Transverse spin effects of sea quarks in unpolarized nucleons

Zhun Lu,1 Bo-Qiang Ma,2† and Ivan Schmidt1‡

1Departamento de Física, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile
2School of Physics, Peking University, Beijing 100871, China

We calculate the non-zero Boer-Mulders functions of sea quarks inside the proton in a meson-baryon fluctuation model. The results show that the transverse spin effects of sea quarks in an unpolarized nucleon are sizable. Using the obtained antiquark Boer-Mulders functions, we estimate the \( \cos 2\phi \) asymmetries in the unpolarized \( pp \) and \( pD \) Drell-Yan processes at FNAL E866/NuSea experiments. The prediction for the \( \cos 2\phi \) asymmetries in the unpolarized \( pp \) Drell-Yan process at the BNL Relativistic Heavy Ion Collider (RHIC) is also given.

PACS numbers: 12.38.Bx, 13.85.-t, 13.85.Qk, 12.39.Ki

I. INTRODUCTION

The transverse spin phenomena appearing in high energy scattering processes [1] are among the most interesting issues of spin physics. Several kinds of asymmetries associated with transverse spin have been observed. One is the single spin asymmetry in the semi-inclusive deeply inelastic scattering (SIDIS) processes [2, 3, 4, 5], which requires the target nucleon to be transversely polarized. Another is the \( \cos 2\phi \) asymmetry in the unpolarized Drell-Yan process [6, 7], where \( \phi \) is the angle between the lepton plane and the hadron plane. It has been demonstrated that these asymmetries can be accounted for by specific leading-twist \( k_T \)-dependent distribution functions, i.e., the Sivers function [8, 9] can explain [10] the single spin asymmetry in SIDIS processes, while the Boer-Mulders function [11] can account for [12] the \( \cos 2\phi \) asymmetry in unpolarized Drell-Yan processes. Despite their naive time reversal-odd property [13], calculations [14, 15, 16, 17, 18, 19] have shown that these functions can be non-zero, due to the gauge-links appearing in their operator definitions. The factorization theorem involving \( k_T \)-dependent distribution functions has been worked out recently.

Sivers or Boer-Mulders functions correspond to a correlation between the transverse spin of the nucleon or the quark and the transverse momentum of the quark inside the nucleon, respectively. Therefore, the investigation on them can provide information on the transverse spin property of the nucleon at the quark level. The experimental study of the Sivers function requires an incident nucleon transversely polarized, with the advantage that this function couples with usual unpolarized distribution or fragmentation functions, and therefore it can be extracted more easily from experimental data. In the case of the Boer-Mulders function, it always couples with itself or another chiral-odd function in the hard scattering process. Its advantage, however, is that the spin structure of hadrons can be studied without invoking beam or target polarization. In fact, the \( \cos 2\phi \) asymmetries due to the Boer-Mulders function of valence quarks have been studied theoretically for the unpolarized \( pp \) [15, 23, 26] and \( \pi N \) [19, 27] Drell-Yan processes, which can be measured in the future PAX [28] or COMPASS experiments, respectively. Measurements of the \( \cos 2\phi \) asymmetries in the unpolarized \( pN \) Drell-Yan process can be performed by the FNAL E866/NuSea collaboration and at the BNL Relativistic Heavy Ion Collider (RHIC) [29]. This process is dominated by the annihilation of valence and sea quarks from the two incident nucleons. In this work we will investigate the role of the Boer-Mulders functions of the nucleon sea, and reveal their impact on the \( \cos 2\phi \) asymmetries in the unpolarized \( pN \) Drell-Yan process. We calculate the Boer-Mulders functions of the intrinsic \( \bar{u} \) and \( d \) inside the proton using a meson-baryon fluctuation model. Based on the resulting sea quark Boer-Mulders functions, we estimate the \( \cos 2\phi \) asymmetries in unpolarized \( pp \) and \( pD \) Drell-Yan processes at E866, and the \( \cos 2\phi \) asymmetries in unpolarized \( pp \) Drell-Yan process at RHIC, respectively. The magnitude of the asymmetry is of several percent, and is sensitive to the choice of the Boer-Mulders functions of valence quarks. Therefore the investigation of the asymmetry in the unpolarized \( pN \) processes can not only provide information on the Boer-Mulders functions of intrinsic sea quarks, but also on those of valence quarks.

