I. INTRODUCTION

The importance of the transverse-momentum-dependent distributions of quarks for a full understanding of the structure of hadrons has been widely recognized in the last decade. Experimentally semi-inclusive deep inelastic scattering (SIDIS) provides a unique playground for these $K_T$-dependent distributions, where the observables of most interest are the single-spin asymmetries (SSA) and other related asymmetries, which have been measured and are currently under direct experimental scrutiny.

The leading-twist distributions, the Sivers function $f_{1T}^1(x, k_T^2)$ and its chiral-odd partner $h_1^+(x, k_T^2)$, are greatly relevant to these asymmetries. These two distributions describe the time-reversal odd correlations between the intrinsic transverse momenta of quarks and transverse spin vectors. In particular, $f_{1T}^1$ represents the distribution of unpolarized quarks inside a transversely polarized hadron, whereas $h_1^+$ describes the transverse spin distribution of quarks inside an unpolarized hadron.

The Sivers function is known to be responsible for the $\sin(\phi - \phi_S)$ single-spin asymmetry in transversely polarized SIDIS, and has been extracted from data by several groups. The Boer-Mulders function produces azimuthal asymmetries in unpolarized reactions. Boer argued that it can account for the observed $\cos 2\phi$ asymmetries in unpolarized $\pi N$ Drell-Yan processes. This is quantitatively confirmed, where it is shown to explain the Drell-Yan dilepton asymmetry fairly well. Many other theoretical calculations and phenomenological analysis have been performed on $h_1^+$.

Another phenomenological implication of $h_1^+$ is its consequences on the $\cos 2\phi$ asymmetry in SIDIS, where $\phi$ is the azimuthal angle of the produced hadron related to the lepton plane, as shown in Fig. 1. In order to generate the $\cos 2\phi$ asymmetry that occurs in unpolarized SIDIS, there are three possible mechanisms. 1) non-collinear kinematics at order $k_T^2/Q^2$, the so-called Cahn effect; 2) the leading-twist Boer-Mulders function coupling to a specular fragmentation function, the so-called Collins function, which describes the fragmentation of transversely polarized quarks into unpolarized hadrons. The authors of Refs. extracted the favored and unfavored Collins functions and suggested that the favored Collins functions and the unfavored ones have opposite signs with comparable absolute values; 3) perturbative gluon radiation. In this paper we will employ the first two mechanisms to study the $\cos 2\phi$ asymmetry in SIDIS process.

In the calculations we will adopt the Boer-Mulders functions extracted from unpolarized $p + D$ Drell-Yan process and the Collins functions extracted in Ref. to calculate the SIDIS $\cos 2\phi$ asymmetries of charged pions measured at ZEUS and JLab experiments. Explicitly, we will apply two sets
of Boer-Mulders functions. One is the set extracted in Ref. [46]. The other is the new set we extract in this
paper from \( p + D \) Drell-Yan data, by assuming the signs of \( h_{1}^{+n} \) and \( h_{1}^{-d} \) to be different. Then we give predictions for both cos \( 2\phi \) asymmetries of the semi-inclusive \( \pi^+ \) and \( \pi^- \) production separately, which can be measured by HERMES Collaboration (data to be analyzed) and the ongoing JLab experiments.

II. THE \( \cos 2\phi \) ASYMMETRY IN UNPOLARIZED SIDIS

The process we are interested in reads:

\[
\ell(l) + p(P) \rightarrow l'(\ell') + h(P_h) + X(P_x),
\]

and the SIDIS cross section is expressed in terms of the invariants

\[
x = \frac{Q^2}{2P \cdot q}, \quad y = \frac{P \cdot q}{P \cdot \ell}, \quad z = \frac{P \cdot P_h}{P \cdot q},
\]

where \( q = \ell - \ell' \) and \( Q^2 \equiv -q^2 \). We adopt a reference frame such that the virtual photon and the target proton or deuteron are collinear and directed along the z axis, with the photon moving in the positive z direction. We denote by \( k_T \) the transverse momentum of the quark inside the proton, and by \( P_T \) the transverse momentum of the hadron \( h \). The transverse momentum of hadron \( h \) with respect to the direction of the fragmenting quark is \( p_T \). All azimuthal angles are referred to the lepton scattering plane and \( \phi \) is the azimuthal angle of the hadron \( h \), as seen in Fig. 1.

