Single Target-Spin Asymmetry in Semi-Inclusive Deep Inelastic Scattering on Transversely Polarized Nucleon Target

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Abstract

We use a new set of Collins functions to update a previous prediction on the azimuthal asymmetries of pion productions in semi-inclusive deep inelastic scattering (SIDIS) process on a transversely polarized nucleon target. We find that the calculated results can give a good explanation to the HERMES experiment with the new parametrization, and this can enrich our knowledge of the fragmentation process. Furthermore, with two different approaches of distribution and fragmentation functions, we present a prediction on the azimuthal asymmetries of pion and kaon productions at the kinematics region of the experiments E06010 and E06011 planned at Jefferson Lab (JLab). It is shown that the results are insensitive to the models for the pion case. However, the results for kaon production are sensitive to different approaches of distribution and fragmentation functions. This is helpful to clarify some points in the study of the azimuthal spin asymmetries and fragmentation functions in hadronization processes.

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I. INTRODUCTION

The history of single spin asymmetries (SSA) can date back to the 1970s when significant SSA were observed in $pp \rightarrow \Lambda X$ \cite{1}. In the early 1990s, large asymmetries in $p^1p \rightarrow \pi X$ were found at FNAL \cite{2}. However, there were no satisfactory theory to describe the phenomena, and pQCD theory had nothing to do then. In recent years, SSA phenomenon were also observed in semi-inclusive deep inelastic scattering (SIDIS) processes, which had attracted many interests, particularly in the case where the transverse polarized targets are used. For example, HERMES collaboration \cite{3, 4} has reported the observation of the azimuthal asymmetries in single-pion productions on both longitudinally and transversely polarized hydrogen targets. More recently, COMPASS collaboration \cite{5} has published their results off a transversely polarized deuterium targets as a complementary measurement to HERMES experiment. On the theoretical side, by taking into the account of the transverse parton momenta inside the nucleon \cite{6, 7, 8}, these asymmetries are now assumed to have correlations with the concept of transversity \cite{9} which we are not familiar with so far.

The idea (though not the term) of transversity was put forward by Ralston and Soper via the Drell-Yan process \cite{10}, where they introduced the concept of parton transverse polarization. A clarification of transversity on the role of chiral-odd parton distributions and the general twist was provided by Jaffe and Ji in Ref. \cite{11}. Detailed twist clarification for various parton distributions can be found in Refs. \cite{9, 12}. Now we know that at the leading twist (twist 2), three fundamental quark distributions provide a complete description of quark momentum and spin in the nucleon. In the last forty years, two of them, the unpolarized and longitudinal polarized parton distributions($q_i$ and $\Delta q_i$) have been precisely measured, yet the third type, the “transversity distribution ($\delta q_i$)”, is still little known both theoretically and experimentally. The difficulty in experiments lies in its chiral-odd property. In the helicity basis, $\delta q_i$ represents a quark helicity flip, which cannot occur in any hard process for massless quarks within QED or QCD \cite{13}. This chiral-odd property makes it inaccessible in inclusive deep inelastic scattering (DIS). However, several researches have shown that the transversity distribution can manifest itself in semi-inclusive deep inelastic scattering (SIDIS) reactions \cite{14, 15, 16}, where the transversity distribution function couple with a chiral-odd fragmentation function—the Collins function \cite{14}. This was verified by observing the SSA in HERMES and COMPASS experiments recently. Results from both
HERMES and COMPASS have offered us a first glimpse at transversity distributions on u and d quarks in proton.

If studying SSA more explicitly, we would find that these asymmetries can be explained in terms of both the Sivers [18, 19, 20, 21] and Collins [14] effects. The Sivers effect involves the so-called Sivers function and the ordinary fragmentation function, while the Collins effect involves the transversity distribution function and the Collins fragmentation function. The two competing contributions have different kinematic dependence. The Collins effect depends on $y$ and strongly correlated with $z$, but the Sivers effect is independent of $y$ and not strongly correlated with $z$. Also, they have different azimuthal angle dependence: the Sivers effect is proportional to $\sin(\phi - \phi_s)$, while the Collins effect is proportional to $\sin(\phi + \phi_s)$, where the definition of $\phi$ and $\phi_s$ can be found in Ref. [17]. Thus we can distinguish the two effects in experiment without much difficulty. In our paper, we are interested in the transversity information provided by SSA, so we only concentrate on the Collins effect in this paper. In the Collins effect, the transversity distribution function describes the correlation between the spin of quarks and spin of nucleons, and the so-called Collins function describes the fragmentation of transversely polarized quarks into unpolarized hadrons. Both functions are important in our numerical calculations and will be discussed in the next section.