II. BOER-MULDERS FUNCTIONS OF SEA QUARKS INSIDE THE PROTON

The intrinsic sea quark content of the nucleon [30] is important for understanding its parton structure. Both experimental measurements and model calculations have shown that there is a sizable proportion of intrinsic sea quarks inside the nucleon, including \( \bar{u}u, \bar{d}d \) and \( s\bar{s} \) sea quarks, which can not be explained by the naive quark model. A qualitatively successful model that accounts for a number of significant features of the intrinsic sea quarks is the meson-baryon fluctuation model [31], which
is based on the light-cone Fock state expansion of the nucleon. The main assumption of this model is that the intrinsic sea quarks are multi-connected to the valence quarks and can exist over a relatively long lifetime within the nucleon bound state, therefore the intrinsic $q\bar{q}$ pairs can arrange themselves together with the valence quarks of the target nucleon into the most energetically-favored meson-baryon fluctuations. It is easy to understand that the most important fluctuations are most likely to be those closest to the energy shell and thus have minimal invariant mass. Such fluctuations are necessary part of any quantum-mechanical description of the hadronic bound state in QCD and have also been incorporated into the cloudy bag model and Skyrmesolution to chiral theories. Therefore, in the meson-baryon fluctuation model, the nucleon can fluctuate into an intermediate two-body system of a baryon and a meson which are in turn composite systems of quarks and gluons. For example, the proton can fluctuate into a $n\pi^+$ or $\Delta^{++}\pi^-$ configuration, and the $\bar{d}$ or $\bar{u}$ inside $\pi^+$ or $\pi^-$ can be viewed as $d$ or $u$ distributed in the proton.

Based on the meson-baryon fluctuation model one can also calculate the momentum distribution of the intrinsic sea quarks inside the proton, from the following convolution form

$$q^{in}(x) = \int_x^1 \frac{dy}{y} f_M/BM(y)q_M\left(\frac{x}{y}\right), \tag{1}$$

where $f_M/BM(y)$ is the probability of finding the meson $M$ in the $BM$ state with light-cone momentum fraction $y$, and $q_M(x/y)$ is the probability of finding a quark $q$ in the meson $M$ with light-cone momentum fraction $x/y$. The function $f_M/BM(y)$ can be determined from the form

$$f_M/BM(y) = \int d^2k_T |\Psi_{BM}(y,k_T)|^2, \tag{2}$$

where $\Psi_{BM}(x,k_T)$ is the light-cone two-body wave function of the baryon-meson system, for which we will choose a Gaussian or a power-law behavior,

$$\Psi_{BM}(x,k_T) = A_D\exp(-M^2/8\alpha_D^2), \tag{3}$$

$$\Psi_{BM}(x,k_T) = A_D'(1 + M^2/2\alpha_D^2)^{-p}, \tag{4}$$

respectively. Here $M^2 = (M_M^2 + k_T^2)/(1 - x)$ is the invariant mass squared of the baryon-meson system, $\alpha_D$ sets the characteristic internal momentum scale, and $A_D$ or $A_D'$ is the normalization constant and can be fixed by

$$\int dx d^2k_T |\Psi_{BM}(x,k_T)|^2 = 1. \tag{5}$$

We point out that Eqs. 3 and 4 are boost-invariant light-cone wavefunctions which emphasize multi-parton configurations of minimal invariant mass.

