Transverse Spin Effects in Future Drell-Yan Experiments

Jen-Chieh Peng[1,a]

[1] *Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*

Abstract. We review the current status and future prospect for probing the transverse momentum dependent (TMD) parton distributions using the Drell-Yan process. We focus on the Boer-Mulders and Sivers functions, which are expected to undergo a sign-change from semi-inclusive deep-inelastic scattering (SIDIS) to Drell-Yan process. The constraints of existing Drell-Yan and SIDIS experiments on the signs of these functions are discussed. Future Drell-Yan measurements for the TMDs are also presented.

1 Introduction

In this article, we review the current status and future prospect for studying the transverse momentum dependent (TMD) parton distributions in the nucleons using the Drell-Yan process. There has been intense theoretical and experimental effort in recent decades to investigate these novel parton distributions. There are many reasons for exploring the transverse structures of the nucleons. For many years after the discovery of scaling in DIS and partonic structures in the nucleons, only the longitudinal momentum distributions of the partons were investigated. The transverse degrees of freedom of the partons, accessed through the TMDs, are expected to provide new insights on the nucleon structure. The characteristics of the TMDs can also provide stringent tests for various nucleon models. Moreover, the progress in lattice QCD also allows direct comparison between the lattice calculations and experiments.

The novel TMDs are accessible by experiments using either lepton or hadron beams. The bulk of the experimental information on TMDs has been obtained thus far from the semi-inclusive DIS (SIDIS) carried out at DESY (HERMES), CERN (COMPASS), and the Jefferson Lab. A promising experimental tool to access the TMDs is the Drell-Yan process [1]. Proposed in 1970 to explain the underlying mechanism for producing massive lepton pairs in high-energy hadron-hadron collisions, the Drell-Yan process involves quark-antiquark annihilating into a virtual photon via electromagnetic interaction. According to Yan [2], "The process has been so well understood theoretically that it has become a powerful tool for precision measurements and new physics". Indeed, the Drell-Yan process has provided unique information on the antiquark distributions in nucleons and nuclei, as well as the parton distributions of mesons and antiproton. Figure 1 shows the proton-induced Drell-Yan cross sections measured at different beam energies and NLO calculations [3]. The
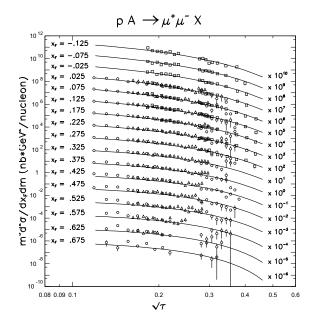

Figure 1. Next-to-leading order Drell-Yan calculations compared to dimuon data taken at various beam energies. From [3].

Drell-Yan data taken at different energies fall on smooth curves corresponding to the NLO calculations. This is reminescent of the good agreement between DIS data and NLO calculations. The well understood mechanism of the Drell-Yan process provides a solid theoretical foundation for extracting novel parton distributions, like the TMDs, using this reaction.

To access the TMDs in the Drell-Yan process would usually require transversely polarized beam and/or target. Such transversely polarized Drell-Yan experiments have never been performed yet, and are being pursued in many hadron facilities. These polarized Drell-Yan experiments could indeed provide qualitatively new information on hadron physics.

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[a]e-mail: jcpeng@illinois.edu

In the following, we first discuss the unique features of the Drell-Yan process in probing the TMDs. We then discuss the status and outstanding issues in TMDs which could be addressed with future Drell-Yan experiments. We conclude with a discussion on the status and prospect for measuring the signs of the Sivers and Boer-Mulders functions in the Drell-Yan process.

2 TMDs and the Drell-Yan Process

Comprehensive discussions on the theoretical and experimental aspects of TMDs can be found in several review articles [4–6]. In this paper, we focus on three TMDs, the transversity distributions, the Boer-Mulders functions [7], and the Sivers functions [8]. There are three transverse quantities for nucleons and quarks, namely, the nucleon's transverse spin ($\vec{S}_\perp^N$), the quark's transverse spin ($\vec{s}_\perp^q$), and quark's transverse momentum ($\vec{k}_\perp^q$). From these three quantities, one could form three different correlations. The correlation between the quark's transverse spin and nucleon's transverse spin is the transversity distribution. The correlation between quark's transverse momentum and nucleon's transverse spin leads to the Sivers function. Finally, the Boer-Mulders function corresponds to the correlation between quark's transverse spin and its transverse momentum. Although there are other TMDs, most of the recent progress in TMD centered on these three distributions. In this paper, we focus our discussion on these distributions.

