Single-Spin Asymmetries at CLAS

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Abstract. Significant single-spin azimuthal asymmetries have been observed in semi-inclusive pion production in the deep-inelastic scattering (DIS) of longitudinally polarized electrons off unpolarized hydrogen and polarized NH₃ targets at CLAS detector at Thomas Jefferson National Accelerator Facility (JLab). Issues related to the separation of current fragmentation, and the factorization of dependencies on x-Bjorken and the fractional energy z, at lowest beam energies where the DIS region is accessible, are also discussed.

Single-spin asymmetries (SSA) in hadronic reactions have been among the most difficult phenomena to understand from first principles in QCD. Large SSAs have been observed in hadronic reactions for decades [1, 2]. Recently, significant SSAs were reported in pion production in semi-inclusive DIS (SIDIS) by the HERMES collaboration at HERA [3, 4] for a longitudinally polarized target, by the SMC collaboration at CERN for a transversely polarized target [5], and by the CLAS collaboration at the Thomas Jefferson National Accelerator Facility (JLab)[6] with a polarized beam.

In general, such single-spin asymmetries require a correlation of a particle spin direction and the orientation of the production or scattering plane and they are related to the orbital angular momentum of partons in the nucleon. The interference of wavefunctions with different orbital angular momentum responsible for single-spin asymmetries [7, 8, 9, 10, 11, 12], also yields the helicity-flip Generalized Parton Distribution (GPD) E [13] entering Deeply Virtual Compton Scattering[14, 15] and the Pauli form factor $F_2$. The connection of SSAs and GPDs also has been discussed in terms of transverse distribution of quarks in the nucleon [16].

It is also argued that in both semi-inclusive [17] and hard exclusive [18, 19] pion production, scaling sets in for cross section ratios and spin asymmetries at lower squared four-momentum transfer, $Q^2$, than it does for the absolute cross section. This makes it possible for the measurement of spin-asymmetries to be a major tool for the study of parton distributions in the $Q^2$ domain of a few GeV².

The complete tree-level description of single pion electroproduction up to order $1/Q$ containing contributions from twist-2 and twist-3 distribution and fragmentation functions has been given in Ref. [20]. Terms contributing to the $\sin \phi$ moment are given by:

$$\sigma_{UT}^{\sin \phi} \propto S_T (1 - y) \sin(\phi + \phi_S) \sum_{a, \bar{a}} e_a^2 x h_1^a(x) H_1^{\perp a}(z)$$

$$\sigma_{UT}^{\sin \phi} \propto S_T (1 - y) \sin(\phi - \phi_S) \sum_{a, \bar{a}} e_a^2 x f_{1T}^a(x) D_1^\perp(z)$$

(1)

(2)
\[
\sigma_{UL}^{\sin \phi} \propto S_L \sin \phi (2 - y) \sqrt{1 - y} \frac{M}{Q} \sum_{a, b} e_a^2 x^2 h_L^a(x) [H^T_{1a}(z) + \eta / 2z]
\]  
(3)

\[
\sigma_{LU}^{\sin \phi} \propto \lambda_e \sin \phi y \sqrt{1 - y} \frac{M}{Q} \sum_{a, b} e_a^2 x^2 e^a(x) H^T_{1a}(z). 
\]  
(4)

Here the first and second subscripts specify the beam and target polarizations with \(U, L, T\) denoting unpolarized, longitudinally polarized and transversely polarized cases, respectively. The azimuthal angle \(\phi\) 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 \(q\). The \(\lambda_e\) is the helicity of the electron and \(S_L\) and \(S_T\) are proton longitudinal and transverse polarizations, \(\sum_{a, b} \rightarrow \) sum over quarks and anti-quarks. The \(x\) is the Bjorken variable, \(y\) and \(z\) are fractions of the incoming electron energy carried by the virtual photon and virtual photon energy carried by the final pion, respectively.

Eq. 1,2 correspond to leading twist contributions from Collins [21, 20, 23, 17] and Sivers [7, 8, 9, 11, 12] effects, and give access to chiral-odd transversity, \(h_1(x)[22]\), and time-reversal odd (T-odd) Sivers function, \(f_{1T}\), respectively. Collins \((H^T_1)\) and Sivers T-odd functions in Eq. 1-4 are first moments of corresponding transverse momentum dependent functions [20, 23]. Eq. 3,4[20, 24, 25] correspond to twist-3 contributions, and may be related to observed SSA at HERMES [3] with polarized target and at CLAS [6] with polarized beam.

Distribution and fragmentation functions responsible for non zero beam SSA in SIDIS (Eq.4) identified by Levett and Mulders [25], include the twist-3 unpolarized distribution function \(e(x)\) introduced by Jaffe and Ji [22] and the Collins function [21]. Contributions to beam SSA were also predicted to arise from the absorbtive part of the one-loop corrections to the \(\gamma^* q \rightarrow q g\) and \(\gamma^* g \rightarrow q \bar{q}\) [26].