Eq. 1 can be extended to calculate the Boer-Mulders functions of the intrinsic $\bar{u}$ and $\bar{d}$ antiquarks inside the proton (denoted as $h_{1/2}^{\bar{u}}$ and $h_{1/2}^{\bar{d}}$). In fact, according to the meson-baryon fluctuation model, there are pion components in the intermediate state of the proton. On the other hand, as shown in Ref. [19], non-zero Boer-Mulders functions of valence quarks inside the pion (denoted by $h_{1/2}^{\pi,q}$) can be calculated using the quark-spectator-antiquark model. Therefore, a convolution form similar to Eq. 1 can be applied to calculate $h_{1/2}^{\bar{u}}$ and $h_{1/2}^{\bar{d}}$, as follows:

$$h_{1/2}^{\bar{u}}(x,k_T^2) = \int_x^1 \frac{dy}{y} f_{\pi^-}/(x,y)h_{1/2}^{\bar{u}}\left(\frac{x}{y},k_T^2\right), \tag{6}$$

$$h_{1/2}^{\bar{d}}(x,k_T^2) = \int_x^1 \frac{dy}{y} f_{\pi^+}/(x,y)h_{1/2}^{\bar{d}}\left(\frac{x}{y},k_T^2\right). \tag{7}$$

The transverse momentum of the antiquark in the nucleon should be a superposition of the transverse momentum of the antiquark in the pion and of the transverse momentum of the pion in the nucleon. For simplicity, we neglect here the transverse momentum of the pion. Assuming that the probabilities of the proton fluctuating to $n\pi^+$ and $\Delta^{++}\pi^-$ (denoted as $P_{p-n\pi^+}$ and $P_{p-\Delta^{++}\pi^-}$, respectively), are both 12%, and using the functions $h_{1/2}^{\pi,q}$ given in Ref. [19], we obtain the numerical results for $h_{1/2}^{\bar{u}}(x,k_T^2)$ and $h_{1/2}^{\bar{d}}(x,k_T^2)$, shown in Fig. 1. Two sets of functions are given, corresponding to the choice of Gaussian (upper panel) and power-law type (lower panel) wavefunctions of the baryon-meson system, respectively.

The transverse momentum of the antiquark in the nucleon is $m = 0.3$ GeV. For the consistency here we use the same value for the mass of the quark inside the proton and the pion, which is different from that in Ref. [19] where we use 0.1 GeV for the quark mass of the pion and 0.3 GeV for the quark mass of the proton. This difference on the numerical result, but the result of the asymmetry and the main conclusion are qualitatively not changed. It is interesting to point out that the Boer-Mulders function of $\bar{u}$ or $\bar{d}$, calculated from the Gaussian type wavefunction, qualitatively agrees with that from the power-law type wave function. We should notice that this result is based on the assumption that the numbers of the sea quark pairs $u\bar{u}$ and $d\bar{d}$ inside the nucleon are the same, since we assume $P_{p-n\pi^+} = P_{p-\Delta^{++}\pi^-}$ here. As we know that there should be an excess of $d\bar{d}$ pair over $u\bar{u}$ pair in the proton, which is a consequence of Gottfried sum rule [33], in next section we will apply another set of $P_{p-n\pi^+}$ and $P_{p-\Delta^{++}\pi^-}$, which is constrained by the existing parametrization that can produce the flavor asymmetry of the sea quarks, and investigate the consequence asymmetries in the unpolarized $pp$ and $pD$ Drell-Yan processes. Boer-Mulders functions for sea quarks may be obtained from other models that also allow sea
FIG. 1: The Boer-Mulders functions of $\bar{u}$ quark $h_1^{\perp,\bar{u}}(x, k_\perp^2)$ (left column) and $\bar{d}$ quark $h_1^{\perp,\bar{d}}(x, k_\perp^2)$ (right column) inside the proton as two-dimensional densities. The upper panel and lower panel correspond to the choice of gaussian type and power-low type light-cone wave functions for the meson-baryon system, respectively.

quarks in the nucleon, such as the chiral quark and meson cloud models. In these models there are also $\pi$ meson components in the Fock state expansion of the nucleon.

