Non-zero transversity distribution of the pion in a quark-spectator-antiquark model

Zhun Lü
Department of Physics, Peking University, Beijing 100871, China

Bo-Qiang Ma
CCAST(World Laboratory), P.O. Box 8730, Beijing 100080, China
and Department of Physics, Peking University, Beijing 100871, China

We calculate the non-zero (naïve) T-odd transverse momentum dependent transversity distribution \( h^1_T(x, k_T^2) \) of the pion in a quark-spectator-antiquark model. The final-state interaction is modelled by the approximation of one gluon exchange between the quark and the antiquark spectator. Using our model result we estimate the unsuppressed \( \cos 2\phi \) azimuthal asymmetry in unpolarized \( \pi^- p \) Drell-Yan process. We find that the transverse momentum dependence of \( h^1_T(x, k_T^2) \) of the pion is the same as that of \( h^1_T(x, k_T^2) \) of the proton calculated from the quark-scalar-diquark model, although the \( x \) dependencies of them are different from each other. This suggests a connection between \( \cos 2\phi \) asymmetries in Drell-Yan processes with different initial hadrons.

PACS numbers: 12.38.Bx; 13.85.-t; 13.85.Qk; 14.40.Aq

I. INTRODUCTION

Recently the study of transverse momentum dependent distribution functions is among the special issues in hadronic physics. Of particular interest, are two leading-twist (naïve) time-reversal odd transverse momentum dependent distribution functions: Sivers function \( f_{1T}(x, k_T^2) \) and its chiral-odd partner \( h^1_T(x, k_T^2) \). Sivers function represents the unpolarized parton distribution in a transversely polarized hadron, while \( h^1_T(x, k_T^2) \) denotes the parton transversity distribution in an unpolarized hadron. One main motivation to investigate these two distributions is that they are the possible sources of the unsuppressed azimuthal asymmetries observed in hadronic reactions. The former distribution function was proposed first by Sivers [1] to illustrate that it can lead to large single-spin azimuthal asymmetries. This nontrivial correlation between the transverse momentum of the quark and the polarization of the hadron was thought to be forbidden by time-reversal invariance [2]. Recently a direct calculation by inclusion of final-state (in semi-inclusive deep inelastic scattering(SIDIS)) or initial-state interaction (in Drell-Yan process) shows that the asymmetry is in principle non-zero. Then it was found that the presence of the Wilson lines in the operators defining the parton densities allows for the Sivers effect without a violation of time-reversal invariance [3], and the final-or initial-state interaction can be factorized into a full gauge-invariance definition of transverse momentum dependent distribution functions [4].

These theoretical developments open a wide range of phenomenological applications. Several model calculations [11, 12, 13, 14] of Sivers function have been performed to estimate single-spin asymmetries in SIDIS processes, which is under investigation by current experiment [15]. On the other hand, it is shown [11] that non-zero \( h^1_T(x, k_T^2) \) can arise from the same mechanism which produces \( f_{1T}(x, k_T^2) \). It has been demonstrated [3] that \( h^1_T(x, k_T^2) \) can account for the substantial \( \cos 2\phi \) asymmetries in unpolarized Drell-Yan lepton pair production from pion-nucleon scattering: \( \pi^- N \rightarrow \mu^- \mu^- X \) [16, 17]. In Ref. [18], Boer, Brodsky, and Hwang computed \( h^1_T(x, k_T^2) \) of the proton in a quark-scalar-diquark model within soft gluon exchange. They found that \( h^1_T(x, k_T^2) \) is equal to \( f_{1T}(x, k_T^2) \) obtained from the same model. Then the maximum magnitude of the \( \cos 2\phi \) asymmetries in \( pp \rightarrow llX \) is estimated to be \( \sim 30\% \), by using the calculated \( h^1_T(x, k_T^2) \). In this paper, we perform the first computation on \( h^1_T(x, k_T^2) \) of the pion (denoted as \( h^1_T(x, k_T^2) \)) in a quark-spectator-antiquark model in presence of final-state interaction, in similar to the quark-scalar-diquark model of the proton. We find that the transverse momentum dependence of \( h^1_T(x, k_T^2) \) in our model is the same as that of \( h^1_T(x, k_T^2) \) of the proton from the quark-scalar-diquark model, although the \( x \) dependence is different. This feature allows one to expect that \( h^1_T(x, k_T^2) \) and \( h^1_T(x, k_T^2) \) are closely related. With the present model result we investigate the \( \cos 2\phi \) asymmetry in unpolarized \( \pi^- p \) Drell-Yan process and obtain an unsuppressed result. The shape of the asymmetry is similar to the \( \cos 2\phi \) asymmetries in \( pp \rightarrow llX \), estimated in Ref. [18]. The result suggests a connection between \( \cos 2\phi \) asymmetries in Drell-Yan processes with different initial hadrons.