The TMDs can be accessed via semi-inclusive DIS via measurements using unpolarized beam and target, polarized target, or polarized beam and polarized target. In leading twist formulation, the different TMDs can be identified through their distinct azimuthal angular distributions. For example, the Boer-Mulders function would give a $\cos 2\phi_h$ azimuthal distribution in unpolarized SIDIS, where ϕ_h is the hadron azimuthal angle relative to the lepton scattering plane. The transversity and Sivers function would yield a $\sin(\phi_h + \phi_s)$ and $\sin(\phi_h - \phi_s)$ angular dependence, respectively, in SIDIS with a transversely polarized target (ϕ_s refers to the azimuthal angle of target spin direction relative to the lepton scattering plane). An impressive progress has been made in the last decade to extract the TMDs in several extensive SIDIS experimental programs, reviewed in Ref. [5, 6].

TMDs can also be accessed via Drell-Yan experiments in unpolarized hadron-hadron collision, singly polarized hadron-hadron collision, or doubly polarized hadron-hadron collision. The earliest discussion of probing TMDs via the Drell-Yan process was by Ralston and Soper [9], who pointed out that the chiral-odd transversity distribution can be measured in doubly transversely polarized p-p Drell-Yan process. Detailed discussions on how various TMDs can be measured in polarized and unpolarized Drell-Yan, including the W/Z boson production which can be considered as generalized Drell-Yan where the photon is replace by W/Z, have been discussed in the literature [10, 11]. Following the demonstration that TMDs can be measured via the SIDIS experiments, it is important to address the question "what can the Drell-Yan experiments offer in probing and understanding the TMDs?". It turns out that the Drell-Yan experiments can provide many unique information on TMDs complementary to what the SIDIS can offer.

First, the Drell-Yan cross section involves the convolution of two parton distributions (one or both of which can be a TMD), while the SIDIS cross section is a convolution of a parton distribution and a fragmentation function. The absence of the fragmentation process in the Drell-Yan implies that no information on the often poorly known fragmentation functions is required to extract the TMDs. This important feature of the Drell-Yan process allows a truly independent measurement of TMDs and provide a very significant check of the results obtained from SIDIS. Second, the TMDs of mesons and antiprotons can not be accessed by SIDIS since they are not available as targets. Fortunately, they can be accessed via the Drell-Yan process since meson and antiproton beams are available. This also applies to hyperons, although no hyperon beams are currently available anywhere. Third, as demonstrated in existing Drell-Yan experiments, the proton-induced Drell-Yan process is sensitive to the antiquark distributions in the nucleons. While the effects of the nucleon's antiquark TMDs are usually overshadowed by those of the valence quark's TMDs in SIDIS, the antiquark's TMDs of the nucleons could be sensitively probed in the Drell-Yan process. Finally, the celebrated prediction that the time-reversal-odd TMDs, namely, the Sivers and the Boer-Mulders functions, must undergo a sign reversal between the space-like SIDIS and the time-like Drell-Yan reactions awaits experimental confirmation. This has become a major physics goal of several proposed polarized Drell-Yan experiments.

3 Status and Outstanding Issues in TMDs

3.1 Transversity

The transversity distribution, described in the quark-parton model as the net transverse polarization of quarks in a transversely polarized nucleon, can be measured in SIDIS using transversely polarized targets. The azimuthal angular modulation in $\sin(\phi_h + \phi_s)$ is proportional to $h_1 \otimes H_1^\perp$, which is the convolution of transversity and the Collins fragmentation function. An important ingredient for extracting the transversity distribution is the measurement of a sizable Collins fragmentation function at Belle [12]. Recent SIDIS experiments using transversely polarized targets have been carried out at HERMES [13, 14], COMPASS [15, 16], and JLab [17, 18].

