Studies of spin-orbit correlations at JLAB

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Abstract. Studies of single spin asymmetries for pion electroproduction in semi-inclusive deep-inelastic scattering are presented using the polarized \( \sim 6 \) GeV electrons from at the Thomas Jefferson National Accelerator Facility (JLab) and the Continuous Electron Beam Accelerator Facility (CEBAF) Large Acceptance Spectrometer (CLAS) with the Inner Calorimeter. The cross section versus the azimuthal angle \( \phi_h \) of the produced neutral pion has a substantial \( \sin \phi_h \) amplitude. The dependence of this amplitude on Bjorken \( x_B \) and on the pion transverse momentum is extracted and compared with published data.

1. Introduction

In recent years it became clear that understanding the orbital motion of partons, and in particular the role of partonic initial and final state interactions of quarks, is crucial for the construction of a more complete picture of the nucleon in terms of elementary quarks and gluons. Parton distribution functions have been generalized to contain information not only on the longitudinal momentum but also on the transverse momentum distributions of partons in a fast moving hadron. Intense investigation of Transverse Momentum Dependent (TMD) distributions of partons both from the experimental and theoretical sides, indicate that QCD-dynamics inside hadrons is much richer than what can be learned from collinear parton distributions.

Two fundamental mechanisms have been identified leading to single-spin asymmetries (SSAs) in hard processes: the Sivers mechanism [1, 2, 3, 4, 5], which generates an azimuthal asymmetry in the distribution of quarks in the nucleon due to their orbital motion, and the Collins mechanism [4, 6], which generates an asymmetry during the hadronization of quarks. TMD distributions also contain unique information on the role of initial and final state interactions of active partons in hard scattering processes [3, 4, 5].

Semi-inclusive deep-inelastic scattering (SIDIS) has emerged as a powerful tool to probe nucleon structure and provide direct access to TMDs through measurements of spin and azimuthal asymmetries. In particular, SSAs, arising from correlations of the transverse parton momentum and the transverse spin of the parton or from the initial or final state hadron, provide unprecedented information about spin-orbit correlations. QCD factorization for semi-inclusive deep-inelastic scattering at low transverse momentum in the current-fragmentation region has been established in references [7, 8, 9]. This new framework provides a rigorous basis to study the TMD parton distributions from SIDIS data using different spin-dependent and independent observables. The analyses of the TMDs strongly depends also on knowledge of the fragmentation functions [10, 11, 12, 13]. Many experiments are currently trying to pin down various TMD effects through 1) semi-inclusive deep-inelastic scattering (HERMES at DESY [14, 15, 16, 17], COMPASS at
The cross section for single pion production by longitudinally polarized electrons scattered from unpolarized protons may be written in terms of a set of structure functions \[ \sigma_{LU} \] \[ \sigma_{U} \] \[ \sigma_{L} \]. The helicity dependent part \( \sigma_{LU} \) arises from the anti-symmetric part of the hadronic tensor:

\[
\frac{d\sigma_{LU}}{dx_Bdy,dz^2P_Td\phi_h} \propto \lambda_e \times \sqrt{y^2 + \gamma^2} \sqrt{1 - y - \frac{1}{4}\gamma^2 \sin \phi_h} F_{LU}^{\sin \phi_h}.
\]

The subscripts on \( \sigma_{LU} \) specify the beam and target polarizations, respectively \( (L \) stands for longitudinally polarized and \( U \) for unpolarized). The azimuthal angle \( \phi_h \) is the angle between leptonic and hadronic plane according to the Trento convention \[28\]. The kinematic variables \( x_B, y, \) and \( z \) are defined as: \( x_B = Q^2/2(P_1 q) \), \( y = (P_1 q)/(P_k k_1) \), \( z = (P_k P)/(P_k q) \), where \( Q^2 = -q^2 = -(k_1 - k_2)^2 \) is the four-momentum of the virtual photon, \( k_1 \) (\( k_2 \)) is the four-momentum of the incoming (scattered) lepton, \( P_1 \) and \( P \) are the four momenta of the target nucleon and the observed final-state hadron (respectively), \( \gamma^2 = 4M^2y^2g^2/Q^2 \), \( M \) is the nucleon mass, and \( \lambda_e \) is the electron beam helicity.