With this understanding, a lot of studies [22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35] have attempted to explain the HERMES measurement or to give more predictions. Particularly, the article [34] predicted the Collins azimuthal asymmetries (Fig. 1) on a transversely polarized hydrogen target in HERMES kinematics, yet the prediction is not consistent with the new released HERMES results [4]. However, as the authors pointed out in the paper that the “unfavored” process might lead to a sizable effect, which is in conflict with our general understanding and might result in the inconsistency. Recently, the authors of Ref. [36] proposed that the polarized “unfavored” Collins function is approximately equal to the “favored” one, but with an opposite sign. They fitted the HERMES data [4] and obtained new sets of parametrization. We will shown in this paper that the updated results of Ref. [34] with these new parametrization of the Collins function, are also consistent with the HERMES data (Fig. 2). Both calculations imply that the “unfavored” Collins function may play an important role in the fragmentation processes.

At Jefferson Lab (JLab), experiments E06010 and E06011 will perform the measurement of single spin asymmetries with a transversely polarized $^3$He target which is an effectively
transversely polarized neutron target, so it may provide a direct measurement of the neutron transversity distributions. In our paper, we will present the predictions of the azimuthal asymmetries in the JLab kinematics region. The influence due to the “unfavored” Collins function is included in the prediction. We conclude that the comparison of the data with the prediction will be able to provide constraints on both the Collins functions and transversity distributions, but not a pure measurement of the transversity distributions.

II. QUARK DISTRIBUTION AND FRAGMENTATION FUNCTIONS

At the leading twist, the differential cross section for a SIDIS reaction includes the contributions from the unpolarized part, the Collins effect and the Sivers effect. It can be written as

$$d\sigma = d\sigma_{UU} - d\sigma_{UT}^{\text{Collins}} - d\sigma_{UT}^{\text{Sivers}},$$

where the beam is not polarized and the target is transversely polarized.

Under the factorization assumption, the cross sections in Eq. (1) can be expressed as product of parton distribution and fragmentation functions. Here we only give the unpolarized and the Collins terms as follows,

$$\frac{d\sigma^{\ell+N\to\ell^*+h+X}}{dx dy dz d\phi^h} = 4\pi\alpha^2 s x \left(1 - y + \frac{y^2}{2}\right) \sum_q e_q^2 q(x) D^q_1(z, P^2_{h\perp})$$

$$\quad - |S_T| (1 - y) \sin(\phi^h + \phi_s^\ell) \sum_q e_q^2 \delta q(x) H_1^{1(1)q}(z, P^2_{h\perp}).$$

(2)

Here $S_T$ is the target transverse polarization; $e_q$ is the charge of the quark with flavor $q$. $\phi^h$ is the angle between the hadron lane and the lepton plane. $\phi_s^\ell$ is the angle between the $S$ and the lepton plane. $q(x)$ and $\delta q(x)$ represent the momentum and transversity distribution functions of the nucleon target respectively. By comparing the cross sections with the opposite polarized target, one obtains the single spin asymmetry

$$A_{UT} = \frac{d\sigma(\vec{S}_T) - d\sigma(-\vec{S}_T)}{d\sigma(\vec{S}_T) + d\sigma(-\vec{S}_T)} = A_T^{\text{Collins}}(x, y, z, p^h_{\perp}) \cdot \sin(\phi^h + \phi_s^\ell).$$

(3)

After integrating the intrinsic transverse momentum $P_{h\perp}$ and the kinematical variable $y$ and $z$, we can get the formula for calculating the $x$ dependence of the Collins asymmetry (denoted as $A_T(x)$)

$$A_T(x) = -|S_T| \frac{\sum_q e_q^2 \int dz dy (1 - y) \delta q(x) H_1^{1(1)q}(z) \int dz dy (1 - y + y^2/2) q(x) D^q_1(z)}{\sum_q e_q^2 \int dz dy (1 - y + y^2/2) q(x) D^q_1(z)}.$$

(4)
$D_1^q(z)$ is the fragmentation function for an unpolarized quark with flavor $a$ into a hadron, defined as

$$D_1^q(z) \equiv \int d^2 P_{h\perp} D_1^q(z, P_{h\perp}^2). \quad (5)$$

$H_1^{1(1)q}(z)$ is the so called Collins function, defined as

$$H_1^{1(1)q}(z) \equiv \int d^2 P_{h\perp} - \frac{P_{h\perp}^2}{z^2 M_h^2} H_1^{1q}(z, P_{h\perp}^2). \quad (6)$$

The kinematical variable $y$ can be calculated from

$$Q^2 = s x y, \quad (7)$$

with $s=51.8$ GeV$^2$.

