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Semi-Inclusive π^0 Target and Beam-Target Asymmetries from 6 GeV Electron Scattering with CLAS

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ABSTRACT

We present precision measurements of the target and beam-target spin asymmetries from neutral pion electroproduction in deep-inelastic scattering (DIS) using the CEBAF Large Acceptance Spectrometer (CLAS) at Jefferson Lab. We scattered 6-GeV, longitudinally polarized electrons off longitudinally polarized protons in a cryogenic $^{14}NH_3$ target, and extracted double and single target spin asymmetries for $ep \to e'\pi^0 X$ in multidimensional bins in four-momentum transfer ($1.0 < Q^2 < 3.2$ GeV^2), Bjorken-x ($0.12 < x < 0.48$), hadron energy fraction ($0.4 < z < 0.7$), transverse pion momentum ($0 < P_T < 1.0$ GeV), and azimuthal angle ϕ_h between the lepton scattering and hadron production planes. We extracted asymmetries as a function of both x and P_T, which provide access to transverse-momentum distributions of longitudinally polarized quarks. The double spin asymmetries depend weakly on P_T. The $\sin 2\phi_h$ moments are zero within uncertainties, which is consistent with the expected suppression of the Collins fragmentation function. The observed $\sin\phi_h$ moments suggest that quark gluon correlations are significant at large x.

Despite several decades of research, the spin structure of the proton remains incompletely understood [1]. The quark and gluon spins can only partially account for the total proton spin of 1/2, leaving the deficit to be found in quark and gluon orbital angular momenta. The orbital motion of quarks about the proton's spin axis can be observed in deep-inelastic lepton scattering (DIS) when a knocked-out quark has momentum transverse to the direction of momentum transfer. Although the struck quark acquires transverse momentum in the hadronization process, there remains enough of a remnant of the original quark orbital motion to probe quark spin–orbit correlations. The theoretical motivations and early experiments measuring these transverse-momentum distributions (TMDs) have demonstrated that the theory is sound and the experiments are feasible [2]. In this Letter we report results of unprecedented accuracy in measurements of spin-azimuthal asymmetries in neutral pion production in semi-inclusive DIS (SIDIS), which provides important information on the quark structure of the proton, complementary to that from charged pions.

DIS experiments have mapped the unpolarized structure function f_1 and the polarized structure function g_1 over a wide range of longitudinal momentum fraction x and momentum transfer Q^2. These provide a one-dimensional picture of nucleon structure. SIDIS provides access to the three-dimensional structure of the nucleon via a new set of structure functions that depend on the transverse motion of the quarks. The scattered lepton and the leading hadron are detected in coincidence. Eight leading-order (i.e. leading twist) [3] transverse-momentum distributions (TMDs) exist for the different beam and target polarizations, which describe the correlations between a quark's transverse momentum and the spin of the quark or the parent nucleon. These correlations mani-

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fest themselves in different spin-dependent azimuthal moments of the cross section, generated either by correlations in the distribution of quarks or in the fragmentation process, often referred as the Sivers [4] and Collins mechanisms [5], respectively.

For a longitudinally polarized nucleon, we have access to two leading-twist TMDs, g_{1L} and $h_{1L}^{\perp}$, which respectively describe longitudinally and transversely polarized quarks in a longitudinally polarized nucleon, and four higher-twist TMDs, $f_L^{\perp}$, $g_L^{\perp}$, h_L, and e_L [6] that describe various quark–gluon correlations that vanish as $Q^2 \to \infty$.

The HERMES Collaboration made the first observation of a single-spin asymmetry (SSA) in semi-inclusive DIS pion electroproduction [7]. This spawned a number of additional measurements of SSAs and double spin asymmetries (DSAs) using polarized hydrogen and deuterium targets [8,9]. The target SSAs for proton and deuteron targets published by HERMES [10–13] and COMPASS [14, 15], provided the first, direct indication of significant interference terms beyond the simple s-wave ($L = 0$) picture. These asymmetries become larger with increasing x, suggesting that spin–orbit correlations are more relevant for the valence quarks.

Measurements of SSAs at Jefferson Lab (JLab) with longitudinally polarized proton [16] and transversely polarized neutron [17–20] targets suggest that spin–orbit correlations are significant for certain combinations of quark and nucleon spins and transverse momenta. Large spin-azimuthal asymmetries were observed at JLab using a longitudinally polarized beam [21,22] in one case and a transversely polarized ^{3}He target in the other [23]. These results are consistent with the corresponding HERMES [24] and COMPASS [25] measurements, which were interpreted in terms of higher-twist contributions related to quark–gluon correlations.