The structure function \( F_{LU}^{\sin \phi_h} \) arises due to the interference of the longitudinal and transverse photon contributions. In the partonic description of SIDIS, assuming factorization holds, contributions to structure functions can be written as convolutions of parton distribution and fragmentation functions dependent on the scaling variables \( x_B \) and \( z \), respectively \[6, 7\].

The beam-spin asymmetries in single-pion production off an unpolarized target are higher-twist by nature \[29, 30\]. Higher-twist observables are important for understanding the long-range quark-gluon dynamics and may also be accessible as leading contributions through the measurements of certain asymmetries \[26, 31, 32, 33\], in particular the beam SSAs.

Recently, higher-twist effects in SIDIS were interpreted in terms of average transverse forces acting on the active quark at the instant after being struck by the virtual photon \[34\]. Different contributions to the beam SSAs discussed so far provide information on leading and sub-leading parton distribution and fragmentation functions, related both to Collins and Sivers production mechanisms. Sizable beam SSAs were predicted \[30\] based on spin-orbit correlations as the dynamical origin. Within this framework, the asymmetry generated at the distribution level, is given by either the convolution of the T-odd parton distribution \( h_T^+ \) with the twist-3 fragmentation function \( E \) \[31\], or the convolution of the twist-3 T-odd distribution function \( g^T \) with the unpolarized fragmentation function \( D_1 \) \[35\].

2. The \( \pi^0 \) beam spin asymmetry

In this section we present measurements from the E01-113 CLAS dataset of beam-spin asymmetries in the electroproduction of neutral pions in deep-inelastic scattering using the 5.776 GeV electron beam and the CEBAF Large Acceptance Spectrometer (CLAS) \[36\] at Jefferson Laboratory. Longitudinally polarized electrons are scattered off a liquid-hydrogen target. The beam polarization, frequently measured with a Möller polarimeter, was on average 0.80 with a fractional systematic uncertainty of 3%. The beam helicity was flipped every 30 ms to minimize systematic instrumental effects. Scattered electrons were detected in CLAS. Electron candidates were selected by a hardware trigger using a coincidence between the gas Cherenkov counters and the lead-scintillator electromagnetic calorimeters (EC).

Neutral pion events were identified by calculating the invariant mass of two photons detected with the CLAS electromagnetic calorimeter and the Inner Calorimeter (IC) \[37\]. In each kinematic bin, \( \pi^0 \) events are selected by a gaussian plus linear fit (see figure 1). The combinatorial background is subtracted in each bin from the number of events inside 3\( \sigma \) using the linear component of the fit.
deep-inelastic scattering events are selected by requiring $Q^2 > 1 \text{ GeV}^2$ and $W^2 > 4 \text{ GeV}^2$, where $W$ is the invariant mass of the hadronic final state. Events with low missing mass of the $e\pi^0$ system ($M_X < 1.5 \text{ GeV}$) were discarded to exclude contributions from exclusive processes. The minimum value of the transverse $\pi^0$ momentum, $P_T > 0.05 \text{ GeV}$, ensures that the azimuthal angle $\phi_h$ is well defined. The total number of selected electron-$\pi^0$ coincidences is $\approx 3.0 \times 10^6$.

The beam-spin asymmetry has been calculated for each kinematic bin as:

$$A_{LU}(\phi_h) = \frac{1}{P} \frac{N^+_{\pi^0}(\phi_h) - N^-_{\pi^0}(\phi_h)}{N^+_{\pi^0}(\phi_h) + N^-_{\pi^0}(\phi_h)}$$

where $P = 0.794 \pm 0.024$ is the absolute beam polarization this data set and $N^+_{\pi^0}$ and $N^-_{\pi^0}$ are the number of $\pi^0$'s with positive and negative beam helicity, respectively. Asymmetry moments are extracted by fitting the $\phi_h$-distribution of $A_{LU}$ in each $x_B$ and $P_T$ bin with the theoretically motivated function $p_0 \cdot \sin(\phi_h)$. An example of this fit is shown in figure 2 for an arbitrarily chosen kinematic bin.

