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Double spin asymmetries of inclusive hadron electroproduction from a transversely polarized ^{3}He target

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We report the measurement of beam-target double spin asymmetries ($A_{\rm LT}$) in the inclusive production of identified hadrons, $\vec{e} + {}^3\mathrm{He}^\uparrow \rightarrow h + X$, using a longitudinally polarized 5.9-GeV electron beam and a transversely polarized ^{3}He target. Hadrons ($\pi^\pm$, $K^\pm$, and proton) were detected at 16° with an average momentum $\langle P_h \rangle = 2.35$ GeV/c and a transverse momentum (p_T) coverage from 0.60 to 0.68 GeV/c. Asymmetries from the ^{3}He target were observed to be nonzero for $\pi^\pm$ production when the target was polarized transversely in the horizontal plane. The π^+ and π^- asymmetries have opposite signs, analogous to the behavior of $A_{\rm LT}$ in semi-inclusive deep-inelastic scattering.

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I. INTRODUCTION

Understanding the spin structure of the nucleon remains an important goal of research in modern hadronic physics. Beam-target double spin asymmetries (DSA) have been used as a powerful tool in polarized lepton-nucleon deep-inelastic scattering (DIS) experiments to extract polarized parton distributions and quark-gluon correlations [1]. Earlier efforts have been focused mainly on the longitudinal spin structure g_1. Recently, with transversely polarized nucleons, DSAs were used to investigate the g_2 structure functions, which involve twist-3 effects. More recently, a measurement of DSA with a transversely polarized nucleon ($A_{\rm LT}$) in a semi-inclusive deep-inelastic scattering (SIDIS) experiment has provided access to the transverse-momentum-dependent parton distribution functions $g_{1T}(x,k_t^2)$, which are related to quark spin-orbit correlations [2]. In this paper, a measurement of $A_{\rm LT}$ in a less explored reaction, $\vec{e} + \mathrm{N}^\uparrow \rightarrow h + X$, in which a single hadron is detected in the final state, is presented.

The mechanism of inclusive hadron photoproduction was studied in Refs. [3,4]. The production of hadrons arises mainly from four types of processes: fragmentation processes, direct processes, resolved photon processes, and soft contributions. Fragmentation processes have quarks and gluons produced in short-range reactions followed by fragmentation at long distances of either a quark or a gluon to produce the observed hadron. Direct processes occur when the hadron is produced in a short-range reaction via a radiated gluon giving a quark-antiquark pair, one of which joins the initial quark to produce the hadron. Resolved processes are contributions in which photons fluctuate into a quark-antiquark pair, which then interact with the partons of the target. Soft contributions are described by the vector meson dominance (VMD) approximation, which is a way to represent the hadronic components of the photon as they enter into soft processes.

In the collinear factorization framework, $A_{\rm LT}$ in inclusive hadron production is an observable associated with twist-3 effects. It can have twist-3 contributions from both the parton distributions inside the polarized nucleon and the parton fragmentation into final-state hadrons. By measuring $A_{\rm LT}$, one has the opportunity to investigate the so-called worm-gear-type function $\tilde{g}(x)$ [5,6] as well as the role of quark-gluon-quark correlations in the nucleon and twist-3 effects in the fragmentating hadron. The $\tilde{g}(x)$ is defined as an integration [5] over k_t^2 of $g_{1T}(x,k_t^2)$, which can be accessed by $A_{\rm LT}$ measurements in a SIDIS process [2]. Furthermore, it has been proposed that $\tilde{g}(x)$ and quark-gluon-quark correlations are responsible for DSAs of inclusive jet (or hadron) production in polarized nucleon-nucleon reactions and lepton-nucleon reactions in Refs. [7,8].

In this paper, we report a measurement of beam-target double-spin asymmetries in inclusive charged-hadron production using a longitudinally polarized electron beam scattered from a transversely polarized ^{3}He target. The measured asymmetry is defined as

$$A_{\rm LT} = \frac{1}{|P_B P_{\rm target}|} \frac{d\sigma^{\uparrow\rightarrow} - d\sigma^{\downarrow\rightarrow}}{d\sigma^{\uparrow\rightarrow} + d\sigma^{\downarrow\rightarrow}}, \tag{1}$$