A recent global analysis of the SIDIS and Collins fragmentation function data has led to the extraction of the transversity distributions of u and d quarks [19]. This global analysis assumes the sea-quark transversity to be zero, and it shows that $u(d)$ valence quark transversity distributions are positive (negative), in agreement with their corresponding helicity distributions. However, the magnitudes of the transversity distributions are significantly smaller than the corresponding helicity distributions. The
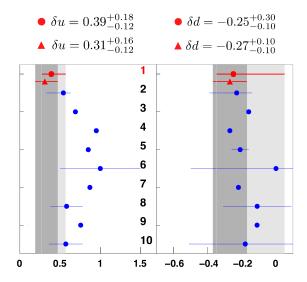
● $\delta u = 0.39^{+0.18}_{-0.12}$ ● $\delta d = -0.25^{+0.30}_{-0.10}$

▲ $\delta u = 0.31^{+0.16}_{-0.12}$ ▲ $\delta d = -0.27^{+0.10}_{-0.10}$

Figure 2. Tensor charges δu and δd obtained from the fits to the semi-inclusive DIS data at $Q^2 = 2.4$ GeV^2 in comparison with various calculations. From [19].

tensor charges δu and δd, defined as $\delta q \equiv \int_0^1 [\delta q(x) - \delta \bar{q}(x)] dx$, have also been determined from this analysis, as shown in Fig. 2. The central values of the tensor charges are $\delta u = 0.31$ and $\delta d = -0.27$, significantly smaller in absolute magnitude than the axial charges, $\Delta u = 0.787$ and $\Delta d = -0.319$. As shown in Fig. 2, the extracted value of δu is significantly smaller than the predictions of various models and lattice calculations [19].

Since sea quark transversity is neglected in the recent extraction of transversity distributions [19], it could introduce systematic uncertainties in the determination of the tensor charges δu and δd. It is interesting to examine the theoretical predictions on the sign and magnitude of the sea-quark transversity. In the non-relativistic limit, one expects the same sea-quark transversity and helicity distributions. Model predictions, however, do not necessarily follow this non-relativistic expectation. In the large N_c limit [20], the chiral-quark soliton model predicts [21] that $\delta \bar{u}(x) - \delta \bar{d}(x) < 0$, which is opposite to the case of helicity distribution, $\Delta \bar{u}(x) - \Delta \bar{d}(x) > 0$. A qualitatively different prediction of $\delta \bar{u}(x) - \delta \bar{d}(x) > 0$ is obtained in a statistical model [22]. Very recently, an interesting new approach to calculate the x dependence of the isovector $\delta \bar{u}(x) - \delta \bar{d}(x)$ in lattice QCD indicated large negative values [23]. It would certainly be very interesting to measure $\delta \bar{u}(x)$ and $\delta \bar{d}(x)$ to test the predictions of these models.

It is clear that remarkable progress has been made in measuring the illusive chiral-odd transversity distributions via SIDIS. Some remaining challenges to be addressed by future experiments include

• Independent measurements of the transversity distributions. There exist other reactions involving two chiral-odd functions which are sensitive to the transversity distributions. First results [24, 25] on dihadron SIDIS using the corresponding interference fragmentation functions determined at Belle [26] are becoming available. The extracted transversity distributions [27] are consis-

tent with those extracted in single-hadron SIDIS [19]. Additional dihadron SIDIS data are expected using the SoLID detector at the 12 GeV JLab. The proposal to measure Drell-Yan with polarized antiproton beam colliding with polarized proton at FAIR [28] would clearly provide a much anticipated measurement of transversity entirely free of the uncertainty of fragmentation functions.

• Magnitude and sign of the sea-quark transversity distribution. As discussed above, some theoretical models and the recent lattice calculation suggest sizable sea-quark transversity. A recent SIDIS measurement [18] at JLab shows a large negative $\sin(\phi_h + \phi_s)$ amplitude for K^- production on a transversely polarized ^{3}He target, suggesting a large sea-quark transversity. Future high-statistics SIDIS experiments at the 12 GeV JLab upgrade, as well as doubly polarized Drell-Yan experiments in pp collision, uniquely sensitive to the antiquark transversity distribution in the proton, are required to pin down the role of sea quarks in transversity distributions.

• Q^2 evolution of the transversity distributions. The absence of the gluon transversity distribution implies a slower Q^2-evolution for the quark transversity distributions. This expectation remains to be tested. The challenge in the SIDIS, however, is to disentangle the Q^2-evolution effect of the Collins fragmentation function. A more definitive measurement would require the Drell-Yan process, which only involves the convolution of two transversity distributions.

