Single Spin Asymmetries in Charged Pion Production from Semi-Inclusive Deep Inelastic Scattering on a Transversely Polarized $^3$He Target at $Q^2 = 1.4$–$2.7$ GeV$^2$


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High-energy lepton-nucleon scattering is a powerful tool to study the partonic structure of the nucleon. While detailed studies of inclusive deep inelastic scattering (DIS) have revealed a great deal of information about the unpolarized (f$_0^T$) and polarized (g$_1^T$) parton distribution functions (PDFs) describing the longitudinal momentum and helicity of quarks in the nucleon, understanding of the nucleon’s spin structure is far from being complete [1]. In particular, the experimental study of quark transverse spin phenomena has just begun [2–5]. Recent reviews can be found in Refs. [6,7]. These progresses also point to an important role for quark or gluon orbital angular motion in the nucleon’s spin structure [2–5]. The Collins moment probes the convolution of the naive parton transverse spin and momentum [2,4,5,11–15] relevant to the kinematics of this work provides a unique opportunity for the study of orbital angular momentum (OAM).

All eight leading-twist TMDs are accessible in SIDIS [10]. The angular dependence of the target spin-dependent asymmetry A in the scattering of an unpolarized lepton beam by a transversely polarized target is

$$A(\phi_h, \phi_S) = \frac{1}{P} \frac{Y_{\phi_h, \phi_S} - Y_{\phi_h, \phi_S + \pi}}{Y_{\phi_h, \phi_S} + Y_{\phi_h, \phi_S + \pi}} = A_C \sin(\phi_h + \phi_S) + A_S \sin(\phi_h - \phi_S).$$

(1)

where P is the target polarization, $\phi_h$ and $\phi_S$ are the azimuthal angles of the hadron momentum and the target spin relative to the lepton scattering plane as defined in the Trento convention [15], Y is the normalized yield, and $A_C$ ($A_S$) is the Collins (Sivers) moment.

The Collins moment probes the convolution of the chiral-odd quark transversity distribution $h_1^q$ [16] and the chiral-odd Collins fragmentation function (FF) [17]. $h_1^q$ describes the transverse polarization of quarks in a transversely polarized nucleon. Because the gluon transversity vanishes, quark transversity is valencelike [18]. The lowest moment of transversity, the tensor charge, provides a test of lattice QCD predictions [19]. Transversity is further constrained by Soffer’s inequality [20], $|h_1^q| \leq \frac{1}{2}(f_0^T + g_1^T)$, which holds under next-to-leading-order QCD evolution [21–23]. However, a possible violation of Soffer’s bound has been suggested [24].

The Sivers moment probes the convolution of the naive T-odd quark Sivers function $f_1^T$ [25] and the unpolarized FF. $f_1^T$ represents a correlation between the nucleon spin and the quark transverse momentum, and it corresponds to the imaginary part of the interference between light-cone wave function components differing by one unit of OAM [26,27]. The Sivers function was originally thought to vanish since it is odd under naive time-reversal transformations [17]. A nonzero $f_1^T$ was later shown to be allowed due to QCD final-state interactions (FSI) between the outgoing quark and the target remnant [26]. It was further demonstrated through gauge invariance that the same Sivers function, which originates from a gauge link, would appear in both SIDIS and Drell-Yan single spin asymmetries (SSAs) but with an opposite sign [28,29].

The HERMES collaboration carried out the first SSA measurement in SIDIS on a transversely polarized proton target using $e^\pm$ beams [2] at $Q^2 = 1.3$–6.2 GeV$^2$. The COMPASS collaboration performed SIDIS measurements with a muon beam on transversely polarized deuteron [4] and proton [5] targets at $Q^2 = 1.3$–20.2 GeV$^2$. Large Collins moments were observed for both $\pi^+$ and $\pi^-$ from the proton, but with opposite sign, indicating that the “unfavoried” Collins FF could be as large as the “favored” one [17]. This finding is consistent with the measured asymmetry of inclusive hadron pair production in $e^+e^-$ annihilation from BELLE [30], which directly accessed the product of Collins FFs. The deuteron Collins asymmetries for $\pi^+$ and $\pi^-$ are consistent with zero, but with relatively large uncertainties for $x > 0.1$, which suggests a cancellation between proton and neutron.