Important issues at low beam energies are the separation of current and target fragmentation regions and the presence of factorization when the fragmentation functions depend only on the fractional energy, \(z\). At low beam energies in DIS the current fragmentation region (CFR) is contaminated with events coming from the target fragmentation region (TFR). At low beam energies and low \(z\) a significant overlap is expected of current and target fragmentation regions [27]. A quantitative estimate is available from LUND Monte-Carlo (MC)[28]. The LUND model was successfully used by different experimental groups for different processes and in a wide energy range. A very good agreement of kinematic distributions measured at CLAS and LUND simulation was shown to take place at energies as low as 4.3 GeV. All this is making the LUND-MC a major tool in SIDIS studies. The relative yield of current fragmentation events extracted from LUND-MC for different beam energies (see, Fig. 1) shows no significant dependence of the CFR fraction on the beam energy in range 0.5 < \(z\) < 0.8. In addition, we find that in that \(z\)-range kinematic distributions of final state electrons and pions at CLAS...
FIGURE 1. The separation of CFR with $0.5 < z < 0.8$ is not changing significantly with beam energy.

FIGURE 2. $z$-distributions of pions in $ep \rightarrow e'\pi^+ + X$ for different bins in $x$ (top plot) and their ratios (bottom plot) for CLAS E1 data at 6 GeV.

are in good agreement with the LUND-MC even though the LUND MC was developed and tuned at much higher beam energies.

Factorization in the $z$-distributions of pions was studied using the 6 GeV data from the CLAS E1 experiment. Distributions of pions in $z$, for different $x$ bins, are shown in Fig. 2. No significant dependence ($<10\%$) within statistical uncertainties was observed in the $z$-distributions for different values of $x$ (bottom plot in Fig.2).

SSA were measured in single pion production scattering of longitudinally polarized electrons off unpolarized liquid-hydrogen and polarized $NH_3$ targets. The total number of $\pi^+$ events in the DIS range ($Q^2 > 1\text{ GeV}^2, W^2 > 4\text{ GeV}^2$) selected by quality, vertex, acceptance, fiducial, and kinematic cuts was $\approx 4 \times 10^5$ and $2.7 \times 10^6$ respectively. The $\phi$-dependent spin asymmetries are formed by extracting moments of the cross section.
for the two helicity states weighted by the corresponding $\phi$-dependent functions. The $\sin \phi$ moment is thus given by:

$$A_{LU[UL]}^{\sin \phi} = \frac{2}{P^\pm N^\pm} \sum_{i=1}^{N^\pm} \sin \phi_i,$$

(5)

where $N^\pm$ and $P^\pm$ are the number of events and the luminosity weighted polarization for positive/negative helicities of the electron and proton, respectively. The azimuthal moment $A_{LU[UL]}^{\sin \phi}$ can be computed for each polarization state, and the comparison of two results provides a strong test of systematics. The $\sin \phi$ azimuthal moment of the cross section, unlike the $\cos \phi$ azimuthal moment, typically is not affected significantly by the detector acceptance and is practically an “acceptance free” observable. The sum of all contributions to the systematic uncertainties including the acceptance, beam polarization, particle mis-identification and radiative corrections is limited to 20% of the value of the measured asymmetry in all kinematic ranges (Fig. 3).

**FIGURE 3.** The left panel shows the beam-spin azimuthal asymmetry ($\sin \phi$ moment of the cross section) extracted from hydrogen data at 4.3GeV as a function of $z$ in a range $0.15 < x < 0.4$. The band represents the systematic uncertainties. The right panel shows the comparison of target SSA from CLAS 4.3 GeV and HERMES data. The squares show the projected error bars expected from the CLAS 5.7GeV running with NH$_3$ target. The dashed line shows the $z$-shape of the fit to Collins function $H_{\pi^+}(z)$ from HERMES $A_{LU}$. While the target SSA ($A_{UL}^{\sin \phi}$) analyzed in terms of the fragmentation effect (Eq. 3), in addition to a contribution from the Collins function, contains other contributions [29, 30], the beam SSA, depends only on the convolution of $e(x)$ and the Collins fragmentation function [20, 25], making it a very attractive observable for extraction of the $z$-shape of the Collins fragmentation function at large $z$, where the analyzing power is large.

The $z$-dependence of the beam SSA for positive pions measured at CLAS (Fig. 3) differs significantly from the shape of the $z$-dependence of the target SSA measured by HERMES [3, 4]. Preliminary results on beam SSA presented by the HERMES collaboration [31] and target SSA from CLAS (see Fig. 3) confirm, that there is a
difference between z-shapes of beam and target SSA, rather than a difference between measurements performed at different beam energies.

The $x$-dependence of beam SSA in SIDIS, analyzed in terms of the fragmentation effect, is defined by the ratio of the twist-3 unpolarized distribution function $e(x)$ and the leading twist distribution function $f_1(x)$. The first extraction of the twist-3 distribution function from CLAS beam SSA data, assuming factorization, was reported recently by Efremov et al.[32].

In conclusion, we have presented measurements of beam and target single-spin asymmetries at CLAS in single-pion electro-production off the unpolarized and longitudinally polarized protons. Beam and target SSA measured at CLAS and HERMES are in good agreement, suggesting there is no significant scale dependence for SSA observables. Higher statistics in the DIS range of ongoing experiments with CLAS at 6 GeV using unpolarized hydrogen and deuteron targets, as well as polarized NH$_3$ and ND$_3$ targets (3 billion triggers accumulated so far) will enable the extraction of the important $Q^2$ dependence at fixed $x$ for different final state particles.

REFERENCES

31. A. Miller, this proceedings.