3.2 Sivers Functions

It was suggested by Sivers that single-spin asymmetries in various processes can originate from the correlations between the transverse momentum of the quark and proton's transverse spin, called the Sivers function [8]. As a time-reversal odd object, the Sivers function requires initial- or final-state interactions via a soft gluon. Such interactions are incorporated in a natural fashion by the gauge link needed for a gauge-invariant definition of the TMD [29–31]. The Sivers function is related to the forward scattering amplitude in which the helicity of the nucleon is flipped. This helicity flip must involve the orbital angular momentum of unpolarized quark. In this respect, the Sivers function is connected to the angular momentum of the quark. An unambiguos measurement of Sivers function is valuable for understanding the nature of the TMDs and the spin content of the nucleons.

Measurements of the $\sin(\phi_h - \phi_s)$ Sivers moment in polarized SIDIS with transversely polarized targets have been performed by HERMES [32], COMPASS [33, 34], and the JLab Hall-A [17] collaborations. The quark and antiquark Sivers functions were extracted in recent global fits to the data [35, 36]. The analysis confirms the theoretical expectations for the signs of the u and d Sivers functions. Non-zero $\bar{d}$ sea-quark Sivers function is also obtained in order to explain the large Sivers moment observed for K^+. In the meson-cloud model, the pseudoscalar meson is in a p state. Since meson contains valence

antiquarks, it is reasonable to expect that antiquarks carry non-zero orbital angular momentum. Using chiral-quark solition model, it was shown that $\bar{u}$ and $\bar{d}$ have significant contributions to the orbital angular momentum component of the proton's spin [37]. Moreover, a recent lattice QCD calculation [38] found a significant fraction of proton's spin comes from the orbital angular momentum of $\bar{u}$ and $\bar{d}$ quarks. These results suggest that the Sivers functions for sea quarks can be sizable and measurable. Future polarized SIDIS experiments at JLab and EIC are expected to provide definitive measurements on the characteristics of the sea-quark Sivers functions.

Unlike collinear parton distribution functions (PDFs), the TMDs are not necessarily universal and could depend on the process they are extracted from. Fortunately, the process-dependence of TMDs is limited to a possible sign-change, due to the invariance of QCD under parity and time-reversal [30]. The TMD, $f_{q/p\uparrow}(x, k_\perp, \vec{S})$, for finding an unpolarized quark inside a transversely polarized proton extracted from SIDIS and Drell-Yan proces satisfies [30, 39]

$$f_{q/p\uparrow}^{SIDIS}(x, k_\perp, \vec{S}) = f_{q/p\uparrow}^{DY}(x, k_\perp, -\vec{S}). \tag{1}$$

The Sivers function, $f_{1T}^\perp(x, k_\perp)$, is proportional to $[f_{q/p\uparrow}(x, k_\perp, \vec{S}) - f_{q/p\uparrow}(x, k_\perp, -\vec{S})]/2$. Therefore, Eq. 1 implies that the Sivers function changes sign from SIDIS to Drell-Yan

$$f_{1T}^{\perp \, SIDIS}(x, k_\perp) = -f_{1T}^{\perp \, DY}(x, k_\perp) \tag{2}$$

This sign-change prediction, which is a consequence of factorization of TMD in QCD, has generated tremendous interest to test it experimentally. Since the signs of valence quark Sivers function have already been determined from SIDIS, the test only requires measurements of valence-quark Sivers functions in singly polarized Drell-Yan experiments utilizing transversely polarized proton beam or target. As discussed by Chiosso in this Workshop [40], a dedicated Drell-Yan experiment at COMPASS using 190 GeV pion beam on transversely polarized target is scheduled to take data in 2015 [41]. Teryaev also presented the plan to measure polarized Drell-Yan at NICA [42]. Other polarized Drell-Yan experiments, proposed at existing or future hadron facilities, include RHIC at BNL [43], PAX [28] and PANDA [44] at FAIR, J-PARC [45], E1027 [46] and E1039 [47] at Fermilab. While it is highly anticipated that the first result on this test would be obtained at COMPASS [40], it is essential to perform experiments using different hadron beams (pion, proton, antiproton) covering different kinematic regions in x and Q^2.

3.3 Boer-Mulders Functions

The Boer-Mulders function [7], $h_1^\perp(x, k_\perp)$, is another example of a time-reversal odd TMD. It represents the correlation between $\vec{k}_\perp$ and the quark transverse spin, $\vec{s}_\perp$, in an unpolarized nucleon. Similar to the Sivers function, the Boer-Mulders function also owes its existence to the presence of initial/final state interactions.