Take the intrinsic motion of quarks into account, in leading order the azimuthal independent part of the SIDIS differential cross section reads

\[
\frac{d\sigma}{dx dy dz d^2\b{p}_T} = \frac{2\pi\alpha_{em}^2 \sum a}{Q^4} \sum a \varepsilon_a^2 x[1 + (1 - y)^2]
\]

\[
\times \int d^2k_T \int d^2p_T \delta^2(\b{P}_T - z\b{k}_T - \b{p}_T) f_1^a(x, \b{k}_T^2) D_1^a(z, \b{p}_T^2),
\]

where \( f_1^a(x, \b{k}_T^2) \) is the \( \b{k}_T \)-dependent unpolarized distribution of quark with flavor \( a \) and \( D_1^a(z, \b{p}_T^2) \) is the \( \b{k}_T \)-dependent fragmentation function of quark. We recall that the non-collinear factorization theorem for SIDIS has been proven by Ji, Ma and Yuan [55] for \( P_T \ll Q \).

We should remind that in above factorization formula an additional soft factor should be taken into account. However in all other phenomenological treatments this soft factor is neglected, too.

According to the Cahn effect [47], the non-collinear transverse-momentum kinematics will generate a \( \cos 2\phi \) contribution to the unpolarized SIDIS cross section

\[
\frac{d\sigma_{(1)}}{dx dy dz d^2\b{p}_T} = \frac{8\pi\alpha_{em}^2 \sum a}{Q^4} \sum a \varepsilon_a^2 x(1 - y)
\]

\[
\times \int d^2k_T \int d^2p_T \delta^2(\b{P}_T - z\b{k}_T - \b{p}_T)
\]

\[
\times \frac{2(\b{k}_T \cdot \b{h})^2 - k_T^2}{Q^2} f_1^a(x, \b{k}_T^2) D_1^a(z, \b{p}_T^2) \cos 2\phi,
\]

where \( \b{h} = \b{P}_T / P_T \). Notice that this contribution is of order \( k_T^2/Q^2 \), so it is a kinematically higher twist (twist-4) effect. Some caution are needed when implementing the Cahn effect into the \( \cos 2\phi \) asymmetries in unpolarized cross-section, since the dynamical twist-4 contribution to SIDIS is still unknown. Doubts about factorization for the twist-3 level were mentioned in Refs. [56, 57]. Such doubts will likely apply even more for twist-4. However we will not discuss the detail of factorization at higher twist in this paper and will apply Eq. (4) to calculate the \( \cos 2\phi \) at the order of \( k_T^2/Q^2 \).

Another mechanism [48] which can produce the \( \cos 2\phi \) asymmetry involves the coupling of \( h_1^- \) and the Collins fragmentation function \( H_1^+ \), which is a leading twist effect. The explicit expression of this contribution to the cross section is

\[
\frac{d\sigma_{(2)}}{dx dy dz d^2\b{p}_T} = \frac{4\pi\alpha_{em}^2 \sum a}{Q^4} \sum a \varepsilon_a^2 x(1 - y)
\]

\[
\times \int d^2k_T \int d^2p_T \delta^2(\b{P}_T - z\b{k}_T - \b{p}_T)
\]

\[
\times \frac{2\b{h} \cdot \b{k}_T \cdot \b{p}_T - k_T \cdot \b{p}_T}{z M_{h}} h_1^a(x, \b{k}_T^2) H_1^a(z, \b{p}_T^2) \cos 2\phi,
\]

where \( M \) represents the mass of the target nucleon and \( M_h \) the mass of final-state produced hadron. It should be noticed that this is a leading-twist contribution, not suppressed by inverse powers of \( Q \).

