Extracting Boer-Mulders functions from $p + D$ Drell-Yan processes

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We extract the Boer-Mulders functions of valence and sea quarks in the proton from unpolarized $p + D$ Drell-Yan data measured by the FNAL E866 Collaboration. Using these Boer-Mulders functions, we calculate the cos 2$\phi$ asymmetries in unpolarized $pp$ Drell-Yan processes, both for the FNAL E866/NuSea and the BNL Relativistic Heavy Ion Collider (RHIC) experiments. We also estimate the cos 2$\phi$ asymmetries in the unpolarized $p\bar{p}$ Drell-Yan processes at GSI.

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I. INTRODUCTION

Recently the E866/NuSea Collaboration at FNAL has measured the cos 2$\phi$ angular distribution of Drell-Yan dimuons in $p + d$ interaction at 800 GeV/c. The magnitude of the asymmetry turned out to be about several percent. This cos 2$\phi$ angular dependence, together with other angular correlations in Drell-Yan processes, constitute remaining challenges which need to be understood from QCD dynamics. Indeed, even before these nucleon-nucleon interaction measurements, the NA10 [2] and E165 [3] Collaborations had also measured the cos 2$\phi$ angular dependence in $p + N$ Drell-Yan processes. The magnitude of the angular dependence is around 30% for modest transverse momenta of the lepton pair, a result which violates the so-called Lam-Tung relation [4], predicted by perturbative QCD. Several attempts have been made to interpret these data, including QCD vacuum effects [5, 6] and higher-twist mechanisms [7, 8]. Furthermore, in the last decade a significant efforts have been put forward on the understanding of the cos 2$\phi$ angular dependence from the view point of the transverse momentum dependent (TMD) Boer-Mulders function $h^+_1$ [9]. In fact, it was shown [10] by Boer that the angular dependence can be related to the product of two functions $h^+_1$, each of which comes from one of the incident hadrons. These $h^+_1$ functions describe a correlation between the transverse spin and the transverse momentum of a quark inside an unpolarized hadron, which originates from initial/final state interactions [11, 12], and which in turn is related to the gauge invariance of the TMD distribution functions [13, 14, 15]. Another distribution having the same QCD origin of $h^+_1$ is the Sivers function [16], which plays a important role in the single spin asymmetries (SSA) [17] measured in semi-inclusive deep inelastic scattering. Measurements of Sivers SSA at HERMES [18, 19] and COMPASS [20, 21] have been used in order to extract the Sivers functions by several groups [22, 23, 24, 25, 26]. All these fittings show that the Sivers functions for $u$ and $d$ quarks have similar size but opposite sign.

In contrast to the Sivers function case, detailed knowledge of $h^+_1$ is more difficult. The reason is that in processes in which the Boer-Mulders function contributes, one finds that it is always convoluted with itself or with other chiral-odd functions, such as the transversity or the Collins fragmentation function [27]. Despite this, some theoretical calculations and phenomenological analysis [12, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38] have been performed on $h^+_1$. An interesting problem is its flavor dependence [39]. Recently lattice calculations [40] and approaches based on generalized parton distributions (GPD) [41, 42] suggest that the sign of $h^+_1$ for both $u$ and $d$ quarks and the corresponding magnitudes are of similar sizes (See also the calculation in Ref. [37]). In this paper, we will extract the Boer-Mulders functions from the unpolarized $p + d$ Drell-Yan data measured by the E866 collaboration, with the assumption that the cos 2$\phi$ angular dependence is produced solely by $h^+_1$. We use the simple parameterization for the Boer-Mulders function given by

$$h^+_1(x, p_T^2) = H_0 x^\lambda (1 - x) F_1^u(x) \exp (-p_T^2/p_{bm}^2)$$

to fit the data points of the asymmetry coefficient $\nu$ vs $p_T$, $x_1$ and $x_2$, where $q$ stands for the $u, d, \bar{u}, \bar{d}$ quarks. The data points of $\nu$ versus $m_{12} = Q^2$ and $x_F$ provide then a cross check of our fitting. Using the resulting valence and sea quarks Boer-Mulders functions, we estimate the cos 2$\phi$ asymmetries in unpolarized $pp$ Drell-Yan processes for both FNAL E866/NuSea and RHIC, and we also give predictions for the cos 2$\phi$ asymmetries in unpolarized $p\bar{p}$ Drell-Yan processes at GSI.

