Measurement of Beam-Spin Asymmetries for Deep Inelastic π^+ Electroproduction

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We report the first evidence for a non-zero beam-spin azimuthal asymmetry in the electroproduction of positive pions in the deep-inelastic region. Data have been obtained using a polarized electron beam of 4.3 GeV with the CLAS detector at the Thomas Jefferson National Accelerator Facility (JLab). The amplitude of the $\sin\phi$ modulation increases with the momentum of the pion relative to the virtual photon, z, with an average amplitude of $0.038 \pm 0.005 \pm 0.003$ for $0.5 < z < 0.8$ range.

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The origin of the spin of the proton has become a topic of considerable experimental and theoretical interest since the EMC [1] measurements implied that quark helicities account for only a small fraction of the nucleon spin. As a consequence, the study of the gluon polarization and the orbital angular momentum of partons have become of central interest. The single-spin asymmetries (SSA) that have been observed in hadronic reactions for decades [2, 3], have emerged as a powerful tool to access transverse momentum distributions of partons and to give access to the total orbital angular momentum.

In this Letter, we present the first measurement of a significant beam-spin asymmetry in the electroproduction of positive pions in deep-inelastic scattering. Recently, significant SSAs have been reported in semi-inclusive DIS (SIDIS) pion production by the HERMES collaboration [4, 5] for a longitudinally polarized target, and by the SMC collaboration at CERN for a transversely polarized target [6]. Such single-spin asymmetries require a correlation between the spin direction of a particle and the orientation of the production (or scattering) plane, and are directly related to the orbital angular momentum of partons in the nucleon. The interference of wavefunctions with different orbital angular momentum that may be responsible for single-spin asymmetries [7, 8, 9, 10, 11, 12, 13] also yields the helicity-flip Generalized Parton Distribution (GPD) E [14, 15] that enters Deeply Virtual Compton Scattering (DVCS) [16, 17] and the Pauli form factor F_2. The connection of SSAs and GPDs has also been discussed in terms of the transverse distribution of quarks in nucleons [18]. Physical observables accessible in SSAs include novel distribution functions; the transversity [19, 20] and the recently introduced [7, 8, 9, 10, 11, 12, 13] *time-reversal odd* (T-odd) distribution functions are prominent examples. Other important quantities are the so-called T-odd fragmentation functions, in particular the Collins function [21].

Spin asymmetries, in both semi-inclusive [22] and in hard exclusive [23, 24] pion production, are particularly suited to access parton distributions as they are less sensitive to a wide range of corrections than cross section measurements. The measurement of spin asymmetries could become a major tool for studying quark transverse momentum dependent distributions [7, 13, 21, 25, 26] and GPDs in the Q^2 domain of a few GeV^2.

Higher-twist effects in hard processes arise from the quantum mechanical interference of amplitudes involving different partons in the interacting hadrons. The higher-twist terms are important for understanding the long-range quark-gluon dynamics, they may be accessible as leading contributions through the measurements of certain asymmetries [20, 25, 26, 27].

Although large beam-spin asymmetries have been observed in measurements of exclusive electroproduction of photons (DVCS) [28, 29], the only existing measurement of the beam-spin asymmetry in semi-inclusive pion electroproduction was reported recently by the HERMES collaboration [4] for relatively low z ($\langle z\rangle \approx 0.4$). Within statistical uncertainties their reported value is consistent with zero.

The cross section for single pion production by longitudinally polarized leptons scattering from unpolarized protons is defined by a set of response functions. The helicity (λ_e) dependent part (σ_{LU}) [25, 27] arises from the anti-symmetric part of the hadronic tensor:

$$\frac{d\sigma_{LU}}{dxdy\,dzd^2P_\perp} \propto \lambda_e\sqrt{y^2+\gamma^2}\sqrt{1-y-\frac{1}{4}\gamma^2}\,\sin\phi\,\mathcal{H}'_{LT}. (1)$$

The subscripts in σ_{LU} specify the beam and target polarizations, respectively (L stands for longitudinally polarized and U for unpolarized). The azimuthal angle ϕ is defined by a triple product:

$$\sin\phi = \frac{[\vec{k}_1 \times \vec{k}_2]\cdot\vec{P}_\perp}{|\vec{k}_1 \times \vec{k}_2||\vec{P}_\perp|},$$

where $\vec{k}_1$ and $\vec{k}_2$ are the initial and final electron momenta, and $\vec{P}_\perp$ is the transverse momentum of the observed hadron with respect to the virtual photon $\vec{q}$. The structure function $\mathcal{H}'_{LT}$ is related to the interference of the longitudinal and transverse photon contributions. The kinematic variables x, y, and z are defined as: $x = Q^2/2(P_1q)$, $y = (P_1q)/(P_1k_1)$, $z = (P_1P)/(P_1q)$, where $Q^2 = -q^2$, $q = k_1 - k_2$ is the momentum of the virtual photon, P_1 and P are the momenta of the target and the observed final-state hadron, and $\gamma^2 = 4M^2x^2y^2/Q^2$.