where $d\sigma^{\uparrow(\downarrow)\rightarrow}$ is the differential cross section for beam helicity $+$ $(-)$ in a certain target spin direction. P_B is the beam polarization and $P_{\rm target}$ is the target polarization. Figure 1 shows the kinematical configuration in the laboratory coordinate system of the measurement. ϕ_s is the azimuthal angle between the target spin direction $\vec{S}$ and the so-called hadron plane which is formed by the incoming electron and the outgoing hadron. The spin-dependent part of the cross section is proportional to the term $\lambda_e \vec{S} \cdot \vec{p}_T$ ($p_T = \sqrt{p_x^2 + p_y^2}$, the transverse momentum of the outgoing hadron), which gives rise to a $\cos(\phi_s)$ modulation in the definition of the asymmetry

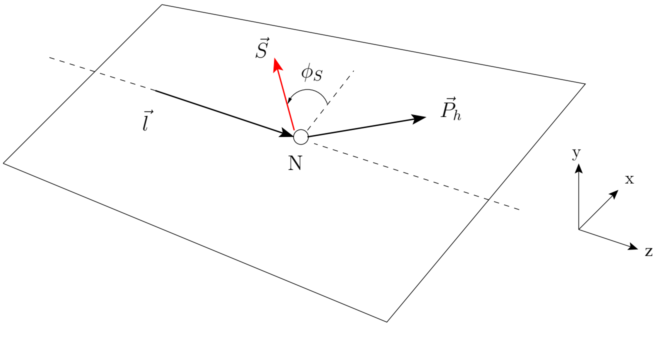

FIG. 1. (Color online) Kinematical configuration in the laboratory coordinate system for the $\vec{e}N^\uparrow \rightarrow hX$ process. $\vec{l}$ ($\vec{P}_h$) represents the momentum direction of the incident electron (produced hadron), and $\vec{S}$ is the spin vector of the nucleon. During the experiment, the target spin was oriented in $\phi_s = 0°(+x), 90°(+y), 180°(-x), 270°(-y)$ directions.

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[5]. In order to form the parity-even structure by using the spin of the nucleon and the momentum of outgoing hadron, $\cos(\phi_s)$ is the only modulation considered in the current theoretical framework [5]. Hence, the asymmetry can be written as

$$A_{\mathrm{LT}} = A_{\mathrm{LT}}^{\cos(\phi_s)} \cos(\phi_s). \qquad (2)$$

The produced hadrons were detected in a high-resolution spectrometer (HRS) [9] at a central angle of 16° on the beam left side with a central momentum of 2.35 GeV/c, a momentum acceptance of ±4.5%, and solid angle acceptance of 6 msr. The data were collected using a singles trigger during the E06-010 experiment [2,10–12] in Hall A at Jefferson Lab.

II. EXPERIMENT

A polarized 5.9-GeV electron beam with an average current of 12 μA was provided by the CEBAF accelerator during the experiment. Polarized electrons were excited from a strained superlattice GaAs photocathode by a circularly polarized laser [13] at the injector. The average beam polarization was (76.8 ± 3.5)%, which was measured periodically by Møller polarimeter [9]. The beam helicity was reversed at 30 Hz by flipping the laser polarization. During the E06-010 experiment, the sequence for beam helicity states followed a quartet structure, $+--+$ or $-++-$, randomly to reduce the systematic bias between the two helicity states. Due to a beam-charge feedback system [14], the beam-charge asymmetry between the two helicity states was kept at less than 150 ppm per 20 min and less than 10 ppm for the entire experiment [2].

The ground state of the ^{3}He nuclear wave function is dominated by the S state, in which the proton spins cancel each other and the nuclear spin is carried by the neutron [15]. About 10 atm of ^{3}He gas was filled in a 40-cm-long cylindrical aluminiosilicate glass cell and ^{3}He nuclei were polarized by spin-exchange optical pumping of a Rb-K mixture [16,17]. Three pairs of Helmholtz coils were used in the experiment to orient the magnetic holding field transversely or vertically with respect to the electron beam. For each orientation, the spin direction of ^{3}He nuclei was flipped every 20 min through adiabatic fast passage. Nuclear magnetic resonance measurements, calibrated by the electron paramagnetic resonance method [18], were performed to monitor the target polarization while the target spin direction was flipped. An average in-beam target polarization of (55.4 ± 2.8)% was achieved during the experiment.