III. THE $\cos 2\phi$ ASYMMETRIES IN THE UNPOLARIZED $pp$ AND $pD$ DRELL-YAN PROCESSES

In this section, we will calculate the $\cos 2\phi$ asymmetries in the unpolarized $pp$ and $pD$ Drell-Yan processes, based on the Boer-Mulders functions of sea quarks obtained above. The general form of the angular differential cross section for the unpolarized Drell-Yan process is

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda + 3} \left( 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi \right) \nu \sin^2 \theta \cos 2\phi. \tag{8}$$

The $\phi$ independent differential cross-section for the unpolarized $pp$ Drell-Yan process is

$$\frac{d\sigma(pp \rightarrow llX)}{d\Omega dx_1 dx_2 d^2 q_\perp} = \frac{\alpha_{em}^2}{12Q^2} (1 + \cos^2 \theta) \sum_{q=u,d} \epsilon_q^2 \mathcal{F}[f_1^q(x_1, p_\perp^2)] \times f_1^\bar{q}(x_2, k_\perp^2) + (q \leftrightarrow \bar{q}), \tag{9}$$

where we have used the notation

$$\mathcal{F}[\cdots] = \int d^2 p_\perp d^2 k_\perp \delta^2(p_\perp + k_\perp - q_\perp) \times \{\cdots\}, \tag{10}$$

and the transverse momentum dependence of the cross-section is implicit.

The corresponding cross section for the unpolarized $pD$ Drell-Yan process is then

$$\frac{d\sigma(pD \rightarrow llX)}{d\Omega dx_1 dx_2 d^2 q_\perp} = \frac{\alpha_{em}^2}{12Q^2} (1 + \cos^2 \theta) \mathcal{F}[(\epsilon_u^2 f_1^u(x_1, p_\perp^2) + e_d^2 f_1^d(x_1, p_\perp^2)) \times (f_1^\bar{u}(x_2, k_\perp^2) + f_1^\bar{d}(x_2, k_\perp^2)) + (q \leftrightarrow \bar{q})] \tag{11}$$

Where we have used the isospin relation $f_1^{u/D} \approx f_1^{u/p} + f_1^{u/n} = f_1^u + f_1^d$. 

Eqs. (9) and (11) are lowest order parton model expressions, where it is extended in order to include transverse parton momenta.

The cos 2φ dependent cross-sections for unpolarized pp and pD Drell-Yan processes, in terms of Boer-Mulders functions, are

\[
\frac{d^2\sigma(pp \to llX)}{d^2q_T dq_{\perp}^2} = \frac{\alpha_s^2}{12Q^2} \sin^2 \theta \cos 2\phi \sum_{q=u,d} \epsilon_2^2 F[\chi(p_\perp, k_\perp)h_1^{-q}(x_1, p_\perp^2)] \\
\times h_1^{-\bar{q}}(x_2, k_\perp^2) \mp (q \leftrightarrow \bar{q});
\]

(12)

\[
\frac{d^2\sigma(pD \to llX)}{d^2q_T dq_{\perp}^2} = \frac{\alpha_s^2}{12Q^2} \sin^2 \theta \cos 2\phi \sum_{q=u,d} \epsilon_2^2 F[\chi(p_\perp, k_\perp)h_1^{-q}(x_1, p_\perp^2)] \\
+ \epsilon_2^2 \frac{1}{2} (x_1, p_\perp^2])(h_1^{-\bar{q}}(x_2, k_\perp^2) + h_1^{-d}(x_2, k_\perp^2) \mp (q \leftrightarrow \bar{q}),
\]

(13)

respectively, where

\[
\chi(p_\perp, k_\perp) = (2h \cdot p_\perp \cdot h) \cdot (k_\perp - p_\perp \cdot k_\perp)/M_p^2,
\]

(14)

where h = q_T/Q_T and M_p is the mass of the proton.

