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Measurement of Single- and Double-Spin Asymmetries in Deep Inelastic Pion Electroproduction with a Longitudinally Polarized Target

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We report the first measurement of the transverse momentum dependence of double-spin asymmetries in semi-inclusive production of pions in deep-inelastic scattering off the longitudinally polarized proton. Data have been obtained using a polarized electron beam of 5.7 GeV with the CLAS detector at the Jefferson Lab (JLab). Modulations of single spin asymmetries over the azimuthal angle between lepton scattering and hadron production planes ϕ have been measured over a wide kinematic range in Bjorken x and virtual photon squared four-momentum Q^2. A significant nonzero $\sin 2\phi$ single spin asymmetry was observed for the first time indicating strong spin-orbit correlations for transversely polarized quarks in the longitudinally polarized proton.

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A measurement of transverse momenta (P_T) of final-state hadrons in semi-inclusive deep-inelastic scattering (SIDIS) $\vec{e}\,\vec{p} \rightarrow e'hX$, for which a hadron is detected in coincidence with the scattered lepton, gives access to the transverse momentum distributions (TMDs) of partons, which are not accessible in inclusive scattering. QCD factorization for SIDIS, established at low transverse momentum in the current-fragmentation region at higher energies [1–3], provides a rigorous starting point for the study of partonic TMDs from SIDIS data using different spin-dependent and spin-independent observables [4].

Measurements of the P_T dependences of spin asymmetries, in particular, allow studies of transverse momentum (k_T) widths of different TMDs, providing quantitative information on how quarks are confined in hadrons. The final transverse momentum of the hadron (for P_T comparable to the proton mass M_p and $\Lambda_{\rm QCD}$) in leading order is defined by the combination $zk_T + p_T$ [5], where p_T is the transverse momentum generated in the hadronization process, and z is the fraction of the energy of the virtual photon carried by the final-state hadron.

Azimuthal distributions of final-state particles in SIDIS, containing information on both magnitude and direction of the hadronic transverse momentum, are sensitive to the orbital motion of quarks and play an important role in the study of transverse momentum distributions of quarks in the nucleon. Two fundamental mechanisms have been identified that lead to single spin asymmetries (SSAs) in hard processes; the Sivers mechanism [6–10], which generates an asymmetry in the distribution of quarks due to orbital motion of partons, and the Collins mechanism [9,11], which generates an asymmetry during the hadronization of quarks.

Measurements of significant azimuthal asymmetries have been reported for pion production in semi-inclusive deep-inelastic scattering by the HERMES and COMPASS Collaborations, as well as the CLAS and Hall-C Collaborations at JLab for different combinations of beam and target polarizations [12–22].

For the longitudinally polarized target case, first discussed by Kotzinian and Mulders [11,23,24], the only SSA, depending on the azimuthal angle ϕ between the lepton scattering and pion production planes [25], arising at leading order is the $\sin 2\phi$ moment. It involves the convolution of the Ralston-Soper-Mulders-Tangerman (RSMT) distribution function $h_{1L}^{\perp}(x, k_T)$ [11,26] describing the transverse polarization of quarks in a longitudinally polarized proton [2,11,23,24,27], and the Collins fragmentation function $H_1^{\perp}(z, p_T)$ [28] describing fragmentation of transversely polarized quarks into unpolarized hadrons.

The only available measurement of the $\sin 2\phi$ moment by HERMES [12] is consistent with zero. The RSMT distribution function has been studied in various QCD inspired models [29–32]. First calculations for $h_{1L}^{\perp}(x, k_T)$ have recently been performed in the perturbative limit [33], and first measurements have been performed using lattice methods [34,35]. A measurably large asymmetry has been predicted [29–32,36] only at large x ($x > 0.2$), a region well covered by JLab.

The $\sin\phi$ moment of the spin-dependent cross section for the longitudinally polarized target is dominated by higher-twist contributions [4]. This moment has been measured for the first time by the HERMES Collaboration [12]. Both $\sin\phi$ and $\sin 2\phi$ moments of the SIDIS cross section for longitudinally polarized targets can be an important source of independent information on the Collins fragmentation mechanism [4], complementary to recent Belle measurements [37].

