Sign Reversal of Boer-Mulders Functions from Sem-inclusive DIS to Drell-Yan Process

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A striking prediction of QCD on the properties of the novel Transverse Momentum Dependent (TMD) distribution functions is that the time-reversal odd Sivers and Boer-Mulders functions extracted from semi-inclusive deep-inelastic scattering (SIDIS) will undergo a sign reversal in the Drell-Yan (DY) process. This prediction is being tested by ongoing and future experiments focussing on the Sivers functions so far. We examine the current status on the theoretical prediction and experimental extraction of the signs of the Boer-Mulders functions from SIDIS and DY. We show that the existing SIDIS and DY data on the Boer-Mulders functions are consistent with either the presence or the absence of the predicted sign reversal. Prospects for future experiments capable of testing the sign-reversal of Boer-Mulders functions are presented. The above two sentences might need to be modified, if we conclude that the existing COMPASS data on TSSA could already determine the sign of the BM function in the DY process.

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Extensive efforts have been devoted to the study of transverse momentum dependent (TMD) parton distributions in the nucleons during the last decade [1–3]. These novel TMDs are required to describe nucleon's structure functions when quarks possess non-zero transverse momentum, $\vec{k}_T$, with respect to nucleon's momentum. Among the various TMDs, the Sivers functions [4] and the Boer-Mulders (BM) functions [5] are time-reversal-odd objects and have attracted much attention both theoretically and experimentally.

The Sivers functions represent a correlation between quark's $\vec{k}_T$ and the nucleon's transverse spin [4], while the BM functions signify a correlation between quark's $\vec{k}_T$ and quark's transverse spin in an unpolarized hadron [5]. Although the very existence of these time-reversal-odd TMDs was in question at one time [6], it was later shown that these functions can arise from initial- or final-state interactions [7]. Such interactions are incorporated in a natural fashion by the gauge link that is required for a gauge-invariant definition of the TMDs [8, 9]. Measurements of the semi-inclusive deep-inelastic scattering (SIDIS) at HERMES [10], COMPASS [11–13] and JLab [14] using transversely polarized targets have shown clear evidence for the presence of the T-odd Sivers functions. These data also allow the extraction [15, 16] of the magnitude and flavor structure of the Sivers functions.

The gauge-link operator leads to a remarkable prediction [8] that the T-odd Sivers and BM functions are process dependent, namely, they must have opposite signs depending on whether they are involved in the space-like SIDIS or the time-like Drell-Yan process. An experimental verification of the sign-reversal prediction of the Sivers and BM functions would provide an important test of QCD at the confinement scale, and represents a significant step towards understanding the properties of these novel TMDs. For a recent review of the Drell-Yan process, see *e.g.* Ref. [17].

Several Drell-Yan experiments have been proposed to test the predicted sign-reversal of the Sivers functions. The COMPASS-II experiment [18], for example, will measure $\pi^- + p$ Drell-Yan utilizing a transversely polarized target. At RHIC, the transversely polarized proton beams allow measurements of single-spin asymmetries in $p + p$ Drell-Yan [19] and W-boson production. First result on the single-spin asymmetry of W production at RHIC energy was recently reported by the STAR Collaboration [20]. Two fixed-target Drell-Yan proposals at Fermilab plan to utilize either a transversely polarized proton beam [21] or a transversely polarized target [22]. The antiproton beam at the FAIR facility offers the unique opportunity to measure $\bar{p} + p$ Drell-Yan reaction [23]. Theoretical calculations have been carried out [16, 24, 25] to assess the feasibility of these experiments to test the predicted sign-reversal of the Sivers functions. The above paragraph needs to be updated, since the published COMPASS result and the preliminary results from COMPASS and STAR, shown in the DIS Conferences, should be mentioned.

