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 Thomas Jefferson National Accelerator Facility (JLab). A significant non-zero $\sin 2\phi$ single spin asymmetry was also observed for the first time indicating strong spin-orbit correlations for transversely polarized quarks in the longitudinally polarized proton. The azimuthal modulations of single spin asymmetries have been measured over a wide kinematic range.

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A measurement of transverse momenta (P_T) of final-state hadrons in semi-inclusive deep inelastic scattering (SIDIS) $\vec{e}\vec{p} \to e'hX$, 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 (for P_T comparable to the proton mass M_p and Λ_{QCD}), in particular, allow studies of transverse momentum (k_T) widths of different TMDs, providing quantitative information on how quarks are confined in hadrons.

The P_T-dependence of the double-spin asymmetry also probes the transition from a non-perturbative to a perturbative description. At large P_T ($\Lambda_{QCD} << P_T << Q$), the double spin asymmetry is expected to be independent of P_T [3].

Azimuthal distributions of final state particles in SIDIS 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. Large Single Spin Asymmetries (SSAs), appearing as azimuthal moments of the cross section, have been observed for decades in hadronic reactions. They have been among the most difficult phenomena to understand from first principles in QCD. Two fundamental mechanisms have been identified that lead to SSAs in hard processes; the Sivers mechanism [5–9], which generates an asymmetry in the distribution of quarks due to orbital motion of partons, and the Collins mechanism [7, 10], 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 [11–21].

For the longitudinally polarized target case, first discussed by Kotzinian and Mulders [10, 22, 23], the only SSA, depending on the azimuthal angle ϕ between the lepton scattering and pion production planes [24], arising at leading order is the $\sin 2\phi$ moment. For a given Bjorken variable (x) and fraction of the energy of the virtual photon carried by the final state hadron (z), it involves the convolution of distribution and fragmentation functions. Corresponding functions are the Ralston-Soper-Mulders-Tangerman (RSMT) distribution function $h_{1L}^{\perp}(x, k_T)$ [10, 25] describing the transverse polarization of quarks in a longitudinally polarized proton [3, 10, 22, 23, 26], and the Collins fragmentation function $H_1^{\perp}(z, p_T)$ [27] describing fragmentation of transversely polarized quarks into unpolarized hadrons. The final transverse momentum of the hadron in leading order is defined by the combination $zk_T + p_T$, where p_T is the transverse momentum generated in the hadronization process.

The only available measurement of the $\sin 2\phi$ moment by HERMES [11] is consistent with zero. The RSMT distribution function has been studied in various QCD inspired models [28–31]. First calculations for $h_{1L}^{\perp}(x, k_T)$ have recently been performed in the perturbative limit [32], and first measurements have been performed using lattice methods [33]. A measurably large asymmetry has been predicted [28–31, 34] only at large x ($x > 0.2$), a region well-covered by JLab. The same distribution function is also accessible in double-polarized Drell-Yan production, where it gives rise to the $\cos 2\phi$ azimuthal moment in the cross section [35].

The $\sin \phi$ moment of the spin-dependent cross section for the longitudinally polarized target is dominated by higher-twist contributions [4] which are suppressed by $1/Q$ at large momentum transfer. This moment has been measured for the first time by the HERMES Collaboration [11]. Higher-twist observables, such as longitudinally polarized beam or target SSAs, are important for understanding long-range quark-gluon dynamics. Recently, higher-twist effects in SIDIS were interpreted in terms of an average transverse force acting on the active quarks in the instant after being struck by the virtual photon [36].

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]. The $\sin 2\phi$ asymmetry, however, provides a cleaner measurement of Collins fragmentation because it doesn't have a Sivers type contribution in the leading order [23].

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 degrees. 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. At large z ($z > 0.7$) the fraction of $\pi^\pm$ from ρ^0-decays can be fairly large and the corrections due to pions coming from the ρ (from 5 to 20% for $z < 0.7$), not accounted for in the current analysis, may be significant.

The double spin asymmetry A_1 is defined as

$$A_1 = \frac{1}{fD'(y)P_B P_t}\frac{N^+ - N^-}{N^+ + N^-} \tag{1}$$

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 $D'(y)$:

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

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

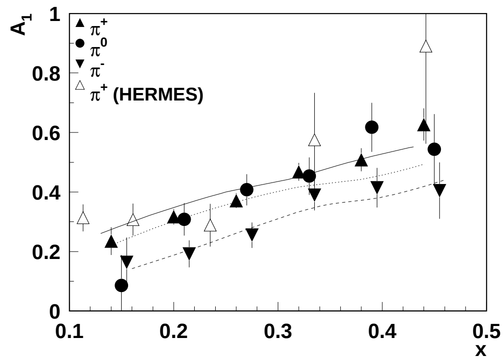

FIG. 1: The double-spin asymmetry as a function of x from a polarized proton target for different pions. Open triangles correspond to the HERMES measurement of A_1 for π^+ [42]. Only statistical uncertainties are shown. The solid, dashed and dotted curves, calculated using LO GRSV PDF [43] and $D_1^{d\to\pi+}/D_1^{u\to\pi+} = 1/(1+z)^2$ [20] correspond to π^+, π^-, and π^0, respectively.

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 [44] were estimated to be below 3% each.

The dependence of the double-spin asymmetry on Bjorken x for different pions obtained from the CLAS data is presented in Fig. 1. The results for A_1 are consistent with the HERMES semi-inclusive data, and at large x have significantly smaller statistical uncertainties. The double spin asymmetries measured by HERMES and CLAS at different beam energies (by a factor of ≈ 5) and different values of average Q^2 (by a factor of ≈ 3), for a fixed x-bin are in good agreement, indicating no significant Q^2 dependence of the double polarization asymmetry A_1. Measured asymmetries are also consistent with calculations performed using leading-order GRSV PDFs [43] and a simple parametrization of the ratio of unfavored and favored fragmentation functions [20].