II. CALCULATION OF \( h^1_T(x, k_T^2) \) OF THE PION

In this section, we present the calculation \( h^1_T(x, k_T^2) \) of the pion. We start our computation from the quark light-cone correlation function of the pion in Feynman...
gauge (we will perform our calculation in this gauge):

$$\Phi_{\alpha\beta}(x, k_{\perp}) = \int \frac{d\xi}{(2\pi)^3} e^{ik_{\perp}x} \langle P_{\pi} | \bar{\psi}_\beta(0) \mathcal{L}_0(0^-, \infty^-) \times \mathcal{L}_\xi(\infty^-, \xi^-) \psi_\alpha(\xi) | P_\pi \rangle |_{\xi^+ = 0}. \tag{1}$$

We use notation $a^\pm = a^0 \pm a^3$, $a \cdot b = \frac{1}{2}(a^+ b^- + a^- b^+)$, and $\mathbf{a} \cdot \mathbf{b}$. The pion momentum is denoted by $P_\pi = (P_{\pi}^+, P_{\pi}^-, P_{\pi} \cdot \mathbf{0}), \quad L_0(0, \infty) = \text{the path-ordered exponential (Wilson line) with the form:}$

$$\mathcal{L}_0(0, \infty) = \mathcal{P} \exp \left( -ig \int_{0^-}^{\infty^-} \! d\xi^- \cdot A(0, \xi^-, 0,) \right). \tag{2}$$

Releasing the constraint of (naive) time-reversal invariance and keeping parity invariance and hermiticity, the quark correlation function of the pion can be parameterized into a set of transverse momentum dependent distribution functions in leading twist as follows \cite{4, 12}:

$$\Phi(x, k_{\perp}) = \frac{1}{2} \left[ f_{1\pi}(x, k_{\perp}^2) \gamma^\mu + h_{1\pi}^\perp(x, k_{\perp}^2) \frac{\sigma_{\mu\nu} k_{\perp}^\nu}{M_\pi} \right] \tag{3},$$

where $n$ is the light-like vector with components $(n^+, n^-, n_\perp) = (1, 0, 0, 0), \quad \sigma_{\mu\nu} = \frac{i}{2} [\gamma^\mu, \gamma^\nu], \quad f_{1\pi}(x, k_{\perp}^2)$ and $h_{1\pi}^\perp(x, k_{\perp}^2)$ denote the unpolarized quark distribution and the quark transversity of the pion, respectively. Knowing $\Phi_{\pi}(x, k_{\perp})$, one can obtain these distribution functions from equations:

$$f_{1\pi}(x, k_{\perp}^2) = \text{Tr}[\Phi(x, k_{\perp}) \gamma^\mu]; \tag{4}$$

$$\frac{2h_{1\pi}^\perp(x, k_{\perp}^2) k_{\perp}^\mu}{M_\pi} = \text{Tr}[\Phi(x, k_{\perp}) \sigma_{\mu\nu} k_{\perp}^\nu / M_\pi]. \tag{5}$$

We will calculate above distribution functions in the quark-spectator-antiquark model. It is similar to the quark-scalar-diquark model for calculating Sivers function and $h_1^\perp$ of the proton, and the differences are that the intermediate state here is the constituent antiquark instead, as shown in Fig. 1, and the pion-quark-antiquark interaction is modeled by pseudoscalar coupling:

$$\mathcal{L}_\xi = -g_\pi \bar{\psi} \gamma_5 \gamma_5 \psi - e_2 \bar{\psi} \gamma_5 \gamma_5 \psi A_\mu, \tag{6}$$

in which $g_\pi$ is the pion-quark-antiquark coupling constant, and $e_2$ is the charge of the antiquark. $f_{1\pi}(x, k_{\perp}^2)$ can be calculated from the lowest order $\Phi(x, k_{\perp})$ without the path-ordered exponential. From Fig. 1 we obtain