While the prospect for checking the sign-reversal of the Sivers functions has been discussed extensively in the literature, very little attention has been paid to the possibility for testing the sign-reversal for the BM functions thus far. This is probably due to the fact that the BM functions are just starting to be extracted from existing SIDIS data. Nevertheless, we note that there already exists some information on the characteristics of the BM functions from the unpolarized Drell-Yan experiment. In fact, BM functions are the first TMD functions measured in the Drell-Yan experiments. Therefore, it is important to understand whether or not the existing SIDIS and Drell-Yan data on the BM functions could already test the predicted sign-reversal of the BM functions. In this paper we will show that the existing data neither rule out nor confirm the predicted sign-reversal of the BM functions. We will also identify some future measurements which can provide sensitive tests for the predicted sign-reversal of the BM functions. the above two sentences need to be modified according to what we find in the analysis of the COMPASS result.

We first discuss the theoretical expectations on the signs and quark-flavor dependence of the BM functions for nucleons and pions. We then examine the current status on the determination of the sign and magnitude of the BM functions from SIDIS and Drell-Yan experiments. The prospects for future experiments to test the sign-reversal of the BM functions will then be presented.

Before addressing the issue of sign-reversal of the BM functions, it is useful to review some general features regarding the signs of the BM functions. Unlike the parton density distributions which are positive-definite, the TMDs can have positive or negative signs. Using the sign convention in Ref. [26] for the TMDs, the Sivers functions for the u and d quarks were predicted in many theoretical models to have opposite signs, namely, negative for u and positive for d, in qualitative agreement with the results obtained in SIDIS [10, 12, 13]. Need to check whether these signs are for the u and d, or for the valence u and valence d. Similarly, one need to check if Table I is for u_N^{Val}, d_N^{Val}, or for u_N and d_N. For the nucleon's BM functions, calculations using the bag model [27], the quark-spectator-diquark model [28], the large-N_c model [29], the relativistic constituent quark model [30], as well as lattice QCD [31], all predict negative signs for both the u and d valence quarks in SIDIS.

The Sivers functions, signifying the correlation between hadron's spin and quark's $\vec{k}_T$, do not exist for spin-zero hadrons such as pions and kaons. The BM functions, On the other hand, can exist for pions, since they do not depend on hadron's spin. Calculations for pion's valence-quark BM functions using the quark-spectator-antiquark model [32] and the light-front constituent approach [33] both predict a negative sign, just like the u and d valence-quark BM functions of the nucleons. Using the bag model, the valence BM functions for mesons and nucleons were predicted [34] to have similar magnitude with the same signs. Since the nucleon's valence-quark BM functions are predicted to be negative, this implies that pion's valence-quark BM functions are also negative. This prediction of a universal behavior of the BM functions for pions and nucleons awaits experimental confirmation.

For nucleon's antiquark BM functions there exists only one model calculation so far. It was pointed out [35] that nucleon's meson cloud could contribute to its sea-quark BM functions. The meson cloud as an important source for sea quarks in the nucleons was evidenced by the large $\bar{d}/\bar{u}$ flavor asymmetry observed in DIS and Drell-Yan experiments [36]. A significant fraction of nucleon's antiquark sea at the $x > 0.15$ region comes from the meson cloud. This suggests that pion cloud can contribute to nucleon's antiquark BM functions [35]. The implication is that nucleon's antiquark BM functions would have negative signs, just like the pion's valence-quark BM functions.

TABLE I: Theoretical predictions for the signs of various BM functions for nucleons (N) and pions (π) in SIDIS and Drell-Yan. V_π signifies the valence quarks in the pions. The parenthesis for V_π in SIDIS is a reminder that it could not be measured in practice.

	u_N	d_N	V_π	$\bar{u}_N$	$\bar{d}_N$
SIDIS	$-$	$-$	$(-)$	$-$	$-$
Drell-Yan	$+$	$+$	$+$	$+$	$+$

Table I summarizes the theoretical expectations for the signs of the BM functions. First, the u and d BM functions of the nucleons have negative signs. Second, the valence BM functions in the pions have the same signs as those of the nucleons, namely, negative. Third, the antiquark BM functions in the nucleons are also negative, based on the meson-cloud model. Finally, the signs of these BM functions will reverse and become positive for the Drell-Yan process. In the remainder of this note, we compare these predictions with analysis of existing data. We then identify future experiments which are capable of testing these predictions.