The flavor and x dependencies of the Boer-Mulders functions have been calculated in various models. In the quark-diquark model taking into account both the scalar and axial-vector diquark configurations, significant differences in the flavor dependence are found between the Sivers and Boer-Mulders functions [48]. In particular, while the Sivers function is negative for the u and positive for the d valence quarks, the u and d valence quark Boer-Mulders functions are predicted to be both negative. Other model calculations using the large-N_c model [49], the MIT bag model [50], the relativistic constituent quark model [51], as well as lattice QCD [52], all predict the u and d valence Boer-Mulders functions to be negative.

While the Sivers functions do not exist for spin-zero hadrons, the Boer-Mulders functions can exist for pions. Calculations for pion's valence-quark Boer-Mulders functions using the quark-spectator-antiquark model predict a negative sign [53], just like the u and d Boer-Mulders functions for nucleons. Using the bag model, the valence Boer-Mulders functions for nucleons and mesons were predicted [54] to have same signs with similar magnitude. This prediction of a universal behavior of the valence-quark Boer-Mulders functions for pions and nucleons also awaits experimental confirmation.

For nucleon's antiquark Boer-Mulders functions there exists one calculation using the meson cloud model [55]. Since the meson cloud is an important source for sea quarks in the nucleons, as evidenced by the large $\bar{d}/\bar{u}$ flavor asymmetry observed in DIS and Drell-Yan experiments (for a recent review see [56]), the valence Boer-Mulders functions in the pion cloud can contribute to nucleon's antiquark Boer-Mulders functions [55]. An interesting prediction is that nucleon's antiquark Boer-Mulders functions would have negative signs, same as the valence Boer-Mulders functions for pion.

For a TMD with a tensor spin projection, $f_{h_{1q}/p\uparrow}(x, k_\perp, \vec{S})$, Eq. 1, which relates the TMDs measured in SIDIS and Drell-Yan, becomes [39, 57]

$$f_{h_{1q}/p\uparrow}^{SIDIS}(x, k_\perp, \vec{S}) = -f_{h_{1q}/p\uparrow}^{DY}(x, k_\perp, -\vec{S}). \tag{3}$$

The minus sign in Eq. 3 relative to Eq. 1 is due to the replacement of the vector spin projection γ^+ in the TMD $f_{q/p\uparrow}(x, k_\perp, \vec{S})$ by the tensor spin projection $\sigma^{+\perp}$ in the TMD $f_{h_{1q}/p\uparrow}(x, k_\perp, \vec{S})$. Since the Boer-Mulders function is proportional to the sum $[f_{h_{1q}/p\uparrow}(x, k_\perp, \vec{S}) + f_{h_{1q}/p\uparrow}(x, k_\perp, -\vec{S})]/2$, it follows from Eq. 3 that the Boer-Mulders function measured in Drell-Yan will have a sign opposite to that measured in SIDIS, namely,

$$h_{1q}^{\perp \, SIDIS}(x, k_\perp) = -h_{1q}^{\perp \, DY}(x, k_\perp). \tag{4}$$

Table 1 summarizes the theoretical expectations relevant to the signs of the Boer-Mulders functions. First, the u and d Boer-Mulders functions of the nucleons have negative signs. Second, the valence Boer-Mulders functions in the pions have the same signs as those of the nucleons, namely, negative. Third, the antiquark Boer-Mulders functions in the nucleons are also negative. Finally, the signs of these Boer-Mulders functions will reverse and become positive for the Drell-Yan process. We discuss next

Table 1. Theoretical predictions for the signs of various Boer-Mulders functions for nucleons (N) and pions (π) in SIDIS and Drell-Yan. V_π signifies the valence quarks in the pions. The paranthesis for V_π in SIDIS indicates that it can not be measured in practice.

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

the experimental status on extracting the Boer-Mulders functions from the SIDIS and Drell-Yan experiments, and we compare the predictions listed in Table 1 with data. We also identify future experiments which can further test these predictions.

