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Colloquia: Transversity 2011

JLAB results: TMD measurements

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Summary. — Studies of single-spin and double-spin asymmetries in pions electroproduction in semi-inclusive deep-inelastic scattering of 5.776 GeV polarized electrons from unpolarized and polarized targets at the Thomas Jefferson National Accelerator Facility, are presented. The dependence of these amplitudes on Bjorken x and on the pion transverse momentum has been extracted with significantly higher precision than previous data and is compared to model calculations.

PACS 13.60.-r – Photon and charged-lepton interactions with hadrons.
PACS 13.87.Fh – Fragmentation into hadrons.
PACS 13.88.+e – Polarization in interactions and scattering.
PACS 24.85.+p – Quarks, gluons, and QCD in nuclear reactions.

1. – Introduction

In recent years it has become clear that understanding the orbital motion of partons is crucial for achieving 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 theoretical investigations of Transverse-Momentum–Dependent (TMD) distributions of partons and the first unambiguous experimental signals of TMDs indicate that QCD-dynamics inside hadrons is much richer than what can be learned from collinear parton distributions.

TMDs were first suggested to explain the large transverse single-spin asymmetries observed in polarized hadron-hadron collisions. Since then, two fundamental mechanisms involving transverse-momentum–dependent distributions and/or fragmentation functions have been identified, which lead to single-spin asymmetries (SSAs) in hard processes: a) internal quark motion as represented by, *e.g.*, the Sivers mechanism [1-5], which generates an asymmetric distribution of quarks in a nucleon that is transversely polarized and b) the Collins mechanism [4, 6], which correlates the transverse spin of the struck quark with the transverse momentum of the observed hadron. The "Sivers-type" mechanism requires non-zero orbital angular momentum of the struck parton together with initial- or final-state interactions via soft-gluon exchange [3-5]. This mechanism involves TMD distributions which describe the correlations between the transverse motion of the parton and its own transverse spin or the spin of the initial- or final-state hadron, thereby providing unprecedented information about spin-orbit correlations.

Semi-inclusive deep-inelastic scattering (SIDIS) has emerged as a powerful tool to probe nucleon structure and to provide access to TMDs through measurements of spin and azimuthal asymmetries. A rigorous basis for such studies of TMDs in SIDIS is provided by TMD factorization in QCD, which has been established in refs. [7-9] for leading twist([1]) single-hadron production with transverse momenta being much smaller than the hard scattering scale. In this kinematic domain, the SIDIS cross section can be expressed in terms of structure functions [6, 10, 11] which are certain convolutions of transverse-momentum–dependent distribution and fragmentation functions. The analysis of TMDs thus strongly depends on the knowledge of fragmentation functions [12-16].

Many different observables, which help to pin down various TMD effects, are currently available from experiments such as: 1) semi-inclusive deep-inelastic scattering (HERMES at DESY [17-22], COMPASS at CERN [23-25], and Jefferson Lab [26-29]), 2) polarized proton-proton collisions (BRAHMS, PHENIX and STAR at RHIC [30-35]) and 3) electron-positron annihilation (Belle at KEK [36, 37]).

This talk reports measurements of single-spin asymmetries in the production of pions by longitudinally polarized electrons scattered off unpolarized protons [38] and by unpolarized electrons scattered off a longitudinally polarized proton (NH_3) target [28]. Target spin asymmetry published in [28, 29, 39] (see also talk [40]). Comparisons of these target spin asymmetries to a new CLAS experiment, along with studies of the dilution factor for the NH_3 target, are given in ref. [41].

2. – Results from transversely polarized ^{3}He target at $Q^2 = 1.4$–$2.7\,\text{GeV}^2$

The ^{3}He nuclei were polarized by Spin Exchange Optical Pumping of a Rb-K mixture. The polarization was monitored by Nuclear Magnetic Resonance (NMR) measurements every 20 minutes as the target spin was automatically flipped through Adiabatic Fast Passage. The NMR measurements were calibrated using the known water NMR signal and cross-checked using the Electron Paramagnetic Resonance method. The average polarization was $55.4 \pm 2.8\%$.

The extracted ^{3}He Collins $A_C \equiv 2\langle\sin(\phi_h + \phi_S)\rangle$ and Sivers $A_S \equiv 2\langle\sin(\phi_h - \phi_S)\rangle$ 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 π^+ Collins moment at $x = 0.35$, which deviates from zero by 2.3σ after combining the statistical and systematic uncertainties in quadrature. The π^+ Sivers moments favor negative values, and the π^- Sivers moments are consistent with zero.