The BM functions can be extracted from the azimuthal angular distribution of charged pions produced in unpolarized SIDIS [5]. At leading twist, the $\cos 2\phi$ term is proportional to the product of the nucleon's BM functions $h_1^\perp$ and the Collins fragmentation functions $H_1^\perp$ for quarks hadronizing into charged pions. The angle ϕ refers to the azimuthal angle of the produced pion in the lepton scattering plane. At the low p_T region, the $\langle \cos 2\phi \rangle$ moment has been measured by the HERMES [37, 38] and COMPASS [39–41] collaborations. An analysis of these $\langle \cos 2\phi \rangle$ data for pion SIDIS was performed [42] by assuming the functional form for the BM functions as

$$h_1^{\perp q}(x, k_T^2) = \lambda_q f_{1T}^{\perp q}(x, k_T^2), \quad (1)$$

where q refers to the quark flavor and $h_1^{\perp q}$ and $f_{1T}^{\perp q}$ are the BM and Sivers functions, respectively. Equation 1 assumes the same x and k_T^2 dependences for the BM and Sivers functions with the sign and magnitude of the proportionality factor λ_q determined from the data. The Sivers functions determined from a fit [15] to the polarized SIDIS data together with the Collins functions from Ref. [43] were used. The analysis yielded the best-fit values of $\lambda_u = 2.0$ and $\lambda_d = -1.1$. Since the Sivers functions for $u(d)$ is negative (positive), these best-fit values imply that BM functions $h_1^{\perp u}$ and $h_1^{\perp d}$ are both negative in agreement with the theoretical expectation shown in Table I.

It should be cautioned that the signs of the Collins fragmentation functions are not determined experimentally, since only the product of two Collins fragmenation functions are measured in the e^+e^- experiments at Belle [44] and Babar. The signs of the Collins fragmentation functions were determined in Ref. [43] such that the extracted u and d quark transversity distributions have the same signs as the corresponding u and d helicity distributions (namely, positive for u quark and negative for d quark transversity distributions). This procedure for determining the signs of the Collins fragmentation functions appears entirely reasonable, and it is re-assuring that the signs of the extracted u and d BM functions are in agreement with theoretical expectation.

The SIDIS data are not yet able to constrain the antiquark BM functions, whose contributions are expected to be overshadowed by their quark counterparts. In the analysis of Ref. [42], the antiquark BM functions were assumed to be equal in magnitude to the corresponding Sivers functions with a negative sign, namely,

$$h_1^{\perp\bar{q}}(x, k_T^2) = -|f_{1T}^{\perp\bar{q}}(x, k_T^2)|. \quad (2)$$

This ad-hoc assumption would add to the systematic uncertainty for the analysis of Ref. [42]. Nevertheless, the results on the extracted BM functions for the valence quarks are expected to be largely insensitive to this assumption.

The HERMES collaboration has reported [38] results on the azimuthal $\cos 2\phi$ modulations for $\pi^\pm$, $K^\pm$, and unidentified hadrons in unpolarized $e+p$ and $e+d$ SIDIS. The $K^\pm$ and unidentified hadron data were not included in the earlier work [42] to extract nucleon BM functions. These new Hermes data could lead to a more precise extraction of the valence BM functions. In addition, these data are sensitive to the sea-quark BM functions. In particular, the $\cos 2\phi$ moments for K^- production are observed to be large and negative [38]. Since the valence quark content of K^-, $s\bar{u}$, is distinct from that of target nucleons, the large negative K^- $\cos 2\phi$ moments suggest sizable sea-quark BM functions. An extension of the global fit in Ref. [42] to include the new $K^\pm$ data would be very valuable and could allow the extraction of the sea-quark BM functions in SIDIS. Check if a new global fit including the kaon SIDIS data has been performed.