II. EXTRACTING THE BOER-MULDERS FUNCTION FROM UNPOLARIZED $p + D$ DRELL-YAN DATA

The angular differential cross section for unpolarized Drell-Yan processes has the general form

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

(1)

where $\theta$ and $\phi$ are, respectively, the polar angle and the azimuthal angle of dileptons in the Collins–Soper frame [43]. The coefficients $\lambda, \mu$ and $\nu$ do not depend on these angles, and
TABLE I: Best fit values of the Boer-Mulders functions

| Function | Value |
|----------|-------|
| $H_u$    | 3.99  |
| $H_d$    | 3.83  |
| $H_b$    | 0.91  |
| $H_f$    | -0.96 |
| $p_{bm}^2$ | 0.161 |
| c        | 0.45  |
| $\chi^2$/d.o.f. | 0.79 |

for scattering that has azimuthal symmetry their values are

\[ \mu = \nu = 0. \]

This angular distribution has been measured in muon pair production by pion-nucleon collisions: $\pi^- N \rightarrow \mu^+ \mu^- X$, with $N$ denoting a nucleon in deuterium or tungsten, and for a $\pi^{-}$ beam with energies of 140, 194, 286 GeV \cite{2} and 252 GeV \cite{3}. The experimental data show large values of $\nu$, near 30%. The most recent measurements of the angular distribution were performed by the E866 Collaboration \cite{1}, in $p + d$ Drell-Yan processes at 800 GeV/c. The measured $\nu$ is about several percent, a result which can not be explained by perturbative QCD. As proposed by Boer \cite{10}, the non-zero cos $2\phi$ term can be produced by the product of two $h^{\perp}$s, each coming from one of the two incident hadrons. In the case of the $p + D$ Drell-Yan processes, the coefficient $\nu$ can be expressed as \cite{3}

$$ v_{pd} = \frac{2F[\chi(e^2h_1^{1+u} + e^2h_1^{1+d})(h_1^{1+u} + h_1^{1+\perp})] + (q \leftrightarrow \bar{q})}{F[(e^2f_1^u + e^2f_1^d)(f_1^u + f_1^d)]) + (q \leftrightarrow \bar{q})} \] (2)

where we have used the notation

$$ F[\cdots] = \int d^2p_\perp d^2k_\perp \delta^2(p_\perp + k_\perp - q_\perp) \times \cdots, \] (3)

and

$$ \chi(p_\perp, k_\perp) = (2\hat{h} \cdot p_\perp \hat{h} \cdot k_\perp - p_\perp \cdot k_\perp)/M^2, \] (4)

where $\hat{h} = q_\perp/Q_T$ and $M$ is the mass of the nucleon. The interacting quarks coming from the incident hadrons have transverse momenta $p_\perp$ and $k_\perp$, and $Q_T$ is the absolute value of the transverse momentum of the photon $q_\perp$. To arrive at Eq. (2) we have used the isospin relation:

$$ f_{u/d} = f_{u'/d'} + f_{u/n} + f_{d'/d'}, \] (5)

for $f_1$ and $h_1^{\perp}$. From this point of view, the angular distribution coefficient $\nu$ measured by the E866 Collaboration provides an opportunity to extract the Boer-Mulders function of the nucleon. For this purpose we parameterize $h_1^{\perp}(x, p_{T}^2)$ in a factorized form as

$$ h_1^{\perp}(x, p_{T}^2) = h_1^{\perp}(x) \frac{\exp(-p_{T}^2/p_{bm}^2)}{\pi p_{bm}^2}, \] (6)