To get the transversity distribution function, we use two models in this paper, the quark-diquark model [38, 39, 40] and a pQCD based counting rule analysis [41, 42, 43, 44, 45]. In the quark diquark model case, the transversity distributions are given by

$$\delta u_v(x) = \left[ u_v(x) - \frac{1}{2} d_v(x) \right] W_s(x) - \frac{1}{6} d_v(x) W_v(x);$$

$$\delta d_v(x) = -\frac{1}{3} d_v(x) W_v(x). \quad (8)$$

$W_s(x)$ and $W_v(x)$ are the Melosh-Wigner rotation factors for spectator scalar and vector diquarks, which come from the relativistic effect of quark transversal motions [46, 47]. For the pQCD based analysis, we adopt the parametrization

$$u_v^{pQCD}(x) = u_v^{para}(x), \quad d_v^{pQCD}(x) = \frac{d_v^{th}(x)}{u_v^{th}(x)} u_v^{para}(x), \quad (9)$$

$$\delta u_v^{pQCD}(x) = \frac{\delta u_v^{th}(x)}{u_v^{th}(x)} u_v^{para}(x), \quad \delta d_v^{pQCD}(x) = \frac{\delta d_v^{th}(x)}{u_v^{th}(x)} u_v^{para}(x), \quad (10)$$

where the superscripts “th” means the theoretical calculation in the pQCD analysis [29, 34], and “para” means the input from parametrization. The CTEQ [48] parametrization is served as the input for both models to get the unpolarized parton distribution functions. Detailed constructions of the quark distributions can be found in Refs. [29, 34, 49].

Both of the two models have successfully predicted the longitudinal polarized parton distribution functions [50]. But two models give different distribution functions at $x \to 1$: the pQCD based counting rule analysis [43] predicts $\delta d(x)/d(x) \to 1$, while the SU(6) quark-spectator-diquark model [40] predicts $\delta d(x)/d(x) \to -1/3$. In a recent literature [51], the
The author extracted the transversity distribution for $u$ and $d$ quarks from the now available data. They found that $\delta u(x)$ and $\delta d(x)$ turned out to be opposite in sign, with $|\delta d(x)|$ smaller than $|\delta u(x)|$. This seems to be coincidence qualitatively with the SU(6) quark-diquark model. But there it predicts $\delta d(x)/d(x) \to 0$ when $x \to 1$, which is coincidence quantitatively with neither models we used in our paper. The correctness of different parametrization is still unclear, and need to be checked by more experiments.

As to the ordinary fragmentation functions for $\pi^\pm$, we follow the parametrization of $D(z)$ given by Kretzer, Leader and Christova [52]:

$$D_{\pi^\pm}(z) = 0.689 z^{-1.039} (1-z)^{1.241},$$
$$\hat{D}_{\pi^\pm}(z) = 0.217 z^{-1.805} (1-z)^{2.037}, \quad (11)$$

and for $K^\pm$, we have [53]

$$D_{K^\pm}(z) = 0.31 z^{-0.98} (1-z)^{0.97},$$
$$\hat{D}_{K^\pm}(z) = 1.08 z^{-0.82} (1-z)^{2.55}, \quad (12)$$

where $D(z)$ denotes the “favored” fragmentation function and $\hat{D}(z)$ denotes the “unfavored” one.

The Collins fragmentation function $H_{1^+(1)}^q(z)$, which describes the transition of a transversely polarized quark into a pion, is theoretically little known and has not yet been measured. In Ref. [20], Collins suggested a parametrization:

$$A_C(z, k_\perp) = \frac{|k_\perp| H_{1^+(1)}^q(z, z^2 k_\perp^2)}{M_h D_1^q(z, z^2 k_\perp^2)} = \frac{M_c|k_\perp|}{M_h^2 + |k_\perp|^2}, \quad (13)$$

where $M_c = 0.3 \sim 1$ GeV. In HERMES analysis, $M_c = 0.7$ GeV is taken as a rough estimate [32]. The transverse momentum dependence of $D_1^q(z, z^2 k_\perp^2)$ is assumed to have a Gaussian type shape:

$$D_1^q(z, z^2 k_\perp^2) = D_1^q(z) \frac{R^2}{\pi z^2} \exp(-R^2 k_\perp^2). \quad (14)$$