In order to test the prediction of sign-reversal from SIDIS to Drell-Yan for the BM functions, we turn next to the extraction of the BM functions from the Drell-Yan experiment. The BM functions can be extracted [45] from the Drell-Yan process using either unpolarized or singly polarized hadron-hadron collision. Up to now, only data from unpolarized Drell-Yan experiments are available. The general expression for the unpolarized Drell-Yan angular distribution is [46]

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2}\sin^2\theta \cos 2\phi, \quad (3)$$

where θ and ϕ are the polar and azimuthal decay angle of the l^+ in the dilepton rest frame. Boer showed [45] that the $\cos 2\phi$ term is proportional to the convolution of the quark and antiquark BM functions in the projectile and target, namely,

$$\langle\cos(2\phi)\rangle \sim \sum_{q,\bar{q}} [h_1^{\perp q}(x_1) h_1^{\perp\bar{q}}(x_2) + h_1^{\perp\bar{q}}(x_1) h_1^{\perp q}(x_2)], \quad (4)$$

where x_1, x_2 refer to the Bjorken-x of the projectile and target hadrons, respectively, and the sum is over the various quark flavors. The BM functions for the quark and antiquark are denoted as $h_1^{\perp q}$ and $h_1^{\perp\bar{q}}$.

Pronounced $\cos 2\phi$ dependencies were observed in the NA10 [47, 48] and E615 [49] pion-induced Drell-Yan experiments. The coefficient ν for the $\cos 2\phi$ term in Eq. 3 was found to be positive with the mean value $\langle\nu\rangle = 0.091 \pm 0.009$ at 194 GeV/c and $\langle\nu\rangle = 0.169 \pm 0.019$ at 252 GeV/c over the $0 < p_T < 3$ GeV/c range. It is important to note that ν was found to be positive in all pion-induced Drell-Yan experiments. Together with Eq. 4 and the dominance of $u - \bar{u}$ annihilation in the π^--nucleon Drell-Yan process, the positive sign of ν implies two possibilities – either the signs of pion's and nucleon's valence BM functions are both positive, or the signs are both negative. Table I shows that the prediction of positive signs for the valence-quark BM functions of pion and nucleon is consistent with the observed positive sign of ν. However, the data are also consistent with the scenario of no sign-change, in which negative signs for both the pion and nucleon valence BM functions are expected in the Drell-Yan process. As discussed later, additional data are required distinguish these two possibilities.

The $\cos 2\phi$ dependencies were also measured in the $p+p$ and $p+d$ unpolarized Drell-Yan experiment [51, 52]. The magnitude of ν was found to be significantly smaller than that observed in the pion Drell-Yan experiment. Since proton-induced Drell-Yan involves both the valence and the sea quarks in the beam and target hadrons, the value of ν now involves the convolution of valence-quark BM function in the pion and the sea-quark BM function in the nucleon. The small values for ν reflect the subdominance of sea-quark BM functions and is consistent with theoretical expectation [35]. The signs of ν for both $p+p$ and $p+d$ Drell-Yan are found to be positive [51, 52]. From Eq. 4, the positive sign for ν suggests that nucleon's sea-quark BM function has the same sign as the valence-quark BM function. This is consistent with the prediction shown in Table I. However, the data could not determine whether the signs are both positive or both negative.

The current status regarding the signs of the BM functions deduced from SIDIS and Drell-Yan experiments is summarized in Table II. Table II needs to be generated. A comparison between the predictions listed in Table I and the experimental status presented in Table II shows that the data are consistent with theoretical expectations with no disagreement found. Unfortunately, the inability for the unpolarized Drell-Yan data on ν alone to distinguish the two possible solutions on the signs of the nucleon BM functions prevent the extraction of the signs of the BM functions in Drell-Yan. In order to test the sign-change prediction for the BM functions, the key measurements would involve singly polarized Drell-Yan where a nucleon is transversely polarized, as discussed next.

We first consider the case of pion-induced Drell-Yan reaction on a transversely polarized proton target. Such a measurement is currently being pursued by the COMPASS experiment at CERN. The primary goal of this experiment is to test the sign-change of the Sivers function. At the leading-twist, the Drell-Yan cross section for pion interacting with a transversely polarized proton target can be written as [53, 54]

$$\begin{aligned}\frac{d\sigma}{dq^4 d\Omega} &\propto 1 + S_T\left[D_1 A_T^{\sin\phi_S}\sin\phi_S\right]\\ &+ S_T\left[D_2 A_T^{\sin(2\phi-\phi_S)}\sin(2\phi-\phi_S)\right]\\ &+ S_T\left[D_2 A_T^{\sin(2\phi+\phi_S)}\sin(2\phi+\phi_S)\right], \qquad (5)\end{aligned}$$