In this Letter, we present measurements of the kinematic dependences of different single- and double-spin asymmetries in semi-inclusive pion production off longitudinally polarized protons. The current analysis is based on recently published data [38] from Jefferson Lab. The CEBAF large acceptance spectrometer [39] in Jefferson Lab's Hall B was used to measure spin asymmetries in the scattering of longitudinally polarized electrons from longitudinally polarized protons. The data were collected in 2001 using an incident beam of 5-nA with $E = 5.7$ GeV energy and an average beam polarization of $P_B = 70\%$. The detector package [39] provided a clean identification of electrons scattered at polar angles between 8° and 45°. Charged and neutral pions were identified using the time-of-flight from the target to the timing scintillators and the signal in the lead-scintillator electromagnetic calorimeter, respectively. Ammonia ($^{15}NH_3$), polarized via dynamic nuclear polarization [40], was used to provide polarized protons. The average target polarization (P_t) was about 75%. The data were divided into 5 bins in Q^2 (0.9–5.4 GeV^2), 6 bins in x (0.12–0.48), 3 bins in z (0.4–0.7), 9 bins in P_T (0–1.12 GeV/c), and 12 bins in ϕ (0–2π). Cuts on the missing mass of $e'\pi X$ ($M_X > 1.4$ GeV) and on the fraction of the virtual photon energy ν carried by the pion z ($z < 0.7$), have been used to suppress the contribution from exclusive processes, including the $\pi\Delta$ production.

The double-spin asymmetry A_1 is defined as

$$A_1 = \frac{1}{fD'(y)P_BP_t}\frac{N^+ - N^-}{N^+ + N^-}, \qquad (1)$$

where $f \approx 0.14$ (dependent on kinematics) is the dilution factor, $y = \nu/E$, and $N^\pm$ are luminosity-weighted counts for antiparallel and parallel electron and proton helicities. The contribution from the longitudinal photon is accounted for in the depolarization factor $D'(y)$:

$$D'(y) = \frac{(1-\varepsilon)(2-y)}{y(1+\varepsilon R)} \equiv \frac{y(2-y)}{y^2 + 2(1-y-\frac{y^2\gamma^2}{4})\frac{(1+R)}{(1+\gamma^2)}}, \qquad (2)$$

where R [41] is the ratio of longitudinal to transverse photon contributions and ε is the ratio of longitudinal and transverse photon fluxes.

The main sources of systematic uncertainties in the measurements of the double-spin asymmetries include uncertainties in beam and target polarizations (4%), dilution factor (5%), and depolarization factor (5%). Contributions from target fragmentation, kaon contamination, and radiative corrections [42] were estimated to be below 3% each.

The double-spin asymmetry A_1 is shown in Fig. 1 as a function of P_T, integrated over all x (0.12–0.48) for $Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2, and $y < 0.85$. Although these plots are consistent with flat distributions, $A_1(P_T)$ may decrease somewhat with P_T at moderately small P_T for π^+. The slope for π^- could be positive for moderate P_T (ignoring the first data point).

A possible interpretation of the P_T dependence of the double-spin asymmetry may involve different widths of the transverse momentum distributions of quarks with different flavor and polarizations [5] resulting from different orbital motion of quarks polarized in the direction of the proton spin and opposite to it [43,44]. In Fig. 1 the measured A_1 is compared with calculations of the Torino group [5], which uses different values of the ratio of widths in k_T for partonic helicity g_1 and momentum f_1 distributions, assuming Gaussian k_T distributions. A fit to $A_1(P_T)$ for π^+ using the same approach yields a ratio of widths of 0.7 ± 0.1 with $\chi^2/\text{d.o.f.} = 1.5$. The fit to A_1 with a straight line (no difference in g_1 and f_1 widths) gives a $\chi^2/\text{d.o.f.} = 1.9$.