Previous CLAS measurements [16] improved the world data set in two ways: they showed the first hint of a non-zero $\sin 2\phi_h$ azimuthal moment for charged pions, and they extracted azimuthal moments in multi-dimensional kinematic bins. COMPASS extended the proton DSAs to low-x [26] using a muon beam and a polarized NH_3 target, and they were able to extract the dependence on P_T, albeit with low statistical accuracy above $x = 0.2$.

The world's SSAs and DSAs are dominated by the charged pion results. High statistical accuracy is still needed to study asymmetries as two-dimensional functions of P_T and x in order to access the transverse-momentum dependence of different partonic distributions, most notably the helicity distribution, g_1^q. This is true especially for the case of the neutral pion. This paper presents new results intended to help correct this deficiency.

The electroproduction of neutral pions has several important advantages compared to charged pions: 1) suppression of higher-twist contributions at large hadron energy fraction z [27], which are particularly important at JLab energies where small-z events are contaminated by target fragmentation; 2) reduction of the background from diffractive ρ decays into pions, which mar the interpretation of the charged single-pion data; 3) similarity of fragmentation functions for u and d quarks leading to π^0, which reduces the dependence of the DSAs on the fragmentation functions at large x, where valence quarks dominate; and 4) suppression of spin-dependent fragmentation for π^0s, due to the roughly equal magnitude and opposite sign of the Collins fragmentation functions for up and down quarks [13,15,28–30]. These factors simplify the interpretation of π^0 SSAs and DSAs. Furthermore, neutral pions are straight-forward to identify with little background using the invariant mass of two detected photons.

The azimuthal angular dependence (ϕ_h) of the asymmetry in the yield for the observed hadron around the direction of momentum transfer provides our experimental observable. Longitudinally polarized beams and targets give access to longitudinal target SSAs and the longitudinal DSAs as a function of ϕ_h, 4-momentum transfer Q^2, Bjorken x, transverse hadron momentum P_T, and hadron energy fraction z. These spin asymmetries are defined in the laboratory frame, for which beam and target polarizations are along the beam-line (L) or unpolarized (U). From the ϕ_h-dependence of these asymmetries (defined on the left-hand side of Eq. (1) for SSAs and Eq. (2) for DSAs) we can extract the experimental azimuthal moments (given on the right-hand side of Eqs. (1) and (2)) using the ϕ_h-dependence:

$$\left[\frac{1}{P_t f}\right] \frac{Y^{\downarrow\downarrow} + Y^{\uparrow\downarrow} - Y^{\downarrow\uparrow} - Y^{\uparrow\uparrow}}{Y^{\downarrow\downarrow} + Y^{\uparrow\downarrow} + Y^{\downarrow\uparrow} + Y^{\uparrow\uparrow}} = \frac{A_{UL}^{\sin\phi_h} \sin\phi_h + A_{UL}^{\sin 2\phi_h} \sin 2\phi_h}{1 + A_{UU}^{\cos\phi_h} \cos\phi_h + A_{UU}^{\cos 2\phi_h} \cos 2\phi_h} \tag{1}$$

and

$$\left[\frac{1}{P_b P_t f}\right] \frac{Y^{\downarrow\uparrow} + Y^{\uparrow\downarrow} - Y^{\uparrow\uparrow} - Y^{\downarrow\downarrow}}{Y^{\downarrow\uparrow} + Y^{\uparrow\uparrow} + Y^{\downarrow\downarrow} + Y^{\uparrow\downarrow}} = \frac{A_{LL} + A_{LL}^{\cos\phi_h} \cos\phi_h}{1 + A_{UU}^{\cos\phi_h} \cos\phi_h + A_{UU}^{\cos 2\phi_h} \cos 2\phi_h}. \tag{2}$$

The first (second) superscript on the yield Y denotes the sign of the beam (target) polarization. The first (second) subscript on the azimuthal moment A denotes whether the beam (target) is polarized or not. The superscript on A denotes the azimuthal moment. No superscript, as in A_{LL}, denotes a ϕ_h-independent asymmetry. The angle ϕ_h is the hadron azimuthal angle with respect to the lepton plane as defined in the Trento convention [31]. We normalized the asymmetries using experimentally determined beam and target polarizations, P_b and P_t, respectively, and the dilution factor f, which accounts for the unpolarized material in the target.

In this letter, we present the results for the target SSA A_{UL} and the longitudinal DSA A_{LL} for π^0 production in SIDIS using the CLAS detector at JLab [32] with the addition of a small-angle inner calorimeter (IC) for photons. The experiment (eg1-dvcs) took place from February to October, 2009 [33,34]. We scattered longitudinally polarized electrons off a longitudinally polarized solid $^{14}NH_3$ target and collected a total of 30 mC of charge at a beam energy of 5.94 GeV. We detected scattered electrons and neutral pions in coincidence using CLAS. The present SIDIS data constitute a subset of our inclusive measurements [33], and they improve the older CLAS eg1b π^0 measurements [16] by an order of magnitude in integrated luminosity.