3.3.1 Boer-Mulders functions from SIDIS

The Boer-Mulders functions can be extracted from the hadron's azimuthal angular distribution in unpolarized SIDIS. The $\cos 2\phi$ term is proportional to the product of the Boer-Mulders function $h_1^\perp$ and the Collins fragmentation function $H_1^\perp$ at leading twist, where ϕ refers to the angle between the hadron plane and the lepton plane. The $\langle \cos 2\phi \rangle$ moments have been measured by the HERMES [58, 59] and COMPASS [60, 61] collaborations. An analysis of the pion SIDIS data, taking into account the higher-twist Cahn effect [62], has been performed [63]. The functional form for the Boer-Mulders function was assumed as

$$h_1^{\perp q}(x, k_\perp^2) = \lambda_q f_{1T}^{\perp q}(x, k_\perp^2), \quad (5)$$

where $h_1^{\perp q}$ and $f_{1T}^{\perp q}$ are the Boer-Mulders and Sivers functions, respectively, for quark q. The best-fit values are found to be $\lambda_u = 2.0 \pm 0.1$ and $\lambda_d = -1.111 \pm 0.001$. Since the Sivers function for $u(d)$ is negative (positive), these values show that $h_1^{\perp u}$ and $h_1^{\perp d}$ are both negative, in agreement with the theoretical expectation listed in Table 1. It must be cautioned that the extracted signs of the Boer-Mulders functions depend on the signs of the Collins functions adopted in the analysis. Although the signs chosen for the Collins functions are based on plausible arguments, some uncertainties do exist in the determination of the signs of the Boer-Mulders functions from this analysis.

New results on the azimuthal $\cos 2\phi$ modulations for $\pi^\pm$, $K^\pm$, and unidentified hadrons in unpolarized $e + p$ and $e + d$ SIDIS were recently reported by HERMES [59]. These new HERMES data are expected to provide a more precise extraction of the valence Boer-Mulders functions. Moreover, these data are sensitive to the sea-quark Boer-Mulders functions. In particular, the $\cos 2\phi$ moments for K^- are observed to be large and negative [59]. Since the valence quark content of K^-, $s\bar{u}$, is different from those of the nucleons, the large K^- $\cos 2\phi$ moments suggest sizable sea-quark Boer-Mulders functions. An extension of the global fit in Ref. [63] to include the new HERMES data could lead to a determination of the sign and magnitude of sea-quark Boer-Mulders functions in SIDIS.

3.3.2 Boer-Mulders functions from Drell-Yan

The Boer-Mulders functions can be extracted [10] from the azimuthal angular distributions in unpolarized Drell-Yan process. The expression for the Drell-Yan angular distribution is

$$\frac{d\sigma}{d\Omega} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi, \quad (6)$$

where θ and ϕ correspond to the polar and azimuthal decay angles of the l^+ in the dilepton rest frame. Boer showed that the $\cos 2\phi$ term is proportional to the convolution of the quark and antiquark Boer-Mulders functions in the beam and target hadrons [10]. The $\cos 2\phi$ angular dependence can be qualitatively understood by noting that the Drell-Yan cross section depends on the transverse spins of the annihilating quark and antiquark. A correlation between the transverse spin and the transverse momentum of the quark, as represented by the Boer-Mulders function, would lead to a correlation between the transverse spin and transverse momentum of the dimuons, resulting in the $\cos 2\phi$ dependence.
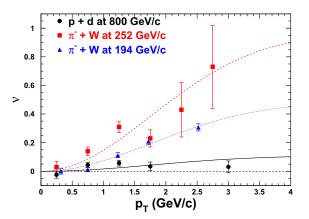

Figure 3. The $\cos 2\phi$ amplitude ν for pion- and proton-induced Drell-Yan measurements. Curves are fits to the data using an empirical parametrization discussed in Ref. [66].

Pronounced $\cos 2\phi$ dependence, observed in the NA10 [64] and E615 [65] pion-induced Drell-Yan experiments, was attributed to the Boer-Mulders function. The $\cos 2\phi$ dependence of proton-induced Drell-Yan process was also measured for the $p + d$ and $p + p$ interactions at 800 GeV/c [66, 67]. Unlike the pion-induced Drell-Yan, significantly smaller (but non-zero) $\cos 2\phi$ azimuthal angular dependence was observed in the $p + d$ and $p + p$ reactions, as shown in Fig. 3. While the pion-induced Drell-Yan cross section is dominated by a valence antiquark in the pion annihilating a valence quark in the nucleon, the proton-induced Drell-Yan process must involve a sea antiquark in the nucleon. Therefore, the $p + d$ and $p + p$ results suggest [66, 67] that proton's Boer-Mulders functions for sea quarks are smaller than those for valence quarks.