The \( \cos 2\phi \) asymmetry measured in experiments is defined as

\[
\nu = \frac{\int d\sigma \cos 2\phi}{\int d\sigma},
\]

where the integrations are performed over the measured ranges of \( x, y, z \) and \( P_T \). Using Eqs. (3) to (6), the \( \cos 2\phi \)
asymmetry for unpolarized SIDIS $\nu$ is given by

$$\nu = \frac{\int \sum_a e_a^2 x(1-y)[\frac{1}{2}B[h_1^{+a}, H_1^{+a}] + C[f_1^a, D_1^a]]}{\int \sum_a e_a^2 x[1 + (1-y)^2]A[f_1^a, D_1^a]},$$

where

$$\int = \int_{P_T^2}^{\infty} dP_T P_T \int_{x_{min}}^{x_{max}} dx \int_{y_{min}}^{y_{max}} dy \int_{z_{min}}^{z_{max}} dz$$

and

$$A[f_1^a, D_1^a] = \int d^2 k_T \int d^2 p_T \delta^2(P_T - zk_T - p_T)$$

$$\times f_1^a(x, k_T^2) D_1^a(z, p_T^2)$$

$$\int_{0}^{\infty} dk_T k_T \int_{0}^{2\pi} d\chi f_1^a(x, k_T^2) D_1^a(z, |P_T - zk_T|^2).$$

In Ref. [46], based on E866/NuSea data, we have extracted a set of $h_1^{+u}(x, k_T^2)$ for $u, d, \bar{u} \text{ and } \bar{d}$ quarks from the following form of parameterizations:

$$h_1^{+u}(x) = \omega H_u x^c (1-x) f_1^u(x),$$

and the possible values of $\omega$ should be constrained by a positivity bound for Boer-Mulders functions:

$$\frac{k_T}{M} h_1^{+}(x, k_T^2) \leq f_1(x, k_T^2).$$

### III. SETS OF THE BOER-MULDERS AND COLLINS FUNCTIONS USED IN OUR CALCULATION

In order to calculate the $\cos 2\phi$ asymmetry given in the last section, the forms of the $k_T$- and $p_T$-dependent distribution and fragmentation functions appearing in Eqs. (11), (10) and (9) should be provided.

Individual information of Boer-Mulders functions can be obtained from the unpolarized $\pi + N$ Drell-Yan data [24, 25] which have been measured two decades ago, and most recently, the unpolarized $p + D$ Drell-Yan data [45] was measured by E866/NuSea Collaboration. In Ref. [46], based on E866/NuSea data, we have extracted a set of $h_1^{+}(x, k_T^2)$ for $u, d, \bar{u} \text{ and } \bar{d}$ quarks from the following form of parameterizations:

| $h_1^{+}(x) = \omega H_u x^c (1-x) f_1^u(x),$ | (12) |

and the possible values of $\omega$ should be constrained by a positivity bound for Boer-Mulders functions:

$$\frac{k_T}{M} h_1^{+}(x, k_T^2) \leq f_1(x, k_T^2).$$

### TABLE I: Best fit of the Boer-Mulders functions extracted from E866/NuSea $p + d$ Drell-Yan data. Set I is the result in Ref. [40], and Set II is the new result in this work.

| $h_1^{+}(x)$ | $H_u$ | $H_d$ |
|-------------|-------|-------|
| $h_1^{+}(x)$ | 3.99  | 4.44  |
| $H_u$       | 3.83  | -2.97 |
| $H_d$       | 0.91  | 4.68  |
| $P_{bm}$    | 0.161 | 0.165 |
| $c$         | 0.45  | 0.82  |

The possible values of $\omega$ should be constrained by a positivity bound for Boer-Mulders functions:

$$\frac{k_T}{M} h_1^{+}(x, k_T^2) \leq f_1(x, k_T^2).$$

| $h_1^{+}(x)$ | $H_u$ | $H_d$ |
|-------------|-------|-------|
| $h_1^{+}(x)$ | 3.99  | 4.44  |
| $H_u$       | 3.83  | -2.97 |
| $H_d$       | 0.91  | 4.68  |
| $P_{bm}$    | 0.161 | 0.165 |
| $c$         | 0.45  | 0.82  |
Therefore for the case of Set I, we can get a constraint for \( \omega \) as \( 0.177 \leq \omega \leq 1.330 \) for all \( x \) and \( k_T \), in order to obey the positive bound. For the case of Set II, the constraint for \( \omega \) is \( 0.490 \leq \omega \leq 1.670 \).