While both the HERMES and COMPASS proton data show significantly positive $\pi^+$ Sivers moments, a possible
in the plane transverse to the beam direction in order to maximize the $\phi_S$ coverage. The holding magnetic field ($\sim 25$ G) remained fixed during spin flips.

The BigBite spectrometer consists of a large-opening dipole magnet in front of a detector stack including three sets of multiwire drift chambers for charged-particle tracking, a lead-glass calorimeter divided into preshower or shower sections for electron identification and a scintillator plane between the preshower and shower for timing. In this experiment, BigBite was positioned to subtend a solid angle of $\sim 64$ msr for a 40 cm target. The large out-of-plane angle acceptance of BigBite ($\pm 240$ mrad) was essential in maximizing the $\phi_S$ coverage of the experiment, given the small ($\sim 6$ msr) solid angle acceptance of the hadron arm. The transport matrix of the BigBite magnet was calibrated using a multifoil carbon target, a slit collimator and $^1$H($e, e'p$) elastic scattering at incident energies of 1.2 and 2.4 GeV. The achieved angular and momentum resolutions were better than 10 mrad and 1%, respectively. Clean $e^-$ identification was achieved using cuts on the preshower energy $E_p$ and the ratio $E/p$ of the total shower energy to the momentum from optics reconstruction. The $\pi^-$ contamination was determined from analysis of the $E_p$ spectrum to be less than 2%, consistent with GEANT3 simulations.

The HRS detector package was configured for hadron detection [33]. A $10^3:1$ $e^-\pi^0$ rejection factor was achieved using a light gas Čerenkov and a lead-glass calorimeter, resulting in a negligible $e^+\pi^-$ contamination. Coincidence timing provided more than $15\sigma$ pion-proton separation. A $10:1$ $K^-\pi^+$ rejection was achieved using the aerogel Čerenkov detector, leaving less than 1% contamination. The $\pm 5\%$ HRS momentum acceptance limited the hadron energy fraction $z$ to about 0.5 (see Table I).

SIDIS events were selected using cuts on the four-momentum transfer squared $Q^2 > 1$ GeV$^2$, the hadronic final-state invariant mass $W > 2.3$ GeV, and the mass of undetected final-state particles $W' > 1.6$ GeV, assuming scattering on a nucleon. The total number of accepted SIDIS events are 254k and 194k for $\pi^+$ and $\pi^-$, respectively. The data were divided into four bins in the Bjorken scaling variable $x$. The central kinematics of the four bins after radiative corrections are presented in Table I. SIDIS yields were obtained by normalizing the number of