The beam-spin dependent asymmetries in single pion inclusive leptoproduction was measured in February 1999 using a 4.3 GeV electron beam and the CEBAF Large Acceptance Spectrometer (CLAS) [30] at JLab. Scattering of longitudinally polarized electrons off a liquid-hydrogen target was studied over a wide range of kinematics. The beam polarization, frequently measured with a Møller polarimeter, was on average 0.70 ± 0.03. The scattered electrons and pions were detected in CLAS. Electron candidates were selected by a hardware trigger using a coincidence between the gas Cerenkov counters and the lead-scintillator electromagnetic calorimeters. Pions in a momentum range of 1.2 to 2.6 GeV were identified using momentum reconstruction in the tracking system and the time-of-flight from the target to the scintillators. The total number of electron-π^+ coincidences in the DIS range ($Q^2 > 1$ GeV^2, $W^2 > 4$ GeV^2) was $\approx 4 \times 10^5$. Averages of the relevant variables for the x and z bins are listed in Table I.

The kinematic cuts to select the current fragmentation region were set by comparing the CLAS data with the Lund [31] Monte Carlo (MC). In the Lund model, pion production is dominated by direct production from string fragmentation for $z > 0.5$, as opposed to secondary processes like target fragmentation and baryonic decays. An upper limit on $z(< 0.8)$ was chosen to exclude the kinematic region where higher-twist and diffractive effects in pion production may be dominant.

We find that in the intermediate range of z ($0.5 < z < 0.8$) the kinematic distributions of final state pions at CLAS are in good agreement with the LUND-MC (see Fig. 1) even though the latter was developed and tuned at much higher beam energies. We verified that the z

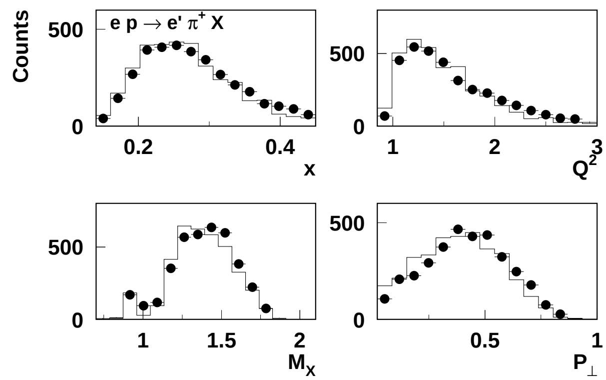

FIG. 1: Comparison of the distributions measured with CLAS at 4.3 GeV (circles) in x, Q^2, missing mass M_X in $\gamma^* p \to \pi^+ + X$, and the transverse pion momentum $P_\perp$ with LUND-MC reconstructed events. The distributions are averages over the range $0.5 < z < 0.8$; the MC results are normalized to the same number of events.

cut selects a region in which the z-distributions of the yields and of the beam SSAs [32] do not exhibit any significant x-dependence. This behavior is consistent with factorization in the chosen kinematic range.

To minimize radiative corrections, a cut on the the energy of the virtual photon relative to the incoming electron ($y < 0.85$) was imposed. The estimated radiative corrections do not exceed a few percent of the value of the SSA [33], and give a minor contribution to the systematic uncertainty.

The ϕ-dependent beam-spin asymmetries are formed by extracting moments of the cross section for the two helicity states weighted by the corresponding ϕ-dependent functions. The $\sin\phi$ moment is given by:

$$A_{LU}^{\sin\phi} = \frac{2}{P^\pm N^\pm}\sum_{i=1}^{N^\pm}\sin\phi_i, \qquad (2)$$

where $N^\pm$ and $P^\pm$ are the number of events and the luminosity-weighted polarization for positive/negative helicities of the electron, respectively. The azimuthal moment $A_{LU}^{\sin\phi}$ can be computed for each polarization state, and the comparison of the two results provides a strong test of systematics. The same quantity can be computed as the $\sin\phi$ moment of the spin asymmetry. The two methods are identical for complete acceptance, but in practice have different sensitivities to acceptance effects. The beam SSA, $A_{LU}^{\sin\phi}$, obtained from data with opposite beam helicities is in good agreement with the result extracted from the $\sin\phi$ azimuthal moment of the spin asymmetry (Fig.2). This indicates that within statistical uncertainties the acceptance corrections are not significant.