The transverse momentum dependence of the distribution function \( f_1(x, k_T^2) \) and fragmentation function \( D_1(z, p_T^2) \) is also given in the Gaussian form adopted in [19]:

\[
f_1^i(x, k_T^2) = f_1^i(x) \exp \left( -\frac{k_T^2}{p_{T,\text{unp}}^2} \right),
\]

\[
D_1^{1-q}(z, p_T^2) = D_1^{1-q}(z) \exp \left( -\frac{p_T^2}{p_{T,\text{unp}}^2} \right).
\]

For the integrated unpolarized distribution function \( f_1^i(x) \) we adopt the MRST2001 (LO set) parametrization [58], and for the unpolarized fragmentation function \( D_1^i(z) \), we adopt the parametrization given by Kretzer [59]. We take the Gaussian width \( p_{T,\text{unp}}^2 = 0.25 \) and \( p_T^2 = 0.2 \), following the choice in Ref. [60], which was obtained by fitting the azimuthal dependence of the unpolarized SIDIS cross section.

Concerning the Collins functions, independent information about them can be obtained from the angular dependence of hadron pair production in \( e^+e^- \to h^+h^- + X \) process through \( H_{1,\perp}^+C \times H_{1,\perp}^C \). Experimental data on \( e^+e^- \) has been obtained by Delphi at CERN a decade ago and recently by Belle [10] at KEK. Access to the Collins function is also possible through the measurement of Collins single-spin asymmetry in transversely polarized SIDIS process, which has been measured by HERMES [3], COMPASS [3, 9] and JLab in recent years. Several groups have extracted the Collins function from the \( e^+e^- \) and the SIDIS data. In Ref. [20] a \( k_T^2-1/2 \) moment of Collins function \( H_{1,\perp}^C(z) \) was introduced and parameterized to fit the HERMES SIDIS data. The authors of Ref. [60] adopted a Gaussian form for the \( k_T \) dependence of \( H_{1,\perp}^C(z, k_T^2) \) to extract the Collins functions from \( e^+e^- \) data of Belle and SIDIS data of HERMES. In Ref. [49] a different parametrization for Collins function is adopted to perform a global analysis based on the \( e^+e^- \) data at Belle and the SIDIS data at HERMES and COMPASS. All the extractions apply the concept of equally sizable favored and unfavored fragmentation function in order to describe the experimental data successfully. In this paper we adopt the parameterizations given in Ref. [49], which have the form

\[
H_{1,\perp}^C(z, p_T^2) = \frac{2m_h N_q^C(z) D_1(z) h(p_T)}{\pi p_T^2} \exp \left( -\frac{p_T^2}{p_{T,\text{unp}}^2} \right),
\]

with

\[
N_q^C(z) = N_q^C z^\gamma (1 - z)^\delta \frac{(\gamma + \delta)(\gamma + \delta)}{\gamma \delta},
\]

\[
h(p_T) = (2e)^{1/2} \frac{p_T}{M} e^{-\frac{p_T^2}{M^2}},
\]

with the parameters as follows

Set I : \( N_{f_{av}}^C = 0.35, N_{unf}^C = -0.85 \),

Set II : \( N_{f_{av}}^C = 0.41, N_{unf}^C = -0.99 \),

\( \gamma = 1.14, \delta = 0.14, M^2 = 0.70 \),

\( \gamma = 0.81, \delta = 0.02, M^2 = 0.88 \).

In all the numerical calculations given below, we will apply the parametrization of Collins functions given in Set I. The results from Set II are very similar.