In figure 3 the extracted $A_{LU}^{\sin \phi_h}$ moment is presented as a function of $P_T$ for different $x_B$ ranges. Systematic uncertainties, presented by the bands, include the uncertainties due to the background subtraction, the event selection and possible contributions of higher harmonics in the extraction of the moments. These contributions are added in quadrature. An additional 3% uncertainty due to the beam polarization measurement and another 3% uncertainty from radiative effects should be added to the systematic uncertainties.

The $A_{LU}^{\sin \phi_h}$ moment increases at low $P_T$ and reaches a plateau at values of about 0.3 GeV. There is an indication that the decrease of $A_{LU}^{\sin \phi_h}$ at large $P_T$, expected from perturbative QCD, starts already at $P_T \sim 0.6 \text{ GeV}$.

The surprising characteristics of favored and unfavored Collins functions, being of roughly equal magnitude but having opposite signs, as indicated by latest measurements at HERMES [14, 15], COMPASS [18] and Belle [25], puts the $\pi^0$ in a unique position in SSA studies. Since the $\pi^0$ fragmentation function (FF) is the sum of $\pi^+$ and $\pi^-$ FFs, its favored and unfavored contributions will be roughly equal and, in the case of the Collins FF, will cancel each other to a large extent. Contributions to the beam-SSA related to spin-orbit correlations can thus be studied without a significant background from the Collins mechanism.
Figure 3. \( A_{LU}^{\sin \phi_h} \) as function of \( P_T \) for different \( x_B \) ranges and integrated over \( 0.4 < z < 0.7 \). The error bars correspond to statistical and the bands to systematic uncertainties. An additional 3% uncertainty arises from the beam polarization measurement and another 3% uncertainty from radiative effects.

The measured beam-spin asymmetry amplitude for \( \pi^0 \) appears to be comparable with the \( \pi^+ \) asymmetry from a former CLAS data set [38] both in magnitude and sign, as shown in figure 4, indicating that contributions from the Collins mechanism cannot be the dominant ones.

A similar measurement has been performed by the HERMES collaboration at a higher beam energy of 27.6 GeV [17]. After taking into account the kinematic factors in the expression of the beam-helicity dependent and unpolarized terms ([27])

\[
f(y) = \frac{y\sqrt{1-y}}{1-y+y^2/2},
\]

CLAS and HERMES measurements are found to be consistent as shown in figures 5 and 6, indicating that at energies as low as 4-6 GeV the behavior of beam-spin asymmetries is similar to higher energy measurements. The CLAS data provide significant improvements in precision of beam SSA measurements in the kinematic region where the two data sets overlap, and extend the measurements to the large \( x_B \) region not accessible by HERMES.

2.1. Contamination from two-hadron production

In this section a study of the beam spin asymmetry of single-pion production from exclusive and non-exclusive vector meson production is presented. In order to investigate a possible contamination of the presented results by pions originating from the decay of exclusively produced vector mesons,
Figure 4. The $\pi^0$ beam-spin asymmetry amplitude $A_{LU}^{\sin \phi_h}$ as function of $x_B$ compared to that for $\pi^+$ from an earlier CLAS measurement [38]. Uncertainties of the $\pi^0$ measurement are as in figure 3. For both data sets $<P_T> \approx 0.38$ and $0.4 < z < 0.7$.

Figure 5. $A_{LU}^{\sin \phi_h}$ multiplied by the kinematic factor $<Q>/f(y)$ as a function of $x_B$ from CLAS and HERMES [17]. The 0.4 GeV/$c < P_T < 0.6$ GeV/$c$ range for the CLAS data was used to compare with HERMES, since this is the closest kinematic range.