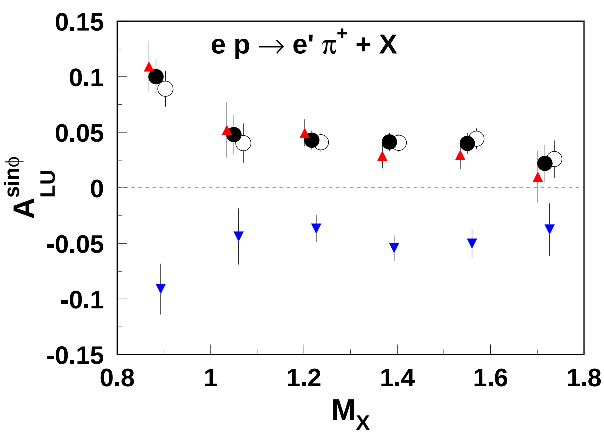

FIG. 2: The beam-spin azimuthal asymmetry as a function of M_X, extracted in the range $0.5 < z < 0.8$. Triangles up and down are the results for positive and negative helicities, respectively, and the filled circles are for their average. Open circles show the measured $A_{LU}^{\sin\phi}$ extracted as a $\sin\phi$ moment of the spin asymmetry.

Contributions to the systematic uncertainties arise from spin-dependent moments of the cross section coupling to corresponding moments in the acceptance to produce corrections to the measured $\sin\phi$ moment. The contribution to uncertainties in these corrections is evaluated to be less than 0.005 in all bins. The systematic uncertainties in the measurement of the beam polarization contribute at an even lower level. Particle mis-identification over the accessible kinematic range changes the observed SSA by less than 0.001. Other systematic uncertainties are negligible.

$A_{LU}^{\sin\phi}$ averaged over the two spin states as a function of x and z is plotted in Fig. 3 and listed in Table II. A cut on the missing mass of the $e'\pi^+$ system, $M_X > 1.1$ GeV, is used to eliminate $ep \to e'\pi^+ n$ events. The asymmetry is positive for a positive electron helicity in the range of $0.15 < x < 0.4$. $A_{LU}^{\sin\phi}$ is large at large z and low M_X (see Fig. 2), where according to LUND-MC the probability of the detected pion to carry the struck quark is maximal.

Early investigations [34] had shown that a non-zero $\mathcal{H}'_{LT}$ could arise from $\mathcal{O}(\alpha_S^2)$ QCD effects; however, the predicted size of the beam-spin dependent asymmetry reaches a maximum of ~ 0.01 at relatively low $z(\sim 0.2)$.

Assuming that the quark scattering and fragmentation processes factorize, the structure function $\mathcal{H}'_{LT}$ can also be evaluated as the convolution of a distribution and a fragmentation function. The functions responsible for non-zero $\mathcal{H}'_{LT}$ in SIDIS were first identified by Levelt and Mulders [27]. They include the twist-3 unpolarized distribution function $e(x)$, introduced by Jaffe and Ji [20], and the polarized fragmentation function $H_1^\perp(z)$ first discussed by Collins [21]. In this picture, the x dependence of the beam SSA is mainly defined by the ratio of the interaction dependent part of the twist-3 unpolarized distribution function, $e(x)$, to the leading-twist unpolarized distribution function, $f_1(x)$. Likewise, the z dependence probes the ratio of polarized to unpolarized fragmentation functions [27] .

Knowledge of the distribution function involved in beam SSA allows a measurement of the fragmentation function, and vice versa. The first extraction of the twist-3 distribution function from the CLAS beam SSA data was reported recently by Efremov *et al.* [35] using a particular parameterization of the Collins fragmentation function. The relatively flat x-dependence of $e(x)$ in the x range $0.14 - 0.4$ that they reported is in qualitative agreement with a calculation using the bag model for a Q^2 of 1 GeV^2 [36].