The resulting neutron Collins/Sivers moments calculated using:

$$A^{C/S}_{^3\text{He}} = P_n \cdot (1 - f_p) \cdot A^{C/S}_n + P_p f_p \cdot A^{C/S}_p, \tag{1}$$

([1]) Each twist increment above leading twist (twist-2) contributes an extra suppression factor of $1/Q$.

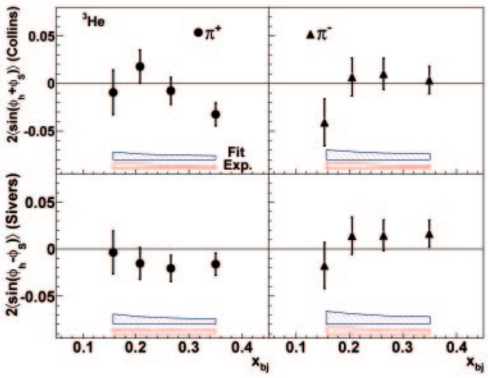

Fig. 1. – (Color online) The extracted Collins/Sivers moments on ^{3}He are shown together with uncertainty bands (See text and [39] for details.) for both π^+ and π^- electro-production.

with f_p from data and proton Collins/Sivers moments from refs. [42-44], are shown in fig. 2. The π^+ Collins moment at $x = 0.34$ is suggestive of a noticeably more negative value at the 2σ level. Data favor negative π^+ Sivers moments, while the π^- moments are close to zero.

3. – Results from longitudinally polarized NH_3 target

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 $P_B = 70\%$. 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 was used to provide polarized protons. The average target polarization (P_t) was about 75%. The double-spin asymmetry A_1 is shown in fig. 3 as a function of P_T, integrated over all x (0.12–0.48) for $Q^2 > 1\,\mathrm{GeV}^2$,

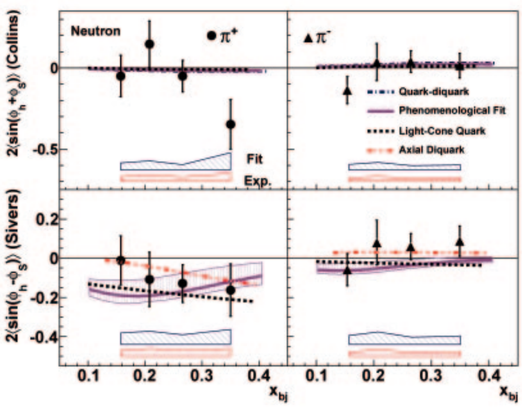

Fig. 2. – (Color online) The extracted neutron Collins and Sivers moments with uncertainty bands for both π^+ and π^- electro-production. See text and [39] for details.

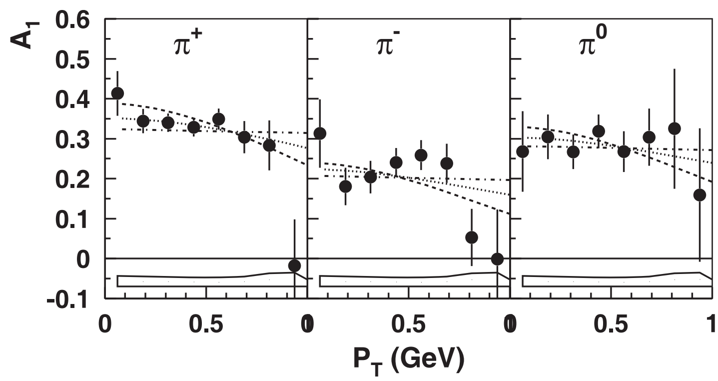

Fig. 3. – The double-spin asymmetry A_1 as a function of transverse momentum P_T, integrated over all kinematical variables. The open band corresponds to systematic uncertainties. The dashed, dotted and dash-dotted curves are calculations for different values for the ratio of transverse momentum widths for g_1 and f_1 (0.40, 0.68, 1.0) for a fixed width for f_1 ($0.25\,\mathrm{GeV}^2$) [45].

$W^2 > 4\,\mathrm{GeV}^2$, 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. 3 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 $\chi^2 = 1.9$.

4. – The π^0 beam spin asymmetry

Deep-inelastic scattering events were selected by requiring $Q^2 > 1\,\mathrm{GeV}^2$ and $W^2 > 4\,\mathrm{GeV}^2$, where W is the invariant mass of the hadronic final state. Events with missing-mass values for the $e\pi^0$ system that are smaller than $1.5\,\mathrm{GeV}$ ($M_x(e\pi^0) < 1.5\,\mathrm{GeV}$) were discarded to exclude contributions from exclusive processes. A minimum value for the π^0 transverse momentum, $P_T > 0.05\,\mathrm{GeV}$, ensures that the azimuthal angle ϕ_h is well defined. The total number of selected $e\pi^0$ coincidences was $\approx 3.0 \times 10^6$ for the presented z range, $0.4 < z < 0.7$, which selects the semi-inclusive region [28].