One can obtain

$$H_{1^+(1)}^q(z) = D_1^q(z) \frac{M_c}{2 M_h} (1 - M_c^2 R^2) \int_0^\infty dx \frac{\exp(-x)}{x + M_c^2 R^2}, \quad (15)$$

with $R^2 = z^2/\langle P_{h_\perp}^2 \rangle$, and $\langle P_{h_\perp}^2 \rangle = z^2 \langle k_\perp^2 \rangle$ being the mean square momentum that the detected hadron acquires in the quark fragmentation process with $\langle P_{h_\perp}^2 \rangle = 0.25$ GeV$^2$ according to HERMES [32].
Recently, Vogelsang and Yuan suggested another model \[36\] which assumes a stronger constraint for the pion Collins functions:

\[
H_1^{\perp(1)\pi^+}(z) + H_1^{\perp(1)\pi^-}(z) + H_1^{\perp(1)\pi^0}(z) \approx 0. \tag{16}
\]

If we consider the isospin and charge symmetry relations between the different fragmentation functions, we can have the following relations,

\[
H_1^{\perp(1)\pi^+}(z) = H_1^{\perp(1)\pi^-}(z) = H_1^{\perp(1)\pi^0}(z) = H(z),
\]

\[
H_1^{\perp(1)\pi^+}(z) = H_1^{\perp(1)\pi^-}(z) = H_1^{\perp(1)\pi^0}(z) = \tilde{H}(z),
\]

\[
H_1^{\perp(1)\pi^0}(z) = H_1^{\perp(1)\pi^0}(z) = H_1^{\perp(1)\pi^0}(z) = \frac{1}{2}[H(z) + \tilde{H}(z)]. \tag{17}
\]

Substituting (17) into (16), one obtains

\[
H(z) + \tilde{H}(z) \approx 0, \tag{18}
\]

which means that the “unfavored” Collins function is approximately equal to the “favored” one, but with an opposite sign. This is in conflict with almost all the theoretical analysis before, and it still needs to be further checked by experiment. In Ref. \[36\], the parametrization of Collins functions is advanced in the forms,

Set I: \( H(z) = C_f z(1-z)D(z), \ \tilde{H}(z) = C_u z(1-z)\hat{D}(z) \),

Set II: \( H(z) = C_f z(1-z)D(z), \ \tilde{H}(z) = C_u z(1-z)\hat{D}(z) \). \tag{19}

The authors of Ref. \[36\] fitted the parametrization to the HERMES data \[3\] and obtained

\[
\text{Set I} : \ C_f = -0.29 \pm 0.04, \ C_u = 0.33 \pm 0.04,
\]

\[
\text{Set II} : \ C_f = -0.29 \pm 0.02, \ C_u = 0.56 \pm 0.07. \tag{20}
\]

The difference between these two sets of parametrization is that in Set I, both favored and unfavored Collins functions are parameterized in terms of favored unpolarized quark fragmentation function, while in Set II the unfavored Collins function is parameterized in terms of the unfavored unpolarized quark fragmentation function. Also in the literature \[51\], the authors provide their own parametrization to the Collins functions, with more parameters compared to the parametrization in Ref. \[36\]. As the author pointed that their parametrization is agree with the extractions obtained in Ref. \[36\], we will use the parametrization with less parameters provided in Ref. \[36\] in our paper.
This parametrization was obtained from the pion data in Ref. [36]. In our paper, we assume that this parametrization is also right for the kaon case. In other words, we assume that with this parametrization, the information depending on the final hadron states is only contained in the ordinary fragmentation functions.

III. COMPARISON WITH THE HERMES DATA

Figs. 1 and 2 show our calculated results on HERMES measurement as function of $x$, using different sets of parametrization. First we find that the quark-diquark model and the pQCD based counting rule analysis give almost the same result in the intermediate region of $x$. Fig. 1 presents the results when we use the parametrization as Eq. (15) shows. However, the calculated results are overestimated compared to the experimental data. Fig. 2 presents the results when we use two sets of parametrization of Collins functions given by Ref. [36], which shows that our calculations fit the HERMES data well. As $u$ quark dominates in the proton, so $u$ to $\pi^+$ is favored while $u$ to $\pi^-$ is unfavored. The calculation indicates that both the “favored” and “unfavored” processes have the sizable effect. This is the direct consequence of Eq. 20 where the favored and unfavored Collins functions have the approximately equal size but with the opposite signs. This is quite different from the ordinary fragmentation functions where the favored process plays much more important roles than the unfavored process. If we ignore the opposite sign, the numerator of formula (4) is nearly of the equal size for both the $\pi^+$ and $\pi^-$ productions, but the denominator is larger in the $\pi^+$ production case than that in the $\pi^-$ production case. So we expect a larger asymmetry in the $\pi^-$ production and this can also be seen from Fig. 2. Besides these, we also notice that both the two sets of parametrization shown in Eq. (20) give similar predictions, so more precise experiments are needed to give the constraints.