Therefore we can express the cos 2φ asymmetry coefficient defined in Eq. (8) as (λ = 1, μ = 0)

\[
\nu_p = \frac{2 \sum_{q=u,d} \epsilon_2^2 F[\chi h_1^{-q} h_1^{-\bar{q}}] + (q \leftrightarrow \bar{q})}{\sum_{q=u,d} \epsilon_2^2 F[f^{2L}(f^{2L})^*]} + (q \leftrightarrow \bar{q}),
\]

(15)

\[
\nu_D = \frac{2 F[\chi(\epsilon_2^2 f_1^{-u} + \epsilon_2^2 f_1^{-d})(h_1^{-\bar{q}} + h_1^{-d})] + (q \leftrightarrow \bar{q})}{F[(\epsilon_2^2 f_1^{-u} + \epsilon_2^2 f_1^{-d})(f_1^{-\bar{q}} + f_1^{-d})] + (q \leftrightarrow \bar{q}),
\]

(16)

where we have omitted the arguments of the distribution functions.

Eqs. (15) and (16) give the explanation for the cos 2φ asymmetry observed in the unpolarized Drell-Yan process from the view of Boer-Mulders function. We note that there are other theoretical approaches that have been proposed to interpret this asymmetry, such as high-twist [35, 36] and QCD vacuum effects [37]. In Ref. [38] detailed comparison between the QCD Vacuum effect and Boer-Mulders effect has been done.

The ES66 Collaboration at FNAL employs a 800 GeV/c proton beam colliding on protons or deuterons fixed targets to measure the unpolarized Drell-Yan processes pp → μ+μ−X and pD → μ+μ−X [39]. The main goal of ES66 is to study the asymmetry of the nucleon sea distribution [40, 41]. These experiments can also be applied to study the cos 2φ asymmetry of the lepton pair, especially the role of the sea quarks contribution to the asymmetry. In the following we will estimate the asymmetry ν_p and ν_D for the ES66 experiment. In order to calculate the asymmetry we also need the specific form of Boer-Mulders functions of valence quarks inside the nucleon. Since there are no experimental measurements on those functions yet, we use some model results for them, such as those given in Ref. [17], within a quark and spectator diquark model of the nucleon. We will take two different extreme options as follows.

- Option I: Consider the limit with only the spectator scalar diquark included, which means that h_1^{-u} = h_1^{-S} and h_1^{-d} = 0. Here we use h_1^{-S} and h_1^{-V} to represent the contributions to the Boer-Mulders functions with only spectator scalar diquark and vector diquark included, respectively. This option was also applied in Ref. [19].

- Option II: Consider the case with both the spectator scalar diquark and vector diquark included. In this option h_1^{-u} = 1/3 h_1^{-S} + 1/3 h_1^{-V} and h_1^{-d} = h_1^{-V}, and they have opposite sign.

The scalar and vector components of the proton are [17]

\[
h_1^{-S}(x, k_T^2) = \frac{4}{3} \alpha_s N_s (1 - x)^3 \frac{M (x M + m)}{[L_s^2 + (L_s^2 + k_T^2)^2]^{3/2}},
\]

(17)

\[
h_1^{-V}(x, k_T^2) = -\frac{4}{3} \alpha_s N_v (1 - x)^3 \frac{M (2x M + m)}{[L_s^2 + (L_s^2 + k_T^2)^2]^{3/2}}
\]

(18)

respectively, where N_s/v is a normalization constant, and

\[
L_s^2 = (1 - x) L^2 + x M_s^2 - x (1 - x) M^2.
\]

(19)

Here \( \Lambda \) is a cutoff appearing in the nucleon-quark-diquark vertex and \( M_\Lambda \) is the mass of the scalar diquark.

With the following kinematical cuts

\[
4.5 \text{ GeV} < Q < 9 \text{ GeV} \quad \text{and} \quad Q > 11 \text{ GeV},
\]

\[
0.1 < x_1 < 1, \quad 0.015 < x_2 < 0.4,
\]