We determined the beam polarization (about 85%) using a Møller polarimeter [35] and deduced the target polarization from the product of beam and target polarization (about 65%) obtained from ep elastic scattering. We polarized the protons in $^{14}NH_3$ via Dynamic Nuclear Polarization [36]. The CLAS acceptance for scattered electrons ($17^\circ < \theta < 50^\circ$) was constrained by the IC at small angles and the polarized target walls at large angles.

Together, the CLAS electromagnetic calorimeter (EC) and the IC were able to detect photons from π^0 decay over a range of angles from 4° to 50°. We selected neutral pions by reconstructing the invariant mass of two photons, $M_{\gamma\gamma}$ [37]. We analyzed separately three neutral pion topologies, EC–EC, EC–IC, and IC–IC, to take full advantage of the improved energy resolution of the IC and the larger angular range of the EC. Neutral pion mass cuts for EC-EC, EC-IC, and IC-IC were (0.10, 0.17), (0.102, 0.17), and (0.105, 0.165) GeV, respectively.

Additionally, we applied fiducial cuts to both the EC and IC and removed tracks around the edges of the EC where there was a higher negative pion contamination in the electron sample. We also removed events on the inner edge of the IC (hot blocks close to the beam line), as well as blocks on the outer edges of the

IC (blocks with incomplete energy reconstruction). Approximately 4.3 M events survived these cuts.

We defined our variables using the Trento Convention [31], and selected SIDIS events by imposing kinematic cuts on the squared 4-momentum transfer ($Q^2 > 1$ GeV^2), Bjorken-x ($0.12 < x < 0.48$), the target plus virtual photon invariant mass ($W > 2$ GeV), the fractional energy of the π^0 ($0.40 < z < 0.70$), and the missing mass ($M_x > 1.5$ GeV), which suppressed the contributions from target fragmentation and exclusive events. We divided the data into 4 bins in x, 9 bins in Q^2, 4 bins in z, 6 bins in P_T, and 12 bins in ϕ_h. Here, ϕ_h is the azimuthal angle around the direction of momentum transfer. Because beam and target polarization lie along the beam direction, all asymmetries were corrected by a depolarization factor.

We calculated the corresponding SIDIS yields by scaling the events by the charge measured with the Faraday Cup in Hall B. We scaled the raw asymmetries by the beam and target polarization for A_{LL} and by the target polarization for A_{UL}. In order to remove contributions from the unpolarized part of the $^{14}NH_3$ target, we normalized the raw asymmetries by the dilution factor (about 3/17), which we calculated using a kinematically dependent model [38] optimized to fit the ratio of SIDIS events [39] from reference targets. The dilution model takes into account the SIDIS cross section per nucleon and an attenuation factor due to final state interactions of the π^0 in the target. The relative uncertainty in the dilution factor, due to the determination of the length of the frozen target, is 3%, and the uncertainty from the model dependence is 5%. Systematic uncertainties also resulted from the beam and target polarizations, background subtractions, and radiative corrections. Additionally, we studied the systematic fitting uncertainties for the moment extraction in detail. The strong dependence of the dilution factor for π^0s on different kinematic variables is one of the main sources of systematic uncertainty. We also estimated via Monte Carlo simulation the uncertainties on the moment extraction, especially due to the imprecisely measured $\cos\phi$ and $\cos 2\phi$ dependence in the asymmetry denominators.

We performed radiative corrections on the data following the theoretical developments in Ref. [40]. We evaluated the spin-dependent radiative corrections using the Mo–Tsai formalism [41] in the angle peaking approximation (photon emission along the incident and scattered electron directions only) and the equivalent radiator approximation (radiation from the same nucleus as the hard scattering process is equivalent to an external radiator of a few percent). We used fits to the world data on spin-dependent exclusive and inclusive π^0 electroproduction cross sections and evaluated the radiative tails for each helicity combination separately using a Monte-Carlo integration technique. The net effect was relatively small in most kinematic bins, and is included in the systematic uncertainty budget.

The main goal of this experiment was the extraction of SSAs and DSAs in fine bins in x and transverse hadron momentum P_T. We show here representative results. Fig. 1 shows A_{LL} for π^0 as a function of P_T, together with curves calculated for our kinematics using different theoretical approaches to parton distributions [42, 43]. The general magnitude is predicted well by these calculations, while the P_T-dependence is less well described. The dependence of the DSA on P_T indicates that spin orbit correlations may be significant, and that these dependencies are sensitive to details of the momentum distributions of the polarized quarks. Because A_{LL} is related to the ratio of polarized to unpolarized structure functions, this suggest that transverse momentum is correlated with spin orientation. Extraction of the underlying quark transverse momentum k_T of the helicity distributions, however, will require an established framework for TMD extraction from a combination of measurements with unpolarized and polarized targets [44].