IV. PREDICTIONS ON THE JLAB EXPERIMENTS

The JLab experiments E06010 and E06011 will measure the target single spin asymmetries in the semi-inclusive deep-inelastic reaction off a transversely polarized $^3$He target for both $\pi^\pm$ and $K^\pm$. Due to the special structure of $^3$He, which can be considered as a nearly free polarized neutron, JLab will provide a measure of the neutron structure. Apply-
ing the same technique, we make predictions of azimuthal asymmetries $A_T$ for $\pi^\pm$ and $K^\pm$ productions at JLab kinematics.

At JLab, the kinematics region is:

$$2.33 < W < 3.05 \text{ GeV}, \quad 0.19 < x < 0.34, \quad 1.77 < Q^2 < 2.73 \text{ GeV}^2, \quad 0.37 < z < 0.56.$$  \hspace{1cm} (21)

The azimuthal asymmetry of $^3\text{He}$ target can be expressed by the neutron and proton asymmetries:

$$A_T(^3\text{He}) = P_{^3\text{He}} \cdot (f_n \cdot \eta_n \cdot A_T(n) + 2f_p \cdot \eta_p \cdot A_T(p)), \quad (22)$$

where $f_n$ and $f_p$ are the effective polarizations of the proton and the neutron within the $^3\text{He}$ nucleus, and $P_{^3\text{He}}$ is the polarization of the $^3\text{He}$ target which is assumed to be 42% in the experiment. A three-body Fadeev calculation [54] shows that in inelastic scattering reactions, $f_n = 0.86 \pm 0.02$ and $f_p = -0.028 \pm 0.004$. $\eta_n(\eta_p)$ in the above formula represents the ratio of $(e, e'\pi)$ events on neutron (proton) over the total $^3\text{He}(e, e'\pi)$ events. At JLab, one expects: $\eta_n \approx 0.32$ and $\eta_p \approx 0.34$. For the case of kaon production, we adopt the same value as a rough estimate.

Fig. 3 shows the prediction of the asymmetry ($A_T$) on proton target. Compared to Fig. 2, we find that the predictions are almost the same. Fig. 4 shows the neutron case, where $d$ quark dominates, so the neutron data will be more sensitive to the $d$ quark in comparison with the hydrogen target. Here $d$ to $\pi^-$ is favored and $d$ to $\pi^+$ is unfavored. Again we get the result that the two processes both have the sizable effect, although the asymmetry in $\pi^+$ production seems not larger than that in the $\pi^-$ production as we argued in the above section due to the different electric charges between $u$ and $d$ quarks. Fig. 5 is for the $^3\text{He}$ target, and we expect a similar prediction as the neutron case shown in Fig. 4 for $^3\text{He}$ can be considered as a nearly free polarized neutron. But the magnitude of the asymmetry is much smaller than the proton result as the HERMES experiments showed, because some small coefficients should be multiplied according to Eq. (22). This is the difficulty measuring the structure of neutron for there is no such a free neutron as a proton. We expect precise experiments that will be done at JLab can give us some information on neutron.

From Fig. 3 to Fig. 5 we find that the quark-diquark model and the pQCD based analysis still give similar predictions. Also the two sets of parametrization predict similarly. So the pion case is insensitive to the models, thus can give constraints on both the Collins functions.
and transversity distributions that are little known yet, rather than give direct information on transversity distributions.

Next we present the predictions on $K^\pm$ productions as Fig. 6 shows. $K^+$ comprises a $u$ and an $\bar{s}$ quark, thus the main contribution for the $K^+$ production comes from the valence $u$ quark with the favored process and the valence $d$ quark with the unfavored process. This is quite similar to the case of $\pi^+$ production. But for $K^-(\bar{u}s)$, the result is quite different from the others. $K^-$ comprises a $\bar{u}$ quark and an $s$ quark, so the favored process do not contribute for the case, because the transversity is mainly the behavior of valence quarks. Consequently, the asymmetry of $K^-$ production only comes from the unfavored process. So the kaon production can give us information about the unfavored Collins function, and we are looking forward to the measurement.