A_1 is shown in Fig. 2 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 [45] resulting from different orbital motion of quarks polarized in the direction of the proton spin and opposite to it [46, 47]. In Fig. 2 the measured A_1 is compared with calculations of the Torino group [45], 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 with no flavor dependence. A fit to $A_1(P_T)$ for π^+ using the same approach yields a ratio of widths of 0.7 ± 0.1 with $\chi^2 = 1.5$. The fit to A_1 with a straight line (no difference in g_1 and f_1 widths) gives a $\chi^2 = 1.9$.

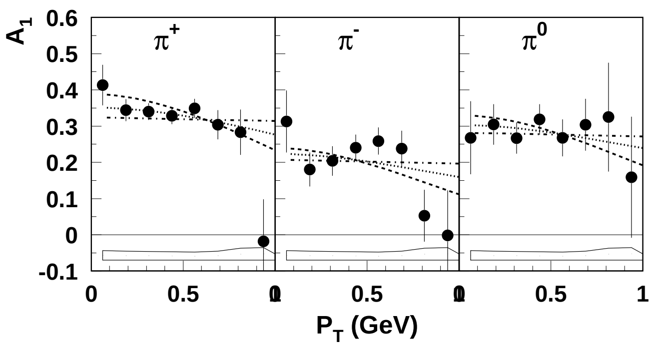

FIG. 2: The double spin asymmetry A_1 as a function of transverse momentum P_T, integrated over all kinematical variables. The open band corresponds to systematic uncertainties. The dashed, dotted and dash-dotted curves are calculations for different values for the ratio of transverse momentum widths for g_1 and f_1 (0.40, 0.68, 1.0) for a fixed width for f_1 (0.25 GeV^2) [45].

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),

$$A_{UL} = \frac{1}{fP_t}\frac{N^+ - N^-}{N^+ + N^-} \tag{3}$$

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

The standard procedure for the extraction of the different moments involves sorting A_{UL} in bins of ϕ and fitting this ϕ-distribution with theoretically motivated

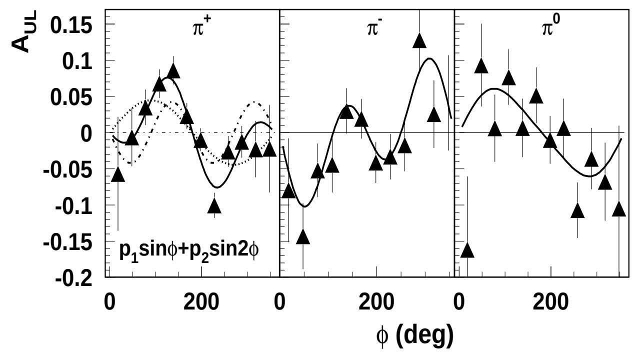

FIG. 3: Azimuthal modulation of the target single spin asymmetry A_{UL} for pions integrated over the full kinematics. Only statistical uncertainties are shown. Fit parameters p_1/p_2 are $0.047\pm0.010/-0.042\pm0.010$, $-0.046\pm0.016/-0.060\pm0.016$, $0.059 \pm 0.018/0.010 \pm 0.019$ for π^+, π^- and 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.

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. 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 [48].

The dependence of the target single spin asymmetry on ϕ, integrated over all other kinematical variables, is plotted in Fig. 3. 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 [13]. 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 [13] 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.

The $\sin 2\phi$ moment $A_{UL}^{\sin 2\phi}$ as a function of x is plotted in Fig. 4. Calculations [28, 34] using $h_{1L}^{\perp}$ from the chiral quark soliton model [49] and the Collins function [50] extracted from HERMES [13] and Belle [37] data, are plotted as filled bands in Fig. 4. 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.

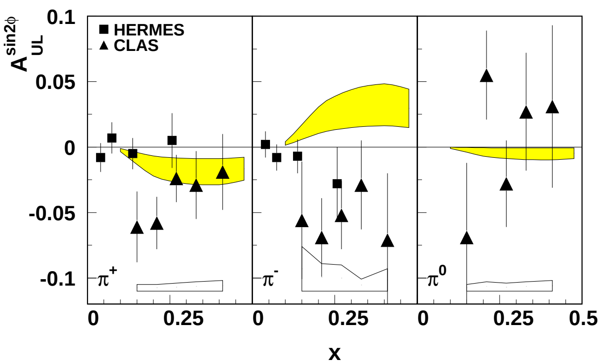

FIG. 4: The measured x-dependence of the longitudinal target SSA $A_{UL}^{\sin 2\phi}$ (triangles). The squares show the existing measurement of $A_{UL}^{\sin 2\phi}$ from HERMES. The lower band shows the systematic uncertainty. The upper band shows the existing theory predictions with uncertainties due to the Collins function [28, 50].

The $\sin 2\phi$ moment of the π^+ SSA at large x is dominated by u-quarks; therefore with additional input from Belle measurements [37] on the ratio of unfavored to favored Collins fragmentation functions, it can provide a first glimpse of the twist-2 TMD function $h_{1L}^{\perp}$.

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 anti-aligned with the nucleon spin. A non-zero $\sin 2\phi$ 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.

New, higher statistics measurements of SSAs in SIDIS at CLAS [51] will allow us to examine the Q^2, x, and P_T dependences of azimuthal moments in multi-dimensional bins and investigate the twist nature of different observables.

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