The HRS detector package was configured for hadron detection. The trigger was formed by the coincidence signal between two scintillator planes which were about 2 m apart. Four detectors were used for particle identification: (1) a threshold CO_2 gas Cerenkov detector for electron identification, (2) a threshold aerogel Cerenkov detector for pion identification, (3) a ring imaging Cerenkov (RICH) detector for $\pi^\pm$, $K^\pm$, and proton identification [11,19], and (4) two layers of lead-glass calorimeter for electron-hadron separation. Contaminations were well controlled and studied carefully in Ref. [11].

III. DATA ANALYSIS

For each target spin direction, the selected data samples were separated into two groups by beam helicity states. These two groups were treated as a local pair. The final beam-target double spin asymmetry A_{LT} was extracted by summing over all local pair measurements.

A small amount of N_2 gas, present in the target cell to reduce depolarization [9], diluted the measured ^{3}He asymmetry and was corrected by the nitrogen dilution factor defined as

$$f_{\mathrm{N}_2} = \frac{\rho_{\mathrm{N}_2}\sigma_{\mathrm{N}_2}}{\rho_{^3\mathrm{He}}\sigma_{^3\mathrm{He}} + \rho_{\mathrm{N}_2}\sigma_{\mathrm{N}_2}}, \qquad (3)$$

where ρ is the density of the gas in the production target cell and σ is the unpolarized inclusive hadron (pion, kaon, and proton) production cross section. The ratio of unpolarized cross sections $\sigma_{\mathrm{N}_2}/\sigma_{^3\mathrm{He}}$ was measured in dedicated runs on targets filled with known amounts of unpolarized N_2 or ^{3}He gas. The f_{N_2} in this experiment was determined to be less than 10%.

The overall systematic uncertainty in the experiment was small due to frequent target-spin and beam-helicity flips. The false asymmetry due to luminosity fluctuations was less than 0.07% and was confirmed by measuring the beam-target double spin asymmetry in the inclusive (e,e') DIS reaction with the target polarized in the $\pm y$ direction, in which the asymmetry vanishes due to parity and time-reversal symmetry. Systematic uncertainties due to contaminations were estimated to be less than 0.02% for pion, kaon, and proton measurements. In addition, there was an overall 5% systematic uncertainty, relative to the asymmetries, from both beam and target polarizations. For the kaon and proton measurements, as described in Ref. [11], there were two additional sources of systematic uncertainties associated with the RICH detector: (1) the value of the cut on the number of hits in the RICH detector and (2) detector inefficiencies. The first contribution was determined to be $<15\%$ for $K^\pm$ and $<3\%$ for protons, relative to the statistical uncertainties. The second contribution was determined to be $<7\%$, $<3\%$, and $<1\%$, relative to the statistical uncertainties, for K^+, K^-, and protons, respectively.

IV. RESULTS

The final A_{LT} results from ^{3}He are shown for different hadron species in Fig. 2. The error bars represent the

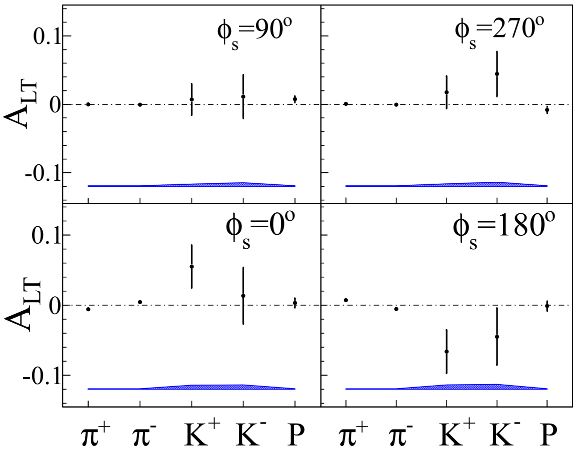

FIG. 2. (Color online) Beam-target double spin asymmetries A_{LT} for $\pi^\pm$, $K^\pm$, and proton production from ^{3}He for different ϕ_s.