Figure 6. $A_{LU}^{\sin \phi_h}$ multiplied by the kinematic factor $<Q>/f(y)$ as a function of $P_T$ from CLAS and HERMES [17] (the same as in figure 5). The $0.1 < x_B < 0.2$ range for the CLAS data was used to compare with, since this is the closest kinematic range.

as advocated in [17], events with at least one $\pi^0$ and $\pi^+$ were selected from the same dataset. Exclusivity was ensured by requiring the missing mass $M_x$ of the $ep \rightarrow e'\pi^0\pi^+X$ system to be within $0.8 \text{ GeV} < M_X(ep \rightarrow e'\pi^0\pi^+X) < 1.1 \text{ GeV}$. The invariant mass distribution of this exclusive two pion sample is presented in the upper panel of figure 7 where the exclusive $\rho^+$ peak is clearly visible along with non-resonant exclusive two-pion production. The vertical lines indicate invariant mass ranges for which the beam spin asymmetry amplitude $A_{LU}^{\sin \phi_h}$ was extracted for each of the two exclusively produced pions following the extraction method as described before. These amplitudes are presented for $\pi^0$ and $\pi^+$ in the second top panel of figure 7 as labeled therein, along with the average values of $<P_T>$ and $<z>$ for the invariant mass ranges.

Figure 8 is the same as figure 7 except for two-hadron events with $M_x(ep \rightarrow e'\pi^0\pi^+X) > 1.5 \text{ GeV}$ (non exclusive).

The $A_{LU}^{\sin \phi_h}$ values for $\pi^0(\pi^+)$ increase (decrease) with increase invariant mass, and reach their maximum absolute value at the highest invariant mass.
In contrast to a similar study for $\rho^0$ presented in [17], the asymmetries for $\pi^0$ and $\pi^+$ have minimal values in the invariant mass range where $\rho^+$ events dominant, and furthermore the highest bin of invariant mass, the asymmetries for $\pi^0$ and $\pi^+$ have different signs. It should be noted also, that in these studies the momentum distributions and the acceptance for the two pions are not similar, while in [17] the two pions have similar momentum distributions and acceptance. $A_{LU}^{\sin \phi_h}$ of the SIDIS $\pi^0$ and $\pi^+$ in the same kinematic bin have the same sign and their amplitudes are roughly equal (figure 4). For the case of two-hadron production (figure 5), in all invariant mass bins (except the first) $A_{LU}^{\sin \phi_h}$ for $\pi^0$ and $\pi^+$ have different signs, which is another reason for careful studies of two hadron production.

Comparison of the measured beam SSAs for pions originating from electroproduction of two-pions in exclusive and non-exclusive processes, suggests that the SSAs depend mainly on the kinematics of the pion, in particular on $z$ and $P_T$, and are comparable for pions from different samples within the same kinematical bin.

3. Conclusions
We have presented measurements of kinematic dependences of the beam-spin asymmetry in semi-inclusive $\pi^0$ electroproduction from the E01-113 CLAS dataset. The $\sin \phi_h$ amplitude is extracted as a function of $x_B$ and the transverse pion momentum $P_T$, integrating over the $z$-range $0 < z < 0.7$.

The asymmetry shows no significant $x_B$-dependence over the measured range. The $P_T$ dependence of $A_{LU}^{\sin \phi_h}$ is consistent with an increase at low values of $P_T$ which reaches a plateau for
values $P_T > 0.3$ GeV. There is an indication that the decrease of $A^{\sin \phi_h}_{LU}$ at large $P_T$, expected from perturbative QCD, already starts at $P_T \sim 0.6$ GeV. The observed asymmetry amplitudes for $\pi^0$ indicate that the major contribution pion beam SSAs may be due to spin-orbit correlations.

The results obtained are compared with published HERMES data [17], providing significant improvement in precision and an important input for studies of higher twist effects. Despite the fact that the partonic formalism is much better suited for higher energy reactions, there is a reasonable agreement in size and behavior of beam SSAs measured over a wide energy range.

Preliminary results on two-hadron production show interesting trends: opposite signs of asymmetries for $\pi^0$ and $\pi^+$, the highest asymmetry for the highest invariant mass range. The beam spin asymmetry from $\pi^0$ and $\pi^+$ two-hadron production has been studied for the first time as a function of the invariant mass of two pions. The $A^{\sin \phi_h}_{LU}$ amplitude of $\pi^0$ from exclusive and non-exclusive two-pion production exhibits a similar magnitude and similar kinematic dependences as for semi-inclusive $\pi^0$ production. Therefore, a possible contribution of this exclusive channel to our semi-inclusive result would not alter the presented asymmetry amplitudes.

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