which is a Gaussian model for the transverse momentum dependence of the Boer-Mulders functions, with width $p_{bm}^2$. As

in Ref. \cite{11}, the x-dependence of the Boer-Mulders functions are modeled relating its behavior with that of the unpolarized distribution functions, as

$$ h_1^{\perp, u}(x) = H_u x^\alpha (1-x)f_1^u(x), \] (7)

$$ h_1^{\perp, d}(x) = H_d x^\alpha (1-x)f_1^d(x), \] (8)

$$ h_1^{\perp, u}(x) = H_u x^\alpha (1-x)f_1^u(x), \] (9)

$$ h_1^{\perp, d}(x) = H_d x^\alpha (1-x)f_1^d(x), \] (10)

where $f_1^u(x)$ is the well-known unpolarized integrated distribution function. Therefore we have $H_u$, $H_d$, $H_u$, $H_d$, $p_{bm}^2$, and $c$ as parameters in our parametrization. The coefficient $(1-x)$ is included in order to give the correct large-x behavior \cite{44} for $h_1^{\perp}$ compared with the unpolarized distribution. The small-x behavior of $h_1^{\perp}$ compared with that of $f_1(x)$ is modeled as $x^\alpha$.

The TMD unpolarized distribution function $f_1(x, p_{T}^2)$ is also given in a Gaussian form

$$ f_1^u(x, p_{T}^2) = f_1^u(x) \frac{\exp(-p_{T}^2/p_{am}^2)}{\pi p_{am}^2} \] (11)

From Eqs. (6) to (11), we can de-convolute the transverse momentum integration in Eq. (2) and arrive at

$$ v_{pd}(x_1, x_2, Q_T) = \frac{p_{am}^2\{\alpha\} Q_T^2 \exp(-Q_T^2/2p_{am}^2)}{2M^2 p_{bm}^2 |\beta| \exp(-Q_T^2/2p_{am}^2)} \] (12)

where

$$ (\alpha) = x_1'(1-x_1)x_2'(1-x_2)(4H_u f_1^u(x_1) + H_d f_1^d(x_1)) \] (13)

$$ (\beta) = (4f_1^u(x_1) + f_1^d(x_1))(f_1^u(x_2) + f_1^d(x_2)) \] (14)

Therefore the coefficient $\nu$ vs $Q_T$ can be obtained from (12) by integrating the numerator and the denominator over $x_1$ and $x_2$ over, respectively:

$$ v_{pd}(Q_T) = \frac{p_{am}^2 \int dx_1 \int dx_2 (\alpha) Q_T^2 \exp(-Q_T^2/2p_{am}^2)}{2M^2 p_{bm}^2 \int dx_1 \int dx_2 (\beta) \exp(-Q_T^2/2p_{am}^2)}, \] (15)

In this equation, $x_1$, $x_2$ and $Q_T$ satisfy the relation $x_1 x_2 s = Q^2 + Q_T^2$, where $s$ and $Q$ are the c.m energy squared and the invariant mass of the lepton pair respectively. In a similar way we can obtain expressions for $v_{pd}(x_1)$ and $v_{pd}(x_2)$.

The E866/NuSea Collaboration has measured $v_{pd}$ vs $Q_T$, $x_1$, $x_2$, $x_T$, and $m_{\nu\mu}$ in the following kinematical region:

\[ 4.5 \text{ GeV} < Q < 9 \text{ GeV} \quad \text{and} \quad 10.7 \text{ GeV} < Q < 15 \text{ GeV}, \]

\[ 0.1 < x_1 < 0.9, \quad 0.02 < x_2 < 0.24 \]

We therefore use the above expressions for $v_{pd}(Q_T)$, $v_{pd}(x_1)$ and $v_{pd}(x_2)$ in order to fit the experimental data of $v$ vs $Q_T$, etc.
$x_1$ and $x_2$ in $pD$ processes measured by E866/NuSea Collaboration. We perform the fitting using the MINUIT program. For the unpolarized distribution function $f_0^c(x)$ we adopt the MRST2001 (LO set) parametrization \cite{45}, with QCD evolution taken into account. We use $p_{\text{imp}}^2 = 0.25$, following the choice in Ref. \cite{46}, a value which was obtained by fitting the azimuthal dependence of the SIDIS unpolarized cross section. Notice that these values are assumed to be constant and flavor independent.