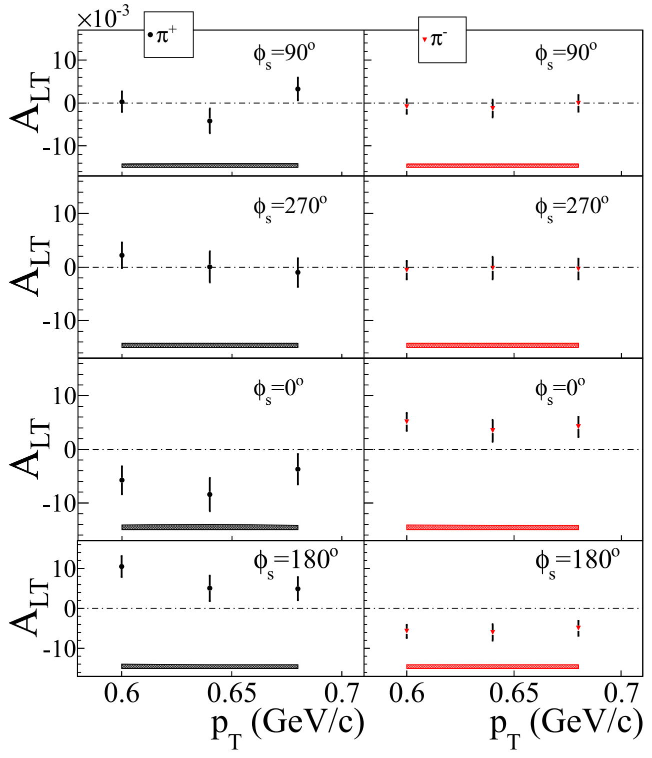

FIG. 3. (Color online) Beam-target double spin asymmetries A_{LT} for $\pi^{\pm}$ production from ^{3}He as a function of p_T for different ϕ_s. The left column is for the π^+ data; the right column is for the π^- data.

statistical uncertainties. Experimental systematic uncertainties, combined in quadrature from different sources, are shown as a band. For $\phi_s = 90^\circ$ and 270°, the asymmetries from pions and kaons are consistent with zero within the experimental uncertainties ($\sim 1 \times 10^{-3}$ level for the pion measurement). For $\phi_s = 0^\circ$ and 180°, the sign of the asymmetry is flipped when the target spin direction is reversed. Pion data were also analyzed in three p_T bins. The results are shown in Fig. 3. The asymmetries for $\phi_s = 0^\circ$ and $\phi_s = 180^\circ$ were combined together to obtain $A_{\mathrm{LT}}^{\cos(\phi_s)}$. The combination was weighted by the statistical uncertainties of the asymmetries. The final p_T-dependent $A_{\mathrm{LT}}^{\cos(\phi_s)}$ asymmetries for $\pi^{\pm}$ production from ^{3}He are shown in Fig. 4 and tabulated in Table I.

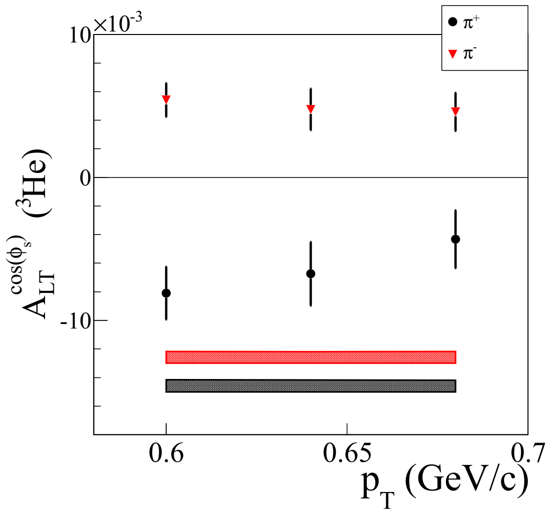

FIG. 4. (Color online) Beam-target double spin asymmetries $A_{\mathrm{LT}}^{\cos(\phi_s)}$ for $\pi^{\pm}$ production from ^{3}He as a function of p_T. The red (top, gray) band is the systematic uncertainty band for π^-, and the black (bottom) band is the systematic uncertainty band for π^+.

TABLE I. Tabulated results of p_T-dependent $A_{\mathrm{LT}}^{\cos(\phi_s)}$ for $\pi^{\pm}$ production from ^{3}He.