The fraction of $\pi^{\pm,0}$ from ρ decays has been studied using the PYTHIA Monte-Carlo generator tuned for CLAS kinematics. While there seems to be no correlation between that fraction (bottom plots in Fig. 1) and observed A_1 behavior, it may be responsible for some structure at $P_T \approx 0.5$ GeV, in particular, for π^-, where that fraction is more significant. In addition, given the measured relatively equal rates of ρ^0 and ρ^+, and their W dependence [45], we can safely exclude the "diffractive" origin of ρ^0s produced in the energy range of our experiment.

Asymmetries as a function of the azimuthal angle ϕ provide access to different combinations of TMD parton distribution and fragmentation functions [4]. The longitudinally polarized (L) target spin asymmetry for an unpolarized beam (U),

$$A_{UL} = \frac{1}{fP_t}\frac{N^+ - N^-}{N^+ + N^-} \qquad (3)$$

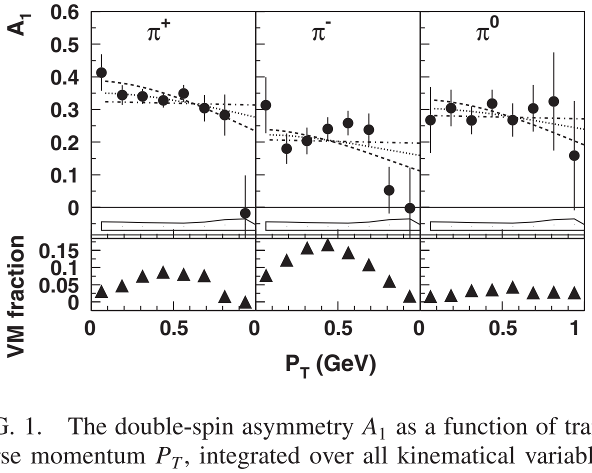

FIG. 1. The double-spin asymmetry A_1 as a function of transverse momentum P_T, integrated over all kinematical variables. The open band corresponds to systematic uncertainties. The dashed, dotted, and dash-dotted curves are calculations for different values for the ratio of transverse momentum widths for g_1 and f_1 (0.40, 0.68, 1.0) for a fixed width for f_1 (0.25 GeV^2) [5]. The lower panel shows the relative contributions to the data from simulated charged and neutral exclusive ρ production.

is measured from data by counting in ϕ bins the difference of luminosity-normalized events with proton spin states antiparallel (N^+) and parallel (N^-) to the beam direction.

The standard procedure for the extraction of the different moments involves sorting $A_{\rm UL}$ in bins of ϕ and fitting this ϕ distribution with theoretically motivated functions. Results for the function $p_1 \sin\phi + p_2 \sin 2\phi$ and, alternatively, for $(p_1 \sin\phi + p_2 \sin 2\phi)/(1 + p_3 \cos\phi)$ are consistent, indicating a weak dependence of the extracted $\sin n\phi$ moments on the presence of the $\cos\phi$ moment in the ϕ dependence of the spin-independent sum, which is the main source for mixing of $\sin n\phi$ moments. The main sources of systematic uncertainties in the measurements of single spin asymmetries include uncertainties in target polarizations (6%), acceptance effects (8%), and uncertainties in the dilution factor (5%). The contribution due to differences between the true luminosity for the two different target spin states is below 2%. Radiative corrections for $\sin\phi$-type moments, for moderate values of y are expected to be negligible [46].

The dependence of the target single spin asymmetry on ϕ, integrated over all other kinematical variables, is plotted in Fig. 2. We observe a significant $\sin 2\phi$ modulation for π^+ (-0.042 ± 0.010). A relatively small $\sin 2\phi$ term in the azimuthal dependence for π^0 is in agreement with observations by HERMES [14]. Since the only known contribution to the $\sin 2\phi$ moments comes from the Collins effect, one can infer that, for π^0, the Collins function is suppressed. Indeed, both HERMES [14] and Belle [37] measurements indicate that favored and unfavored Collins functions are roughly equal and have opposite signs, which means that they largely cancel for π^0. On the other hand, the amplitudes of the $\sin\phi$ modulations for π^+ and π^0 are comparable in size. This indicates that the contribution from the Collins effect to the $\sin\phi$ SSA, in general, is relatively small.