The best fitting values for the parameters are given in Table I and in Fig. 1 we show the fitting result compared with the E866/NuSea data. Notice that the results for the Boer-Mulders functions given in Table I are obtained for the Drell-Yan process, and to obtain the corresponding Boer-Mulders functions in SIDIS one should reverse their signs \cite{15}. Therefore our results agree with the Boer-Mulders functions for $u$ and $d$ quarks in SIDIS are negative and have the same sign. We also want to emphasize that the Boer-Mulders functions we extracted are within a positive bound \cite{47}:

$$\frac{|p_T h_1^u(x, p_T^2)|}{M} \leq f_1(x, p_T^2).$$

We also find that at

$$p_T = \sqrt{p_{\text{imp}}^2 p_{\text{fin}}^2/(2(p_{\text{imp}}^2 - p_{\text{fin}}^2))} = 0.45 \text{GeV},$$

the ratio $p_T h_1^u(x, p_T^2)/(M f_1(x, p_T^2))$ has its maximum for all $x$. As an example, in Fig. 2 we show a comparison of $p_T h_1^u(x, p_T^2)/M$ and $x f_1(x, p_T^2)$, for both $u$ and $d$ quarks at $p_T = 0.45 \text{ GeV}$ and $Q = 1 \text{ GeV}$, and therefore we conclude that our results obey the positive bound for all $p_T$.

As a cross check, we give results for the coefficient $\nu$ versus $x_f$ and $m_{\nu}$ in $pD$ Drell-Yan processes for E866/NuSea, using the extracted Boer-Mulders functions and comparing them with data, as shown in Fig. 3. In the calculation we use the relation $x_{1/2} = (\pm x_f + (Q^2 + Q_{T}^2)/s)/2$. The results in the figure show good agreement with data.

### III. PREDICTIONS FOR $pp$ AND $p\bar{p}$ PROCESS

In the previous section we have performed a fitting on the unpolarized $pd$ Drell-Yan data, and obtained a set of Boer-Mulders functions. In this section, we will use the extracted functions to predict the result in other processes. We first focus on unpolarized $pp$ Drell-Yan processes. The $\cos 2\phi$ angular distribution in this process can be also measured at E866/FNAL, and the expression that we get for $\nu$ using our parametrization of the Boer-Mulders functions is

$$\nu_{pp}(x_1, x_2, Q_T) = \frac{p_{\text{imp}}^2 |\varsigma| Q_{T}^2 \exp \left(-\frac{Q_{T}^2}{2 p_{\text{fin}}^2}\right)}{2 M^2 p_{\text{fin}}^2 |\lambda| \exp \left(-\frac{Q_{T}^2}{2 p_{\text{fin}}^2}\right)},$$

where

$$|\varsigma| = x_f^2 (1-x_1)x_f^2 (1-x_2)(4H_0 f_0^u(x_1)H_0 f_0^u(x_2)$$

$$+H_0 f_0^u(x_1)H_0 f_0^d(x_2) + (q \leftrightarrow \bar{q}),$$

$$|\lambda| = (4f_0^u(x_1) f_0^u(x_2) + f_0^d(x_1) f_0^d(x_2))$$

$$+(q \leftrightarrow \bar{q})$$

(19)

With the Boer-Mulders functions for both valence and sea quarks in the proton that we obtained above, and taking the same integration regions for $Q, x_1, x_2$ in evaluating Eq. (13), we get the results for $\cos 2\phi$ asymmetry in unpolarized $pp$ and $pD$ Drell-Yan processes that are shown in Fig. 4 (solid and dashed lines respectively).