$\langle p_T \rangle$ (GeV/c)	π^+ ($A_{\mathrm{LT}}^{\cos(\phi_s)}$ ± Stat. ± Sys.)	π^- ($A_{\mathrm{LT}}^{\cos(\phi_s)}$ ± Stat. ± Sys.)
0.60	$-0.0081 \pm 0.0018 \pm 0.0009$	$0.0054 \pm 0.0012 \pm 0.0008$
0.64	$-0.0067 \pm 0.0022 \pm 0.0008$	$0.0048 \pm 0.0014 \pm 0.0008$
0.68	$-0.0043 \pm 0.0020 \pm 0.0008$	$0.0046 \pm 0.0013 \pm 0.0008$

Neutron asymmetries for pion production were obtained from the ^{3}He asymmetries using the effective polarizations of the proton and neutron in polarized ^{3}He using the equation [20]

$$A_{\mathrm{LT}}^{^3\mathrm{He}} = P_n(1 - f_p)A_{\mathrm{LT}}^{n} + P_p f_p A_{\mathrm{LT}}^{p}, \tag{4}$$

where $A_{\mathrm{LT}}^{^3\mathrm{He}}$ is the measured ^{3}He asymmetry. $P_n = 0.86^{+0.036}_{-0.02}$ and $P_p = -0.028^{+0.009}_{-0.004}$ are the effective polarization of the neutron and proton, respectively. The proton dilutions, $f_p = \frac{2\sigma_p}{\sigma_{^3\mathrm{He}}}$, in ^{3}He were measured directly by measuring yields from unpolarized hydrogen and ^{3}He targets. The averages of f_p were 0.844 ± 0.007 for π^+ and 0.732 ± 0.005 for π^-. Since there were no A_{LT} experimental data from the proton, and the contribution to the final ^{3}He asymmetry from polarized protons in polarized ^{3}He is small due to the small P_p, the proton A_{LT}^{p} was treated as a systematic uncertainty while the neutron asymmetry was extracted from the ^{3}He asymmetry. The beam-target double spin asymmetry from a polarized proton target was assumed to be no more than ±5% based on the calculations for a proton target in Ref. [5]. The final p_T-dependent asymmetries $A_{\mathrm{LT}}^{\cos(\phi_s)}$ for $\pi^{\pm}$ production from the neutron are shown in Fig. 5 and tabulated in Table II. In addition, the kinematic variable x_F was also calculated. It is defined as $x_F = 2p^{c.m.}/\sqrt{s}$, where $p^{c.m.}$ is the momentum of the outgoing hadron along the polarized nucleon's momentum direction in the $e + N$ center-of-mass (c.m.) frame.

TABLE II. Tabulated results of p_T-dependent $A_{\mathrm{LT}}^{\cos(\phi_s)}$ for $\pi^{\pm}$ production from the neutron. A negative x_F indicates that the produced hadron is moving backwards with respect to the nucleon momentum direction in the center-of-mass frame of the $e + N$ system.

$\langle p_T \rangle$ (GeV/c)	$\langle x_F \rangle$	π^+ ($A_{\mathrm{LT}}^{\cos(\phi_s)}$ ± Stat. ± Sys.)	π^- ($A_{\mathrm{LT}}^{\cos(\phi_s)}$ ± Stat. ± Sys.)
0.60	-0.269	$-0.063 \pm 0.014 \pm 0.012$	$0.024 \pm 0.005 \pm 0.006$
0.64	-0.263	$-0.049 \pm 0.016 \pm 0.011$	$0.020 \pm 0.006 \pm 0.006$
0.68	-0.254	$-0.032 \pm 0.015 \pm 0.011$	$0.019 \pm 0.005 \pm 0.005$