Finally we should emphasize that the the signs of T-odd distribution functions should be reversed [6] from Drell-Yan process to DIS process, by the presence of the path-ordered exponential (Wilson line) in the gauge-invariant definition of the transverse momentum dependent parton distributions. Therefore the sets of Boer-Mulders functions shown in Table. [4] should be reversed the signs when they are applied in the calculation of SIDIS process.

**IV. RESULTS AND PREDICTIONS**

First, we will calculate the \( \cos 2\phi \) asymmetries in SIDIS under the kinematics of ZEUS, and compare our prediction with their data [12]. ZEUS employs an unpolarized positron beam with energy 27.6 GeV to collide with a proton beam of 820 GeV. The fragmenting hadrons are detected with pseudorapidity \( \eta^{HCM} = \frac{1}{2} \ln \frac{y}{\sqrt{s}} \) and minimum transverse energy \( E_{T,\text{min}}^{HCM} \). Here \( x = \sqrt{Q^2 + m^2} e^{\eta^{HCM}} \) and \( y = \sqrt{Q^2 + m^2} e^{-\eta^{HCM}} \). The \( \cos 2\phi \) asymmetries of charged hadrons are measured, most of which are charged pions. Therefore we will calculate the \( \cos 2\phi \) asymmetries of charged pions as an approximation to the \( \cos 2\phi \) asymmetries of charged hadrons.
HERMES data\textsuperscript{62} indicate that the Sivers and Collins asymmetries of production are also sizable. Therefore one can expect that the $\cos 2\phi$ asymmetries of $K^\pm$ production could be not so small. However the contribution of $K^\pm$ to the $\cos 2\phi$ asymmetry of charged hadron production will be minor comparing to that of pions, as the production rate of $K^\pm$ is much smaller than that of pions.

The ZEUS kinematics is characterized by the following:

\begin{align}
0.01 < x < 0.1, \; 0.2 < y < 0.8, \\
100 < Q^2 < 8000 \text{GeV}^2, \; p_T > 0.15 \text{GeV}.
\end{align}

Therefore the ZEUS experiment was taken at small $x$ and very high $Q^2$, with average values of $Q^2$ around 750 GeV$^2$. In this kinematics regime the perturbative contribution \cite{51,52,53,54} from gluon emission and splitting in NLO QCD is highly relevant. In Ref. \textsuperscript{63} this contribution to the $\cos 2\phi$ asymmetry in SIDIS has been calculated showing that it is substantial at ZEUS kinematics.

In this paper, the contribution by the Boer-Mulders functions as well as the Cahn effect to the $\cos 2\phi$ asymmetries is primarily devoted to making predictions for the low-$x$ asymmetries as a function of transverse momentum $p_T$. At larger $Q^2$ (of few GeV$^2$) and low $p_T$ \textsuperscript{64} regimes, where gluon emission is quite irrelevant. Therefore in the entire paper, we will not consider perturbative contribution in our calculation.

For the case of Set I, considering the constraint for $\omega$ value by the positivity bound for Boer-Mulders functions, with $\omega$ from 0.2 to 0.5 which is a reasonable range, we give our prediction for the $\cos 2\phi$ asymmetries as function of the minimum transverse energy $E_{T_{\text{min}}}^\text{HCM}$ and $\eta^\text{HCM}$, as shown in the left sides of Figs. 3 and 4 respectively. In the same figures, we also give prediction from Boer-Mulders functions of Set II, with $\omega$ from 0.5 to 0.8.

The earlier ZEUS experiment \cite{11} measured the $\cos 2\phi$ asymmetries as the function of transverse momentum cutoff $P_c$. In Fig. 5 we also give our prediction for this experiment with both sets of Boer-Mulders functions. Furthermore, we give the predictions for the $\cos 2\phi$ asymmetries of $\pi^+$ and $\pi^-$ production vs $P_c$, separately in Fig. 6. As shown in Figs. 5 and 6, our results are only reliable for low values $P_c$. At larger $P_c$ our result underestimates the asymmetry. The reason is that we have not included perturbative contribution which gives the main contribution at high-$P_c$. In Ref. \textsuperscript{65} the perturbative contribution for ZEUS has been calculated and an agreement between the theoretical calculation and data at large $P_c$ was found.