The results in these two processes present little difference between them.

Another promising testing ground of the $\cos 2\phi$ asymmetry in unpolarized $pN$ Drell-Yan processes is BNL RHIC \cite{48}, since this experiment is also feasible at this accelerator. With the Boer-Mulders functions given in Table I we also estimate the $\cos 2\phi$ asymmetry $\nu$ at RHIC for an unpolarized experiment, with kinematical constraints $Q^2 = 200 \text{ GeV}$ and $-1 < y < 2$. Here $y$ is the rapidity defined as $y = \frac{1}{2} \ln \frac{Q^2 + \omega^2}{Q^2 - \omega^2}$, with $x_{1/2} = \sqrt{Q^2 + Q_{T}^2}$.

After integrating over $x_1$ in Eq. (19), we get the $Q_T$-dependent asymmetries for $Q = 4 \text{ GeV}$ (solid line) and $Q = 20 \text{ GeV}$ (dashed line) shown in Fig. 5.

We should notice that in the extraction of the Boer-Mulders functions with the MINUIT program, the coefficients of Boer-Mulders functions for valence quarks $H_0$ and $H_0$ are always coupled with the coefficients of sea quarks $H_0$ and $H_0$, as seen in Eq. (13). We cannot separate them except by introducing free coefficients $\omega_0$ with possible flavor dependence.

With the free coefficient $\omega_0 = \omega_d = \omega$, the Boer-Mulders functions are modeled comparing its behavior with that of the unpolarized distribution functions, as

$$h_1^u(x) = \omega H_0 x^c (1-x) f_0^u(x),$$

$$h_1^d(x) = \omega H_0 x^c (1-x) f_0^d(x),$$

$$h_1^{u,d}(x) = \frac{1}{\omega} H_0 x^c (1-x) f_0^{u,d}(x),$$

(20)

The results we get above for the $\nu_{pp}, \nu_{p\bar{p}}$ are independent of the free coefficient $\omega$ because when we use Eqs. (20)-(23) into the $\nu_{pp}, \nu_{p\bar{p}}$ in Eqs. (12) and (18), the free coefficient $\omega$ cancels in the product of sea and valence components.

Recently the $\cos 2\phi$ azimuthal asymmetry of $p\bar{p}$ Drell-Yan processes has also received much attention, since there have been proposals to study spin phenomena in polarized and unpolarized $p\bar{p}$ scattering at the High-Energy Storage Ring (HERS) of GSI \cite{49,50}. The $\nu_{p\bar{p}}, x_1$ and $x_2$-dependent $\cos 2\phi$ asymmetry $\nu_{p\bar{p}}$, obtained using our parametrization for the Boer-Mulders functions with the free coefficient $\omega$ are

$$\nu_{p\bar{p}}(x_1, x_2, Q_T) = \frac{p_{\text{imp}}^2 |\varsigma| Q_{T}^2 \exp \left(-\frac{Q_{T}^2}{2 p_{\text{fin}}^2}\right)}{2 M^2 p_{\text{fin}}^2 |\lambda| \exp \left(-\frac{Q_{T}^2}{2 p_{\text{fin}}^2}\right)},$$

(24)

where

$$|\varsigma| = \omega^2 x_f^2 (1-x_1)x_f^2 (1-x_2)(4H_0 f_0^u(x_1)H_0 f_0^d(x_2)$$

$$+H_0 f_0^u(x_1)H_0 f_0^d(x_2) + (q \leftrightarrow \bar{q}),$$

$$|\lambda| = (4f_0^u(x_1) f_0^u(x_2) + f_0^d(x_1) f_0^d(x_2))$$

$$+(q \leftrightarrow \bar{q})$$

(21)
FIG. 1: Fits to the \( p_T, x_1, x_2 \)-dependent cos \( 2\phi \) asymmetries \( v_{p\bar{D}} \) for Drell-Yan processes. Data are from the FNAL E866/NuSea collaboration.