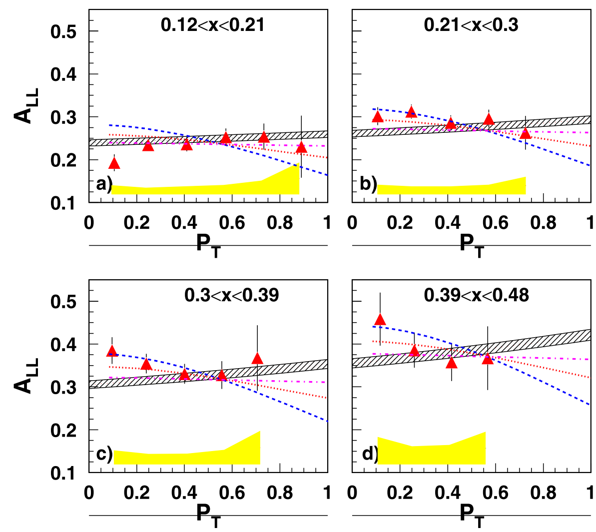

Fig. 1. The moment A_{LL} versus P_T for π^0 compared with calculations using the quantum statistical approach to parton distributions [42,43] (gray bands). The dashed, dotted, and dash-dotted curves are calculations assuming that the g_1 to f_1 transverse-momentum width ratios are 0.40, 0.68, and 1.0, respectively, using a fixed width for f_1 (0.25 GeV^2) [45]. The error bars represent the statistical uncertainties, whereas the yellow bands represent the total experimental systematic uncertainties.

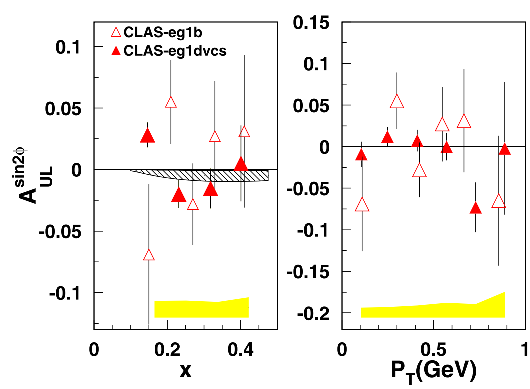

Fig. 2. The $\sin 2\phi_h$ moments for A_{UL} plotted versus x (left) and P_T (right) compared to previous CLAS measurements [16] (which had a lower z threshold of 0.3, no IC, and much lower integrated luminosity) and theory predictions (gray band) 10.1103/PhysRevD.77.014023. The error bars represent the statistical uncertainties, whereas the yellow bands represent the total experimental systematic uncertainties.

Studies of the Collins fragmentation functions at the e^+e^- machines, BELLE, [28,46,47], BABAR [48,29], and BESIII [30], indicate that the $\pi^\pm$ Collins fragmentation functions $H_1^\perp$ are large and have opposite signs for the favored and unfavored cases. Because fragmentation into π^0 is essentially the average of the π^+ and π^- cases, this suggests a significant suppression of the Collins fragmentation function for π^0. The measured $\sin 2\phi_h$ moment of the single target spin asymmetry $A_{UL}^{\sin 2\phi_h}$, which at leading twist has only a contribution from the Collins function coupled to the chiral-odd TMD, $h_{1L}^\perp$, is shown in Fig. 2. This Kotzinian–Mulders SSA [49], provides a unique opportunity to check the Collins effect. Our measurement of $A_{UL}^{\sin 2\phi_h}$ for π^0 is consistent with zero as expected.

A significant $\sin\phi_h$ modulation of the target spin asymmetry has been observed for neutral pions by the HERMES Collaboration [8]. There have been several attempts to describe the $\sin\phi_h$ moment of this asymmetry using twist-3 contributions originating from the unpolarized fragmentation function D_1 and the Collins fragmentation function $H_1^\perp$ [50–53]. Recently the effects of the