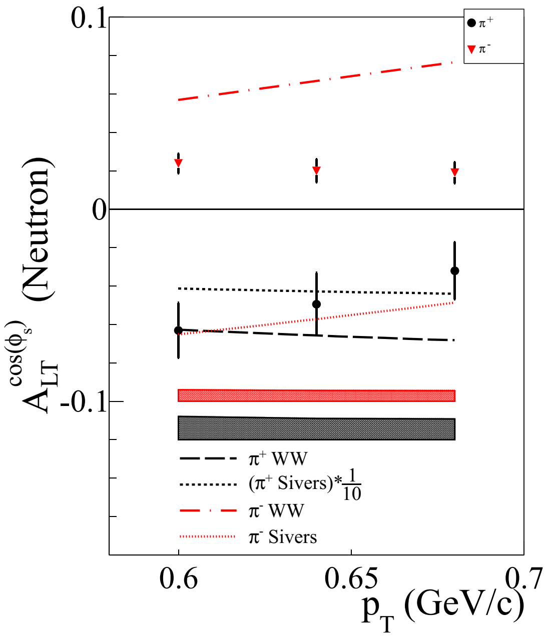

FIG. 5. (Color online) Beam-target double spin asymmetries $A_{LT}^{\cos(\phi_s)}$ for $\pi^\pm$ production from the neutron as a function of p_T. The systematic uncertainty is shown as a band. The red (top, gray) band is the systematic uncertainty band for π^-, and the black (bottom) band is the systematic uncertainty band for π^+. Predictions from collinear factorization by using two different scenarios [5] [Sivers function and Wandzura-Wilczek (WW)–type approximation] are shown as well. Please note that the prediction for π^+ by using the Sivers function is scaled by a factor of $\frac{1}{10}$.

V. CONCLUSION

The observed π^+ and π^- asymmetries from ^{3}He and effective neutron targets have opposite signs when the target is transversely polarized. The π^+ and π^- asymmetries for a vertically polarized target are consistent with zero within the experimental uncertainties. Although the uncertainty is large, the sign of the $K^\pm$ A_{LT} is flipped as the target spin direction is reversed transversely (in the x direction). The K^+ asymmetry is larger than that of π^+ and they are different in sign. If the kaon asymmetry is of partonic origin, it might indicate that sea-quark contributions or unfavored fragmentation functions play a more important role. In addition, higher-order or higher-twist effects might also be possible reasons. For the proton A_{LT}, the sign of the asymmetry is flipped as the target spin direction is reversed vertically (in the y direction), while the asymmetry is consistent with zero within the experimental uncertainty with the target polarized transversely (in the x direction). A hypothesis testing was performed to the proton asymmetries, and the $\cos(\phi_s)$ dependence of the asymmetry cannot be excluded within 2-σ of significance. One of possible reasons for the interesting behavior of the proton asymmetries might be that the protons were mostly knocked out from ^{3}He with nuclear effects. In the collinear factorization approximation, A_{LT} in inclusive pion production was estimated in the JLab 6-GeV kinematic region [5]. The estimations were done using two approximations to calculate the $\widetilde{g}(x)$ while doing numerical predictions for A_{LT} in inclusive pion production. One is using the approximate relation, $\widetilde{g}(x) \approx -f_{1T}^{\perp}(x)$, where $f_{1T}^{\perp}(x)$ is the Sivers function; the other one is using Wandzura-Wilczek (WW)–type approximation, $\widetilde{g}(x) \approx x\int_x^1 \frac{dy}{y} g_1(y)$. Calculations based on the two approximations shown in Fig. 5 give different predictions. Our data are consistent in sign with the prediction using the WW approximation, while the magnitude of the predictions is larger than that of our data. The calculation using the Sivers function is not consistent with our data. However, one needs to take into account the current uncertainty of the Sivers function and potential large next to leading order corrections, which are not included in the calculation. We point out that p_T in our experiment is around 0.64 GeV/c, which is lower than 1 GeV/c where the theoretical predictions are believed to be reliable. In addition, the A_{LT} measurements in inclusive hadron production and SIDIS processes are linked by the definition of $\widetilde{g}(x)$. The behavior of the π^+ and π^- $A_{LT}^{\cos(\phi_s)}$ with opposite sign is similar to that in the SIDIS measurement in Ref. [2], while the size of the asymmetries in inclusive and SIDIS processes are different. However, one has to be aware that the kinematic coverage for the nondetected electrons in the inclusive hadron production processes is larger than that of the electrons in the SIDIS processes and the production mechanism can also be different. To fully interpret the data, one has to understand the mechanism of inclusive hadron production in different kinematic regions and the main contributions to the double-spin asymmetry.

In summary, we have reported the measurement of A_{LT} in the inclusive hadron production reaction using longitudinally polarized electrons scattered from a transversely polarized ^{3}He target. Nonzero asymmetries were observed for charged pions from a transversely polarized target. The asymmetries in π^+ and π^- production have opposite signs. The asymmetries are compared to calculations from collinear factorization, and the signs of the asymmetries are consistent with calculations using the WW approximation. To fully understand inclusive hadron production in terms of parton distributions and correlations among partons, new theoretical and experimental efforts should be carried out. Future experiments at Jefferson Lab [21,22] and a future electron-ion collider (EIC) [23] will extend the measurement to a broad p_T range and a much higher precision.

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