The $\cos 2\phi$ asymmetries were also measured at CERN by EMC \textsuperscript{8}, but with low precision. The $\cos 2\phi$ asymmetries measured at an earlier ZEUS experiment \cite{11} and at EMC \textsuperscript{8}, were estimated in Ref. \textsuperscript{39} with a $u$-quark dominating model for $h_1^T$ and Gaussian ansatz for the Collins function. In the case of Set I, our results for the $\cos 2\phi$ asymmetries as a function of the $P_T$ cutoff $P_c$ up to 0.5 GeV agree with the predictions of Ref. \textsuperscript{39}.

The experiment in Jefferson Lab (JLab) also measured \textsuperscript{13} the $\cos 2\phi$ asymmetries of the semi-inclusive charged pion production as a function of $x$ and $z$, from both proton and deuteron targets, using an electron beam with energy 5.5 GeV \textsuperscript{13}. The kinematics at JLab is characterized by the following ranges:

\begin{align}
0.2 < x < 0.5, \; 0.4 < y < 0.9, \; 0.3 < z < 1, \\
2 < Q^2 < 4 \text{GeV}^2, \; P_T^2 < 0.2 \text{GeV}^2.
\end{align}

In Ref. \textsuperscript{13}, the asymmetries for $\pi^\pm$ on proton or deuteron targets are combined together. Here we calculate $x$-dependent and $z$-dependent $\cos 2\phi$ asymmetry at JLab in the same way, and the results are shown in Fig. 7 and Fig. 8 respectively. All the results are obtained with the range of $\omega$ from 0.2 to 0.5 for Set I and $\omega$ from 0.5 to 0.8 for Set II. In the calculation for a deuteron target,
we have used the isospin relation:

\[
\begin{align*}
    f_\up/D &\approx f_\up/p + f_\up/n = f_\up + f_\up, \\
    f_\down/D &\approx f_\down/p + f_\down/n = f_\down + f_\up, \\
    f_\up/N &\approx f_\up/p + f_\up/n = f_\up + f_\down, \\
    f_\down/N &\approx f_\down/p + f_\down/n = f_\down + f_\up,
\end{align*}
\]

(26) for both \( f_1 \) and \( h_1^\top \).

Our predictions for ZEUS and JLab show that the \( \cos 2\phi \) asymmetries of charged hadrons (pions) are rather small. This is due to the that the favored Collins functions adopted here are positive while the unfavored ones are negative. Therefore when the contribution of \( \pi^+ \) and \( \pi^- \) production are combined together, there is a cancellation which leads a small value.

Thus we suggest to measure and analyze the asymmetries of \( \pi^+ \) and \( \pi^- \) production separately, where larger asymmetries may be obtained. In Fig. 6 and Fig. 11 for the case of Set I, we predict the \( \cos 2\phi \) asymmetries as the functions of \( x, z \) and \( P_T \), of both \( \pi^+ \) and \( \pi^- \) production on proton target and deuteron target respectively, with a 5.5 GeV beam at JLab, showing a larger asymmetry for \( \pi^- \) production than that of \( \pi^+ \) production. In the case of Set II (Fig. 10 and Fig. 12), we obtain a larger asymmetry for the \( \pi^- \) production and a smaller asymmetry for the \( \pi^+ \) production. Therefore we expect the separate analysis of \( \cos 2\phi \) asymmetries on \( \pi^+ \) and \( \pi^- \) production of JLab [13] will make us know more information about the Boer-Mulders functions, especially for distinguishing which sets are better to describe data.