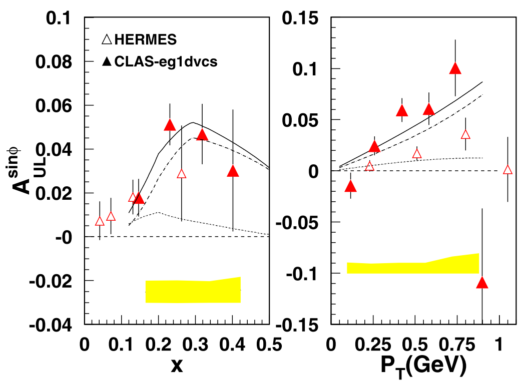

Fig. 3. The $\sin\phi_h$ moments for A_{UL} vs. x (left) and P_T (right). The open triangles are the data from HERMES [9], and the solid triangles are our new measurements with $z > 0.4$. The long dashed line is zero for reference. The short-dashed and dotted lines are twist-3 calculations from Sivers (larger) and Collins (smaller) terms [54,55], respectively, and the solid line is the sum of the two. The error bars represent the statistical uncertainties, whereas the yellow bands represent the total experimental systematic uncertainties.

twist-3 TMDs $f_L^{\perp}$ and h_L have been calculated in two different spectator-diquark models [54,55]. Our data for $A_{UL}^{\sin\phi_h}$ (shown in Fig. 3 together with equivalent data from [9] at higher beam energies) is plotted versus x and P_T. The data suggest that a Sivers-type contribution coming from the convolution of $f_L^{\perp}$ and D_1 (dashed curve from Ref. [55] in Fig. 3) indeed may be dominating the $\sin\phi_h$ moment of A_{UL}, and quark–gluon correlations are significant for $x > 0.2$.

The x-dependence of A_{UL} is consistent with HERMES measurements [9] in both magnitude and x-dependence. The increasing P_T-dependence is also consistent with HERMES. Precise direct comparisons, however, require taking out the kinematic factor $\sqrt{2\epsilon(1+\epsilon)}$ from the structure functions, and adding a factor of Q to account for the higher twist nature of this asymmetry, as defined in Ref. [6]. Tables with detailed relevant information on double and single target spin asymmetries for $ep \to e'\pi^0 X$, extracted for multidimensional bins including x, z and P_T-dependences, are available at arXiv:1709.10054.

In summary, kinematic dependencies of single and double spin asymmetries for neutral pions have been measured in multidimensional bins over a wide kinematic range in x and P_T using CLAS with a polarized proton target. Measurements of the P_T-dependence of the double spin asymmetry, performed for the first time for different x-bins, indicate the possibility of different average transverse momenta for quarks aligned or anti-aligned with the nucleon spin. A non-zero $\sin\phi_h$ target single-spin asymmetry was measured for neutral pions with high precision, indicating that the target SSA may be generated through the Sivers mechanism. A small $\sin 2\phi_h$ moment of the target SSA is consistent with expectations of strong suppression of the Collins effect for neutral pions, due to cancellation of roughly equal favored and unfavored Collins functions. The extent to which higher twist contributes to these extracted moments at relatively low Q^2 constitutes a large part of the upcoming CLAS program with 11 GeV beams.

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Appendix A. Supplementary material

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References

[1] C.A. Aidala, S.D. Bass, D. Hasch, G.K. Mallot, The spin structure of the nucleon, Rev. Mod. Phys. 85 (2013) 655–691, https://doi.org/10.1103/RevModPhys.85.655, arXiv:1209.2803.

[2] A. Bacchetta, Where do we stand with a 3-D picture of the proton?, Eur. Phys. J. A 52 (6) (2016) 163, https://doi.org/10.1140/epja/i2016-16163-5.

[3] P.J. Mulders, R.D. Tangerman, The complete tree level result up to order $1/Q$ for polarized deep inelastic leptoproduction, Nucl. Phys. B 461 (1996) 197–237, https://doi.org/10.1016/S0550-3213(96)00648-7; Erratum: Nucl. Phys. B 484 (1997) 538, https://doi.org/10.1016/0550-3213(95)00632-X, arXiv:hep-ph/9510301.

[4] D.W. Sivers, Single spin production asymmetries from the hard scattering of point-like constituents, Phys. Rev. D 41 (1990) 83, https://doi.org/10.1103/PhysRevD.41.83.

[5] J.C. Collins, Fragmentation of transversely polarized quarks probed in transverse momentum distributions, Nucl. Phys. B 396 (1993) 161–182, https://doi.org/10.1016/0550-3213(93)90262-N, arXiv:hep-ph/9208213.

[6] A. Bacchetta, M. Diehl, K. Goeke, A. Metz, P.J. Mulders, M. Schlegel, Semi-inclusive deep inelastic scattering at small transverse momentum, J. High Energy Phys. 02 (2007) 093, https://doi.org/10.1088/1126-6708/2007/02/093, arXiv:hep-ph/0611265.

[7] A. Airapetian, et al., Observation of a single spin azimuthal asymmetry in semi-inclusive pion electro production, Phys. Rev. Lett. 84 (2000) 4047–4051, https://doi.org/10.1103/PhysRevLett.84.4047, arXiv:hep-ex/9910062.