| TABLE I. Central kinematics for the four $x$ bins. The fractional $e^-$ energy loss $y$, the hadron energy fraction $z$ with respect of electron energy transfer and the transverse momentum $p_{h,\perp}$ are all defined following the notation of Ref. [10]. The pair production background $f_{\text{pair}}^{\pi^+}$ and the proton dilution $1 - f_p^{\pi^+}$ are shown with their total experimental systematic uncertainties. The numbers in parentheses represent the model uncertainties corresponding to unpolarized FSI effects. |
|---|---|---|---|---|---|---|---|---|---|---|
| $x$ | $Q^2$ GeV$^2$ | $y$ | $z$ | $p_{h,\perp}$ GeV | $W$ GeV | $W'$ GeV | $f_{\text{pair}}^{\pi^+}$ | $f_p^{\pi^+}$ | $1 - f_p^{\pi^+}$ | $1 - f_p^{\pi^+}$ |
| 0.156 | 1.38 | 0.81 | 0.50 | 0.435 | 2.91 | 2.07 | 22.0 ± 4.4$^a$ | 24.0 ± 4.8$^a$ | 0.212 ± 0.032(0.027) | 0.348 ± 0.032(0.022) |
| 0.206 | 1.76 | 0.78 | 0.52 | 0.38 | 2.77 | 1.97 | 8.0 ± 2.0$^a$ | 14.0 ± 2.0$^a$ | 0.144 ± 0.031(0.029) | 0.205 ± 0.037(0.027) |
| 0.265 | 2.16 | 0.75 | 0.54 | 0.32 | 2.63 | 1.84 | 2.5 ± 0.9$^a$ | 5.0 ± 1.8$^a$ | 0.171 ± 0.029(0.028) | 0.287 ± 0.036(0.024) |
| 0.349 | 2.68 | 0.70 | 0.58 | 0.24 | 2.43 | 1.68 | 1.0 ± 0.5$^a$ | 2.0 ± 1.0$^a$ | 0.107 ± 0.026(0.030) | 0.220 ± 0.032(0.026) |
identified SIDIS events by the accumulated beam charge and the data acquisition live time. The data were divided into ~2850 pairs of measurements in opposite target spin states to extract the raw asymmetries. The false asymmetry due to luminosity fluctuations was confirmed to be less than 4 × 10^{-4} by measurements of the SSA in inclusive \((e, e')\) scattering with transverse target polarization oriented horizontally, which vanishes due to parity conservation. The raw Collins or Sivers moments were obtained by fitting the asymmetries in 2-D \((\phi_p, \phi_S)\) bins according to Eq. (1). This procedure was confirmed by an unbinned maximum-likelihood method. The \(^3\)He moments were obtained after correcting the directly measured N\(_2\) dilution (~10% contribution).

The dominant background in the SIDIS electron sample comes from \(e^+/e^-\) pair production. This background (listed in Table I) was directly measured by reversing the polarity of the BigBite magnet to detect \(e^+\) in identical conditions as \(e^-\). The contamination was treated as a dilution effect in the analysis, as the measured asymmetries were consistent with zero for \(e^+ - \pi^+\) coincidence events, which mirror the pair-produced \(e^- - \pi^-\) events. Additional experimental uncertainties in the extracted \(^3\)He Collins or Sivers moments include: (i) \(K^\pm\) contamination in the \(\pi^\pm\) sample, (ii) bin-centering, resolution and radiative effects estimated using simulations, (iii) the effect of the target collimator, estimated by varying the scattering vertex cut, (iv) target density fluctuations, and (v) the false asymmetry due to yield drift caused by radiation damage to the BigBite preshower calorimeter. The quadrature sum of all above contributions is below 25% of the statistical uncertainty in each \(x\) bin.

In addition, there are fitting systematic uncertainties resulting from the neglect of other \(\phi_h\) and \(\phi_S\)-dependent terms, such as \(2(\sin(3\phi_h - \phi_S))\), higher-twist terms including \(2(\sin\phi_S)\) and \(2(\sin(2\phi_h - \phi_S))\), azimuthal modulations of the unpolarized cross section including the Cahn \(2(\cos\phi_h)\) and Boer-Mulders \(2(\cos\phi_h)\) effects [10], and leakage from the longitudinal SSA \(A_{UL}\) due to the small longitudinal component of the target polarization. The effects of these terms were estimated by varying each term within an allowed range derived from the HERMES data [34,35], assuming the magnitude of each term for the neutron is similar to that of the proton. The \(2(\sin\phi_S)\) term gives the largest effect, followed by the \(2(\sin(3\phi_h - \phi_S))\) and \(2(\sin(2\phi_h - \phi_S))\) terms.