$$f_{1\pi}(x, k_{\perp}^2) = -\frac{1}{4(1-x)P_\pi^+} \frac{g_\pi^2}{2(2\pi)^3} \sum_\nu \bar{v}^\nu \gamma_5 \frac{k^\mu + m}{k^2 - m^2} \times \gamma^\mu \frac{k^\mu + m}{k^2 - m^2} \gamma_5 v^\nu, \tag{7}$$

where $m$ is the mass of the outgoing quark which is the same of the antiquark, $\nu^\nu$ is the spinor of the antiquark and the quark momentum $k = (xP^+, (k_{\perp}^2 + m^2)/xP^+, k_{\perp}), \quad m_\pi^2/k_{\perp}^2$, We take the spin sum as $\sum_s v^s \bar{v}^s = (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad (P_\pi - \vec{k} - m), \quad \ldots$, and

$$B_\pi = m^2 - x(1-x)M_\pi^2. \tag{9}$$

The T-odd distribution $h_{1\pi}^\perp(x, k_{\perp}^2)$, however, is absent in the lowest order $\Phi(x, k_{\perp})$. In order to produce this T-odd distribution, the path-ordered exponential which ensures gauge invariance of the distribution function has to be included. The exponential serves as the final-state interaction (FSI) or initial-state interaction (ISI) between the struck quark and the remnant of the hadron, which is also viewed as the soft gluon scattering, to provide nontrivial phase to generate T-odd distribution function. In our calculation we expand path-ordered exponential to first order, means that the final- or initial-state interaction is modelled by one gluon exchange, as shown in Fig. 2. Thus the nonzero $h_{1\pi}^\perp(x, k_{\perp}^2)$ can be calculated from the expression

$$\frac{2h_{1\pi}^\perp(x, k_{\perp}^2) k_{\perp}^\mu}{M_\pi} = \sum_\xi \frac{1}{2} \int \frac{d\xi^- d\xi^+}{(2\pi)^3} e^{ik_{\perp} \xi^+} \psi_{\beta\gamma}(0) |\bar{\psi}_\beta(0)| \langle \bar{q} | \psi_{\gamma}(\xi) | P_\pi \rangle \bigg|_{\xi^+ = 0} + h.c., \tag{10}$$

in which $|\bar{q} \rangle$ represents the antiquark spectator state, and $e_1$ is the charge of the struck quark. In momentum space
we write down:
\[
\frac{2h_{1s}^T(x, k_2^2)}{M_\pi} = \frac{-ie_1e_2}{8(2\pi)^3(1-x)P_\pi^2} \sum \int \frac{d^4q}{(2\pi)^2} \bar{v}^s \gamma_5 \times \frac{k + m}{k^2 - m^2} \sigma^{\mu\nu}(k + q + m) \frac{k + \bar{q} - P_\pi + m}{(k + q)^2 - m^2 \gamma_5 (k + q + P_\pi)^2 + m^2} \times \gamma^\mu v^s \frac{1}{q^2 + ic q^2 - i\epsilon + h.c.}. \tag{11}
\]