[8] A. Airapetian, et al., Single spin azimuthal asymmetries in electroproduction of neutral pions in semiinclusive deep inelastic scattering, Phys. Rev. D 64 (2001) 097101, https://doi.org/10.1103/PhysRevD.64.097101, arXiv:hep-ex/0104005.

[9] A. Airapetian, et al., Measurement of single spin azimuthal asymmetries in semiinclusive electroproduction of pions and kaons on a longitudinally polarized deuterium target, Phys. Lett. B 562 (2003) 182–192, https://doi.org/10.1016/S0370-2693(03)00566-5, arXiv:hep-ex/0212039.

[10] A. Airapetian, et al., Single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarized hydrogen target, Phys. Rev. Lett. 94 (2005) 012002, https://doi.org/10.1103/PhysRevLett.94.012002, arXiv:hep-ex/0408013.

[11] A. Airapetian, et al., Quark helicity distributions in the nucleon for up, down, and strange quarks from semi-inclusive deep-inelastic scattering, Phys. Rev. D 71 (2005) 012003, https://doi.org/10.1103/PhysRevD.71.012003, arXiv:hep-ex/0407032.

[12] A. Airapetian, et al., Observation of the naive-T-odd Sivers effect in deep-inelastic scattering, Phys. Rev. Lett. 103 (2009) 152002, https://doi.org/10.1103/PhysRevLett.103.152002, arXiv:0906.3918.

[13] A. Airapetian, et al., Effects of transversity in deep-inelastic scattering by polarized protons, Phys. Lett. B 693 (2010) 11–16, https://doi.org/10.1016/j.physletb.2010.08.012, arXiv:1006.4221.

[14] V.Yu. Alexakhin, et al., First measurement of the transverse spin asymmetries of the deuteron in semi-inclusive deep inelastic scattering, Phys. Rev. Lett. 94 (2005) 202002, https://doi.org/10.1103/PhysRevLett.94.202002, arXiv:hep-ex/0503002.

[15] M.G. Alekseev, et al., Measurement of the Collins and Sivers asymmetries on transversely polarised protons, Phys. Lett. B 692 (2010) 240–246, https://doi.org/10.1016/j.physletb.2010.08.001, arXiv:1005.5609.

[16] H. Avakian, et al., Measurement of single and double spin asymmetries in deep inelastic pion electroproduction with a longitudinally polarized target, Phys. Rev. Lett. 105 (2010) 262002, https://doi.org/10.1103/PhysRevLett.105.262002, arXiv:1003.4549.

[17] X. Qian, et al., Single spin asymmetries in charged pion production from semi-inclusive deep inelastic scattering on a transversely polarized ^{3}He target, Phys. Rev. Lett. 107 (2011) 072003, https://doi.org/10.1103/PhysRevLett.107.072003, arXiv:1106.0363.

[18] J. Huang, et al., Beam-target double spin asymmetry A_{LT} in charged pion production from deep inelastic scattering on a transversely polarized ^{3}He target at $1.4 < Q^2 < 2.7$ GeV^2, Phys. Rev. Lett. 108 (2012) 052001, https://doi.org/10.1103/PhysRevLett.108.052001, arXiv:1108.0489.

[19] Y.X. Zhao, et al., Single spin asymmetries in charged kaon production from semi-inclusive deep inelastic scattering on a transversely polarized ^{3}He target, Phys. Rev. C 90 (5) (2014) 055201, https://doi.org/10.1103/PhysRevC.90.055201, arXiv:1404.7204.

[20] Y. Zhang, et al., Measurement of pretzelosity asymmetry of charged pion production in semi-inclusive deep inelastic scattering on a polarized ^{3}He target, Phys. Rev. C 90 (5) (2014) 055209, https://doi.org/10.1103/PhysRevC.90.055209, arXiv:1312.3047.

[21] H. Avakian, et al., Measurement of beam-spin asymmetries for pi + electroproduction above the baryon resonance region, Phys. Rev. D 69 (2004) 112004, https://doi.org/10.1103/PhysRevD.69.112004, arXiv:hep-ex/0301005.

[22] M. Aghasyan, et al., Precise measurements of beam spin asymmetries in semi-inclusive π^0 production, Phys. Lett. B 704 (2011) 397–402, https://doi.org/10.1016/j.physletb.2011.09.044, arXiv:1106.2293.

[23] Y.X. Zhao, et al., Double spin asymmetries of inclusive hadron electroproductions from a transversely polarized ^{3}He target, Phys. Rev. C 92 (1) (2015) 015207, https://doi.org/10.1103/PhysRevC.92.015207, arXiv:1502.01394.