where S_T is the transverse spin of the nucleon with respect to the hadron plane. The hadron plane is formed by the momentum vectors of the beam and target hadrons, which are non-collinear in the dilepton rest frame. The Collins-Soper frame, in which the z-axis bisects the beam and target momentum vectors, is usually chosen as the reference frame. The azimuthal angles ϕ_S and ϕ refer to the target spin direction and the charged lepton direction, respectively. The amplitudes of various azimuthal angular modulations are denoted as $A_T^{m(\phi_S,\phi)}$ with $m(\phi_S,\phi)$ specifying the form of the azimuthal angular modulation. D_1 and D_2 are the depolarization factors, and ϕ_S is the azimuthal angle of the target polarization vector.

Equation 5 shows that three amplitudes, $A_T^{\sin\phi_S}$, $A_T^{\sin(2\phi-\phi_S)}$, and $A_T^{\sin(2\phi+\phi_S)}$, depend on the transverse spin direction of the polarized target nucleon. The first amplitude, $A_T^{\sin\phi_S}$, is a convolution of the nucleon Sivers function and the pion unpolarized distribution. Since pion's unpolarzied parton distributions are positive-definite, the sign of $A_T^{\sin\phi_S}$ directly reflects the sign of the nucleon Sivers function, allowing a test of the sign-change prediction for nucleon Sivers functions.

The other two amplitudes in Eq. 5, $A_T^{\sin(2\phi-\phi_S)}$ and $A_T^{\sin(2\phi+\phi_S)}$, are related to the convolution of the pion Boer-Mulders function and nucleon's transversity (h_1) and pretzelosity ($h_{1T}^{\perp}$) distributions, respectively. For π^--induced Drell-Yan process on transversely polarized proton target, such as in the COMPASS-II experiment, u-quark dominance implies that $A_T^{\sin(2\phi-\phi_S)}$ is proportional to the product of pion's $\bar{u}$ valence-quark BM function and proton's u-quark transversity distribution. Since the sign of proton's u-quark transversity distribution is found to be positive [55], a measurement of the sign of $A_T^{\sin(2\phi-\phi_S)}$ in polarized π^-p Drell-Yan would determine the sign of pion's valence-quark BM function. As shown in Table II, pion's valence quark BM function has the same sign as proton's u valence quark BM function in the Drell-Yan process. Therefore, once the sign of pion's valence-quark BM function is known, the sign of proton's u-quark BM function in the Drell-Yan process can be determined. More specifically, if $A_T^{\sin(2\phi-\phi_S)}$ in polarized π^-p Drell-Yan is found to be positive, then the sign of proton's u-quark BM function in the Drell-Yan process will be positive and the predicted sign-change of BM function will be confirmed. In contrast, a negative $A_T^{\sin(2\phi-\phi_S)}$ would cast doubt on the sign-change prediction. It is very interesting that the COMPASS paper, PRL 119 (2017) 112002, already showed that the sign for this $A_T^{\sin(2\phi-\phi_S)}$ is negative. (See figure 5 of this paper). However, the coordinate system used by COMPASS is opposite to the usual convention (as adopted by the STAR), namely, the z-axis is along the unpolarized pion beam direction, rather than the direction of the polarizied target nucleon (in the CM frame). Therefore, the negative sign reported by the COMPASS actually corresponds to a postitive sign in the usual convention. Hence, we can conclude that the preliminary results from COMPASS supports the expectation that the BM function indeed changes sign in the DY process. This would be a very important conclusion of this paper!

We mention in passing that the amplitude $A_T^{\sin(2\phi+\phi_S)}$ in Eq. 5, though interesting, would not lead to a determination of pion's BM function, since nucleon's prezelocity distribution is yet unknown.

We could also mention briefly how one could check the sign-change of the pion's BM function. One could use the Sullivan process to perform SIDIS on the virtual pion target at the EIC. This would determine the sign of the pion's BM function from DIS, and the sign of the pion BM function in DY can be obtained from the pion-induced DY at COMPASS.

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