The $\gamma^+$ in the second line of Eq. \ref{eq:11} comes from the antiquark-gluon interaction vertex. The $q^-$ integral can be done from the contour method. $q^+$ integral is realized from taking the imaginary part of the eikonal propagator: $1/(q^+ + i\epsilon) \rightarrow -i\pi\delta(q^+)$. Then we obtain
\[
\frac{h_{1s}^T(x, k_2^2)}{M_\pi} = \frac{g_2^2 e_1 e_2 (1-x)}{2(2\pi)^3(k_2^2 + B_\pi)} \int \frac{d^2q_\perp}{(2\pi)^2} \times \frac{2mq_\perp^i}{q_\perp^i ([k_\perp + q_\perp]^2 + B_\pi)}. \tag{12}
\]
To arrive at above equation, we have calculated the trace in the numerator in Eq. \ref{eq:11} as follows
\[
\sum \bar{v}^s \gamma_5 (k + m) \sigma^{\mu\nu}(k + \bar{q} + m) \gamma_5
\times (k + \bar{q} - P_\pi + m) \gamma^+ v^s
= \text{Tr}[(P_\pi - k - m)(k - m)\gamma^+ \gamma^+(k + \bar{q} - m)]
\times (k + \bar{q} - P_\pi + m) \gamma_5^+(k + \bar{q} - m)
= 8P_\pi^2 m q_\perp^i \quad \text{when } q^+ = 0. \tag{13}
\]
After integrating over $q_\perp$, we obtain the expression for $h_{1s}^T(x, k_2^2)$ in the antiquark spectator model:
\[
h_{1s}^T(x, k_2^2) = \frac{g_2^2 e_1 e_2}{2(2\pi)^3} mM_\pi (1-x) \ln \left( \frac{k_2^2 + B_\pi}{B_\pi} \right)
= \frac{A_\pi}{k_2^2 (k_2^2 + B_\pi)} \ln \left( \frac{k_2^2 + B_\pi}{B_\pi} \right). \tag{14}
\]
with $B_\pi$ given in Eq. \ref{eq:Bpi} and
\[
A_\pi = \frac{g_2^2}{2(2\pi)^3} \left( \frac{e_1 e_2}{4\pi} \right) mM_\pi (1-x). \tag{15}
\]
In Ref. \ref{eq:15} $h^T_{1s}(x, k_2^2)$ of the proton is computed in the quark-scalar-diquark model as:
\[
h^T_{1s}(x, k_2^2) = \frac{A_p}{k_2^2 (k_2^2 + B_p)} \ln \left( \frac{k_2^2 + B_p}{B_p} \right). \tag{16}
\]
Comparing Eq. \ref{eq:14} with Eq. \ref{eq:15} one can find that the calculated $h_{1s}^T(x, k_2^2)$ in the spectator antiquark model has a same transverse momentum dependence of $h^T_{1s}(x, k_2^2)$ of the proton obtained from the quark-scalar-diquark model, although the $x$ dependence is different in $A_{p/\pi}$ and $B_{p/\pi}$ respectively, due to the different mass parameters in them. This feature may not be held generally, but one can expect that there is close relation between $h^T$ distributions of different hadrons since both functions are generated by the same underling mechanism.

We can also calculate the T-odd distribution of the transversity distribution of the valence antiquark $h_{1s}^T$ of the pion from the same model, by replacing the antiquark spectator with the quark spectator. A similar calculation yields $h_{1s}^T = h_{1s}^T$, showing that the magnitudes of the distributions for two valence quarks are the same.

With $f_{1s}(x, k_2^2)$ and $h_{1s}^T(x, k_2^2)$ we estimate $|k_1 h_{1s}^T(x, k_2^2)|/|f_{1s}(x, k_2^2)|$, which is proportional to the $\cos 2\phi$ asymmetries in unpolarized Drell-Yan process. We choose the mass parameters $m = 0.1$ GeV for the constituent quark mass and $M = 0.137$ GeV for the pion mass. To generalize our model result to the consequence in QCD we extrapolate the coupling constant $e_1 e_2 / 4\pi \rightarrow C_F \alpha_s$, and take $\alpha_s = 0.3$ which is adopted in Ref. \ref{eq:16}. We plot the $x$ dependence of the ratio at $|k_\perp| = 0.3$ GeV in Fig. \ref{fig:3}, and the $|k_\perp|$ dependence at $x = 0.15$ in Fig. \ref{fig:3}. The ratios are comparable in magnitude with $|k_1 h_{1s}^T(x, k_2^2)|/|f_{1s}(x, k_2^2)|$ of the proton (one can see Ref. \ref{eq:16}, where $|k_1 f_{1s}^T|/(M f_1)$ is given, since $h_{1s}^T = f_{1s}^T$) in the quark-scalar-diquark model, where $M$ is the proton mass and $f_{1s}(x, k_2^2)$ is the unpolarized quark distribution of the proton.

\section{III. COS2\phi ASYMMETRIES IN UNPOLARIZED DRELL-YAN PROCESS}

The general form of the angular differential cross section for unpolarized $\pi^- p$ Drell-Yan process is
\[
\frac{1}{\sigma_{\Omega}} \frac{d\sigma}{d\Omega} = \frac{3}{4\pi \lambda + 3} \left( 1 + \lambda \cos^2 \theta + \mu \sin^2 \theta \cos 2\phi + \nu \sin^2 \theta \cos 2\phi \right), \tag{17}
\]
where $\phi$ is the angle between the lepton plane and the plane of the incident hadrons in the lepton pair center of mass frame (see Fig. \ref{fig:4}). The experimental data show large value of $\nu$ near to 30%, which can not be explained by perturbative QCD. Many theoretical approaches have been proposed to interpret the experimental data, such as high-twist effect \cite{21, 22}, and factorization breaking mechanism \cite{23}. In Ref. \ref{eq:22} Boer demonstrated that unsuppressed $\cos 2\phi$ asymmetries can arise from a product
of two chiral-odd $h_1^\perp$ which depends on transverse momentum. In Ref. [18] the $\cos^2\phi$ asymmetry in unpolarized $p\bar{p} \rightarrow l\bar{l}X$ Drell-Yan process has been estimated from $h_1^\perp(x, k_1^\perp)$ for the proton computed by quark-scalar-diquark model. The maximum of $\nu$ in that case is in the order of 30%.

