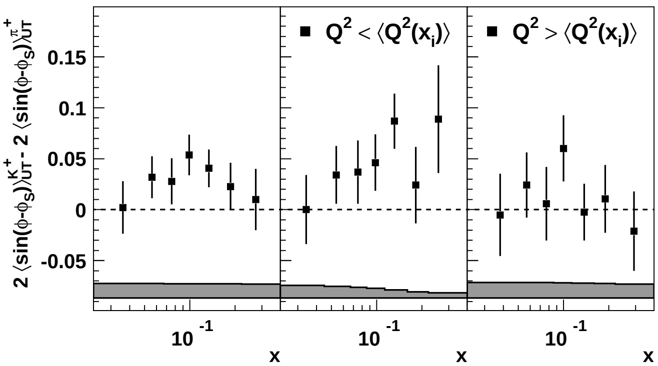

FIG. 4: Difference of Sivers amplitudes for K^+ and π^+ as functions of x for all Q^2 (left), and separated into "low-" and "high-Q^2" regions as done for Fig. 3.

to additional z-dependences, but also to a difference in size of the Sivers amplitude for π^+ and K^+. Higher-twist effects in kaon production might also contribute to the difference observed: in the low-Q^2 region, where higher-twist should be more pronounced, the π^+ and K^+ amplitudes disagree at the confidence level of at least 90%, based on a Student's t-test, while being statistically consistent in the high-Q^2 region.

As scattering off u-quarks dominates in these data, the positive Sivers amplitudes for π^+ and $K^\pm$ suggest a large and negative Sivers function for u-quarks. This is supported by the positive amplitudes of the difference asymmetry, which is dominated by the contribution from valence u-quarks. The vanishing amplitudes for π^- require cancelation effects, e.g., from a d-quark Sivers function opposite in sign to the u-quark Sivers function. In combination with deuteron data from the COMPASS collaboration [34], a large positive d-quark Sivers function can be deduced [35]. These fits have yet to be updated with the final results presented here, as well as with preliminary proton data from COMPASS [36].

In summary, non-zero Sivers amplitudes in semi-inclusive DIS were measured for production of π^+, π^0, and $K^\pm$, as well as for the pion-difference asymmetry. They can be explained by the non-vanishing naive-T-odd, transverse-momentum-dependent Sivers distribution function. This function also plays an important role in transverse single-spin asymmetries in pp collisions, and is linked to orbital angular momentum of quarks inside the nucleon. Although no quantitative conclusion about their orbital angular momentum can be inferred, the Sivers function provides important constraints on the nucleon wave function and thus indirectly on the total quark orbital angular momentum. For instance, in the approach of Ref. [11], the measured positive Sivers asymmetries for π^+ and K^+ mesons correspond to a positive contribution of u-quarks to the orbital angular momentum, under the assumption that the production of π^+ and K^+ mesons is dominated by scattering off u-quarks.

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