The beam-spin asymmetry $A_{LU}(\phi_h)$ has been calculated for each kinematic bin as

$$A_{LU}(\phi_h) = \frac{1}{P}\frac{N^+_{\pi^0}(\phi_h) - N^-_{\pi^0}(\phi_h)}{N^+_{\pi^0}(\phi_h) + N^-_{\pi^0}(\phi_h)}\,, \qquad (2)$$

where $P = 0.794 \pm 0.024$ is the absolute beam polarization for this data set and $N^+_{\pi^0}$ and $N^-_{\pi^0}$ are the number of π^0's for positive and negative beam helicity, normalized to the respective integrated charges. The number of π^0's is estimated by the integral of

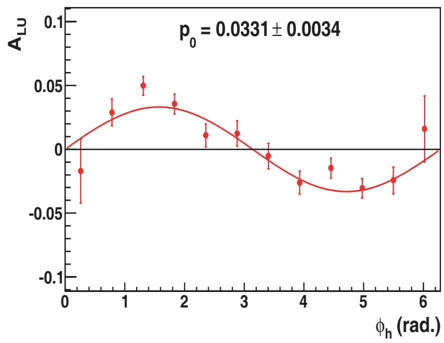

Fig. 4. – Example of a $p_0 \sin\phi_h$ fit to the A_{LU} asymmetry for $0.4 < z < 0.7$, $0.1 < x < 0.2$ and $0.2\,\mathrm{GeV} < P_T < 0.4\,\mathrm{GeV}$. Only statistical error bars are shown.

the histogram in the $\pm 3\sigma$ range, minus the integral of the linear component of the fit. Asymmetry moments were extracted by fitting the ϕ_h-distribution of A_{LU} in each x and P_T bin with the theoretically motivated function $p_0 \sin\phi_h$. An example of this fit is shown in fig. 4 for a representative kinematic bin.

In fig. 5, the extracted $A_{LU}^{sin\phi}$ moment is presented as a function of P_T for different x ranges. Systematic uncertainties, represented by the bands at the bottom of each panel, include the uncertainties due to the background subtraction, the event selection and possible contributions of higher harmonics. The first two contributions were estimated as the difference between the asymmetry moment extracted from data sets obtained with or without background subtraction, and by selecting the π^0 from the combination of all photons in an event or from events with exactly two photons. The contribution of higher harmonics was estimated by employing the fit functions $p_0 \sin\phi_h$ or $p_0 \sin\phi_h/(1 + p_1 \cos\phi_h)$. The contributions from other harmonics such as $\sin 2\phi_h$ or $\cos 2\phi_h$ were also tested and found to be negligible. All the above contributions were added in quadrature.

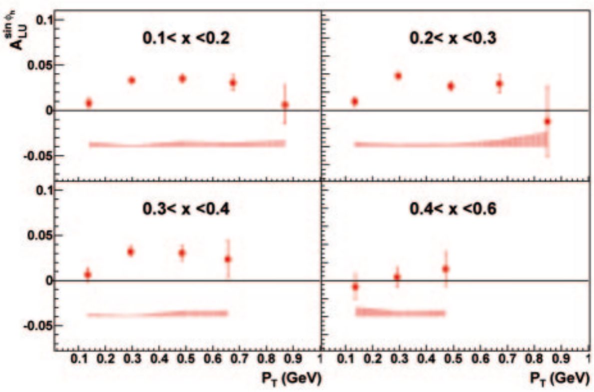

Fig. 5. – Asymmetry moment $A_{LU}^{\sin\phi_h}$ *versus* P_T for different x ranges and $0.4 < z < 0.7$. The error bars correspond to statistical and the bands to systematic uncertainties. An additional 3% uncertainty arises from the beam polarization measurement and another 3% uncertainty from radiative effects which are not included in the band.