Several authors have extracted Boer-Mulders functions from the $p + p$ and $p + d$ Drell-Yan data [68–70]. The re-
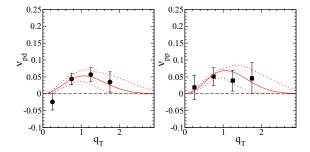
Figure 4. Fits to the $\cos 2\phi$ amplitude ν for the $p + d$ and $p + p$ Drell-Yan data [69]. The dotted lines indicate the uncertainty of the fitted parameters. q_T in unit of GeV refers to the transverse momentum of the dimuon pair.

sults obtained by Lu and Schmidt [69] are shown in Figure 4. Although the statistical precision of the data does not yet allow an accurate extraction of the Boer-Mulders functions, the analysis shows that both the $\bar{u}$ and $\bar{d}$ Boer-Mulders functions can be extracted from the Drell-Yan. Ongoing unpolarized proton- and pion-induced Drell-Yan experiments at Fermilab and COMPASS are expected to provide new information on the Boer-Mulders functions.

3.3.3 prospect for tesing the sign-reversal of Boer-Mulders functions

While the prospect for testing the sign-reversal of the Sivers functions has been discussed extensively in the literature, much less attention has been devoted to examining the possibility for checking the sign-reversal for the Boer-Mulders functions. This is possibly due to the fact that the Boer-Mulders functions are just beginning to be extracted from SIDIS data. On the other hand, while the Sivers functions have only been extracted from the SIDIS data, information on the Boer-Mulders functions has been obtained from both the SIDIS and the Drell-Yan experiments. In fact, Boer-Mulders functions are the only TMD functions ever measured in the Drell-Yan experiments so far. It is natural to ask whether these existing data have already tested the prediction that the Boer-Mulders function changes sign from SIDIS to Drell-Yan.

As shown in Table 1, theoretical models predict that the valence quark Boer-Mulders functions have negative signs in SIDIS. This prediction is consistent with the analysis of the existing SIDIS data on the $\cos 2\phi$ angular dependence, showing that both $h_{1u}^\perp$ and $h_{1d}^\perp$ in SIDIS are negative [70]. Unfortunately, SIDIS data do not yet allow the extraction of sea-quark Boer-Mulders functions, whose effects are overshadowed by the valence quarks. Nevertheless, the $\cos 2\phi$ dependence in $p + p$ and $p + d$ Drell-Yan is proportional to the convolution of the valence and sea Boer-Mulders functions, namely, $\nu \sim h_{1q}^\perp(x_1) h_{1\bar{q}}^\perp(x_2)$, allowing a direct extraction of sea-quark Boer-Mulders function in the Drell-Yan experiment. Assuming u-quark dominance, the positive values of ν shown in Fig. 4 already suggest that the Boer-Mulders functions for u and $\bar{u}$ have the same sign in Drell-Yan. The Boer-Mulders function

for u quark, determined in SIDIS to have negative sign, is expected to become positive in Drell-Yan. It follows that both the u and $\bar{u}$ Boer-Mulders functions in Drell-Yan should have positive signs. This is consistent with the results obtained by Lu and Schmidt [69] and by Barone et al. [70]. However, one can not exclude the alternative possibility that both u and $\bar{u}$ Boer-Mulders functions in Drell-Yan have negative signs. At this moment, one can only conclude that all existing SIDIS and Drell-Yan data are not in disagreement with the predictions shown in Table 1. Future SIDIS and Drell-Yan data are required to provide a definitive test on the sign-change of the Boer-Mulders functions.

3.4 Summary

The massive Drell-Yan process in hadron-hadron collisions continues to be a powerful tool for probing the partonic structure of hadrons and for understanding the dynamics of QCD in perturbative and nonperturbative regimes. The Drell-Yan process is complementary to the DIS in many aspects, and together, they provide interesting and often surprising information on the quark and antiquark contents of the nucleons.

The Drell-Yan process is also complementary to SIDIS in extracting TMDs. It is necessary to use both the Drell-Yan process and SIDIS to study TMDs, because of the non-universality of TMDs and the expected sign change. In this respect, the Sivers and Boer-Mulders functions are the most interesting TMDs to explore. The Drell-Yan production of massive lepton pairs with polarized beam and/or target provide the immediate access to these two TMDs. With several ongoing and future experiments at existing or future hadron facilities dedicated to measuring singly or doubly polarized Drell-Yan, the full potential of the Drell-Yan process in studying TMDs is just beginning to be explored.

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