[24] A. Airapetian, et al., Subleading-twist effects in single-spin asymmetries in semi-inclusive deep-inelastic scattering on a longitudinally polarized hydrogen target, Phys. Lett. B 622 (2005) 14–22, https://doi.org/10.1016/j.physletb.2005.06.067, arXiv:hep-ex/0505042.

[25] C. Adolph, et al., Measurement of azimuthal hadron asymmetries in semi-inclusive deep inelastic scattering off unpolarised nucleons, Nucl. Phys. B 886 (2014) 1046–1077, https://doi.org/10.1016/j.nuclphysb.2014.07.019, arXiv:1401.6284.

[26] M.G. Alekseev, et al., Quark helicity distributions from longitudinal spin asymmetries in muon–proton and muon–deuteron scattering, Phys. Lett. B 693 (2010) 227–235, https://doi.org/10.1016/j.physletb.2010.08.034, arXiv:1007.4061.

[27] A. Afanasev, C.E. Carlson, C. Wahlquist, Probing polarized parton distributions with meson photoproduction, Phys. Lett. B 398 (1997) 393–399, https://doi.org/10.1016/S0370-2693(97)00219-0, arXiv:hep-ph/9701215.

[28] K. Abe, et al., Measurement of azimuthal asymmetries in inclusive production of hadron pairs in $e^+ e^-$ annihilation at Belle, Phys. Rev. Lett. 96 (2006) 232002, https://doi.org/10.1103/PhysRevLett.96.232002, arXiv:hep-ex/0507063.

[29] J.P. Lees, et al., Measurement of Collins asymmetries in inclusive production of charged pion pairs in e^+e^- annihilation at BABAR, Phys. Rev. D 90 (5) (2014) 052003, https://doi.org/10.1103/PhysRevD.90.052003, arXiv:1309.5278.

[30] M. Ablikim, et al., Measurement of azimuthal asymmetries in inclusive charged dipion production in e^+e^- annihilations at $\sqrt{s} = 3.65$ GeV, Phys. Rev. Lett. 116 (4) (2016) 042001, https://doi.org/10.1103/PhysRevLett.116.042001, arXiv:1507.06824.

[31] A. Bacchetta, U. D'Alesio, M. Diehl, C.A. Miller, Single-spin asymmetries: the Trento conventions, Phys. Rev. D 70 (2004) 117504, https://doi.org/10.1103/PhysRevD.70.117504, arXiv:hep-ph/0410050.

[32] B.A. Mecking, et al., The CEBAF large acceptance spectrometer (CLAS), Nucl. Instrum. Methods A 503 (2003) 513–553, https://doi.org/10.1016/S0168-9002(03)01001-5.

[33] Y. Prok, et al., Precision measurements of g_1 of the proton and the deuteron with 6 GeV electrons, Phys. Rev. C 90 (2) (2014) 025212, https://doi.org/10.1103/PhysRevC.90.025212, arXiv:1404.6231.

[34] P.E. Bosted, et al., Target and beam-target spin asymmetries in exclusive π^+ and π^- electroproduction with 1.6- to 5.7-GeV electrons, Phys. Rev. C 94 (5) (2016) 055201, https://doi.org/10.1103/PhysRevC.94.055201, arXiv:1604.04350.

[35] B. Wagner, H.G. Andresen, K.H. Steffens, W. Hartmann, W. Heil, E. Reichert, A Moller polarimeter for CW and pulsed intermediate-energy electron beams, Nucl. Instrum. Methods A 294 (1990) 541–548, https://doi.org/10.1016/0168-9002(90)90296-I.

[36] D.G. Crabb, W. Meyer, Solid polarized targets for nuclear and particle physics experiments, Annu. Rev. Nucl. Part. Sci. 47 (1997) 67–109, https://doi.org/10.1146/annurev.nucl.47.1.67.

[37] A. Kim, et al., Target and double spin asymmetries of deeply virtual π^0 production with a longitudinally polarized proton target and CLAS, Phys. Lett. B 768 (2017) 168–173, https://doi.org/10.1016/j.physletb.2017.02.032, arXiv:1511.03338.

[38] P.E. Bosted, V. Mamyan, Empirical fit to electron-nucleus scattering, arXiv:1203.2262, unpublished.

[39] T. Mineeva, Hadronization Studies via π^0 Electroproduction off D, C, Fe, and Pb, Ph.D. Thesis, Connecticut U, 2013, http://www.jlab.org/Hall-B/general/thesis/Mineeva_thesis.pdf.

[40] I. Akushevich, A. Ilyichev, M. Osipenko, Complete lowest order radiative corrections to five-fold differential cross-section of hadron leptoproduction, Phys. Lett. B 672 (2009) 35–44, https://doi.org/10.1016/j.physletb.2008.12.058, arXiv:0711.4789.