we calculate the \( Q_T \)-dependent cos 2φ asymmetries in the unpolarized pp and pD Drell-Yan processes as ES66, as shown in Fig. 2. In the calculation we adopt the anti-quark Boer-Mulders functions \( h_1^{-d} \) calculated from the Gaussian type wavefunction of the baryon-meson system. One observation from Fig. 2 is that the asymmetry calculated according to option I is of several percent, while that according to option II is around one percent, indicating that the size of the asymmetry is sensitive to the choice of the Boer-Mulders functions of valence quarks. Nevertheless, our calculation predicts a quite smaller cos 2φ asymmetry in the unpolarized pN Drell-Yan process compared to that in the unpolarized πN Drell-Yan case [6, 19]. Again, comparing the asymmetries calculated from the two different options, we find that \( \nu_p \) and \( \nu_D \) have similar sizes in option I, while those of \( \nu_p \) and \( \nu_D \) in option II can be very different, and even have opposite signs. Therefore, the investigation of the cos 2φ asymmetry in the unpolarized pN Drell-Yan process can not only give information on the Boer-Mulders functions of sea quarks, but also about those of valence quarks.
The main success of the baryon-meson fluctuation model is that it can qualitatively describe a variety of asymmetries of the nucleon sea distributions, such as the flavor asymmetry $\bar{d}(x) - \bar{u}(x)$, the strange sea asymmetry $s(x) - \bar{s}(x)$, and the polarized sea asymmetry $\Delta s(x) - \Delta \bar{s}(x)$. In the previous section we have assumed that the probabilities of the proton fluctuating to $n\pi^+$ and $\Delta^{++}\pi^-$ are 12\% (here we denote it as Set I for the sea quark distributions). From this set we calculate the flavor asymmetry $x(\bar{d} - \bar{u})$, as shown by the dashed line in Fig. 3, and compare it with that from the CTEQ6L parametrization at $Q = 0.6$ GeV (shown by the solid line in the same figure). None-zero asymmetry of the sea quark densities is found in this case, but is quantitatively much lower than the known parametrization. In a further consideration, we will take into account the flavor asymmetry of the sea quark and adopt $P_{p\rightarrow n\pi^+} = 15\%$ and $P_{p\rightarrow \Delta^{++}\pi^-} = 1\%$ (denoted as Set II), motivated by the expectation that there should be an excess of $u\bar{u}$ pair over $d\bar{d}$ pair, which is a consequence of Gottfried sum rule [33]. This set has also been adopted in Ref. [42]. We show the asymmetry $x(\bar{d} - \bar{u})$ from Set II by the dotted line in Fig. 3, and find that it agrees with the flavor asymmetry from CTEQ6L parametrization fairly well. From the sea quark distributions of Set II, we give the cos$2\phi$ asymmetries in the unpolarized $pp$ (thick line) and $pD$ (thin line) Drell-Yan process at E866, as shown in Fig. 4. Two options of the valence quark distribution are applied in this calculation. Again, the asymmetries $\nu_p$ and $\nu_D$ have similar sizes in option I, and those in option II are very different. In Fig. 4 a larger negative $\nu_p$ from option II is predicted compared to that given in Fig. 2.

As we don’t know the exact form of Boer-Mulders functions of valence quarks, we admit that our prediction, in a certain aspect, relies on functions given in [17], where the Boer-Mulders functions for the $u$ and $d$ quarks are of the opposite sign. Actually different models or theoretical considerations predict different flavor dependence of valence Boer-Mulders functions. A calculation based on the MIT bag model gave $h_1^{+\perp} = 1/2 h_1^{+\perp}$, while the ar-
to calculate the asymmetries at E866, we estimate the \( \cos 2\phi \) asymmetry \( \nu_p \) at RHIC with the kinematical constraints \( \sqrt{s} = 200\text{ GeV}, -1 < y < 2 \), here \( y \) is the rapidity defined as \( y = \frac{1}{2}\ln \frac{1 + \nu}{1 - \nu} \). The \( Q_T \)-dependent asymmetries for \( Q = 4 \) (thin line) and \( Q = 20\text{ GeV} \) (thick line) are shown in Fig. 5. Here we do not average the asymmetry over a range of \( Q \), as we have done for the asymmetry at E866, since we would like to choose two different fixed values of \( Q \) to study the \( Q \)-dependence of the asymmetry at RHIC. Since the evolution equations of unintegrated parton distributions, especially that of the Boer-Mulders functions, are unknown, we assume that they scale with \( Q \). Therefore the different asymmetries at different \( Q \) values, as shown in Fig. 5, is not a consequence of evolution, but just a kinematical effect.