In this section we give a simple estimate of $\cos^2\phi$ asymmetry in unpolarized $\pi^- p$ Drell-Yan process, from $h_1^\perp$ computed by our model. The leading order unpolarized Drell-Yan cross section expressed in the Collins-Soper frame [24] is

$$\frac{d\sigma(h_1 h_2 \rightarrow l\bar{l}X)}{d\Omega dxF_{1\perp} d^2q_{1\perp}} = \frac{\alpha^2}{3Q^2} \sum_{a,a'} \left\{ A(y) F[f_1 f_1] + B(y) \times \cos^2\phi F \left[ (2\hat{h} \cdot P_{1\perp} \hat{h} \cdot k_{1\perp}) - (P_{1\perp} \cdot k_{1\perp}) \frac{h_1^\perp h_1^\perp}{M_1 M_2} \right] \right\},$$

(20)

where $Q^2 = q^2$ is the invariance mass square of the lepton pair, and the vector $\hat{h} = q_{1\perp}/Q_T$. We have used the notation

$$F[f_1 f_1] = \int d^2 P_{1\perp} d^2 P_{2\perp} \delta^2(P_{1\perp} + k_{1\perp} - q_{1\perp}) f_1^i(x, P_{1\perp}^2) \times f_1^j(x, k_{1\perp}^2).$$

(21)

From Eq. (20) one can give the expression for the asymmetry coefficient $\nu$ [4]:

$$\nu = 2 \sum_{a,a'} e_a^2 F_a \left[ (2\hat{h} \cdot P_{1\perp} \hat{h} \cdot k_{1\perp}) - (P_{1\perp} \cdot k_{1\perp}) \frac{h_1^\perp h_1^\perp}{M_1 M_2} \right] / \sum_{a,a'} e_a^2 F_a$$

$$= \frac{2}{M_1 M_2} \sum_{a,a'} e_a^2 F_a.$$

(22)

Our model calculation has shown $h_1^\perp = h_1^\perp$. Thus in $\pi^- p$ unpolarized Drell-Yan process we can assume $u$-quark dominance, which means the main contribution to asymmetry comes from $h_1^\perp u(x, k_1^2) \times h_1^\perp u(x, P_{1\perp}^2)$, since $\bar{u}$ in $\pi^-$ and $u$ in proton are both valence quarks. Then we have $\nu \approx 2F_u/(M_1 M_2)$. To evaluate $\nu$, we use our model result for $h_1^\perp u$ and $f_1$, and we adopt $h_1^\perp u$ and $f_1$ from Ref. [15]. Using the $P_{1\perp}$ integration to eliminate the delta function in the denominator and numerator in Eq. (22) one arrives at

$$F_u = \int d|k_{1\perp}| \int_0^{2\pi} d\theta_{qk} \frac{A_{\pi} A_{p} |k_{1\perp}|}{k_{1\perp}^2 (k_{1\perp}^2 + B_\pi)} \ln \left( \frac{k_{1\perp}^2 + B_\pi}{B_\pi} \right) \times \left( \frac{2k_{1\perp}^2 \cos^2\theta_{qk} + k_{1\perp} |q_{1\perp} cos\theta_{qk}|}{(k_{1\perp}^2 + f)(k_{1\perp}^2 + f + B_p)} \right) \times \ln \left( \frac{k_{1\perp}^2 + f + B_p}{B_p} \right),$$

(23)

$$G_u = \int d|k_{1\perp}| \int_0^{2\pi} d\theta_{qk} C_{\pi} C_p |k_{1\perp}| (k_{1\perp}^2 + D_\pi) \times \left( \frac{k_{1\perp}^2 + f + D_p}{(k_{1\perp}^2 + f + B_p)^2} \right),$$

(24)

where $f = q_{1\perp}^2 - 2|q_{1\perp}| |k_{1\perp}| cos\theta_{qk}$, and $\theta_{qk}$ is the angle between $k_{\perp}$ and $q_{\perp}$. In above equations we change the

FIG. 3: Model prediction of $|k_{1\perp} h_1^\perp (x, k_1^2)/[M_1 f_1 (x, k_1^2)]$ as a function of $x$ and $|k_{\perp}|$.