The predictions on kaon productions are shown in Fig. 6. This time, we can see clearly that the quark-diquark model and the pQCD based analysis still give similar results on $K^+$, but the two different approaches of Collins functions seem to have differences. Thus we expect the experiments to give constraints on the Collins functions through $K^+$ production. For the $K^-$ case, not only the two different approaches of Collins functions, but also the two models of distributions predict differently. So it is concluded that we can get information on Collins functions through $K^+$ production, and then distinguish the two models of distributions through $K^-$ production. However we should notice that the asymmetries for kaon productions are very small, and the differences between the models are also small, approximately the same order as the asymmetries. Since the measurements at JLab cannot reach such precision, we have to admit that distinguishing models through experiments is still difficult, and high precision experiments are needed to clarify the details.

The results of JLab on a polarized $^3$He target can give complementary results to HERMES hydrogen measurement. Compared with COMPASS deuterium measurement which is an indirectly measurement of neutron, JLab data will have a unique advantage because of the higher Bjorken $x$, since the transversity property is mainly a valence behavior. In addition, we expect that JLab results will give more detailed information on fragmentation functions.
V. SUMMARY

Using quark-diquark model and pQCD based analysis for distributions, and new sets of parametrization of Collins functions, we reanalyzed the HERMES experiment and found that with the new parametrization of the Collins functions advanced by [36], the predictions are consistent with the new released HERMES data [4], which implies that the “unfavored” Collins functions may play an important role.

Furthermore, we calculated the azimuthal spin asymmetries of pion and kaon productions in semi-inclusive deep-inelastic scattering of an unpolarized charged lepton beam on a transversely polarized $^3$He target in the JLab kinematics region. Due to the lack of independent measurement of Collins functions, it is difficult to obtain transversity distribution functions directly from the measurement on pion productions. The comparison of the data with the prediction can give constraints on both the Collins functions and transversity distributions, but not a direct measurement of the transversity distributions.

Using different models for distribution functions and Collins functions, we found that the $K^+$ production is sensitive to different sets of Collins functions but insensitive to different models of distributions and the $K^-$ production is sensitive to both different approaches of distributions and Collins functions. So we suggest distinguishing the quark-diquark model and pQCD based analysis through this process after the Collins functions being constrained by the $K^+$ production. But due to the small magnitude of the asymmetry, the measurement through this suggestion can only be achieved by experiments with much higher precision compared to the coming JLab experiment. The $\pi^\pm$ productions are sensitive to neither the different approaches of distributions and Collins functions, so they might not give much exciting results, but these processes can be useful to give constraints on the results. Additionally, we point here that the asymmetry of $K^-$ production is contributed by pure unfavored processes, thus is an ideal process to study the unfavored Collins functions.

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FIG. 1: The azimuthal asymmetries $A_T^{\sin(\phi + \phi_s)}$ for the semi-inclusive $\pi^+$ and $\pi^-$ productions in deep inelastic scattering of unpolarized charged lepton on a transversity polarized proton target in the HERMES kinematics region, with the the parametrization for the Collins function of (15). The solid and dashed curves correspond to the calculated results for quark-diquark model and the pQCD based analysis, respectively.

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FIG. 2: The azimuthal asymmetries $A_T^{\sin(\phi+\phi_s)}$ for the semi-inclusive $\pi^+$ and $\pi^-$ productions in deep inelastic scattering of unpolarized charged lepton on a transversely polarized proton target in the HERMES kinematics region. We use the parametrization of equations (19). The upper row corresponds to the Set I parametrization while the lower row corresponds to the Set II parametrization. The solid and dashed curves correspond to the calculated results for quark-diquark model and the pQCD based analysis, respectively.

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FIG. 3: The azimuthal asymmetries $A_T^{\sin(\phi+\phi_s)}$ for the semi-inclusive $\pi^+$ and $\pi^-$ productions in deep inelastic scattering of unpolarized charged lepton on a transversely polarized proton target with the JLab kinematics cut. We use the parametrization of equations (19). The upper row corresponds to the Set I parametrization while the lower row corresponds to the Set II parametrization. The solid and dashed curves correspond to the calculated results for quark-diquark model and the pQCD based analysis, respectively.

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FIG. 4: Same as Fig. 3 but for the neutron target.

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