### IV. CONCLUSION

In summary, we have applied a meson-baryon fluctuation model to calculate the Boer-Mulders functions of \( \bar{u} \) and \( d \) inside the proton, and provided a first estimate of the transverse spin effect of sea quarks in the unpolarized nucleon. In the calculation we adopted both the Gaussian and the power-law type wavefunctions for the meson-baryon system. We found the sizes of \( h_1^{1u} \) or \( h_1^{1d} \) from these two types of wavefunctions to be qualitatively similar. From the obtained antiquark Boer-Mulders functions, we analyzed the \( \cos 2\phi \) asymmetries in the unpolarized \( pp \) and \( pD \) Drell-Yan processes at E866. Two sets of the sea quark distributions are applied in the calculation, in which Set I is flavor symmetric and Set II reflects the sea quark flavor asymmetry indicated by Gottfried sum rule. The size of the asymmetries is at most several percent, in the case that the Boer-Mulders functions of valence quarks are chosen with only spectator scalar-diquark contributed. The size of the asymmetries, as well as the relative size between the asymmetries in the unpolarized \( pp \) and \( pD \) Drell-Yan processes, relies significantly on the choice of Boer-Mulders functions of valence quarks. We also estimated the \( \cos 2\phi \) asymmetry in the unpolarized \( pp \) Drell-Yan process at RHIC. This investigation suggests that unpolarized \( pN \) Drell-Yan processes on hadron colliders are very helpful for a better understanding about the role of transverse spin of both valence and sea quarks in the unpolarized nucleon.