FIG. 4: Angular definitions of unpolarized Drell-Yan process in the lepton pair center of mass frame.
the asymmetry as a function of $Q$. $\bar{A}$ shows an unsuppressed result of the order of $0.1 \text{ GeV}$, and $x = \bar{x} = 0.2$. The dashed line corresponds to the same asymmetry in $\bar{p}p$ Drell-Yan process estimated in the quark-scalar-diquark model (see Ref. [18]).

Besides this, the shape of the asymmetry is similar to that of the quark-spectator-antiquark process estimated in the quark-scalar-diquark model in presence of final-state interaction, and investigate the $\cos 2\phi$ asymmetry in unpolarized Drell-Yan process with our model result. The calculated $h^\perp_{1T}(x, k^2_{\perp})$ shows a same form of transverse momentum dependence as that of $h^\perp_{1T}(x, k^2_{\perp})$ for the proton computed from a quark-scalar-diquark model. The similarity of $h^\perp_{1T}(x, k^2_{\perp})$ for different hadrons (for example, nucleon and pseudoscalar meson) implies that these functions are closely related, because the mechanism that generates them is the same. Besides this, $h^\perp_{1T}(x, k^2_{\perp})$ is an interesting observable that can account for the large $\cos 2\phi$ asymmetry in $\pi^- N$ unpolarized Drell-Yan process.

The contributed asymmetry of $h^\perp_{1T}(x, k^2_{\perp})$ is proportional to $|\mathbf{k}_{\perp} h^\perp_{1T}|/(M_{f_1})$, which is comparable with $|\mathbf{k}_{\perp} h^\perp_{1T}|/(M_{f_1})$ of the proton in magnitude. With nonzero $h^\perp_{1T}(x, k^2_{\perp})$ we reveal an unsuppressed $\cos 2\phi$ asymmetry in unpolarized $\pi^- p$ Drell-Yan process from our calculation. The shape of the asymmetry is similar to that of $\cos 2\phi$ asymmetries in $\bar{p}p$ Drell-Yan process estimated in Ref. [18], suggesting a connection between $\cos 2\phi$ asymmetries in Drell-Yan processes with different initial hadrons.

**IV. CONCLUSION**

In this paper we calculate the (naive) T-odd $\mathbf{k}_{\perp}$-dependent quark transversity distribution $h^\perp_{1T}(x, k^2_{\perp})$ of the pion for the first time in a quark-spectator-antiquark model in presence of final-state interaction, and investigate the $\cos 2\phi$ asymmetry in unpolarized Drell-Yan process with our model result. The calculated $h^\perp_{1T}(x, k^2_{\perp})$ shows a same form of transverse momentum dependence as that of $h^\perp_{1T}(x, k^2_{\perp})$ for the proton computed from a quark-scalar-diquark model. The similarity of $h^\perp_{1T}(x, k^2_{\perp})$ for different hadrons (for example, nucleon and pseudoscalar meson) implies that these functions are closely related, because the mechanism that generates them is the same. Besides this, $h^\perp_{1T}(x, k^2_{\perp})$ is an interesting observable that can account for the large $\cos 2\phi$ asymmetry in $\pi^- N$ unpolarized Drell-Yan process. The contributed asymmetry of $h^\perp_{1T}(x, k^2_{\perp})$ is proportional to $|\mathbf{k}_{\perp} h^\perp_{1T}|/(M_{f_1})$, which is comparable with $|\mathbf{k}_{\perp} h^\perp_{1T}|/(M_{f_1})$ of the proton in magnitude. With nonzero $h^\perp_{1T}(x, k^2_{\perp})$ we reveal an unsuppressed $\cos 2\phi$ asymmetry in unpolarized $\pi^- p$ Drell-Yan process from our calculation. The shape of the asymmetry is similar to that of $\cos 2\phi$ asymmetries in $\bar{p}p$ Drell-Yan process estimated in Ref. [18], suggesting a connection between $\cos 2\phi$ asymmetries in Drell-Yan processes with different initial hadrons.

**Acknowledgments**

This work is partially supported by National Natural Science Foundation of China under Grant Numbers 10025523 and 90103007.
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