By applying the two sets of Boer-Mulders functions, we also give the prediction on the \( \cos 2\phi \) asymmetries of semi-inclusive pion production with electron beam energy of 12 GeV both for proton and deuteron targets, which are applicable at JLab after the upgrade of the beam energy. The asymmetries as the functions of \( x, z \) and \( P_T \) are calculated with the kinematical regime

\[
0.08 < x < 0.7, \quad 0.2 < y < 0.9, \quad 0.3 < z < 0.8, \quad 1 < Q < 3 \text{GeV}, \quad 1 < E_\pi < 9 \text{ GeV},
\]

(30) and are shown in Fig. 13, Fig. 15, Fig. 14, and Fig. 16.

Finally, we give the prediction on the \( \cos 2\phi \) asymmetries of \( \pi^+ \) and \( \pi^- \) production in SIDIS at HERMES.
FIG. 9: The $x$-dependent $\cos 2\phi$ asymmetries at JLab with 6 GeV on proton target. In the calculation we apply Boer-Mulders functions in Set I and take $0.2 \leq \omega \leq 0.5$.

FIG. 10: Same as Fig. 9 but from Boer-Mulders functions in Set II. In the calculation we take $0.5 \leq \omega \leq 0.8$.

FIG. 11: The $x$-dependent $\cos 2\phi$ asymmetries at JLab with 6 GeV on deuteron target. In the calculation we apply Boer-Mulders functions in Set I and take $0.2 \leq \omega \leq 0.5$.

which employs an electron beam with energy 27.5 GeV off the proton target. From the kinematics regime of HERMES:

\[ 0.2 < x < 0.42, \quad 0.2 < y < 0.8, \quad 0.2 < z < 0.7, \quad 1 < Q < 3.87\text{GeV}, \quad 4.5 < E_\pi < 13.5\text{GeV}, \]

we calculate the $x$-, $z$- and $P_T$-dependent $\cos 2\phi$ asymmetries respectively from Boer-Mulders functions of Sets I and II, as shown in Fig. 11 and Fig. 18 respectively. We expect to know more information on the Boer-Mulders functions with our prediction comparing with the data to be analyzed in HERMES.

From our prediction for forthcoming JLab and the HERMES experiments, we arrive at a conclusion that the size of $\cos 2\phi$ asymmetries in semi-inclusive $\pi^-$ production are somewhat larger than that in $\pi^+$ production for the case of Set I, and the $\cos 2\phi$ asymmetries of semi-inclusive $\pi^-$ production are larger than that of $\pi^+$ production for the case of Set II. On the calculations of the $\cos 2\phi$ asymmetries of semi-inclusive $\pi^+$ production, the negative result from Boer-Mulders functions and positive result from Cahn effect combine to yield a very small $\pi^+$
asymmetry, while on the calculations of the cos2φ asymmetries of semi-inclusive π⁻ production, the positive result from Boer-Mulders functions and positive result from Cahn effect combine to yield a several percent π⁻ asymmetry. These results are also predicted in Ref. [43], while the second set (Set II) is the new result presented in this work by explicitly assuming that the signs of h⁺,h⁻,h⁺,u and h⁺,d are different.

V. CONCLUSION

In summary, we use the Boer-Mulders functions extracted from unpolarized p + D Drell-Yan process to study the cos2φ asymmetries in SIDIS processes. Two sets of Boer-Mulders functions are applied. The first set (Set I) is the result extracted in Ref. [46], while the second set (Set II) is the new result presented in this work by explicitly assuming that the signs of h⁺,h⁻,h⁺,u and h⁺,d are different.

p + p Drell-Yan from two sets of Boer-Mulders functions defer by 50%, indicating that the measurement in p + p Drell-Yan can distinguish which set is preferred by data. With both sets of h⁺, we estimate the cos2φ asymmetries of charged pion production measured at ZEUS, and at JLab with 5.5 GeV beam energy, respectively. Then we give predictions for the cos2φ asymmetries of π⁺ and π⁻ production at HERMES and at 12 GeV JLab experiments. We suggest that measuring the cos2φ asymmetries of π⁺ production and π⁻ production separately will help to provide further information on Boer-Mulders functions.

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FIG. 18: Same as Fig. [17] but from Boer-Mulders functions of Set II. In the calculation we take $0.5 \leq \omega \leq 0.8$.

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