FIG. 2: Comparison of \(|p_T, x h_1\perp(x, p_T^2)|/M\) and \(x f_1(x, p_T^2)\) for \( u \) and \( d \) quarks at \( p_T = 0.45 \) GeV and \( Q = 1 \) GeV. Here \( f_1 \) is a combination of valence and sea quark distributions.

FIG. 3: The \( Q \)-dependent cos \( 2\phi \) asymmetry \( v_{p\bar{D}} \) for Drell-Yan processes at FNAL E866/NuSea, presenting both the experimental data and the results we estimate with the best fit values of the Boer-Mulders functions in Table I (line).

FIG. 4: The \( p_T \)-dependent cos \( 2\phi \) asymmetries \( v \) in both \( pp \) (dotted curve) and \( p\bar{D} \) (solid curve) Drell-Yan processes at FNAL E866/NuSea, calculated with the fitted Boer-Mulders functions presented in Table I.

FIG. 5: The \( y \)-dependent cos \( 2\phi \) asymmetries \( v \) for \( pp \) Drell-Yan process at RHIC, with the kinematical conditions \( \sqrt{s} = 200 \) GeV, \( -1 < y < 2 \), and calculated with the Boer-Mulders functions that we got. The dotted and dashed lines show the asymmetries at \( Q = 4 \) and 20 GeV, respectively.
FIG. 6: The \( p_T \)-dependent \( \cos 2\phi \) asymmetries \( \nu \) for \( p\bar{p} \) Drell-Yan process at GSI, with the kinematics: c.m. energy \( s = 45 \text{ GeV}^2 \), and invariance mass square of the lepton pair \( Q^2 = 2.5 \text{ GeV}^2 \). The solid, dashed and dotted curves correspond to the free coefficient \( \omega = 1, 0.5, 0.25 \) respectively.

\[
\tau = (4f_1^{u}(x_1)f_2^{d}(x_2) + f_1^{d}(x_1)f_2^{u}(x_2)) + (q \leftrightarrow \bar{q}).
\] (25)

In the expression above, we use charge-conjugation relations such as:

\[
\begin{align*}
    f_1^{\bar{d}/\bar{p}} &= f_1^{u/p}, & f_2^{\bar{d}/\bar{p}} &= f_2^{d/p} \\
    f_1^{u/p} &= f_1^{\bar{d}/\bar{p}}, & f_2^{d/p} &= f_2^{\bar{u}/\bar{p}}.
\end{align*}
\] (26)

In Eq. (25), we can see that the result for this \( p\bar{p} \) process depends on the free coefficient \( \omega \). Therefore we give predictions for \( \nu_{p\bar{p}} \) at GSI, as shown in Fig. 6 for three different values of \( \omega \). The kinematics in GSI can be chosen as c.m. energy \( s = 45 \text{ GeV}^2 \) and \( Q^2 = 2.5 \text{ GeV}^2 \), where the \( x \) is in the valence region and the asymmetry can be larger than the asymmetry in \( pp \) processes at E866/NuSea and RHIC. The coming experimental data can fix \( \omega \) to give the exact Boer-Mulders functions for both quarks and antiquarks.

**IV. CONCLUSION**

In summary, we have extracted the Boer-Mulders functions of valence and sea quarks inside the proton from unpolarized \( p + D \) Drell-Yan data at 800 GeV/c, measured by the FNAL E866/NuSea Collaboration. With the Boer-Mulders functions that we get, we estimated the \( \cos 2\phi \) asymmetries in unpolarized \( pp \) Drell-Yan processes at E866/NuSea and RHIC. We also presented an estimation of the \( \cos 2\phi \) azimuthal asymmetry in \( p\bar{p} \) Drell-Yan processes at GSI. We hope that future measurement for the \( \cos 2\phi \) asymmetry at pp and p\( \bar{p} \), as well as in SIDIS, can help to pin down the Boer-Mulders functions for the valence and sea quarks.

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