[41] L.W. Mo, Y.-S. Tsai, Radiative corrections to elastic and inelastic e p and mu p scattering, Rev. Mod. Phys. 41 (1969) 205–235, https://doi.org/10.1103/RevModPhys.41.205.

[42] C. Bourrely, J. Soffer, F. Buccella, The extension to the transverse momentum of the statistical parton distributions, Mod. Phys. Lett. A 21 (2006) 143–150, https://doi.org/10.1142/S0217732306019244, arXiv:hep-ph/0507328.

[43] C. Bourrely, J. Soffer, New developments in the statistical approach of parton distributions: tests and predictions up to LHC energies, Nucl. Phys. A 941 (2015) 307–334, https://doi.org/10.1016/j.nuclphysa.2015.06.018, arXiv:1502.02517.

[44] H. Avakian, H. Matevosyan, B. Pasquini, P. Schweitzer, Studying the information content of TMDs using Monte Carlo generators, J. Phys. G 42 (2015) 034015, https://doi.org/10.1088/0954-3899/42/3/034015.

[45] M. Anselmino, A. Efremov, A. Kotzinian, B. Parsamyan, Transverse momentum dependence of the quark helicity distributions and the Cahn effect in double-spin asymmetry A(LL) in semi inclusive DIS, Phys. Rev. D 74 (2006) 074015, https://doi.org/10.1103/PhysRevD.74.074015, arXiv:hep-ph/0608048.

[46] A. Ogawa, M. Grosse Perdekamp, R.-C. Seidl, K. Hasuko, Spin dependent fragmentation functions analysis at Belle, AIP Conf. Proc. 915 (2007) 575–578, https://doi.org/10.1063/1.2750847.

[47] R. Seidl, et al., Measurement of azimuthal asymmetries in inclusive production of hadron pairs in e^+e^- annihilation at s**(1/2) = 10.58-GeV, Phys. Rev. D 78 (2008) 032011, https://doi.org/10.1103/PhysRevD.78.032011; Erratum: Phys. Rev. D 86 (2012) 039905, https://doi.org/10.1103/PhysRevD.86.039905, arXiv:0805.2975.

[48] I. Garzia, Measurement of Collins asymmetries in the inclusive production of pion pairs in electron–positron collisions at BaBar, Nuovo Cimento C 034 (06) (2011) 49–51, https://doi.org/10.1393/ncc/i2011-11034-5.

[49] A.M. Kotzinian, P.J. Mulders, Longitudinal quark polarization in transversely polarized nucleons, Phys. Rev. D 54 (1996) 1229–1232, https://doi.org/10.1103/PhysRevD.54.1229, arXiv:hep-ph/9511420.

[50] M. Anselmino, F. Murgia, Spin effects in the fragmentation of a transversely polarized quark, Phys. Lett. B 483 (2000) 74–86, https://doi.org/10.1016/S0370-2693(00)00519-0, arXiv:hep-ph/0002120.

[51] A.V. Efremov, K. Goeke, P. Schweitzer, Azimuthal asymmetry in electroproduction of neutral pions in semiinclusive DIS, Phys. Lett. B 522 (2001) 37–48, https://doi.org/10.1016/S0370-2693(01)01258-8, Erratum: Phys. Lett. B 544 (2002) 389, https://doi.org/10.1016/S0370-2693(02)02518-2, arXiv:hep-ph/0108213.

[52] A.V. Efremov, K. Goeke, P. Schweitzer, Predictions for azimuthal asymmetries in pion and kaon production in SIDIS off a longitudinally polarized deuterium target at HERMES, Eur. Phys. J. C 24 (2002) 407–412, https://doi.org/10.1007/s100520200918, arXiv:hep-ph/0112166.

[53] B.-Q. Ma, I. Schmidt, J.-J. Yang, Reanalysis of azimuthal spin asymmetries of meson electroproduction, Phys. Rev. D 66 (2002) 094001, https://doi.org/10.1103/PhysRevD.66.094001, arXiv:hep-ph/0209114.

[54] W. Mao, Z. Lu, Beam single spin asymmetry of neutral pion production in semi-inclusive deep inelastic scattering, Phys. Rev. D 87 (1) (2013) 014012, https://doi.org/10.1103/PhysRevD.87.014012, arXiv:1210.4790.

[55] Z. Lu, W. Mao, Single-spin symmetries $A_{UL}^{\sin\phi h}$ in semi-inclusive pions production, Int. J. Mod. Phys. Conf. Ser. 40 (2016) 1660045, https://doi.org/10.1142/S2010194516600454.