A Monte Carlo simulation of the experiment was adapted from the package SIMC used in the analysis of SIDIS cross section measurements on \(^1\)H and \(^2\)H from JLab Hall C [12] to include models of our target and spectrometers. SIMC was used to estimate the combined effects of acceptance, resolution and radiative corrections on the extraction of the Collins and Sivers moments, and these effects were included in the experimental systematic uncertainties. Additionally, the contamination in identified SIDIS events from decays of diffractively produced \(\rho\) mesons was estimated to range from 3%-5% (5%-10%) for \(\pi^+ (\pi^-)\) by PYTHIA6.4 [36]. Consistent with the HERMES analysis, no corrections for this background have been applied to our results. The contamination from radiative tails of exclusive electroproduction, estimated by normalizing the MC spectrum to the data in the low-\(W\) region, was found to be less than 3%.

The extracted \(^3\)He Collins \(A_C\) and Sivers \(A_S\) moments are shown in Fig. 1. The error bars represent statistical uncertainties only. The experimental systematic uncertainties combined in quadrature are shown as the band labeled “Exp.” The combined extraction model uncertainties due to neglecting other allowed terms are shown as the band labeled “Fit.” The extracted \(^3\)He Collins and Sivers moments are all below 5%. The Collins moments are mostly consistent with zero, except the \(\pi^+\) Collins moment at \(x = 0.35\), which deviates from zero by 2.3\(\sigma\) after combining the statistical and systematic uncertainties in quadrature. The \(\pi^+\) Sivers moments favor negative values, and the \(\pi^-\) Sivers moments are consistent with zero.

To extract the neutron Collins or Sivers SSAs \(A_n^{C/S}\) from the measured \(^3\)He moments \(A_{He}^{C/S}\), we used,

\[
A_{He}^{C/S} = P_n(1 - f_p)A_n^{C/S} + P_p f_p A_p^{C/S},
\]

which was shown to be valid in a calculation by Scopetta [37] including initial-state nuclear effects. Here, \(P_n = 0.86^{+0.036}_{-0.02}\) \((P_p = -0.028^{+0.009}_{-0.003})\) is the neutron (proton) effective polarization [38]. The proton dilution \(f_p = \frac{2\sigma_x}{\sigma_{3\pi}}\) of \(^3\)He was measured by comparing the yields of unpolarized hydrogen and \(^3\)He targets in the SIDIS kinematics. An additional model uncertainty from spin-independent FSI was
consistent with our data. However, the model calculations, which assume Soffer’s bound [20], predict rather small Collins asymmetries which are mostly below 1% across the entire x range with a simple Glauber rescattering model.

The resulting neutron Collins moments calculated using Eq. (2), with $f_p$ from our data and proton Collins moments from Refs. [41–43], are shown in Fig. 2. Corrections from the proton Collins moments are less than 0.012. Our Collins moments are consistent with the phenomenological fit [42], a light-cone quark model calculation [44,45] and quark-diquark model [46,47] calculations. The phenomenological fit and the model calculations, which assume Soffer’s bound [20], predict rather small Collins asymmetries which are mostly consistent with our data. However, the $\pi^+$ moments at $x = 0.34$ is suggestive of a noticeably more negative value at the 2σ level. Our data favor negative $\pi^+$ Sivers moments, while the $\pi^-$ moments are close to zero. Such behavior independently supports a negative $d$ quark Sivers function within the parton model picture, which has been suggested by predictions of the phenomenological fit [41,43] to HERMES and COMPASS data, a light-cone quark model calculation [48,49] and an axial diquark model calculation [50].

In summary, we have reported the first measurement of the SSA in charged pion electroproduction on a transversely polarized $^3$He target in the DIS region. Our data provide the best current measurement of the neutron Sivers moments in the valence region ($x > 0.1$), and the best neutron Collins moments for $x > 0.2$, which will further improve the extraction of $d$ quark distributions in these regions. This experiment has demonstrated the power of polarized $^3$He as an effective polarized neutron target, and has laid the foundation for future high-precision measurements of TMDs with a large acceptance detector SoLID following the JLab 12 GeV upgrade [51] and at an electron-ion collider [52]. These future SIDIS data taken over a broad range of $Q^2$ will also allow an accurate determination of higher-twist contribution [53,54].

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**References**

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