**Acknowledgements.** We acknowledge helpful discussions with J.C. Peng and L. Zhu. This work is partially supported by National Natural Science Foundation of China (Nos. 10421003, 10575003, 10505011, 10528510), by the Key Grant Project of Chinese Ministry of Education (No. 305001), by the Research Fund for the Doctoral Program of Higher Education (China), by Fondecyt (Chile) under Project No. 3050047 and No. 1030355.
[1] For a review on transverse polarization phenomena, see V. Barone, A. Drago, P.G. Ratcliffe, Phys. Rep. 359, 1 (2002).
[2] A. Bravar et al., SMC Collaboration, Nucl. Phys. A 666, 314 (2000).
[3] A. Airapetian et al., HERMES Collaboration, Phys. Rev. Lett. 94, 012002 (2005).
[4] V.Yu. Alexakhin et al., COMPASS Collaboration, Phys. Rev. Lett. 94, 202002 (2005).
[5] M. Diefenthaler, HERMES Collaboration, in Proceedings of DIS 2005, Madison, Wisconsin (USA), hep-ex/0507013.
[6] S. Falciano et al. NA10 Collaboration, Z. Phys. C 31, 513 (1986); M. Guanziroli et al. NA10 Collaboration, Z. Phys. C 37, 545 (1988).
[7] J.S. Conway et al. Phys. Rev. D 39, 92 (1989).
[8] D. Sivers, Phys. Rev. D 41, 83 (1990); D. Sivers, Phys. Rev. D 43, 261 (1991).
[9] M. Anselmino, M. Boglione, F. Murgia, Phys. Lett. B 362, 164 (1995).
[10] S.J. Brodsky, D.S. Hwang, I. Schmidt, Phys. Lett. B 530, 99 (2002).
[11] D. Boer, P.J. Mulders, Phys. Rev. D 57, 5780 (1998).
[12] D. Boer, Phys. Rev. D 60, 014012 (1999).
[13] J.C. Collins, Nucl. Phys. B 396, 161 (1993).
[14] G.R. Goldstein, L. Gamberg, Talk given at 31st International Conference on High Energy Physics (ICHEP 2002), Amsterdam, The Netherlands, 24-31 July 2002, hep-ph/0209085.
[15] D. Boer, S.J. Brodsky, D.S. Hwang, Phys. Rev. D 67, 054003 (2003).
[16] F. Yuan, Phys. Lett. B 575, 45 (2003).
[17] A. Bacchetta, A. Schäfer, J.-J. Yang, Phys. Lett. B 578, 109 (2004).
[18] Z. Lu and B.-Q. Ma, Nucl. Phys. A 741, 200 (2004); Z. Lu, B.-Q. Ma, Phys. Rev. D 70, 094044 (2004).
[19] Z. Lu, B.-Q. Ma, Phys. Lett. B 615, 200 (2005).
[20] J.C. Collins, Phys. Lett. B 536, 43 (2002).
[21] X. Ji and F. Yuan, Phys. Lett. B 543, 66 (2002); A.V. Belitsky, X. Ji, F. Yuan, Nucl. Phys. B 656, 165 (2003).
[22] D. Boer, P.J. Mulders, and F. Pijlman, Nucl. Phys. B 667, 201 (2003).
[23] X. Ji, J.P. Ma and F. Yuan, Phys. Lett. B 597, 299 (2004).
[24] J.C. Collins, A. Metz, Phys. Rev. Lett. 93, 252001 (2004).
[25] G. R. Goldstein, L. Gamberg, hep-ph/0506127.
[26] V. Barone, Z. Lu and B.-Q. Ma, to appear in European physical journal.
[27] Z. Lu, B.-Q. Ma and I. Schmidt, Phys. Lett. B 639 494 (2006).
[28] PAX Collaboration, V. Barone, et al., hep-ex/0505054.
[29] G. Bunce, N. Saito, J. Soffer and W. Vogelsang, Ann. Rev. Nucl. Part. Sci. 50, 525 (2000).
[30] For reviews, see, e.g., S. Kumano, Phys. Rep. 303 (1998) 183; G.T. Garvey, J.C. Peng, Prog. Part. Nucl. Phys. 47 (2001) 203.
[31] S.J. Brodsky and B.-Q. Ma, Phys. Lett. B 381, 317 (1996).
[32] G.P. Lepage and S.J. Brodsky, Phys. Rev. D 22, 2157 (1980).
[33] K. Gottfried, Phys. Rev. Lett. 18, 1174 (1967).
[34] J.C. Collins and D.E. Soper, Phys. Rev. D 16, 2219 (1977).
[35] A. Brandenburg, S.J. Brodsky, V.V. Khoze, and D. Müller, Phys. Rev. Lett. 73, 939 (1994).
[36] K.J. Eskola, P. Hoyer, M. Vänttinen, and R. Vogt, Phys. Lett. B333, 526 (1994).
[37] A. Brandenburg, O. Nachtmann, and E. Mirkes, Z. Phys. C 60, 697 (1993).
[38] D. Boer, A. Brandenburg, O. Nachtmann and A. Utermann, Eur. Phys. J. C 40 55 (2005).
[39] J.C. Collins, et al., (FNAL E866 Collaboration), hep-ex/0302019.
[40] E.A. Hawker et al., (FNAL E866/NuSea Collaboration), Phys. Rev. Lett. 80, 3715 (1998).
[41] R.S. Towell et al., (FNAL E866/NuSea Collaboration), Phys. Rev. D 64, 052002 (2001).
[42] B.-Q. Ma, I. Schmidt and J.-J. Yang, Eur. Phys. J. A 12, 353 (2001).
[43] P.V. Pobylitsa, hep-ph/0301236.
[44] M. Gockeler et al., Nucl. Phys. Proc. Suppl. 153, 146 (2006).
[45] M. Burkardt, Phys. Rev. D 72, 094020 (2005); B. Pasquini, M. Pincetti and S. Boffi, Phys. Rev. D 72 094029 (2005).
[46] J. Soffer, M. Stratmann and W. Vogelsang, Phys. Rev. D 65, 114024 (2002).
[47] J.C. Collins et al., Phys. Rev. D 73, 094023 (2006).
[48] M. Anselmino, U. D’Alesio and F. Murgia, Phys. Rev. D 67, 074010 (2003).