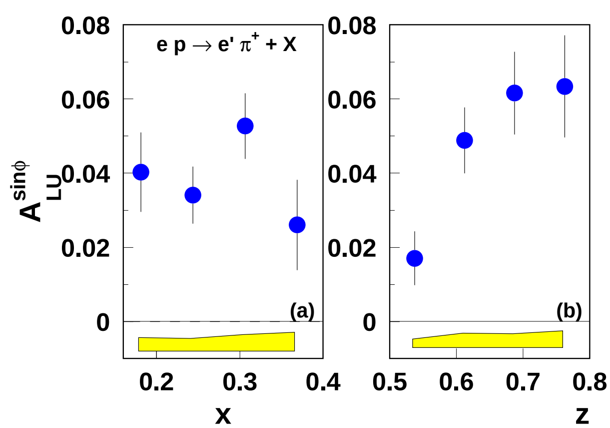

FIG. 3: The beam-spin azimuthal asymmetry as a function of x (a) and z (b) in a range $0.15 < x < 0.4$. The error bars show the statistical uncertainty, and the band represents the systematic uncertainties.

Our reported beam SSA value at the exclusive limit, both at large z (Fig. 3b) and low M_X (Fig. 2) differs significantly from the behavior of the target SSA reported by HERMES [37, 38]. We observe a positive beam SSA value in this region, where the HERMES target SSA results show a negative value. There are indications [32, 39] that in fact beam and target SSAs have different z-shapes, and that the behavior of beam SSAs measured at CLAS and HERMES are consistent.

The study of transversity, the third essentially unknown parton distribution function, is the object of experiments running at HERA [40], CERN SPS [41], and will be an important part of the upgraded JLab program at 12 GeV [42]. The interpretation of these experiments will require a detailed knowledge of the Collins fragmentation function, $H_1^\perp(z)$, describing the fragmentation of a transversely polarized quark into an unpolarized hadron [21]. Despite first attempts to extract the Collins function from e^+e^- annihilation [43, 44] as well as from semi-inclusive DIS data [4, 45], at present no convincing information is available on the magnitude or on the shape of the Collins function. The beam SSA analyzed in terms of the fragmentation effect depends on the product of $e(x)$ and the Collins function [25, 27], making it an important source of independent information on the z-dependence of $H_1^\perp(z)$. Measurements at JLab utilizing high luminosity could help constrain the Collins function.

In conclusion, we have presented the first measurement of a significant beam-spin asymmetry in semi-inclusive π^+ electroproduction in the DIS region. Significant differences are observed in the behavior of beam and target SSA in the exclusive limit. The higher statistics expected from ongoing experiments at CLAS using 6 GeV polarized beams and both polarized and unpolarized targets will allow the extraction of the Q^2-dependence of the SSAs at fixed x and z. This will enable us to further examine the factorization hypothesis and to identify the higher-twist nature of the process.

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TABLE I: Average values of Q^2 (GeV^2), W^2 (GeV^2), y, $P_\perp$ (GeV) and z/x in each of x and z bins

x	$\langle Q^2\rangle$	$\langle W^2\rangle$	$\langle y\rangle$	$\langle P_\perp\rangle$	$\langle z\rangle$	z	$\langle Q^2\rangle$	$\langle W^2\rangle$	$\langle P_\perp\rangle$	$\langle x\rangle$
0.18	1.1	6.0	0.78	0.48	0.60	0.54	1.34	5.3	0.45	0.27
0.24	1.4	4.9	0.67	0.42	0.61	0.61	1.32	5.2	0.43	0.27
0.31	1.6	4.7	0.68	0.41	0.61	0.69	1.31	5.1	0.42	0.27
0.37	2.1	4.4	0.71	0.38	0.61	0.77	1.31	5.2	0.35	0.27

TABLE II: SSA: x and z-dependence

x	$A_{LU}^{\sin\phi} \pm \Delta_{stat} \pm \Delta_{syst}$	z	$A_{LU}^{\sin\phi} \pm \Delta_{stat} \pm \Delta_{syst}$
0.18	0.041 ± 0.011 ± 0.004	0.54	0.017 ± 0.007 ± 0.002
0.24	0.034 ± 0.008 ± 0.003	0.61	0.049 ± 0.009 ± 0.004
0.31	0.053 ± 0.009 ± 0.004	0.69	0.062 ± 0.011 ± 0.004
0.37	0.026 ± 0.012 ± 0.005	0.76	0.063 ± 0.014 ± 0.005