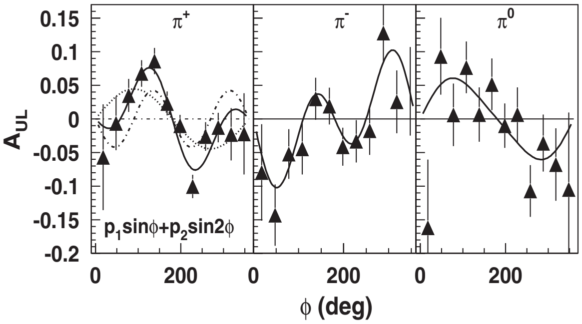

FIG. 2. Azimuthal modulation of the target single spin asymmetry $A_{\rm UL}$ for pions integrated over the full kinematics. Only statistical uncertainties are shown. Fit parameters p_1/p_2 are (0.047 ± 0.010, -0.042 ± 0.010), (-0.046 ± 0.016, -0.060 ± 0.016), (0.059 ± 0.018, 0.010 ± 0.019) for π^+, π^-, and π^0, respectively. Dotted and dash-dotted lines for π^+ show separately contributions from $\sin\phi$ and $\sin 2\phi$ moments, whereas the solid line shows the sum.

The $\sin 2\phi$ moment $A_{\rm UL}^{\sin 2\phi}$ as a function of x is plotted in Fig. 3. Calculations [30,36] using $h_{1L}^{\perp}$ from the chiral quark soliton model [47] and the Collins function [48] extracted from HERMES [14] and Belle [37] data, are plotted as filled bands in Fig. 3. The kinematic dependence of the SSA for π^+ from the CLAS data is roughly consistent with these predictions. The interpretation of the π^- data, which tend to have SSAs with a sign opposite to expectations, may require accounting for additional contributions (e.g., interference effects from exclusive $\rho^0 p$ and $\pi^-\Delta^{++}$ channels). This will require a detailed study with higher statistics of both double and single spin asymmetries from pions coming from ρ decays.

In summary, kinematic dependencies of single and double-spin asymmetries have been measured in a wide kinematic range in x and P_T with CLAS and a longitudinally polarized proton target. Measurements of the P_T dependence of the double-spin asymmetry, performed for the first time, indicate the possibility of different average transverse momentum for quarks aligned or antialigned with the nucleon spin. A nonzero $\sin 2\phi$ single-target spin asymmetry is measured for the first time, indicating that spin-orbit correlations of transversely polarized quarks in the longitudinally polarized nucleon may be significant.

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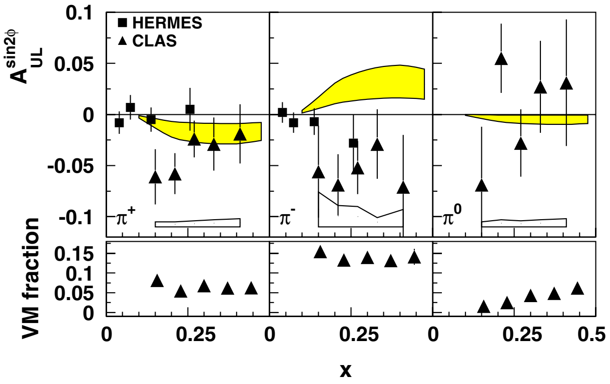

FIG. 3 (color online). The measured x dependence of the longitudinal target SSA $A_{\rm UL}^{\sin 2\phi}$ (triangles). The squares show the existing measurement of $A_{\rm UL}^{\sin 2\phi}$ from HERMES. The lower band shows the systematic uncertainty. The upper band shows the existing theory predictions with uncertainties due to the Collins function [30,48].

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