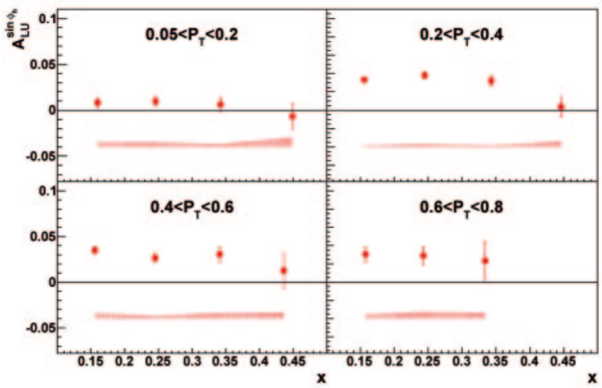

Fig. 6. – Asymmetry moment $A_{LU}^{\sin\phi_h}$ *versus* x for different P_T ranges and $0.4 < z < 0.7$. The error bars correspond to statistical and the bands to systematic uncertainties. This is the complementary plot to fig. 5.

An additional 3% scaling uncertainty due to the beam polarization measurements should be added to the above-mentioned systematic uncertainties. Radiative corrections have not been applied. However they have been estimated to be negligible [28, 48] with an accuracy of 3%.

The $A_{LU}^{\sin\phi_h}$ moment increases with increasing P_T and reaches a maximum at $P_T \approx 0.4\,\text{GeV}$. There is an indication, within the available uncertainties, that the expected decrease of $A_{LU}^{\sin\phi_h}$ at larger P_T could start already at $P_T \approx 0.7\,\text{GeV}$. As a function of x, $A_{LU}^{\sin\phi_h}$ appears to be flat in all P_T ranges shown in fig. 6.

The measured beam-spin asymmetry moment for π^0 appears to be comparable with the π^+ asymmetry from a former CLAS data set [49] both in magnitude and sign, as shown in fig. 7. For both data sets the average P_T is about 0.38 GeV. Also shown are

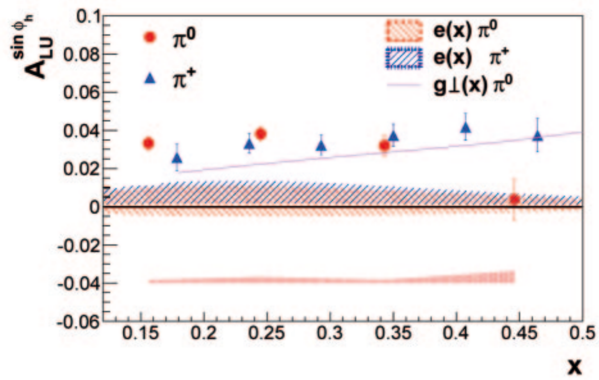

Fig. 7. – The π^0 beam-spin asymmetry moment $A_{LU}^{\sin\phi_h}$ *versus* x compared to that of π^+ from an earlier CLAS measurement [49]. Uncertainties are displayed as in fig. 5. For both data sets $\langle P_T\rangle \approx 0.38\,\text{GeV}$ and $0.4 < z < 0.7$. The right-hatched and left-hatched bands are model calculations involving solely the contribution from the Collins effect [50]. Preliminary calculations of $A_{LU}^{\sin\phi_h}$ for pions [51], based on the models from refs. [14, 52], demonstrate a non-zero contribution from $g^\perp$ (red line).

model calculations of $A_{LU}^{\sin\phi_h}$, as indicated in the figure (right-hatched and left-hatched bands), which take only the contribution from Collins-effect $eH_1^{\perp}$ into account [53, 54, 50, 55], suggesting that contributions from the Collins mechanism cannot be the dominant ones. In contrast, preliminary calculations of $A_{LU}^{\sin\phi_h}$ for pions [51], based on the models from refs. [14, 52], demonstrate a non-zero contribution from $g^{\perp}$. Because this DF can be interpreted as the higher-twist analog of the Sivers function, it underscores the potential of beam SSAs for studying spin-orbit correlations.

In summary, we have presented measurements of the kinematic dependences of the beam-spin and target-spin asymmetries in semi-inclusive pions electroproduction from the JLAB. The extracted ^{3}He Collins and Sivers moments are all below 5%. The Collins moments are mostly consistent with zero, except the π^+ Collins moment at $x = 0.35$, which deviates from zero by 2.3σ after combining the statistical and systematic uncertainties in quadrature. A possible interpretation of the P_T-dependence of the double-spin asymmetry from longitudinally polarized target 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. The $\sin\phi_h$ amplitude of beam spin asymmetry was extracted as a function of x and transverse pion momentum P_T, for $0.4 < z < 0.7$. The asymmetry moment shows no significant x dependence for fixed P_T. The observed asymmetry moment for π^0 suggests that the major contribution to the pion beam SSAs originate from spin-orbit correlations. The results are compared with published data and models. They provide a significant improvement in precision and an important input for studies of higher-twist effects. Measured beam SSAs are in good agreement, both in magnitude and kinematic dependences, with measurements at significantly higher energies [20, 25].

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